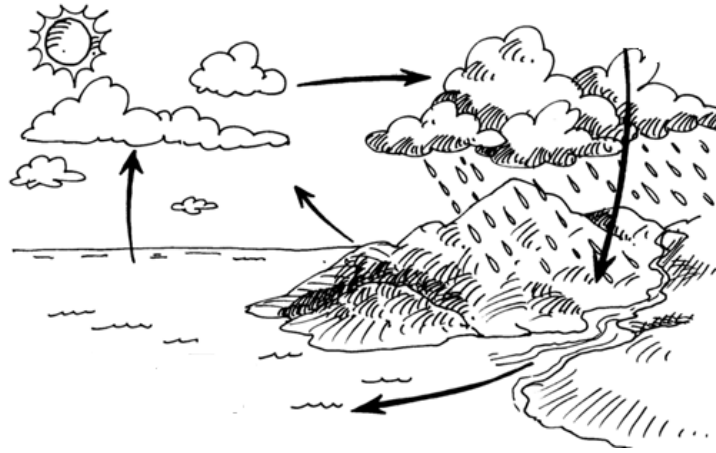


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# EVAPOTRANSPIRATION: PRINCIPLES AND APPLICATIONS FOR WATER MANAGEMENT



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Megh R Goyal, Ph.D., P.E., Editor-in-Chief  
Eric W. Harmsen, Ph.D., P.E., Coeditor

# **EVAPOTRANSPIRATION: PRINCIPLES AND APPLICATIONS FOR WATER MANAGEMENT**

by

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## List of Abbreviations and Symbols

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### *a. Abbreviations*

AAP- Apple Academic Press Inc.  
AC-FT – acre foot  
ACTMO - Agricultural Chemical Transport Model (USDA)  
ARS - Agricultural Research Service  
ASABE – American Society of Agricultural and Biological Engineers  
ASCE - American Society of Civil Engineers  
ASCS - Agriculture Stabilization & Conservation Service  
AWRA - American Water Resources Association  
AWWA - American Water Works Association  
BOR - Bureau of Reclamation  
°C - Degree Celsius  
cfs - cubic feet per second  
cfsm - cubic feet per second per square mile  
CLENS - Computing Loading Estimates from Non-point Sources  
EPA - Environmental Protection Agency  
ET - evapotranspiration  
FAO - Food and Agriculture Association  
FWS - Fish & Wildlife Service  
ICRAF - International Council for Research in Agroforestry  
IMMI - International Irrigation Management  
mgd - million gallons per day  
mg/l - milligrams per liter  
MSL - Mean Sea Level  
NAE - National Academy of Engineers  
NAS - National Academy of Sciences  
NAWDEX - National Water Data Exchange  
NBS - National Biological Survey (Dept. of the Interior)  
NCPC - National Capital Planning Commission  
NEPA - National Environmental Policy Act  
NEWS - Northeastern US Water Supply Study  
NIWR - National Institutes of Water Resources  
NOAA - National Oceanographic and Atmospheric Administration  
NPS - non-point source  
NURP - Nationwide Urban Runoff Program (EPA)  
NWSRFS - National Weather Service River Forecasting System  
pH - acidity/alkalinity measurement scale  
ppb - one part per billion  
ppm - one part per million  
ppt - one part per trillion  
SDWA - Safe Drinking Water Act  
SWCB - State Water Control Board  
SWMM - Storm Water Management Model  
µg/g - micrograms per gram  
µg/L - micrograms per liter  
USDAHL - US Department of Agriculture Hydrograph Laboratory Model  
USDA - US Department of Agriculture  
USGS - United States Geological Survey (Department of Interior)  
USNPS - US National Park Service (Department of the Interior)  
VITA - Volunteers in Technical Assistance  
WEC - World Environment Center  
WED - World Environment Day  
WDSD - Water Data Sources Directory  
WFI - World Forest Institute  
WFP - World Food Program, United Nations  
WRI - World Resources Institute  
WRSIC - Water Resources Scientific Information Center

### *b. Physical parameters*

|       |                                                         |
|-------|---------------------------------------------------------|
| $C_p$ | Specific heat capacity of air, in J/(g·°C)              |
| $e$   | Vapor pressure, in kPa                                  |
| $E$   | Evapotranspiration rate, in g/(m <sup>2</sup> ·s)       |
| $E_s$ | Saturation vapor pressure, in kPa                       |
| $ET$  | Evapotranspiration rate, in mm/year                     |
| $ETa$ | Reference ET, in the same water evaporation units as Ra |

|                |                                                                                                          |
|----------------|----------------------------------------------------------------------------------------------------------|
| $G$            | Soil heat flux at land surface, in W/m <sup>2</sup>                                                      |
| $h$            | Canopy height, in m                                                                                      |
| $H$            | Sensible heat flux, in W/m <sup>2</sup>                                                                  |
| $HBRE$         | Sensible heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method,  |
| $B$            | in W/m <sup>2</sup>                                                                                      |
| $K_o$          | Extinction coefficient of hygrometer for oxygen, in m <sup>3</sup> /(g·cm)                               |
| $KRS$          | An empirical coefficient usually estimated as 0.16 and 0.19 for inland and coastal areas, respectively   |
| $K_w$          | Extinction coefficient of hygrometer for water, in m/(g·cm)                                              |
| $P_a$          | Atmospheric pressure, in Pa                                                                              |
| $q$            | Specific humidity, g water/g moist air                                                                   |
| $R_a$          | Extraterrestrial radiation, in the same water evaporation units as ET <sub>a</sub>                       |
| $R_d$          | Gas constant for dry air, equal to 0.28704 J/oC/g                                                        |
| $R_n$          | Net radiation, in W/m <sup>2</sup>                                                                       |
| $R_s$          | Incoming solar radiation on land surface, in the same water evaporation units as ET <sub>a</sub>         |
| $S$            | Change in storage of energy in the biomass, air, and any standing water, in W/m <sup>2</sup>             |
| $T_a$          | Air temperature, in oC                                                                                   |
| $u$            | Lateral wind speed along coordinate x-direction, in m/s                                                  |
| $v$            | Lateral wind speed along coordinate y-direction, in m/s                                                  |
| $w$            | Wind speed along coordinate z-direction, in m/s                                                          |
| $x$            | One of two orthogonal coordinate directions within a plane parallel to canopy surface                    |
| $y$            | One of two orthogonal coordinate directions within a plane parallel to canopy surface                    |
| $z$            | Coordinate direction perpendicular to canopy surface                                                     |
| $z_m$          | Roughness length of canopy for momentum, in m                                                            |
| $z_s$          | Height of sensors above land surface, in m                                                               |
| $\alpha$       | Priestley-Taylor coefficient, dimensionless                                                              |
| $\gamma$       | Psychrometric constant, in kPa/oC                                                                        |
| $\Delta$       | Slope of the saturation vapor pressure curve, in kPa/oC                                                  |
| $\eta$         | Angle of rotation about the z-axis to align u into the x-direction on the x-y plane, in radians          |
| $\theta$       | Angle of rotation in the y-direction to align w along the z-direction, in radians                        |
| $\lambda$      | Latent heat of vaporization, in J/g                                                                      |
| $\lambda E$    | Latent heat flux, in W/mo                                                                                |
| $\lambda EBRE$ | Latent heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method, in |
| $B$            | W/m <sup>2</sup>                                                                                         |
| $\lambda EREB$ | Latent heat flux as estimated by the residual energy-budget variant of the                               |
|                | eddy-covariance method, in W/m <sup>2</sup>                                                              |
| $\rho$         | Air density, in g/m <sup>3</sup>                                                                         |
| $\mu$          | Ratio of molecular weight of air to molecular weight of water                                            |
| $\sigma$       | Ratio of vapor density (p <sub>v</sub> ) to air density (ρ)                                              |

## Preface

---

Due to increased agricultural production and extreme drought in some regions, irrigated land has increased in the arid and sub-humid and humid zones around the world. Agriculture has started to compete for water use with industries, municipalities and other sectors. This increasing demand along with increments in water and energy costs have made it necessary to develop new technologies for the adequate management of water. The intelligent use of water for crops requires understanding of evapotranspiration processes.

Evapotranspiration (ET) is a combination of two processes: Evaporation and transpiration. Evaporation is a physical process that involves conversion of liquid water into water vapor released into the atmosphere. Evaporation of water into the atmosphere occurs from the surface of rivers, lakes, soils and vegetation. Transpiration is a physical process that involves flow of liquid water from the soil (root zone) through the trunk, branches and surface of leaves through the stomates. An energy gradient exists between the soil water and the evaporative surface in the stomate, which causes the water movement into the root hairs and out of the leaf stomates. In the majority of green plants, stomates remain open during the day and stay closed during the night. If the soil is too dry, the stomates will remain closed during the day in order to slow down the transpiration.

Evaporation, transpiration and ET processes are important for estimating crop water requirements and for irrigation scheduling. To determine crop water requirements, it is necessary to estimate ET on-site site measurements or by using meteorological data. On-site measurements are very costly and are mostly employed to calibrate ET methods utilizing climatological data. There are a number of proposed mathematical equations that require meteorological data and are used to estimate ET for periods of one day or more. The simplest methods require only limited data, for example, average air temperature, day length and the crop. Other equations require daily radiation data, temperature, vapor pressure and wind velocity. Based on a comparison of the Penman-Monteith [PM] method with 20 other methods worldwide, the FAO has recommended using the PM method over all other methods even when local data are missing. Studies have shown that using estimation procedures for missing data with the PM equation will generally provide more accurate estimates of reference ET than will other available methods requiring less data input.

Potential ET is the ET from a well-watered crop which completely covers the surface. Meteorological processes determine the ET of a crop. Closing of stomates and reduction in transpiration are usually important only under drought or under water stress conditions of a plant. The ET depends on four factors: (1) climate, (2) vegetation, (3) water availability in the soil and (4) behavior of stomates. Vegetation affects the ET in various ways. It affects the ability of the soil surface to reflect light, and affects the amount of energy absorbed by the soil surface. Soil properties, including soil moisture, also affect the amount of energy that flows through the soil. The height and density of vegetation influence efficiency of the turbulent heat interchange and the water vapor of the foliage.

The mission of this compendium is to serve as a text book or a reference manual for graduate and under graduate students of agricultural sciences and engineering. This book will be a valuable reference for professionals and technicians that work with water management for agriculture and forestry; and will be beneficial to students, hydrologists, engineers, meteorologists, water managers and others.

There are several books on ET, such as: ET in the Soil-Plant-Atmosphere System by Viliam Novák, Springer; ET by Jesse Russell et al. by Book on Demand Ltd; Evaporation and ET: Measurements and Estimations by Wossenu Abteu et al., Springer; ET Covers for Landfills and Waste Sites by Victor L. Hauser, CRC Press; The ASCE Standardized Reference ET Equation by Richard G. Allen et al., American Society of Civil Engineers; ET: Webster's Timeline History by Icon Group International; Evaluating ET for six sites in Benton, Spokane, and Yakima counties, Washington by Stewart A. Tomlinson, University of Michigan Library; ET and Irrigation Water Requirements ASCE Manual No 70 by M. E. Jensen et al., ASCE; Crop Evapotranspiration: Guidelines for computing crop water requirements (FAO Report 56); Water Requirements for Irrigation and the Environment by Marinus G. Bos et al., Springer; Evapotranspiration by Leszek Labeledzki, InTech Open Access.

This compendium complements all books on evapotranspiration that are currently available in the market and our intention is not to replace anyone of these. This book on evapotranspiration is unique because it is complete and simple, a one stop manual, with worldwide applicability to water management in agriculture. Its coverage of the field of ET includes: historical review; basic principles and applications; how to generate missing climatic data; research results using remotely sensed climatic data; research studies from Colombia, India, Mexico, Puerto Rico, Saudi Arabia, Thailand, Trinidad and USA; studies related to agronomic crops and forest trees in arid, humid, semiarid, and tropical climates; and methods and techniques that can be easily applied to other locations [not included in this book]. This book offers basic principles, knowledge and techniques of evapotranspiration to water management in agriculture and forestry, that are necessary to understand before designing/developing and evaluating an agricultural water management system. This book is a must for those interested in water resources planning and management, namely: researchers, scientists, educators and students.

This book on *“Evapotranspiration: Principles and Applications for Water Management”* includes 31 chapters that are presented in three parts --- Part I: Principles, Part II: Applications and Part III: Water Management in the Tropics. Book chapters include: Historical evolution of ET methods by M.E. Jensen; Water vapor flux models for agriculture by V. H. Ramirez and E. W. Harmsen; Direct measurement of transpiration by V. H. Ramirez; Design of lysimeter for turfgrass water use by B. Whereley, T. Sinclair, M. Dukes and G. Miller; ET: Meteorological methods by M. R. Goyal; Evaporation estimations with neural networks by P. Shurgure and G. S. Rajput; Pan evaporation modeling: Indian agriculture by P. Shurgure and G. S. Rajput; ET for cypress and pine forests: Florida – USA by D. M. Sumner; ET for pinelands in New Jersey – USA by

D. M. Sumner, R. S. Nicholson and K. L. Clark; Water management in citrus by P. Shirgure, A. K. Srivastava and S. Singh; Vegetation water demand and basin water availability in Mexico by J. Ramos, F. J. Gonzalez, L. Marrufo and R. Dominguez; Turfgrass deficit irrigation practices for water conservation by B. Wherley; ET for Saudi Arabia: Modified Hargreaves model by M. N. El Naser ; ET with distant weather stations: Saudi Arabia by M. N. El Naser; Actual ET using LANDSAT 5 TM in Thailand by P. Kosa; Sensor based irrigation scheduling by K. Bellingham; Snow budgeting and water resources by K. Bellingham; Historical overview of ET in Puerto Rico by E. W. Harmsen; Reference ET for Colombia by V. H. Ramírez; Water management for agronomic crops in Trinidad by M. R. Goyal; Crop water stress index for common beans by V. H. Ramírez, E. W. Harmsen and T. Porch; Temperature versus elevation relationships: ET by M. R. Goyal; Generation of missing climatic data: Puerto Rico by M. R. Goyal; Estimation of pan evaporation coefficients by E. W. Harmsen, A. González and A. Winter; Daily ET estimations using satellite remote sensing by E. W. Harmsen, J. Mecikalski, M. J. Cardona, A. Rojas and R. Vasquez; Vapor flux measurements by E. W. Harmsen, V. H. Ramirez, M. D. Dukes, X. Jia, L. R. Pérez, and R. Vasquez; Climate change impacts on agricultural water resources: 2090 by E. W. Harmsen, N. L. Miller, N. J. Schlegel and J. E. Gonzalez; ET using satellite remote sensing for the tropical climate by E. W. Harmsen, J. Mecikalski, A. Mercado and P. Tosado; Water management for sweet peppers by E. W. Harmsen, J. Colón, C. L. Arcelay and D. Cádiz; Web based irrigation scheduling by E. W. Harmsen; Calibration of pyranometers and satellite derived solar radiation by E. W. Harmsen and P. Tosado and J. Mecikalski; Glossary of Technical Terms by Megh R Goyal; Appendices; and Subject Index.

The contribution by all cooperating authors to this edition has been most valuable in the compilation of this compendium. Their names are mentioned in each chapter. This book would not have been written without the valuable cooperation of these investigators, many of whom are renowned scientists who have worked in the field of evapotranspiration throughout their professional careers.

Dr Eric W Harmsen and I will like to thank editorial staff, Sandy Jones Sickles – Vice President and Ashish Kumar – Publisher and President at Apple Academic Press, Inc., [<http://appleacademicpress.com/contact.html>] for making every effort to publish the book when the diminishing water resources is a major issue worldwide. Special thanks are due to ?????? [PLEASE ADD the name] for typesetting the entire manuscript and for the quality production of this book. We request the reader to offer us your constructive suggestions that may help to improve the next edition. The reader can order a copy of this book for their library, the institute or for a gift from “CRC Press [Taylor & Francis Group] 6000 Broken Sound Parkway NW Suite 300, Boca Raton – FL – 33487 – USA; telephone at 800-272-7737 or search at weblink:

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Eric W. Harmsen joins me to express thanks to our families for their understanding and collaboration during the preparation of this book. With our whole heart and best affection, we dedicate this book to our mothers: Daya W. Goyal and June Rose Harmsen, whose hopes were that their sons would add their drop to the ocean of service to the world of humanity.

Megh R. Goyal, Ph.D., P.E., Editor-in-Chief  
December 31, 2013

## Preface

---

Knowledge of evapotranspiration (ET) is critically important for efficient management of water resources. ET is often an overlooked component of the hydrologic cycle, unlike rainfall or surface water, which are perceptible to the human eye. Nevertheless, this invisible flux of water vapor is relentless in its ability to remove water from the soil, and in many cases lead to devastating drought. Only by understanding its complex nature can we hope to manage our water resources in a wise manner.

During the last century great advances have been made in our understanding of the process of evapotranspiration. Initially, the methods for estimating ET were simple, yet effective, as for example non-weighing lysimeters and pan evaporation tanks. This was followed by a rich period of development of meteorological methods, some empirically-based, others physically-based. This period also included the development and increased use of weighing lysimeters in research.

Two important milestones were reached with the publication of the United Nations Food and Agriculture Organization (FAO) 1977 and 1998 documents on estimating crop water requirements, representing concrete examples of the global promotion of increasing agricultural water use efficiency. The more recent FAO publication resulted in the worldwide adoption of the Penman-Monteith (PM) methodology for estimating crop ET, and enumerated data and knowledge gaps which scientists have been addressing since the date of that publication. Recent studies have led to the widespread adoption of the eddy covariance and satellite remote sensing methods; while the former method has remained a research instrument because of its relatively high cost and complexity, the latter has evolved into a practical tool which farmers can utilize on a daily basis via web-based applications (e.g., see Chapter 30).

Despite the advances, many farmers, especially in developing countries, are not aware of crop water requirements and are consequently over- or under-applying irrigation. This is a serious problem leading to loss in crop yields, wasting of resources (water, energy, chemicals) and in many cases contamination of the environment. During an era of climate change, over population, and extreme poverty, such inefficiency is morally unacceptable.

I first became interested in the phenomenon referred to as ET during my graduate work at Michigan State University. This of course was coupled with the need to explain to my family and friends that ET did not mean Extra-Terrestrial (as in the Hollywood movie by Steven Spielberg), but rather that it meant evapotranspiration, after which their eyes glazed over and the conversation quickly changed to another subject. During my Ph.D. at the University of Wisconsin-Madison, a postdoc at North Carolina State University, and eight years in private environmental consulting, I would focus on such topics as groundwater flow and transport, and vadose zone processes. During the last thirteen years I have had the privilege to pursue various studies related to ET in the Tropics, with the goal of promoting agricultural water conservation, especially within the island nations of the Caribbean. This region is rich with problems to be solved, and God willing, I will spend the remainder of my career working on the solution to some of these problems.

I am indebted to my wife Rhea Howard Harmsen, who has been my unwavering support since we initiated our undergraduate studies together so many years ago. I would also like to acknowledge the NOAA-CREST (grant NA06OAR4810162) and USDA Hatch (H-402) projects, which provided partial financial support for my participation on this book project. It is my hope that this book may serve as a stepping stone for further development in the field and for the promotion of water conservation during the 21<sup>st</sup> Century.

- Eric W. Harmsen, Ph.D., P.E., Co-editor  
December 31, 2013.

## Forward

Megh Raj Goyal, PhD, P.E., and Eric W. Harmsen, PhD, P.E., have chosen to write a textbook on a very important topic in soil and water conservation engineering. “*Evapotranspiration: Principles and Applications for Water Management*” present principles, procedures and applications evapotranspiration as they apply to the more critical components of water management, concentrating on the engineering approaches to understanding the water management problems in agriculture. All chapters provide more comprehensive coverage of evaporation and transpiration processes in the hydrological cycle. The book should serve as a text for a course or as a valuable reference with practical applications and values of evapotranspiration processes that will be useful to students, instructors, researchers and irrigation designers alike. Engineering, scientists, and students should find this book equally valuable. I am honored to write the forward for this valuable and unique compendium.

I want to share with the readers of this compendium the revised/ edited version of my article: “**Basics of Evapotranspiration**, <<http://www.stevenswater.com/articles/etbasics.aspx>>”. Evapotranspiration (ET) is a combination of direct evaporation and plant transpiration. ET represents the loss of water from the Earth’s surface. ET is usually expressed as a rate such as inches per day or milliliters per day. Knowledge of ET is important for irrigation scheduling but it is also an important factor for other land use applications such as septic tank drain fields, urban planning, water shed budgeting, and climate and weather models. ET can be used as a historical tool but usually it is predicted or used in a forecast to help irrigators optimize irrigation.

**Factors affecting ET are:**

- 1. Current weather conditions:** Conditions include wind speed, air temperature, relative humidity, and sun light. The affect weather has on ET rate is rather intuitive. Warm, sunny, and dry weather with a lot of wind will have greater ET rates;
- 2. Plant type:** The ET rates between different plant species can vary greatly. For example, needle leaf trees such as pine trees will have a much greater ET than a deciduous tree such as an oak tree. Even though the pine needle can be very small, the needles have much more surface area than deciduous leaves allowing for more transpiration;
- 3. Soil chemistry (Soil conditions):** The chemical makeup of soil is also a major factor affecting ET rates. At the molecular level, most clays will have a chemical affinity (attraction) for water. Clay’s chemical affinity for water results from a planner geometry and the charge distribution at the molecular level. The chemical affinity for water is much less for sands and silts. The chemical interaction between the clay and the water impedes both the evaporation and the plant transpiration. The evaporation rate of a soil the is mostly sand on the other hand, will be close to what the evaporation rate would be out of a pan. For example, if the soil moisture is 20% by volume, the ET rate in sand would be very high and very low in clay under the same weather conditions. On the other hand, if the soil moisture is 30% by volume, the sandy soil will dry out quicker than the clay rich soil and the clay rich soil will have a higher ET rate over a longer period of time;
- 4. Soil salinity (Soil conditions):** Another factor affect the plant transpiration is the salt content of soil. Plant transpiration is the movement of water from the roots and the subsequent loss of water vapor from the stomata in the leaves. The primary driving force of the movement of water from the roots to the leaves is osmoses. Osmosis is the diffusion or movement of water that is driven by a salt concentration gradient. Increasing soil salinity will decrease plant transpiration because the salt concentration gradient will diminish thus affecting the overall ET;
- 5. Geographical locations:** In general ET rates increase toward the equator [Figure 1] and will be higher in summer than in winter. Figure 1 shows area on Earth where ET is the highest. In areas where ET is greater than precipitation, there will be very little recharge to the aquifer and a net upward movement of water. This net upward movement of water followed by ET will cause salts and minerals to accumulate near the surface. This explains why soils in arid lands tend to have a high pH and a higher salinity. Conversely, if precipitation is greater than ET, minerals and nutrients will be leached out of the soil, and there will be a shallow aquifer. Highly leached soils will develop more clay loam textured soils and will typically have a lower base saturation;

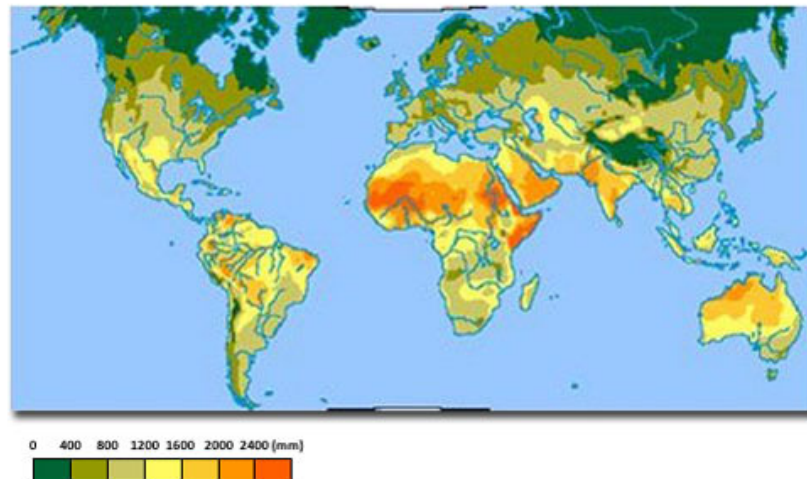
and **Geographical location:** Elevation, longitude, latitude and time of year for the location for which ET data are needed.

**ET Methods:** The simplest method for approximating ET is the pan evaporation method. Measuring the rate of evaporation of water in a pan provides a quick and reasonable approximation of ET with little or no cost. While convenient, the pan evaporation method does not take into account the contribution of plant transpiration, and it makes the assumption that water evaporates out of the soil at the same rate it would out of a pan. Developed in the late 1940s, the Penman-Monteith method provides a correlation between ET and the energy the earth’s surface receives. One of the problems with the previous ET models such as pan evaporation methods does not take into account the variability of ET from one kind of crop to the next. The Penman-Monteith method became a widely accepted ET method because a reference ET could be obtained from weather data. A reference ET is the calculated ET for a standard grass of a standard height. The ET for a specific crop could then be calculated by simply multiplying the reference ET by a crop coefficient. With the development of better and more reliable weather instruments, farm agencies could publish reference ET values along with the crop coefficients so the ET could be determined for the entire crop in a particular region. Despite the advances in weather measurements in the 1950s, the Penman-Monteith method had a few drawbacks. The reference ET calculation was mathematically tedious and few computers in the past had the computational power to calculate it and few mathematicians were able to calculate with a pencil and paper. In the 1980s the Priestly-Taylor method was introduced as an alternative to Penman-Monteith method. Based on the same heat budget principles as the Penman-Monteith Method, the Priestly-Taylor method relies on several assumptions and simplifies the calculation of reference ET. However, with advances in computers in the 1990s the Priestly-Taylor method was shot lived and the Penman-Monteith Method became standard method for calculating ET by the scientific community and organizations such as the American Society of Civil Engineers and the Food and Agriculture Organization [FAO] of the United Nations. While much emphasis has been placed on calculating ET from weather calculation modules such and the Penman-Monteith method, a previously over looked method for calculating ET using Darcy’s Law and soil hydrology has been slow to emerge. ET rates can also be measured with soil moisture

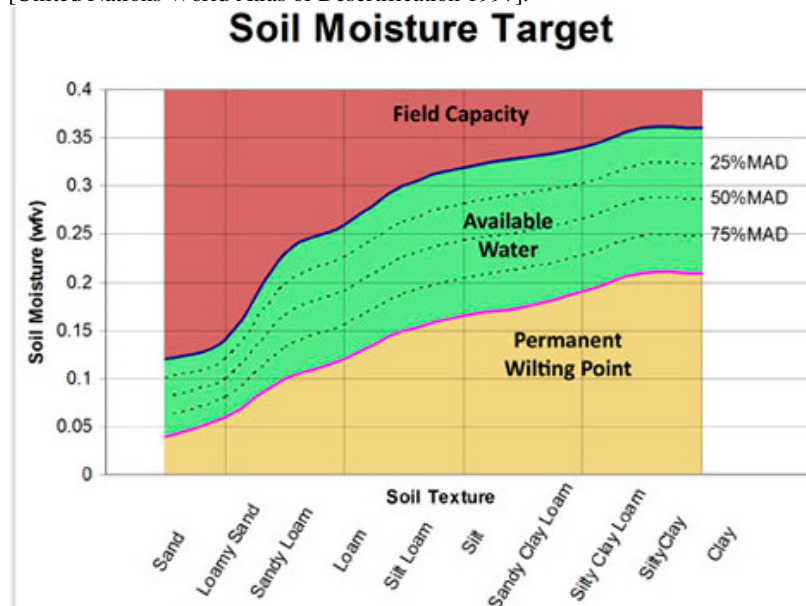
sensors by looking at the water balance in the soil. For example, the amount of water recharging the water table can be measured with a deeply placed soil moisture sensor while changes in soil moisture can be monitored with soil sensors throughout the profile. By examining changes in soil moisture through the soil profile over a period of time, an ET rate can be calculated.

**Evapotranspiration Measurement Networks:** An ET station consists of weather sensors, a data logger, a solar panel to provide electric power and radio telemetry. The radio telemetry communicates the weather data in real time back to a computer where a computer program calculates the reference ET. The typical sensors included on an ET station are an anemometer for wind speed and direction, a relative humidity sensor, air temperature sensor, pyranometer for solar radiation measurements, a barometer, and rain gauge.

Federal agencies such as the US Bureau of Reclamation, The US Department of Agriculture National Resources Conservation Service (NRCS) and state soil water conservation districts provide daily ET rates along with crop coefficients for local crops for network of ET stations. One of the most comprehensive ET networks in the western US is the AgriMET network provided by the US Bureau of Reclamation. In the Midwestern US, many states provide ET rates from State funded Mesonet.



**Figure 1.** Regional annual evapotranspiration rates. ET rate increase toward the equator [United Nations World Atlas of Desertification 1997].



**Figure 2.** Available soil water vs. soil texture.

**ET and Irrigation Management:** Perhaps the most important application for ET rates is irrigation scheduling. The weekly irrigation schedule can be calculated from forecasted ET rates, sprinkler efficiencies, root zone depth, and the available water capacity of the soil. With ET irrigation scheduling, an irrigator will know the approximate amount of water the crop will need for any given week. While ET based irrigation scheduling has shown to save water and to optimize crop yields, ET based irrigation scheduling has been based on many assumptions to give an approximation of the actual water requirements of the crops. Micro climates and highly varying soil conditions introduce a lot of error in weather station based ET calculation which in turn

will increase error in the scheduling. Because of this uncertainty, crop advisors and irrigation scheduling calculators will manipulate factors in the ET calculation so that the schedule will over irrigate by 10 to 20%. In other words, if there is a 10 to 20% error in the ET based irrigation schedule calculation, adding 10 to 20% more water will insure that the crop will not be stressed. The ultimate goal for an irrigation scheduling is to keep the soil moisture at a level that is best for the crops. ET based calculations basically estimate what the soil moisture would be based on weather data. Figure 1 indicates regional annual evapotranspiration rates. ET rate increase toward the equator. Figure 2 shows the range of plant available water based on soil texture and illustrates the changes in field capacity and permanent wilting point as the soil becomes clay rich.

Basically, with almost any crop, the soil moisture needs to be maintained above permanent wilting point and in general stay below field capacity. Permanent wilting point is a condition where the soil moisture is at low level where a plant can't uptake any water. Field capacity is the amount of water that can be held in soil before gravity will begin to drain the soil. Deep infiltration and aquifer recharge will occur in the soil moisture stays above field capacity.

In precision agriculture, the most accurate irrigation schedules use regional ET forecasts in combination with soil moisture sensors to ensure that the soil moisture values stay at a level that is best for the crop health and yields. The ET forecasts help the irrigator create a weekly irrigation schedule, while soil moisture data takes into account microclimates and soil conditions and fine tune the weekly schedule on a daily basis. With the growing demands on agricultural products and the growing importance to protect and restore natural aquatic habitats, water conservation is more important than ever. Proper irrigation management is a key to ensure healthy, high quality crops while protecting valuable water resources. Knowledge of ET is critical for environmental and economic best irrigation management practices.

In addition to ET models to help manage crops, products such as the Stevens Hydra Probe or SAM (Stevens Agricultural Monitoring) system can further help define exactly how much water is needed and when it should be applied. Combining actual soil moisture measurements with a local ET forecast can give the user an incredibly detailed look at actual soil moisture information, leading to better managed crops with increased yield and reduced waste.

Professors Goyal and Harmsen are well qualified to present this important book. I have learned a great deal while browsing this book. I recommend to Apple Academic Press Inc., for publishing more books on water management.



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## Warning/Disclaimer

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### USER MUST READ IT CAREFULLY

This text book guides the world community on “*Evapotranspiration: Principles and Applications for Water Management*” for water conservation. The reader must be aware that the dedication, commitment, honesty, and sincerity are most important factors in a dynamic manner for a complete success. It is not a one time reading of this manual. Read and follow every time, it is needed. To err is human. However, we must do our best. Always, there is a space for learning new experiences.

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## **PART I: PRINCIPLES**

# Chapter 1

## Historical Evolution of Evapotranspiration Methods<sup>1, 2</sup>

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### INTRODUCTION

This chapter is a condensation of a more detailed paper that I and Rick Allen prepared in 2000 [Jensen and Allen 2000, 53] for presentation at the Fourth National Irrigation Symposium - ASAE in Phoenix - Arizona. Also this chapter is an edited version of my original paper that was prepared for a workshop on Evapotranspiration. This chapter emphasizes my involvement or association with my colleagues in the development and dissemination of new technology for estimating evapotranspiration [ET] in the United States of America [USA]. I reviewed current ET literature and older documents relating to the development of early evapotranspiration estimating methods in the USA. In this chapter, I have included some history of the development of the “ASCE Manual 70 Evapotranspiration and Water Requirements [Jensen et al. 1990, 54]”, “FAO-56 Crop Evapotranspiration [Allen et al. 1998, 4]”, development of programs to calculate ET using satellite data [Bastiaanssen 9 and 10; Allen et al. 2007, 5], the new “ASCE Standardized Reference ET Equation [ASCE-EWRI 2005, 8]”, a proposal for a one-step approach to estimate ET, and an update on the second edition of ASCE Manual 70. More detailed but less personnel-oriented, progress in measuring and modeling ET in agriculture can be found in a recent review article by Farahani et al. [2007, 34].

### EARLY STUDIES

With the rapid development of irrigation in the western USA after about 1850, efforts to reduce water losses from both beneficial and non-beneficial vegetation became more important. Measured water deliveries varied widely and deliveries often greatly exceeded consumptive use. This problem was recognized early on as Buffum [1892, 24] stated that over-irrigation was the first and most serious mistake made by early settlers. Most early methods that were developed for estimating evapotranspiration (ET) or consumptive use (CU) for irrigated areas were for seasonal values based on observed or measured water deliveries. Air temperature was the main weather variable that was used. Solar radiation was not considered directly as a separate variable. For monthly values, crop stage of growth effects became important. As developers of empirical estimating methods adjusted and modified their temperature-based methods, the methods tended to become more complex. A measured change in soil moisture content over periods of seven or more days was the main source of measured ET data before and during the 1950s. Reliable published data were scarce, especially for measured ET rates by stage of crop growth.

### MY INVOLVEMENT

My involvement in methods of estimating ET began in 1960, when I evaluated monthly coefficients for the Blaney-Criddle equation. In the late 1950s, the United States Department of Agriculture - Soil Conservation Service [USDA-SCS] asked the USDA Agricultural Research Service [USDA-ARS] to develop monthly coefficients for the Blaney-Criddle [B-C] method. Howard Haise and Harry Blaney had requested USDA-ARS researchers to use their available data to calculate monthly coefficients for the B-C method. A stack of data sheets was collected and given to me when I arrived in Fort Collins in 1959. Before this request, the data had not been analyzed, because Harry Blaney went to Israel for a year and Howard Haise went to University of California, Davis - California for a six-month sabbatical. I was asked to work on the data during their absence. I started reviewing the numbers and the results were highly variable. Researchers with little or no prior experience with the B-C method had calculated monthly coefficients. Many did not have the experience to judge good input data from bad data such as drainage that may have occurred following rains. Also, some time periods were too short to be reliable. The plotted monthly coefficients were widely scattered. I revised the questionnaire that was sent to ARS researchers by Howard Haise as he was well-known to ARS researchers at that time. As part of this task, I reviewed current literature and many early publications on development of irrigation and ET estimating methods. These reviews were never published, but served as a good personal reference and the main source of information for a later 1962 ET workshop report [55].

The main difference in the new questionnaire that I prepared was that we asked for basic soil water and weather data, mainly air temperature and precipitation along with supporting data and not the B-C coefficients that they had computed. We established criteria for reviewing data sets before making our own calculations. Where possible, we estimated solar radiation for each measurement period, usually from cloud cover at one or more nearby weather stations. We ended up with about 1,000 ET rates for periods of seven or more days. When searching for full crop cover ET data, we found only about 100 data sets represented reasonably reliable values. The general equation [Jensen and Haise, 56] summarizing the ET rates and solar radiation (Rs) data from the full cover data sets was developed:

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<sup>1</sup> Marvin E. Jensen, PhD, Retired Research Program Leader at USDA-ARS and Irrigation Consultant. 1207 Spring Wood Drive, Fort Collins, Colorado 80525, USA. Email: <mjensen419@aol.com>. I thank the organizers of Evapotranspiration Workshop on 10 of March of 2010 by Colorado State University and USDA – ARS for giving me an opportunity to express my personal involvement in the ET research. I ask the readers of this chapter to bear with me, as I have over emphasized my involvement, it is because I have been associated with the development of ET estimating methods for the past 50 years.

<sup>2</sup> Numbers in parentheses refer to references in the bibliography.

$$ET = [(0.014 * T) - 0.37] * [Rs]$$

/1/

Where: T is an air temperature in °F, and Rs is solar radiation in mm/day or inches/day. A tabulated summary of the results was presented at an Consumptive Use [CU] workshop that was organized by ARS-SCS in March 1972 and later at the annual meeting of the Soil Science Society of America [80]. The workshop report contained: Charts of the ratio of ET to solar radiation for seven crops versus percent of the growing season and between cuttings of alfalfa grown in lysimeters at Reno – Nevada; a summary of solar radiation relationships; and tabulated weekly mean solar radiation, mean air temperature and cloud cover for 20 locations in the western USA. Copies of this workshop report were sent to others involved in estimating ET who did not attend the workshop such as Jerry Christiansen at Utah State University and David Robb at U.S. Bureau of Reclamation (USBR) in Denver - Colorado.

The main results of my research were published in 1963 [56]. The main purpose of this paper was to encourage engineers, soil scientists and agronomists to begin thinking about radiant energy as the primary source of energy for evaporation instead of air temperature which had been the practice for decades. Using our 1962 report, Dave Robb [75] with the USBR in Denver - Colorado developed a set of nine crop coefficient curves for use with the Jensen - Haise equation /1/.

## EARLY RESEARCH: IRRIGATION AND CONSUMPTIVE USE

Many books on irrigation had been written on irrigation in England, France and Italy from 1846 to 1888 along with reports on irrigation in California [Carpenter 1890, 25]. In 1897, joint efforts were started for irrigation research by USDA - Experiment Stations under the supervision of the Office of Experiment Stations [Teele 1904, 82]. These investigations were continued for the next 55 years under various USDA departments, but were transferred to the Soil Conservation Service (USDA-SCS) in 1939 [Knoblauch et al. 1962, 59]. In 1902, the Bureau of Plant Industry was established in the USDA and detailed studies of transpiration were conducted by this organization in the early 1900s.

From about 1890 to 1920, the term **duty of water** was used to describe the water use in irrigation with no standard definition [48]. Duty of water was sometimes reported as the number of acres that could be irrigated by a constant flow of water such as 1 cubic foot per second or as depth of water applied. Water measured at farm turnouts was referred to as net duty of water. Examples of early studies were those by: Widstoe [1912, 93 and 94] in Utah from 1902 to 1911 on 14 crops; Harris [1920, 41 and 42] who summarized 17 years of study in the Cache Valley of Utah; Lewis [1919, 61] who conducted studies near Twin Falls - Idaho from 1914 to 1916; Hemphill [1922, 44] who summarized studies in the Cache La Poudre river valley of northern Colorado; Israelson and Winsor [1922, 47 and 48] who made duty of water studies in the Sevier River valley in Utah from 1914 to 1918; and Crandall [1918, 28] who worked in the Snake River area near Twin Falls – Idaho in 1917 and 1918. An excellent summary of early seasonal CU studies was presented in a progress report of the Duty of Water Committee in the Irrigation Division of the American Society of Civil Engineers (ASCE). It was presented in 1927 by O.W. Israelson and later published [Anonymous 1930, 7].

L. J. Briggs, a biophysicist, and H. L. Shantz, a plant physiologist, conducted highly significant studies of transpiration in eastern Colorado [Briggs and Shantz, 19 to 22]. Briggs and Shantz recognized that solar radiation was the primary cause of the cyclic change of environmental factors [Briggs and Shantz 1917, 23]. They developed hourly transpiration prediction equations using: the vertical component of solar radiation and temperature rise, solar radiation, and vapor saturation deficit. They also recognized the significance of advected energy. A summary of the Briggs and Shantz 1910-1917 studies was later published by Shantz and Piemeisel [1927, 76]. Widstoe [1909, 92] began studying the influence of various factors affecting evaporation and transpiration in 1902. Harris and Robinson [1916, 42] conducted similar studies from 1912 through 1916. Widstoe and McLaughlin [1912, 94] concluded that temperature is the most important factor than the sunshine and relative humidity.

Other studies conducted during the 1900-1920 period were related with the factors causing and controlling water loss due to irrigation. During the next two decades emphasis was on the development of procedures to estimate seasonal CU using available climatic data.

## EARLY ESTIMATING METHODS: EVAPOTRANSPIRATION

In 1920, the U.S. Bureau of Reclamation [USBR] began studying the relationships between CU and temperature [Lowry and Johnson 1942, 62]. Hedke [1924, 43] proposed a procedure to the ASCE Duty of Water Committee in 1924 for estimating valley CU based on heat available. Heat available was estimated using degree-days. Radiant energy was not considered directly. The ASCE committee concluded in 1927 that there was an urgent need for a relatively simple method of estimating CU [Anonymous 1930, 7]. In the 1920s, Harry Blaney began measuring CU of crops based on soil samples. He worked on crops grown along the Pecos River for the Division of Irrigation and Water Conservation under the USDA-SCS. His first procedure for estimating seasonal and annual CU used mean temperature, percent of annual daylight hours and average humidity [Blaney and Morin 1942, 17]. From 1937 to 1940, Lowry with the National Resources Planning Board, and Johnson with the USBR, developed a procedure for estimating: Seasonal CU using maximum temperature above 32° F during the growing season, and annual inflow minus outflow data for irrigation projects [Lowry and Johnson 1942, 62]. Thornthwaite [1948, 84] correlated mean monthly temperature with ET based on eastern river basin water balance studies and developed an equation for potential evapotranspiration which was widely used for years. Thornthwaite recognized the limitations of his equation pointing out the lack of understanding of why potential ET at a given temperature is not the same everywhere. Because of its simplicity, the equation was applied everywhere and, in general, underestimated ET in arid areas. All of these early methods were based on correlations of measured or estimated CU data with various available or calculated climatic data. The resulting equations were relatively

simple because computers were not available — only slide rules and perhaps hand-operated adding machines. This may be difficult for young people to comprehend today since they are very dependent on personal computers.

Numerous other reports and publications were prepared between 1920 and 1945 by various state and federal agencies. Many of them dealt with investigations of water requirements for specific areas and measured farm deliveries and not on techniques for estimating CU or ET. Bibliographies of publications on seasonal CU can be found in books such as Israelsen [1950, 47] and Houk [1951, 45].

### Blaney-Criddle Method

In the 1950s and 1960s, the most widely known empirical ET estimating method used in the USA was the Blaney-Criddle [BC] method. The procedure was first proposed by Blaney and Morin in 1942 [Blaney and Morin 1942, 17]. It was modified later by Blaney and Criddle [12 to 15]. The equation /2/ was well-known older engineers:

$$U = KF = \sum k \cdot f \quad /2/$$

Where: U = estimated CU (or ET) in inches; F = the sum of monthly CU factors, f, for the period ( $f = t \cdot p / 100$ ); t = mean monthly air temperature in °F; p = mean monthly percent of annual daytime hours (daytime is defined as the period between sunrise and sunset); K = empirical CU coefficient (irrigation season or growing period); and k = monthly CU coefficient.

For long-time periods mean air temperature was considered to be a good measure of solar radiation [Blaney-Criddle 1962, 15]. Phelan [73] developed a procedure for adjusting monthly k values as a function of air temperature which later became part of SCS publication on the BC method [USDA-SCS 1970, 86]. Criddle also developed a table of daily peak ET rates as a function of depth of water to be replaced during irrigation. Hargreaves [1956] developed a procedure similar to the BC method for transferring CU data to other areas of the globe. Christiansen and Hargreaves developed a series of regression equations for estimating monthly grass ET based on pan evaporation, air temperature and humidity data [Christiansen 1968, 26; Christiansen and Hargreaves 1969, 27]. They initiated efforts to reduce weather data requirements to only air temperature, calculated extraterrestrial radiation and the difference between maximum and minimum air temperature to predict the effects of relative humidity and cloudiness. A culmination of these efforts was the well-known 1985 Hargreaves equation for grass reference ET [Hargreaves et al. 1985, 39; Hargreaves and Samani 1985, 40].

A summary of early studies and the BC method was published in a USDA technical bulletin in cooperation with the Office of Utah State Engineer [Blaney and Criddle 1962, 15]. Criddle was Utah State Engineer at that time. This publication presented the BC equation in English and metric units and updated records of measured CU by crops, percent of daytime hours of the year for latitudes of 0 to 65° N and 0 to 50° S, monthly CU factors by states, suggested monthly crop coefficients (k) for selected locations, monthly CU factors (f) and average precipitation in various foreign countries, and a summary of BC method applications that were made by various consultants such as Claude Fly in Afghanistan, Tipton and Kalmbach in Egypt and West Pakistan. The BC method is still used in some states because historical water records such as water rights have been based on this method.

Prior to about 1960 and U.S. engineers were usually taught only the Blaney-Criddle method of estimating CU or ET. Today, students and young engineers generally have had a fairly broad training in modern methods of estimating ET and ET-climate relationships.

It is unfortunate that Blaney and Criddle did not select extraterrestrial solar radiation as an index of solar energy instead used percent of daytime hours. Daytime hours from sunshine tables of Marvin [1905, 65] do not adequately account for effects of solar angle, especially in higher latitudes as illustrated in Figure 1. “Smithsonian Meteorological Tables” would have had an equation for calculating total daily solar radiation at the top of the atmosphere and total daily solar radiation for selected dates during the year at that time.

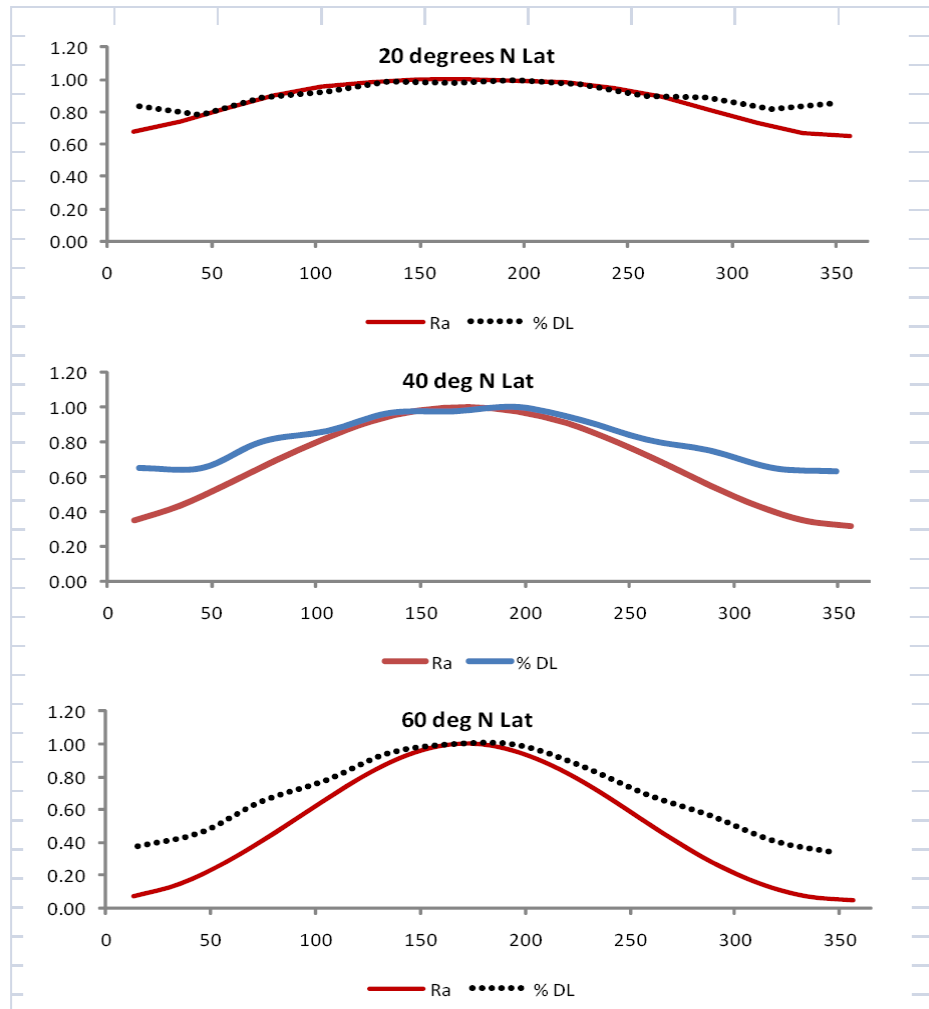
### Transition Methods in the USA

In the 1960s, estimating ET methods in the USA began to change from methods based primarily on mean air temperature to methods considering both temperature and solar radiation. Several of these methods are listed below:

|                                                                                                                                                                                                                                                                                                   |                                                                   |                                                              |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|--------------------------------------------------------------|-----|
| Alfalfa reference ET                                                                                                                                                                                                                                                                              | Jensen and Haise [1963, 56]                                       | $ET = [(0.014 \cdot T - 0.37)] \cdot [R_s]$                  | /3/ |
| Grass reference ET                                                                                                                                                                                                                                                                                | Hargreaves and Samani [1985, 40] and Hargreaves et al. [1985, 39] | $ET = [0.0023] \cdot R_a \cdot [T + 17.8] \cdot [TD]^{0.50}$ | /4/ |
| Grass reference ET, Florida                                                                                                                                                                                                                                                                       | Stephens and Stewart [1963, ]                                     | $ET = [0.0082 \cdot T_f - 0.19] \cdot [R_s]$                 | /5/ |
| Where: ET = Potential evapotranspiration in mm/day, T is a mean air temperature in °C, R <sub>s</sub> is solar radiation in mm per day or inches per day, R <sub>a</sub> = Extraterrestrial radiation, mm/ day, and TD is the difference between maximum and minimum daily air temperature in °C. |                                                                   |                                                              |     |

### Theoretical Methods

The Bowen ratio is the ratio of temperature to vapor pressure gradients,  $\Delta t / \Delta e$ , [Bowen 1926]. Bowen ratio and energy balance concepts were not incorporated at an early date into methods for estimating ET as they were for estimating evaporation from water surfaces. Examples of early work on evaporation from water using the Bowen ratio were those of Cummings and Richardson [1927, 31], McEwen [1930, 96], Richardson [1931, 97], Cummings [1936, 29], Kennedy and Kennedy [1936, 58] and Cummings [1940, 30].



**Figure 1.** Change in relative solar radiation vs. change in relative percent daylight hours.

In contrast to development of largely empirical methods in the USA, Penman [1948, 67] in the United Kingdom took a basic approach and related ET to energy balance and rates of sensible heat and water vapor transfer. Penman's work was based on the physics of the processes, and it laid the foundation for current ET estimating methodology using standard weather measurements of solar radiation, air temperature, humidity, and wind speed. The Penman equation [69 to 71] stands out as the most commonly applied physics-based equation. Penman [1948, 69] utilized the Bowen ratio principle in developing the well-known equation for estimating evaporation from a water surface along with reduction coefficients for grass. Later, a surface resistance term was added [Penman and Long 1960, 72; Monteith 1965, 66; and Rijtema 1965, 74]. Howell and Evett [2002, 46] provided an excellent summary of the Penman equation and its evolution to the development of a standardized equation by the American Society of Civil Engineers. The modern combination equation applied to standardized surfaces is currently referred to as the Penman-Monteith equation (PM). It represents the state of the art in estimating hourly and daily ET. When applied to standardized surfaces, it is now called the Standardized Reference ET Equation [ASCE-EWRI 2005, 8].

Other methods of estimating and measuring ET range from eddy covariance and energy balance using Bowen ratio or sensible heat flux based on surface temperature, radiosonde measurements of complete boundary layer profiles of temperature, humidity and energy balance estimates based on satellite imagery.

A **radiosonde** (*Sonde* is French and German for *probe*) is a unit for use in things such as weather balloons that measures various atmospheric parameters and transmits them to a fixed receiver. Radiosondes may operate at a radio frequency of 403 MHz or 1680 MHz and both types may be adjusted slightly higher or lower as required. A **rawinsonde** is a radiosonde that is designed to only measure wind speed and direction. Colloquially, rawinsondes are usually referred to as radiosondes. Modern radiosondes measure or calculate the following variables: Pressure, Altitude, Geographical position (Latitude/Longitude), Temperature, Relative humidity, Wind (both wind speed and wind direction), Cosmic ray readings at high altitude. Radiosondes measuring ozone concentration are known as ozonesondes [<http://en.wikipedia.org/wiki/Radiosonde>].

## Other Methods

During the 1950s and early 1960s, many other equations were proposed, but they have not been widely used in the USA. Some of these are Halkias et al. [1955, 37], Ledbedevich [1956, 60], Romanov [1956, 98], Makkink [1957, 63] and Vitkevich [1958, 90]. In 1957, Makkink published a formula for estimating potential ET based on solar radiation and air temperature [Rijtema 1958, 74] that is still used in Western Europe. Makkink utilized the energy-weighting term of the Penman equation, solar radiation and a small negative constant. The Makkink equation formed the basis of the subsequent FAO Radiation method that was included in FAO Irrigation and Drainage Paper No. 24 on crop water requirements by Doorenbos and Pruitt [1975 33; 1977, 34]. Turc developed a formula in 1960 which was later modified [Turc 1961, 85]. It was based on mean air temperature and solar radiation for 10-day periods. Rijtema [1958, 74] proposed the Turc formula for individual crops using crop factors and length of growing season. Olivier [1961, 68] in England developed a procedure for estimating average monthly CU for planning new projects where climatic data were limited. The Olivier's equation used average monthly wet-bulb depression and a factor based on clear sky solar radiation values.

In 1968, I described the process of using the rate of ET from a well-watered crop with an aero-dynamically rough surface like alfalfa with 30-50 cm of growth as a measure of potential ET or Eo [Jensen 1968, 50]. ET for a given crop could be related to Eo using a coefficient, now commonly known as a crop coefficient:

$$ET = [Kc] * [Eo] \quad /6/$$

Where: Kc is a dimensionless crop coefficient similar to that proposed by van Wijk and de Vries [1954, 89] representing the combined effects of resistance to water movement from the soil to the evaporating surfaces, resistance to diffusion of water vapor from the evaporating surfaces through the laminar boundary layer, resistance to turbulent transfer to the free atmosphere, and relative amount of radiant energy available as compared to the reference crop. At that time, methods other than those based on air temperature were not well known. In order to facilitate the understanding of the of the "[Eo \* Kc] process", illustrating the change in the Kc as crop cover develops enabled users to visualize how the coefficient changed from a value near 0.15 for bare soil to 1.0 at full cover.

Routine use of computers for estimating ET was in its infancy. Estimates of alfalfa reference ET and ETr, that were used in our first computerized irrigation scheduling program [Jensen 1969, 51] were calculated using the Penman method with alfalfa wind speed coefficients developed at Kimberly, ID [Jensen et al. 1970, 57]. Since we did not have a computer at Kimberly – Idaho, we used a time-share computer located in Phoenix - Arizona connected via the telephone system with a teletype paper tape reader and printer at Kimberly. In 1970, copies of a FORTRAN computer program that Ben Pratt and I had written for estimating daily ET and scheduling irrigations using the Penman equation was widely distributed following an informal workshop at Kimberly - Idaho in 1970.

The method of using reference ET and crop coefficients has been widely used for nearly a half century. In general, it has been relatively robust. For example, in 2004, Ivan Walter and I estimated ET for the Imperial Irrigation District in California using this approach. Our estimate of ET for agricultural land for CY 1998 was 2% higher than that of a SEBAL estimate for entire district; and 5% higher for agricultural crops for water year 1998 [83] of 2.01 million ac-ft or 2.5 km<sup>3</sup>. Whether the [ETref \* Kc] method, also known as the two-step method, will be replaced by the direct PM method, or one-step method, in the near future is uncertain.

Various methods of measuring ET and methods of estimating ET were summarized during a conference held in Chicago following the ASAE winter meeting on Dec. 5-6, 1966. Leading researchers from many different organizations and disciplines presented papers on the current state of the art of estimating ET in the early 1960s. I was the conference chairman and program committee members represented ASCE, American Meteorological Society, Soil Science Society of America, International Commission of Irrigation and Drainage, and several Canadian organizations. W.O. Pruitt assisted in editing the proceedings [Jensen 1966, 49].

Unfortunately, we not did get anyone to specifically discuss the Penman method. I tried to get Howard Penman to attend and present a paper, but he declined after several letters and a phone call. Leo Fritschen discussed the energy balance method, C.H.M. van Bavel discussed combination methods [van Bavel 1966, 87 and 88], and Champ Tanner discussed a comparison of energy balance and mass transfer methods for measuring ET [Tanner 1966, 81]. The conference proceedings contained pictures of the authors who were leaders in their field at the time and session chairmen.

## DISSEMINATING AND ADOPTING NEW ESTIMATING TECHNOLOGY FOR EVAPOTRANSPIRATION

Disseminating and adopting advances in ET estimating technology has not been rapid as compared with many other fields because dissemination-adaption involves many disciplines such as agricultural engineering, hydrology, water science, meteorology, soils, and plants. Dissemination and adaption of new technology did not occur rapidly as it did in single disciplines. The users of the technology, a half century ago, were mainly engineers.

Penman had a comprehensive understanding of the physical processes involved in ET. He presented an introductory paper at the informal meeting on physics that was held in The Netherlands in September 1955 [Penman 1956, 70]. He concluded with the sentence: *"Though the physicist still has some problems he can solve by himself, much of his future contribution to understanding evaporation in agriculture must be in collaboration with the biologist and the soil scientist"*.

In my 1960 review of old and current literature, it was clear that new advances in estimating ET had to depart from the traditional use of temperature as the primary input variable. The Penman equation had been developed, but was not in general use by engineers designing and managing irrigation projects. Generally, the Penman equation was thought to be too complicated for



use by engineers given the status of computational tools and weather data commonly collected at that time. In developing countries, it is still considered complex.

During the 1966 meeting of the Irrigation and Drainage Division of ASCE in Las Vegas – Nevada, I was asked to chair the ASCE committee on Irrigation Water Requirements, formerly the Committee on CU of Crops and Native Vegetation. The committee was charged with developing a manual on CU. The committee had been chaired by Harry Blaney, but it was not making much progress on this task. A few papers that had been prepared were reproductions of old temperature- based methods of estimating ET. My one condition on accepting chairmanship was that I could bring in non-ASCE members into the committee such as Bill Pruitt. Bill, who was with the University of California at Davis and was not an ASCE member then. Bill had been measuring ET using weighing lysimeters and collecting associated basic meteorological data. The committee had control of the Corresponding and Non-member advisors. Control members were: Robert Burman, University of Wyoming; Harlan Collins, SCS; Albert Gibbs, USBR; Marvin E. Jensen, ARS-USDA; and Arnold Johnson, USGS. Harry Blaney remained on the committee, but never attended any of our meetings. We made progress and produced a report that was the start of the ASCE manual on ET. In 1973, we prepared as a camera-ready document at Kimberly – Idaho that was printed as the ASCE report Consumptive Use and Irrigation Requirements [Edited by Jensen 1974, 52] and widely disseminated in the U.S. and in other countries like China.

I left the ET committee for three years when I became a member of the executive committee of the ASCE-I&D Division in October 1974. Members of the ET committee continued to work on the manual. Several members served as ET committee chairman between October 1973 and 1986. In 1986, a subcommittee of the ET committee was formed. Its members were Rick Allen, Ron Blatchley, Bob Burman, Marvin E. Jensen, Eldon Johns, Jack Stone and Jim Wright. I was designated as chairman. We were charged with the task of preparing the CU or ET manual. The first draft, which had both English and metric units, was completed for review by one or several ASCE committees in 1988. One reviewer suggested that we use only metric units. This was a good advice, but delayed the manuscript another year as changes were made in the manuscript. The manual was published in 1990 as ASCE Manual No. 70 [Jensen et al. 1990, 54]. The ASCE-PM equation from ASCE Manual 70 has been widely accepted for standardized calculations such as in the Natural Resources Conservation Service National Engineering Handbook [Martin and Gilley 1993, 64].

Allen et al. [1989, 2] prepared a paper for publication in the Agronomy Journal to disseminate new information to soil scientists and agronomists. In 1990, the FAO needed to update its 1975- 1977 publication on crop water requirements [FAO-24]. It organized an expert's consultation on the revision of FAO-24 in Rome on 28-30 May 1990 [Smith et al. 1991, 79]. There were 10 participants from seven countries: John Monteith from the International Crops Research Institute for Semi- arid Tropics, D. Rijks from WMO, and several participants from FAO. USA participants were Rick Allen, Marvin E. Jensen, and William O. Pruitt. At this conference several manuscript copies of the ASCE Manual 90 were made available and it became a key reference. The revision of FAO-24 with major contributions by Rick Allen resulted in the well-known FAO-56 publication on crop evapotranspiration by Allen et al. [1998, 4].

In the Netherlands, R.A. Feddes had been working on models of ET, plant root systems and soil water extraction [Feddes et al. 1993, 35]. In 1998, Bastiaanssen et al., including Feddes, published a paper describing a surface energy balance model for land (SEBAL) using satellite- based imagery [Bastiaanssen et. al. 1998, 9 and 10]. In the USA, Allen et al. developed a high resolution mapping model with internalized calibration using principles and similar techniques as used in the SEBAL model [Allen et al. 2007, 5]. It uses a near-surface temperature gradient, dT, that is indexed to the radiometric surface as in SEBAL. The METRIC technique [5] uses the SEBAL technique for estimating dT. METRIC also uses weather-based reference ET to establish energy balance conditions for a cold pixel and is internally calibrated at two extreme conditions (wet and dry) using local available weather data. The auto-calibration is done for each image using alfalfa-based reference ET. Both of these models are now being used in the U.S. to map ET at a high resolution over large areas.

In 2000, the Irrigation Association and landscape industry requested the *ASCE Irrigation Water Requirements Committee* [now renamed Committee on Evapotranspiration in Irrigation and Hydrology] to recommend a single procedure for estimating reference ET for use in the USA. This request in part resulted in an ASCE task committee of the ET Committee consisting of engineers and scientists from around the USA. They agreed on a single equation for estimating reference crop ET. The equation is a simplification of the ASCE-PM equation. The request was made to help standardize the basis for the myriad of landscape (i.e., crop) coefficients that have been developed since the late 1980s. The task committee suggested applying the PM equation to both a tall reference crop like alfalfa and short reference crop like clipped grass by changing several coefficients in order to support usage in both agricultural and landscape industries. A reduced form of the PM equation was adopted for both reference types, with the grass form being the same as in the FAO-56 publication. This was done to promote agreement in usage between the USA and other countries. Sets of coefficients were presented in a table for estimating daily or hourly reference ET for the short and tall references. Details of that equation and its development were presented in separate papers at the 2000 ASAE National Irrigation Conference in Phoenix - Arizona [Walter et al. 2000, 91]. The various forms and applications of the PM and Penman equations, as well as commonly used empirical equations, were implemented in REF-ET software [Allen 2000: Personal communication] that was available for free downloading from:

[<http://www.kimberly.uidaho.edu/ref-et>] Current Version: 3.1.08, updated January, 2012]

Rick Snyder also has several reference ET programs (monthly, daily, and hourly) for Excel spreadsheets on the web site:

<http://biomet.ucdavis.edu/evapotranspiration.html>.

A summary of the reference ET methodology and tables of mean and basal crop coefficients were published as a major chapter in the 2nd edition of the ASABE book Design and Operation of Farm Irrigation Systems [Allen et al. 2007, 6]. It contains

a great deal of detail on factors controlling ET and on estimating ET. There are numerous recent publications on many different crop coefficients written by authors in the USA and other countries. Before using these coefficients, the users need to carefully review how the calculations were made. FAO-56 crop coefficients have been refined incorporating the fraction of ground cover and plant height [Allen and Pereira 2009, 3]. Others have used remote sensing with ground-based or aircraft-based cameras, and satellite images to measure the normalized difference vegetation index [NDVI] and then related NDVI to ET<sub>ref</sub>-based crop coefficients. The use of the reference ET and crop coefficient method is expected to continue because of the extensive collection of available crop coefficients.

Some scientists are suggesting a more direct approach to estimating crop water requirements such a one-step method or direct PM [Monteith 1965, 66]. Shuttleworth derived a Penman-Monteith based, one-step estimation equation that allows for different aerodynamic characteristics of crops in all conditions of atmospheric aridity to estimate crop ET from any crop of a specified height using standard 2-m climate data [Shuttleworth 2006, 77]. Not everyone agrees that the concept can adequately account for surface soil water conditions. Shuttleworth called for field studies to address the problem of effective values for surface resistance for different crops equivalent to that for crop coefficients. Shuttleworth and Wallace summarized a detailed study that was conducted in Australia using the one-step approach [Shuttleworth and Wallace 2009, 78]. I am not aware of any specific applications that have been made in the USA. In the second edition of Manual 70, we have a chapter on “Direct Penman-Monteith method”.

The first edition of Manual 70 is out of print. In 2000, the ET committee decided to have a technical committee prepare a second edition. Marvin E. Jensen and Rick Allen were designated co- chairmen. Other members were Terry Howell, Derrel Martin, Rick Snyder, and Ivan Walter. The second edition has been completely restructured. We are near having a final draft ready for review by ASCE committees. I hope that this can be completed this year.

Major progress on developing improved methods of estimating ET was made during the past third of a century because of the efforts of many Europe and U.S. individuals. Some are R. Feddes and W. Bastiaanssen in the Netherlands; L. Pereira in Portugal; and M. Smith with FAO who led the FAO effort. Many individuals in the U.S. were major contributors to ET development technology. Some of these are Rick Allen, Terry Howell, Bill Pruitt, Joe Ritchie, Rick Snyder and Jim Wright. Bill Pruitt measured ET in weighing lysimeters near Davis - California along with detailed weather data for many years. His technical guidance and data were very valuable in the development of new technology. Jim Wright measured ET from various crops using a weighing lysimeter at Kimberly, ID over an eight year period and he developed the concept of the basal crop coefficient representing conditions when soil evaporation is minimal and most of the ET is transpiration [Wright 1982, 95]. Wright’s measured data were also used to refine net radiation and crop coefficients.

## SUMMARY

This chapter summarizes a century of progress in the development of modern methodology for accurately estimating daily and hourly evapotranspiration. Why did this process take so long? Evaporation from soil and plant services is a complex process involving plants, soils, local weather data like wind speed and humidity, solar and long-wave radiation. Its developments involved many disciplines. It has only been 200 years since hydrologic principles were first understood and described by Dalton so perhaps a century is not that unreasonable.

Most of the progress in developing new methodology in the U.S. was made during the last third of a century. Many scientists and engineers were involved in the evolution of ET-estimating technology. Scientists and engineers in Europe have also been instrumental in advancing the technology. In this chapter, I tried to highlight major contributions of people many of whom I knew personally or at least I had met them briefly. My involvement in the process of development better ET estimating technology and association with other engineers and scientists was a learning experience. It started me on a very rewarding career path. The experience that I gained working leading scientists and engineers over the past half century has been very rewarding personally. If I have emphasized my involvement too much it is because I have been associated with the development of ET estimating methods for the past 50 years. More detailed progress on measuring and modeling ET can be found in a review paper by Farahani et al. [2007, 34].

## KEYWORDS

Allen, R. G.  
Blaney  
Blaney – Criddle  
Bowen ratio  
Colorado  
Consumptive use  
Crop coefficient  
Crop water requirement  
Duty of water  
Energy balance  
Evaporation  
Evapotranspiration  
FAO

Ground cover  
Irrigation  
Irrigation engineering  
Jensen and Haise  
Jensen, M.E.  
Meteorology  
Monteith  
Penman - Monteith  
Penman  
Satellite- based imagery  
SEBAL  
Soil moisture  
Solar angle  
Solar radiation  
Transpiration  
USA  
USDA – ARS  
USDA – SCS  
Water requirement

## **BIBLIOGRAPHY**

Refer to the bibliography for the literature cited.

## Chapter 2

### Water Vapor Flux Models for Agriculture<sup>1,2</sup>

#### INTRODUCTION

The water vapor flux in agroecosystems is the second largest component in the hydrological cycle. Water vapor flux or evapotranspiration (ET) from the vegetation to the atmosphere is a widely studied variable throughout the world. ET is important for determining the water requirements of crops, climatic characterization, and for water management. The estimation of ET from vegetated areas is a basic tool to compute water balances and to estimate water availability and requirements. During the last sixty years various methods and models to measure the water flux in agroecosystems have been developed. The aim of this chapter is to provide a literature review on the subject, and provide an overview of methods and models developed which are widely used to estimate and/or measure ET in agroecosystems.

Evapotranspiration constitutes an important component of the water fluxes of our hydrosphere and atmosphere [21], and is a widely studied variable throughout the world, due to its applicability in various disciplines, such as hydrology, climatology, and agricultural science. Pereira *et al.* [80] has reported that the estimation of ET from vegetated areas is a basic tool for computing water balances and to estimate water availability and requirements for plants. Measurement of ET is needed for many applications in agriculture, hydrology and meteorology [102]. ET is a major component of the hydrologic water budget, but one of the least understood [120]. ET permits the return of water to the atmosphere and induces the formation of clouds, as part of a never-ending cycle. ET also permits the movement of water and nutrients within the plant; water moving from the soil into the root hairs, and then to the plant leaves.

ET is a complicated process because it is the product of different processes, such as evaporation of water from the soil, and water intercepted by the canopy, and transpiration from plant leaves. Physiological, soil and climatic variables are involved in these processes. Symons in 1867 described evaporation as “...the most desperate art of the desperate science of meteorology” [69]. The first vapor flux measurements were initiated by Thornthwaite and Holzman in the 1930s, but that work was interrupted by World War II [69]. In the late 1940s Penman [78] published the paper “*Natural Evaporation from open Water, Bare Soil and Grass*” in which he combined a thermodynamic equation for the surface heat balance and an aerodynamic equation for vapor transfer. The “Penman equation” is one of the most widely used equations in the world. The equation was later modified by Monteith [67, 68] and is widely known as the “*The Penman-Monteith Model*”. It is also necessary to introduce a review of the work of Bowen, who in 1926 [11] published the relationship between the sensible and latent heat fluxes, which is known as the “*Bowen ratio*”. Measurement of the water vapor flux has become a common practice by means of the “*Bowen ratio energy balance method*” [106]. Allen *et al.* [5] classified the factors that affect the ET into three groups:

- a. **Weather parameters**, such as radiation, air temperature, humidity and wind speed: The evapotranspirational component of the atmosphere is expressed by the reference crop evapotranspiration ( $ET_o$ ) in the Penman-Monteith method (FAO-56), or using direct measurements of pan evaporation data [22], or using other empirical equations;
- b. **Crop factors** such as the crop type, variety and developmental stage should be considered when assessing the ET from crops grown in large, well-managed fields. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different ET levels in different types of crops under identical environmental conditions. Crop ET under standard conditions ( $ET_c$ ) refers to excellent management and environmental conditions, and achieves full production under a given climatic condition (equation /2/); and
- c. **Management and environmental conditions** ( $ET_{adj}$ ). Factors such as soil salinity, poor land fertility, limited applications of fertilizers, the presence of hard or impermeable soil horizons, the absence of control of disease and pests, and poor soil management may limit the crop development and reduce the ET, ( $ET_{adj}$  equation /3/).

One of the most common and fairly reliable techniques for estimating  $ET_o$  is using pan evaporation data, where adjustments are made for the pan environment [31] using the pan evaporation and a pan coefficient ( $K_p$ ).

$$ET_o = K_p \cdot E_p \quad 1/$$

Where:  $E_p$  is the pan evaporation ( $\text{mm day}^{-1}$ ), and  $K_p$  is the pan coefficient, and depends on location and time of year. It is important to know or calculate the pan coefficient before calculating the  $ET_o$ . Allen *et al.*, [5] gave a methodology to calculate the pan coefficient.  $K_p$  is essentially a correction factor that depends on the prevailing upwind fetch distance, average daily wind speed, and relative humidity conditions associated with the siting of the evaporation pan [22].

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<sup>2</sup> Numbers in parentheses indicate the bibliographical references in the bibliography.

## CROP WATER FLUX USING SINGLE CROP COEFFICIENTS: THE FAO APPROACH

The FAO approach is also known as the “*Two steps method*”, which is very useful for single crops and when “reference” conditions are available (i.e., no crop water stress). In this case, crop evapotranspiration ( $ET_c$ ) can be estimated using equation /2/ [5, 22]:

$$ET_c = K_c \cdot ET_o \quad /2/$$

Where:  $K_c$  is the coefficient expressing the ratio between the crop and reference ET for a grass surface. The crop coefficient can be expressed as a single coefficient, or it can be split into two factors, one describing the effect of evaporation and the other the effect of transpiration. As soil evaporation may fluctuate daily, as a result of rainfall and/or irrigation, the single crop coefficient expresses [5] only the time-average (multi-day) effects of crop ET, and has been considered within four distinct stages of growth [5]. When stress conditions exist, the effects can be accounted for by a crop water stress coefficient ( $K_s$ ) as follows:

$$ET_{cadj} = K_s \cdot K_c \cdot ET_o \quad /3/$$

### Crop Coefficients

Although a number of  $ET_c$  estimation techniques are available, the crop coefficient ( $K_c$ ) approach has emerged as the most widely used method for irrigation scheduling [45]. As ET is not only a function of the climatic factors, the crop coefficients can include conditions related to the crop development ( $K_c$ ), and non-standard conditions ( $K_s$ ). The  $K_c$  is based on two concepts [5]: a. Crop transpiration represented by the basal crop coefficient ( $K_{cb}$ ); and b. The soil evaporation,  $K_e$ , and is calculated using equation /4/:

$$K_c = K_{cb} + K_e \quad /4/$$

$K_c$  is an empirical ratio between  $ET_c$  and  $ET_o$  over grass or alfalfa, based on historical measurements. The curve for  $K_c$  is constructed for an entire crop growing season, and which attempts to relate the daily water use rate of the specific crop to that of the reference crop [45]. The United Nations Food and Agriculture Paper FAO # 56 by Allen et al. [5] provided detailed instructions for calculating these coefficients. For limited soil water conditions, the fractional reduction of  $K_c$  by  $K_s$  depends on the crop, soil water content, and magnitude of the atmospheric evaporative demand [22].

The value for  $K_c$  equals  $K_{cb}$  when the soil surface layer is dry (i.e., when  $K_e = 0$ ) and the soil water within the root zone is adequate to sustain the full transpiration (non-stressed conditions, i.e.,  $K_s = 1$ ). When the available soil water of the root zone becomes low enough to limit potential  $ET_c$ , the value of the  $K_s$  coefficient is less than 1 [5,44, 45].

The soil evaporation coefficient accounts for the evaporation component of  $ET_c$  when the soil surface is wet, following irrigation or rainfall [5,45]. When the available soil water of the root zone becomes low enough, crop water stress can occur and reduce  $ET_c$ . In the FAO-56 procedure, the effects of water stress are accounted for by multiplying  $K_{cb}$  (or  $K_c$ ) by the water stress coefficient ( $K_s$ ):

$$K_c \cdot K_s = (K_{cb} + K_e) = ET_c/ET_o \quad /5/$$

Where:  $K_s < 1$  when the available soil water is insufficient for the full  $ET_o$  and  $K_s = 1$  when there is no soil water limitation on  $ET_c$ . Thus, to determine  $K_s$ , the available soil water within the crop zone for each day needs to be measured or calculated using a soil water balance approach [45].

The estimation of  $K_e$  using the FAO-56 method, requires the use of the soil field capacity (FC), the permanent wilting point (PWP), total evaporable water (TEW), the fraction of the soil surface wetted ( $f_w$ ) during each irrigation or rain, and the daily fraction of the soil surface shaded by vegetation ( $f_c$ ), or conversely the unshaded fraction ( $1-f_c$ ). Hunsaker et al. [45] reported an exponential relation between  $1-f_c$  and height of an Alfalfa crop.

The measurement of  $K_e$  and  $K_{cb}$  can be made by performing a *daily water balance*, and use of the following equations from FAO Paper 56 [5].

$$ET_c = (K_{cb} + K_e) ET_o \quad /6/$$

$$K_{cb} = (ET_c/ET_o) - K_e \quad /7/$$

The soil evaporation (E) can be calculated using the equations /8/ and /9/:

$$E = K_e ET_o \quad /8/$$

$$K_e = E/ET_o \quad /9/$$

The soil evaporation (E) can be measured using the water balance equation /10/:

$$E = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{f_i}{f_{ew}} + T_{ew,i} + DP_{e,i} \quad /10/$$

Where:  $D_{e,i-1}$  is the cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil at the end of day i-1 (mm),  $P_i$  is the precipitation on day i (mm);  $RO_i$  is precipitation runoff from the surface on day i (mm),  $I_i$  is the irrigation depth on day i that infiltrates into the soil (mm),  $E_i$  is evaporation on day i (i.e.,  $E_i = K_e/ET_o$ ) (mm),  $T_{ew,i}$  is depth of transpiration from the exposed and wetted fraction of the soil surface layer on day i (mm),  $f_w$  is fraction of soil surface wetted by irrigation (0.01 to 1), and  $f_{ew}$  is the exposed and wetted soil fraction (0.001 to 1).

The ratio of reference evaporation to reference transpiration depends on the developmental stage of the leaf canopy expressed as “ $\delta$ ”, the dimensionless fraction of incident beam radiation that penetrates the canopy (Cambell and Norman, 1998; mentioned by Zhang et al. [124]).

$$\delta = \exp(-K \cdot LAI) \quad /11/$$

Where:  $K$  is the dimensionless canopy extinction coefficient, and therefore evaporation and transpiration can be calculated using equations /12/ and /13/:

$$E_o = \delta \cdot ET_o \quad /12/$$

$$T = (1 - \delta).ET_o \quad /13/$$

$$K_{cb}K_s = 1.5 \text{ with high frequency irrigation; and } K_{cb}K_s = 1.4 \text{ with lower frequency irrigation} \quad /14/$$

Hunsaker [44] found that  $ET_c$  in cotton was higher when the crop was submitted to higher depths of irrigation (820-811mm) than for lower depths of irrigation (747-750mm), similarly to the  $K_{cb}K_s$  curves, obtaining higher values when treated with high frequency irrigation (i.e.;  $K_{cb}K_s = 1.5$ , 90 days after planting) than with lower frequency irrigation (i.e.;  $K_{cb}K_s = 1.4$ , 90 days after planting), as shown in equation /14/.

### Limitations in the use of $K_c$

Katerji and Rana [52] reviewed recent literature related to  $K_c$  and found differences of  $\pm 40\%$  between  $K_c$  values reported in the FAO-56 paper [5] and the values experimentally obtained, especially in the mid growth stage. According to the authors, these large differences are attributable to the complexity of the coefficient  $K_c$ , which actually integrates several factors: aerodynamic factors linked to the height of the crop, biological factors linked to the growth and senescence of the surface leaves, physical factors linked to evaporation from the soil, physical factors linked to the response of the stomata to the vapor pressure deficit and agronomic factors linked to crop management (distance between rows, use of mulch, type of irrigation system, etc.). For this reason  $K_c$  values need to be evaluated for local conditions

The variation in crop development rates between location and year have been expressed as correlations between crop coefficients and indices such as the thermal base index, ground cover, days after emergence or planting, and growth rate (e.g., [122, 44, 14, 72, 34, 61, 87]). The  $K_c$  is well related with the growing degree days (GDD) and with the fraction of the soil cover by vegetation ( $f_c$ ) (Fig. 1), and depends on the genotype and plant densities [87]. The equations /15/ and /16/ are for common bean genotype Morales with 13.6 plants.m<sup>-2</sup>. The equations /17/ and /18/ are for common bean genotype SER 16, with 6.4 plants.m<sup>-2</sup>.

$$K_c = -3 \times 10^{-6} CGDD^2 + 0.0033 CGDD - 0.053; R^2 = 0.76; p < 0.0001 \quad /15/$$

$$K_c = -1.4019 f_c^2 + 2.5652 f_c - 0.2449; R^2 = 0.70; p < 0.0003 \quad /16/$$

$$K_c = -3 \times 10^{-6} CGDD^2 + 0.0034 CGDD - 0.0515; R^2 = 0.60; p < 0.0001 \quad /17/$$

$$K_c = -0.6726 f_c^2 + 1.90086 f_c - 0.2560; R^2 = 0.60; p < 0.0032 \quad /18/$$

### Water Stress Coefficient ( $K_s$ )

The soil water stress coefficient,  $K_s$ , is mainly estimated by its relationship to the average soil moisture content or matric potential in a soil layer and it can usually be estimated by an empirical formula based on soil water content or relative soil water available content [124].

The  $K_s$  is an important coefficient because it indicates the sensitivity of the crop to water deficit conditions, for example corn grain yield is especially sensitive to moisture stress during tasselling and continuing through grain fill. Roygard et al. [94] observed that depletion of soil water to the wilting point for 1 or 2 days during tasselling or pollenization reduced yield by 22%. Six to eight days of stress reduced yield by 50%. Allen et al. [5] presented the following methodology for estimating  $K_s$ :

$$K_s = \frac{TAW - Dr}{TAW - RAW} = \frac{TAW - Dr}{(1 - p)TAW} \quad /19/$$

Where: TAW is total available water and refers to the capacity of the soil to retain water available for plants (mm); Dr is root zone depletion (mm); RAW is the readily available soil water in the root zone (mm), p is the fraction of TAW that the crop can extract from the root zone without suffering water stress.

$$TAW = 1000(\theta_{FC} - \theta_{wp})Z_t \quad /20/$$

Where:  $\theta_{FC}$  is the water content at field capacity (m<sup>3</sup>.m<sup>-3</sup>),  $\theta_{wp}$  is the water content at wilting point (m<sup>3</sup>.m<sup>-3</sup>), and  $Z_t$  is the rooting depth (m).

$$RAW = pTAW \quad /21/$$

Allen et al. [5] give values for different crops (FAO Paper No. 56, page 163). Roygard et al. [94] and Zhang et al. [124] reported that  $K_s$  is a logarithmic function of soil water availability (Aw), and can be estimated as follows:

$$K_s = \ln(Aw + 1) / \ln(101) \quad /22/$$

Where: Aw is calculated according to the equation /23/:

$$Aw = 100 \left( \frac{\theta_a - \theta_{wp}}{\theta_{FC} - \theta_{wp}} \right) \quad /23/$$

Where:  $\theta_a$  is average soil water content in the layers of the root zone depth. An example of the relationships between  $K_s$  and available soil water changes, estimated as root zone depletion, is presented by Ramirez [87]. The root zone depletion ( $D_r$ ) can be calculated using the water balance equation /24/:

$$D_{r,i} = D_{r,i-1} - (P - RO)_i - I_i + ET_{c,i} + DP_i \quad /24/$$

Where:  $D_{r,i}$  is the root zone depletion at the end of day  $i$ ;  $D_{r,i-1}$  is water content in the root zone at the end of the previous day,  $i-1$ ;  $(P-RO)_i$  is the difference between precipitation and surface runoff on day  $i$ ;  $I_i$  is the irrigation depth on day  $i$ ;  $ET_{c,i}$  is the crop ET on day  $i$  and  $DP_i$  is the water loss from the root zone by deep percolation on day  $i$ ; all the units are in mm.

The root zone depletion associated with a  $K_s = 1.0$  (i.e., no water stress), was up to 10 mm for a root depth between 0 to 20 cm, and up to 15 mm for a root depth of 0 to 40 cm in common beans. Fifty percent of the transpiration reduction was reached for  $D_r = 22$  mm and 25 mm for the common bean genotypes Morales and SER 16, respectively. Transpiration ceased completely ( $K_s = 0$ ) when  $Dr = 37$  mm and 46 mm, respectively, for Morales and SER 16 [87].

## DIRECT WATER VAPOR FLUX MEASUREMENT: LYSIMETERS

The word ‘*lysimeter*’ is derived from the Greek root ‘*lysis*,’ which means dissolution or movement, and ‘*metron*,’ which means to measure [41]. Lysimeters are tanks filled with soil in which crops are grown under natural conditions to measure the amount of water lost by evaporation and transpiration [5]. A lysimeter is the method of determining ET directly. Lysimeter are tanks buried in the ground to measure the percolation of water through the soil. Lysimeters are the most dependable means of directly measuring the ET rate, but their installation must meet four requirements for the data to be representative of field conditions [19]:

**Requirement 1:** The lysimeter itself should be fairly large and deep to reduce the boundary effect and to avoid restricting root development. For short crops, the lysimeter should be at least one cubic meter in volume. For tall crops, the size of the lysimeter should be much larger.

**Requirement 2:** The physical conditions within the lysimeter must be comparable to those outside. The soil should not be loosened to such a degree that the root ramification and water movement within the lysimeter are greatly facilitated. If the lysimeter is unclosed on the bottom, precaution must be taken to avoid the persistence of a water table and presence of an abnormal thermal regime. To ensure proper drainage, the bottom of an isolated soil column will often require the artificial application of a moisture suction, equivalent to that present at the same depth in the natural soil [20].

**Requirement 3:** The lysimeter will not be representative of the surrounding area if the crop in the lysimeter is taller, shorter, denser, or thinner, or if the lysimeter is on the periphery of a non-cropped area. The effective area of the lysimeter is defined as the ratio of the lysimeter ET per unit area to that of the surrounding field. The values of this ratio, other than unity, are caused by the inhomogeneity of the surface. The maintenance of uniform crop height and density is not an easy task in a tall crop, spaced in rows. If the surface is indeed inhomogeneous, there is no adequate way to estimate the effective area from tank area overlap corrections or plant counts.

Figure 1A for 13.6 plants.m<sup>-2</sup>.

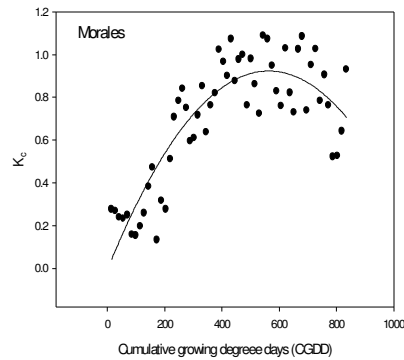


Figure 1B for 6.4 plants.m<sup>-2</sup>.

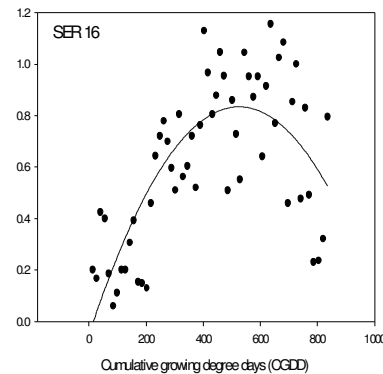


Figure 1C for Morales

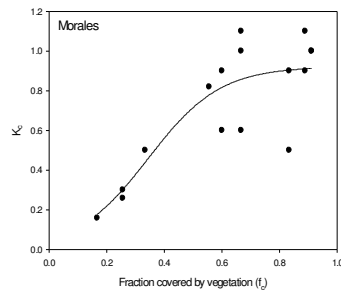
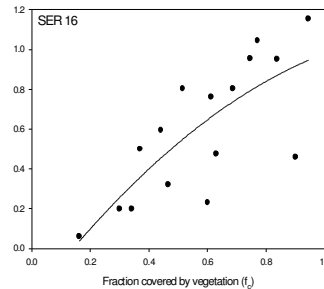


Figure 1D for SER16



**Figure 1.** Crop coefficients ( $K_c$ ) as related to cumulative growing degree days (CGDD) and fraction covered by vegetation ( $f_c$ ) for two common bean genotypes: **A.** Morales CGDD vs.  $K_c$ , **B.** SER 16

CGDD vs.  $K_c$ , C. Morales  $f_c$  vs  $K_c$ , D. SER 16  $f_c$  vs  $K_c$ . The curves were fitted from growth periods V1 to R9 (Data from [87]). (These data were obtained under the project sponsored by NOAA-CREST (NA17AE1625), NASA-EPSCoR (NCC5-595), USDA-TSTAR-100, and University of Puerto Rico Agricultural Experiment Station – Mayaguez - USA).

**Requirement 4:** Each lysimeter should have a “guard-ring” area around it maintained under the same crop and moisture conditions in order to minimize the clothesline effect. In arid climates, Thornthwaite in 1954, suggested that a “guard-ring” area of ten acres may or may not be large enough. Where several lysimeters are installed in the same field, the “guard-ring” radius may have to be about ten times the lysimeter separation [19].

Lysimeters surrounded by sidewalks or gravel will not provide reliable data, nor will lysimeters planted to a tall crops if it is surrounded by short grass, or planted to grass and surrounded by a tall crop. Differences in growth and maturity between the lysimeters plants and surrounding plants can result in significant differences in measured ET in and outside the lysimeter [4]. The lysimeters are classified basically in two types: Weighing and Non-weighing.

#### A. Non-Weighing Lysimeters [Also called Drainage Lysimeters]

These operate on the principle that ET is equal to the amount of rainfall and irrigation water added to the system, minus percolation, runoff and soil moisture changes. Since the percolation is a slow process, the drainage lysimeters is accurate only for long periods for which the water content at the beginning exactly equals that at end. The length of such a period varies with the rainfall regime, frequency and amount of irrigation water application, depth of the lysimeters, water movement, and the like. Therefore, records of drainage lysimeters should be presented only in terms of a long-period, more than one day [19], and they are not useful for estimating hourly ET.

Allen et al. [4] discusses two types the non-weighing lysimeters: a) *non- weighing constant water-table type*, which provides reliable data in areas where a high water table normally exists and where the water table level is maintained essentially at the same level inside as outside the lysimeters; b) *Non-weighing percolation type*, in which changes in water stored in the soil are determined by sampling or neutron methods or other soil moisture sensors like TDR, and the rainfall and percolation are measured.

#### General principles of a drainage lysimeter

Provisions are made at the bottom of the lysimeter container to collect and measure volumetrically the deep percolation. Precipitation is measured by rain gauge(s). *Evapotranspiration* is considered as the difference among *water applied*, *water drainage* and *soil water change* [108,123].

When filling-in a lysimeter, the soil dug out from the pit of a lysimeter is replaced in the container, special precautions are needed to return the soil to its original status by restoring the correct soil profile and compacting the soil layers to the original density. It is desirable to have a similar soil state inside the lysimeter relative to the outside. However if the roots are well developed and nutrients are available, and as long as the water supply to the roots is unrestricted, dissimilar soil will not give significant variation in water use and yield, provided other conditions are similar. [123]

Although disturbed soil in filled-in lysimeters does not pose serious problems in ET measurement, the soil can affect plant growth. Breaking up the soil, will change soil structure, aeration, and soil moisture retention characteristics. The lysimeters should provide a normal rooting profile. It should be large enough to render the effect of the rim insignificant. It can give relatively large errors in the ET measurement if the container is small. However, the greater the lysimeters area, the more costly and complicated the installation and operation becomes. [123].

Installation and walls: The wall can be different materials: reinforced concrete, polyester reinforced with steel, fiberglass or plastic. The installation proceeds in the following steps: Excavation (e.g. 1m x 1m x 1.2m) in the experimental site. Each layer of soil (e.g. 0-30 cm, 30-60cm and 60-100 cm) is separated. Once the excavation it completed, the lysimeter is placed in the excavated hole with 4 wooden boards outside. Before repacking the soil layers, make a V-shaped slope at the bottom and place a 25 mm inside diameter perforated PVC pipe (horizontal). There should be a screen material placed around the perforated pipe to avoid the soil particles from entering the pipe. Connect an access tube (25 mm PVC), approximately 1 m long (vertical). Cover the horizontal pipe with fine gravel approximately 3-5 cm thick. Fill the container with the excavated soil where each layer is repacked inside the lysimeter to match the original vertical soil state. [123].

#### B. Weighing Lysimeter

A weighing Lysimeter is capable of measuring ET for periods as short as ten minutes. Thus, it can provide more information than a drainage lysimeter can. Problems such as diurnal patterns of ET, the phenomenon of midday wilt, the short-term variation of energy partitioning, and the relationship between transpiration and soil moisture tension, can be investigated only by studying the records obtained from a weighing lysimeter. [5, 19, 60, 76, 92,101, 105,117].

Weighing lysimeters make direct measurements of water loss from a growing crop and the soil surface around a crop and thus, provide basic data to validate other water vapor flux prediction methods [23, 59, 85, 116]. The basic concept of this type of lysimeter is that it measures the difference between two mass values; the mass change is then converted into ET (mm) [47, 62].

During periods without rainfall, irrigation and drainage, the ET rate is computed as indicated by Howell [41], as:

$$ET = \left[ A_i \left[ (M_i - M_{i-1}) / A_i \right] / A_f \right] / T_i \quad /25/$$

Where: ET is in units of (mm.h<sup>-1</sup> or Kg. h<sup>-1</sup>) for time interval i; M is the lysimeter soil mass, (Kg); A<sub>i</sub> is lysimeter inner tank surface area (m<sup>2</sup>); A<sub>f</sub> is lysimeter foliage area (mid wall-air gap area) (m<sup>2</sup>); T is the time period (h). The ratio A<sub>f</sub> /A<sub>i</sub> is the



correction factor for the lysimeter effective area. This correction factor assumes the outside and inside vegetation foliage overlap evenly on all of the sides or edges. If there is no overlap, as occurs in short grass, the  $A_f/A_r=1.0$  [41].

Weighing lysimeters provide the most accurate data for short time periods, and can be determined accurately over periods as short as one hour with a mechanical scale, load cell system, or floating lysimeters [4]. Some weighing lysimeters use a weighing mechanism consisting of scales operating on a lever and pendulum principle (Harrold and Dreibelbis (1951), cited by Malone et al. [62]). However, some difficulties are very common like: electronic data logger replacement, data logger repair, load cell replacement, multiplexor installation, etc [62].

The measurement control in these lysimeters are important because of the following issues: a) re-calibration requirements, b) measurement drift (e.g., slope drift, variance drift), c) instrument problems (e.g., localized non-linearity of load cell, load cell damage, data logger damage), d) human error (e.g.; incorrectly recording data during calibration) and e) confidence in measurement results [62].

A load cell is a transducer that converts a load acting on it into an analog electrical signal. The electrical signal is proportional to the load and the relationship is determined through calibration, employing linear regressions models (mV/mm water), and it is used to determine mass changes of a lysimeter over the period of interest (e.g. day, hour, etc.).

The lysimeter characteristics can be different, for example: Malone et al., [62] built a lysimeter of the following form: 8.1 m<sup>2</sup> in surface area and 2.4 m depth, the lysimeter is constructed without disturbing the soil profile and the underlying fracture bedrock. The soil monolith is supported by a scale frame that includes a 200:1 lever system and a counterweight for the deadweight of the soil monolith. The gap between the soil in the lysimeters and the adjacent soil is between 5.1 cm and 7.0 cm except at the bottom slope where the runoff trough is located, this same author has given instructions for achieving a good calibration for this type of lysimeter.

Tyagi et al., [114] in wheat and sorghum, used two rectangular tanks, an inner and outer tank, constructed from 5-mm welded steel plates. The dimensions of the inner tank were 1.985 x 1.985 x 1.985 m and those of the outer tank were 2.015 x 2.015 x 2.015 m. The lysimeters were situated in the center of a 20-ha field. The size ratio of the outer tank to the inner tank is 1.03, so the error due to wall thickness is minimal. The effective area for crop ET was 4 m<sup>2</sup>. The height of the lysimeter rim was maintained near ground level to minimize the boundary layer effect in and around the lysimeter. The lysimeter tank was suspended on the outer tank by four load cells. The load cells were made out of the steel shear beam with 40,000-kg design load capacity. The total suspended mass of the lysimeter including tank, soil, and water was about 14,000 kg. This provided a safety factor of 2.85. The high safety factor was provided to allow replacement of a load cell without the danger of overloading and also to account for shock loading. A drainage assembly connected with a vertical stand and gravel bedding to facilitate pumping of drainage water was provided. The stand pipe also can be used to raise the water table in the lysimeter.

To calculate the ET using lysimeters, we need to employ the soil water balance (SWB) equation:

$$ET = R + I - P - R_{ff} \pm \Delta SM \quad /26/$$

Where: R is the rain, I is the irrigation,  $R_{ff}$  is the runoff, and  $\pm \Delta SM$  soil moisture changes, all in mm. The size of the lysimeter is an important element to be considered in water vapor flux studies with this method. For example, Dugas et al. [23] evaluated small lysimeters (<1.0 m<sup>2</sup>) and reported significant differences in the ET estimations, basically associated with the differences in the leaf area index (LAI) inside the lysimeters, which differed among lysimeters, this problem can be addressed using LAI corrections

### Calibration of the weighing lysimeter

Seyfried et al. [98] made a weighing lysimeter calibration by placing known weights on the lysimeters and then recording the resultant pressure changes. The weights used in that study were as follows: 19.9 kg for supportive blocks placed on the lysimeter, 43.4 kg for the tank which contained the weights, and then twenty-four 22.7 kg sacks of rock added in four-sack increments. The weight of each sack corresponded to about a 13 mm addition of water; so that weight increments were equivalent to ~52 mm and the total range was ~360 mm of water. Measurements were made both as weight was added and removed.

**The main arguments against the use of weighing lysimeters for monitoring water balance parameters and measuring solute transport parameters in the soil and unsaturated zone has been the discussion of potential sources of error, such as the well known oasis effect, preferential flow paths at the walls of the lysimeter cylinders due to an insufficient fit of soil monoliths inside the lysimeters, or the influence of the lower boundary conditions on the outflow rates [25].**

## THE MICROMETEOROLOGICAL METHODS

For many agricultural applications, micrometeorological methods are preferred since they are generally non-intrusive, can be applied on a semi-continuous basis, and provide information about the vertical fluxes that are occurring on scales ranging from tens of meter to several kilometres, depending on the roughness of the surface, the height of the instrumentation, and the stability of the atmospheric surface layer. Meyers and Baldocchi [65] have separated micrometeorological methods into four categories: 1) eddy covariance, 2) flux-gradient, 3) accumulation, and 4) mass balance. Each of these approaches are suitable for applications that depend on the scale; of interest and surface type, and instrumentation availability. Some of these methods are described in the following sections of this chapter.

### Humidity and Temperature Gradient Methods

Movement of energy, water and other gases between the field surface and atmosphere represent a fundamental process in the soil-plant-atmosphere continuum. The turbulent transport in the surface boundary layer affects the sensible (H) and latent ( $\lambda E$ ) heat fluxes, which along with the radiation balance, govern the evapotranspiration and canopy temperature [33].

Monteith and Unsworth [70] presented the functional form of the gradient flux equation, and which has applied by Harmsen et al. [36], Ramírez et al. [88] and Harmsen et al. [37]:

$$ET = \left( \frac{\rho_a \cdot c_p}{\gamma \cdot \rho_w} \right) \cdot \frac{(\rho_{vL} - \rho_{vH})}{(r_a + r_s)}$$

/27/

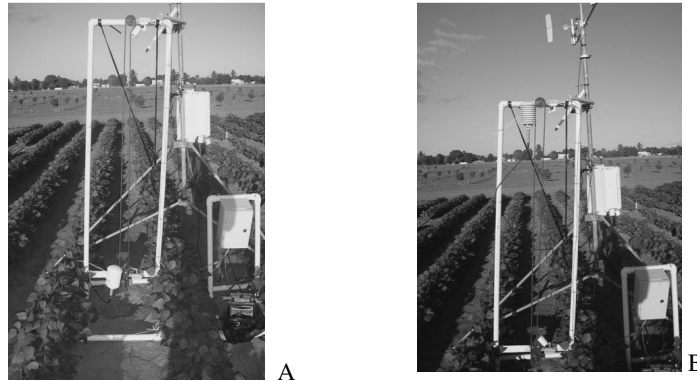
Where:  $\rho_w$  is the density of water,  $\rho_v$  is the water vapor density of the air,  $\rho_a$  is the air density,  $\gamma$  is the psychrometric constant,  $c_p$  is specific heat of air,  $r_a$  and  $r_s$  are aerodynamic and bulk surfaces resistances (all these variables are discussed in detail below). L and H are vertical positions above the canopy (L: low and H: High positions), for example in small crops like beans or grass, possible values of L and H could be 0.3 m and 2 m above the ground, respectively.

Harmsen et al. [36] developed an automated elevator device (ET Station) for moving a temperature and relative humidity sensor (Temp/RH) between the two vertical positions [Figure 2]. The device consisted of a plastic (PVC) frame with a 12 volt DC motor (1/30 hp) mounted on the base of the frame. One end of a 2-m long chain was attached to a shaft on the motor and the other end to a sprocket at the top of the frame. Waterproof limit switches were located at the top and bottom of the frame to limit the range of vertical movement. For automating the elevator device, a programmable logic controller (PLC) was used which was composed of “n” inputs and “n” relay outputs. To program the device, a ladder logic was used which is a chronological arrangement of tasks to be accomplished in the automation process. The Temp/RH sensor was connected to the elevator device, which measured relative humidity and temperature in the up position for two minutes then changed to the down position where measurements were taken for two minutes. This process started each day at 0600 hours and ended at 1900. When the elevator moves to the up position it activates the limit switch which sends an input signal to the PLC. That input tells the program to stop and remain in that position for two minutes. At the same time it activates an output which sends a 5 volt signal to the control port C2 in the CR10X data logger in which a small subroutine is executed. This subroutine assigns a “1” in the results matrix which indicates that the temperature and relative humidity corresponding to the up position. At the end of the two minute period, the elevator moves to the down position and repeats the same process, but in this case sending a 5 volts signal to the data logger in the control port C4, which then assigns a “2” in the results matrix. All information was stored in the weather station data-logger CR-10X (Campbell Scientific, Inc.) for later downloading to a personal computer.

### The Bowen Ratio Energy Balance Method

The basis for this method is that the local energy balance is closed in such a way that the available net radiative flux ( $R_n$ ) is strictly composed of the sensible (H), latent ( $\lambda E$ ), and ground heat (G) fluxes, and other stored terms such as those related to canopy heat storage and photosynthesis are negligible [65].

This method combines measurements of certain atmospheric variables (temperature and vapor concentration gradients) and available energy (net radiation and changes in stored thermal energy) to determine estimates of ET [58]. The method incorporates energy-budget principles and turbulent-transfer theory. Bowen showed that the ratio of the sensible- to latent-heat flux ( $\beta$ ) could be calculated from the ratio of the vertical gradients of temperature and vapor concentration over a surface under certain conditions.



**Figure 2.** Automated elevator device developed for moving the Temp/RH sensor between the two vertical positions: **A.** Temp/RH sensor in down position and **B.** Temp/RH sensor in up position. Measuring over common bean (*Phaseolus vulgaris* L.). [Picture obtained by the project sponsored by NOAA-CREST (NA17AE1625), NASA-EPSCoR (NCC5-595), USDA-TSTAR-100, and University of Puerto Rico Experiment Station]

Often the gradients are approximated from air-temperature and vapor-pressure measurements taken at two heights above the canopy. The Bowen-ratio method assumes that there is no net horizontal advection of energy. With this assumption, the

coefficients (eddy diffusivities) for heat and water vapor transport,  $K_h$  and  $K_w$ , respectively, are assumed to be equal. Under advective conditions,  $K_h$  and  $K_w$  are not equal [112] and the Bowen-ratio method fails to accurately estimate ET.

Based on the assumption that  $K_h$  and  $K_w$  are equal, and by combining several terms to form the psychrometric constants, the Bowen-ratio takes the form of the equation /2/. Although the theory for this method was developed in the 1920s by Bowen [11], its practical applications has only been possible in recent decades, due to the availability of accurate instrumentation [77]. The Bowen ratio initial concept is shown below:

$$\beta = \frac{PC_p K_h \frac{dT}{dz}}{\lambda \epsilon K_w \frac{de}{dz}} \quad /28/$$

If it is assumed that there is no net horizontal advection of energy, equation /28/ can be simplified as shown below:

$$\beta = \frac{PC_p \frac{dT}{dz}}{\lambda \epsilon \frac{de}{dz}} \quad /29/$$

Where:  $P$  is the atmospheric pressure (kPa),  $C_p$  is the specific heat of air (1.005 J/g°C),  $\epsilon$  is the ratio molecular weight of water to air = 0.622 and  $\lambda$  is the latent-heat flux (Jg<sup>-1</sup>). Once the Bowen ratio is determined, the energy balance can be solved for the sensible-heat flux ( $H$ ) and latent-heat flux ( $\lambda E$ ).

$$R_n = \lambda E + H + G \quad /30/$$

Where:  $R_n$  is the net radiation,  $\lambda E$  is the latent-heat flux,  $H$  is the sensible-heat flux and  $G$  is the soil-heat flux.

$$H = \beta \lambda E \quad /31/$$

$$\lambda E = \frac{(R_n - G)}{(1 + \beta)} \quad /32/$$

The latent heat flux can be separated into two parts: the evaporative flux  $E$  (g m<sup>-1</sup> day<sup>-1</sup>) and the latent heat of vaporization  $\lambda$  (Jg<sup>-1</sup>), which can be expressed as a function of air temperature ( $T$ ) ( $\lambda = 2,502.3 - 2.308 T$ ). The latent-heat of vaporization ( $\lambda$ ) is defined as the amount of energy required to convert 1 gram of liquid water to vapor at constant temperature  $T$ . Sensible-heat flux ( $H$ ) is a turbulent, temperature-gradient driven heat flux resulting from differences in temperature between the soil and vegetative surface and the atmosphere.

The soil-heat flux ( $G$ ) is defined as the amount of energy moving downward through the soil from the land surface, caused by temperature gradient. This flux is considered positive when moving down through the soil from the land surface and negative when moving upward through the soil toward the surface [111]. The soil heat flux is obtained by measuring two soil heat flux plates below the soil surface at 2 and 8 cm, soil moisture at 8 cm, and soil temperature at 6 cm between the two soil heat flux plates [15].

Because the soil-heat flux is measured below the soil surface, some of the energy crossing the soil surface could be stored in, or come from, the layer of soil between the surface and flux plate located closest to the surface, and for this reason a change in storage term,  $S$  [33] is added to the measured heat flux (equation /33/):

$$S = \left[ \frac{\Delta T_s}{\Delta t} \right] d \rho_b (C_s + (WC_w)) \quad /33/$$

Where:  $S$  is the heat flux going into storage (Wm<sup>-2</sup>),  $\Delta t$  is the time interval between measurement (sec),  $\Delta T_s$  is the soil temperature interval between measurement,  $d$  is the depth to the soil-heat-flux plates (0.08m),  $\rho_b$  is the bulk density of dry soil (1300 kgm<sup>-3</sup>),  $C_s$  is the specific heat of dry soil (840 J/Kg°C),  $W$  is the water content of soil (kg the water/ Kg the soil) and  $C_w$  is the specific heat of water (4.190 J/Kg°C). The soil heat flux ( $G$ ) at the surface is obtained by including the effect of storage between the surface and depth,  $d$ , using equation 11.

$$G = \left( \frac{FX_1 + FX_2}{2} \right) + S \quad /34/$$

Where:  $FX_1$  is the soil-heat flux measured flux plate 1 (Wm<sup>-2</sup>),  $FX_2$  is the soil-heat flux measured flux plate 2 (Wm<sup>-2</sup>).

One of the requirements for using the Bowen-ratio method is that the wind must pass over a sufficient distance of similar vegetation and terrain before it reaches the sensors. This distance is referred to as the fetch, and the fetch requirement is generally considered to be 100 times the height of the sensors above the surface [16]. More detail about determination of the minimum fetch requirement is presented later in this chapter.

Frank [27] reported a ratio  $\lambda E/R_n$  of 0.16 for dry soil conditions and 0.97 for wet soil conditions; On the other hand he found  $\lambda E/R_n$  to be lowest in grazed prairie, suggesting that defoliation changes the canopy structure and energy budget components, which may have contributed to increase water loss through evaporation compared with the non-grazed prairie treatment. Hanson and May [34], using the Bowen Ratio Energy Balance Method to measure ET in tomatoes, found that ET rates decreased substantially in respond to drying of the soil surface. Perez et al. [83] proposed a simple model for estimating the Bowen ratio ( $\beta$ ) based on the climatic resistance factors:

$$\beta = \frac{\Delta + \gamma}{\Delta} \cdot \frac{1 + S}{1 + C} - 1 \quad /35/$$

$$C = \frac{\gamma \cdot r_i}{\Delta \cdot r_a} \quad /36/$$

$$S = \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_c}{r_a} \quad /37/$$

Where:  $r_c$  is the canopy resistance ( $s \cdot m^{-1}$ ) based on the “big leaf” concept, and  $r_a$  is the aerodynamic resistance ( $s \cdot m^{-1}$ ). These resistance factors are described in detail in the next section. The factor  $r_i$  is the climatological resistance as reported by [66]:

$$r_i = \frac{\rho_a C_p VPD}{\gamma(R_n - G)} \quad /38/$$

Where:  $\rho_a$  is the air density at constant pressure ( $Kg \cdot m^{-3}$ ),  $C_p$  is the specific heat of moist air at constant pressure ( $1004 J \cdot Kg^{-1} \cdot ^\circ C^{-1}$ ), VPD is the vapor pressure deficit of the air (Pa),  $\gamma$  is the psychrometric constant ( $Pa \cdot ^\circ C^{-1}$ ) and  $R_n$  and  $G$  are in  $W \cdot m^{-2}$ . For homogeneous canopies, the effective crop surface and source of water vapor and heat is located at height  $[d + z_{oh}]$ , where  $d$  is the zero plane displacement height and  $z_{oh}$  is the roughness length governing the transfer of heat and vapor [5].

### The Penman-Monteith Method

The important contribution of Monteith and Penman's original equation was the use of resistances factors, which was based on an electric analogy for the potential difference needed to drive unit flux systems that involve the transport of momentum, heat, and water vapor [69,70]. The resistances have dimensions of time per unit length, as will describe later. This methodology calculates the latent heat flux using the vapor pressure deficit, the slope of the saturated vapor-pressure curve and aerodynamic resistance to heat, and canopy resistance in addition to the energy-budget components of the net radiation, soil heat flux, and sensible heat flux. Field measurements of air temperature, relative humidity, and wind speed are needed to determine these variables [11]. Equation /21/ describes the Penman-Monteith (P-M) method to estimate the  $\lambda E$  [5,54]:

$$\lambda E = \frac{\Delta s(R_n - G) + \rho_a C_p \frac{VPD}{r_a}}{\Delta s + \gamma \left( 1 + \frac{r_s}{r_a} \right)} \quad /39/$$

Where:  $\lambda E$ ,  $R_n$ , and  $G$  in  $W \cdot m^{-2}$ , VPD is vapor pressure deficit (kPa),  $\Delta s$  is slope of saturation vapor pressure curve ( $kPa \cdot ^\circ C^{-1}$ ) at air temperature,  $\rho$  is density of air ( $Kg \cdot m^{-3}$ ),  $C_p$  in  $J \cdot Kg^{-1} \cdot ^\circ C^{-1}$ ,  $\gamma$  in  $kPa \cdot ^\circ C^{-1}$ ,  $r_a$  is aerodynamic resistant ( $s \cdot m^{-1}$ ), and  $r_s$  surface resistance to vapor transport ( $s \cdot m^{-1}$ ).

According to Monteith [69], the appearance of a wind-dependent function in the denominator as well as in the numerator implies that the rate of evaporation calculated from the P-M model is always less dependent on wind speed than the rate corresponding to the Penman equation when other elements of the climate are unchanged. In general, estimated rates are usually insensitive to the magnitude of  $r_a$  and the error generated by neglecting the influence of the buoyancy correction is often small. In contrast, the evapotranspiration rate is usually a strong function of the surfaces resistance ( $r_s$ ).

Kjelgaard and Stockle [54] say the surface resistance ( $r_s$ ) parameter in the P-M model is particularly difficult to estimate due to the combined influence of plant, soil and climatic factors that affect its value. The magnitude of the stomatal resistance can be estimated in principle from the number of stomata per unit leaf area and from the diameter and length of pores, which is difficult and therefore rarely measured; therefore, the stomatal resistance is usually calculated from transpiration rates or estimated gradients of vapor concentration [69].

Knowing the value of the *aerodynamic resistance* ( $r_a$ ) permits estimation of the transfer of heat and water vapor from the evaporating surface into the air above the canopy. The aerodynamic resistance for a single leaf to diffusion through the boundary layer surrounding the leaf, within which the transfer of heat, water vapor, etc., occurs, proceeds at a rate governed by molecular diffusion. Provided the wind speed is great enough and the temperature difference between the leaf and air is small enough to ensure that transfer processes are not affected by gradients of air density. The boundary layer resistance depends on air velocity and on the size, shape, and altitude of the leaf with respect to the air stream. In very light wind, the rates of transfer are determined mainly by gradients of temperature and therefore by density, so that the  $r_a$  depends more on the mean leaf-air temperature difference than on wind speed. According to Thom [109], the  $r_a$  for heat transfer can be determined as follows:

$$r_{ah} = \frac{\rho C_p (T_s - T_a)}{H} \quad /40/$$

At the field level,  $r_a$  for homogeneous surfaces, such as bare soil or crop canopies, there is a large-scale analogous boundary layer resistance, which can be estimated or derived from measurements of wind speed and from a knowledge of the aerodynamic properties of the surface as is described later [69]. The  $r_a$  can be determined given values of roughness length ( $Z_o$ ) and zero plane displacement height ( $d$ ), that depend mainly on crop height, soil cover, leaf area and structure of the canopy [1]:

$$r_a = \frac{Ln \left[ \frac{(Z_m - d)}{Z_{om}} \right] Ln \left[ \frac{(Z_h - d)}{Z_{oh}} \right]}{K^2 u_z} \quad /41/$$

Where:  $Z_m$  is height of wind measurements (m),  $Z_h$  is height of humidity measurements (m),  $d$  is zero displacement height (m),  $Z_{om}$  is roughness length governing momentum transfer of heat and vapor (m) equal to  $0.123h$ ,  $h$  is crop height,  $Z_{oh}$  is roughness length governing transfer of heat and vapor (m) equal to  $0.1Z_{om}$ ,  $K$  is the von Karman's constant (0.41), and  $u_z$  is wind speed at height  $z$ .

The equation /41/ is restricted for neutral stability conditions, i.e., where temperature, atmospheric pressure, and wind speed velocity distribution follow nearly adiabatic conditions (no heat exchange). The application of the equation for short time periods (hourly or less) may require the inclusion of corrections for stability. However, when predicting  $ET_o$  in the well watered reference surface, heat exchange is small, and therefore the stability correction is normally not required [5].

Alves et al. [1] state that though this is the most used expression for  $r_a$ , in fact it is not entirely correct, since it assumes a logarithmic profile from the source height ( $d + Z_{oh}$ ) with increasing  $z$  in the atmosphere, using the concept to the “big leaf”, equation /41/ can be modified as follows:

$$r_a = \frac{Ln\left(\frac{z-d}{h_c-d}\right)Ln\left(\frac{z-d}{Z_{om}}\right)}{K^2 u_z} \quad /42/$$

Where:  $h_c$  is the height of the crop canopy. According to Tolk et al. [110], the  $r_a$  to momentum transport in the absence of buoyancy effects (neutral stability) follows the equation /43/:

$$r_{am} = \ln[(Z_i - d)/Z_{om}]^2 / k^2 u_z \quad /43/$$

Under adiabatic conditions, the equations must be corrected using the Richardson number for stability correction, assuming similarity in transport of heat and momentum, yielding:

$$r_{ah} = r_{am}(1 + 5R_i) \quad /44/$$

The  $R_i$  for stability conditions is considered when  $(-0.008 \leq R_i \leq 0.008)$  and is calculated by:

$$R_i = [g(T_a - T_s)(Z - d)] / T_{av} u_z^2 \quad /45/$$

Where:  $g$  is the acceleration of the gravity ( $9.8 \text{ m.s}^{-2}$ ),  $T_a$  is the air temperature (K),  $T_c$  is the plant canopy temperature (K),  $T_{av}$  is the average temperature taken as  $((T_a + T_c)/2)$ . The advantage of the  $R_i$  over other stability corrections is that it contains only experimentally determined gradients of temperature and wind speed and does not depend directly on sensible heat flux [110].

The **bulk surface resistance** ( $r_s$ ) describes the resistance of vapor flow through transpiring crop leaves and evaporation from the soil surface. Where the vegetation does not completely cover the soil, the resistance factor should indeed include the effects of the evaporation from the soil surface. If the crop is not transpiring at a potential rate, the resistance depends also on the water status of the vegetation [5,115], and for this case they proposed the use of the following approximate:

$$r_s = \frac{r_L}{LAI_{active}} \quad /46/$$

Where:  $LAI_{active}$  is 0.5 times the leaf area index ( $\text{m}^2$  of leaf per  $\text{m}^2$  of soil), and  $r_L$  is bulk stomatal resistance, which is the average resistance of an individual leaf, and can be measured using an instrument called a porometry. The first stomatal readings were developed by Francis Darwin who developed horn hygrometer [113].

The  $r_L$  readings are highly variable and depend on several factors, such as: crop type and development stage, the weather and soil moisture variability, the atmospheric pollutants and the plant phytohormone balance [113]. Typically to determine minimum  $r_L$  using a porometer, fully expanded, sunlit leaves near to the top of the canopy are surveyed during maximum solar irradiance (approximately solar noon under cloudless conditions) and low VPD periods [54]. This “standard” value from literature or porometer measurements are hereafter identified as  $r_{Lmin}$ . In addition,  $r_L$  has been shown to increase with increasing VPD and/or reduced solar irradiance ( $R_s$ ). Adjustment factors for VPD ( $f_{VPD}$ ) and  $R_s$  ( $f_{Rs}$ ) were empirically derived and used as multipliers of  $r_{Lmin}$ . The dependence of  $r_L$  on VPD can be represented by a linear function [46] as:

$$f_{VPD} = a + b[VPD] \quad /47/$$

Where:  $a$  and  $b$  are linear regression coefficients, and  $f_{VPD}$  is equal to 1 (no adjustment) for  $VPD \leq$  a threshold value, which can be taken as 1.5 kPa. The same authors presented a calibrated form of equation 47 for corn as,  $f_{VPD} = 0.45 + 0.39(VPD)$ . Kjelgaard and Stockle [54] presented a modified form of the adjustment factor:

$$f_{Rs} = \frac{R_{smax}}{C_2 + R_s} \quad /48/$$

Where:  $R_s$  and  $R_{smax}$  are the actual and maximum daily solar irradiance ( $\text{MJ m}^{-2} \text{ day}^{-1}$ ) and  $C_2$  is a fitted constant. Taking the maximum of the adjustment factors for VPD and  $R_s$ ,  $r_{Lmin}$  is modified to give  $r_L$  [54]:

$$r_L = r_{Lmin} \max\{f_{VPD}, f_{Rs}\} \quad /49/$$

Where:  $f_{VPD}$  and  $f_{Rs}$ , are equal to or greater than 1. Alves et al. [1] indicated that the surface resistance term ( $r_s$ ) has been the most discussed in the literature. Several components to be considered here include: a) The resistances to water vapor at the evaporating surfaces: plants and their stomates ( $r_s^c$ ) and soil ( $r_s^b$ ); b) the resistance to vapor transfer inside the canopy from these evaporating surfaces up to the “big leaf” ( $r_s^a$ ). The resistance  $r_s^c$ , can be approximated using equation /50/.

$$r_s^c = \frac{\left( \sum_{i=1}^n \frac{1}{r_{sti}} \right)^{-1}}{LAI} \quad /50/$$

Where:  $r_{st}$  is the single leaf stomatal resistance ( $\text{sm}^{-1}$ ),  $n$  is a leaf number. The bulk surface resistance can also be calculated using the inversion of the Penman-Monteith equation with incorporation of the Bowen ratio as follow [1, 3]:

$$r_s = r_a \left( \frac{\Delta s}{\gamma} \beta - 1 \right) + \frac{\rho_a C_p VPD}{\gamma \lambda E} \quad /51/$$

Accurate prediction of  $r_s$  requires a good estimate of the Bowen ratio ( $\beta$ ). Ramirez [87] has used the following inversion form of the Penman-Monteith equation to obtain estimates of  $r_s$ :

$$r_s = r_a \cdot \left[ \frac{\Delta(R_n - G) + \rho_a C_p \left( \frac{VPD}{r_a} \right)}{\lambda E} - \Delta - \gamma \right] \quad /52/$$

Similarly these authors, analysing the resistance concepts, concluded that the  $r_s$  of dense crops cannot be obtained by simply averaging stomatal resistance because the driving force (vapor pressure deficit) is not constant within the canopy.

Saugier [96] addressed canopy resistance ( $r_c$ ), stating that it is normally a mixture of soil and plant resistances to evaporation. If the top the soil is very dry, direct soil evaporation may be neglected and  $r_c$  is approximately equal to the leaf resistance ( $r_L$ ) divided by the LAI. Baldocchi *et al.* [10], indicated that the inverse of the ‘big-leaf’ model (eg., inverse of the P-M model) will be a good estimate of canopy resistance or surface resistances if certain conditions are met. These conditions include: i) a steady-state environment; ii) a dry, fully developed, horizontally homogeneous canopy situated on level terrain; iii) identical source-sink levels for water vapor, sensible heat and momentum transfer, and negligible cuticular transpiration and soil evaporation. Szeicz and Long [104] described a profile method to estimate  $r_s$  as:

$$r_s = \frac{\rho_a C_p VPD}{\gamma \lambda E} \quad /53/$$

These methods can be used in the field when the rate of evapotranspiration is measured by lysimeters or calculated from the Bowen ratio energy balance method, and the temperature, humidity and wind profiles are measured within the boundary layer simultaneously. Ortega-Farias *et al.* [74], evaluated a methodology for calculating the canopy surface resistance ( $r_{cv} \approx r_s$ ) in soybean and tomatoes, using only meteorological variables and soil moisture readings. The advantage of this method is that it can be used to estimate  $\lambda E$  by the general Penman-Monteith model with meteorological readings at one level, and without  $r_L$  and LAI measurements.

$$r_s = \frac{\rho_a C_p VPD}{\Delta(R_n - G)} \cdot \frac{\theta_{FC} - \theta_{WP}}{\theta_i - \theta_{WP}} \quad /54/$$

Where:  $\theta_{FC}$  and  $\theta_{WP}$  are the volumetric moisture content at field capacity (fraction) and wilting point (fraction), respectively, and  $\theta_i$  is a volumetric soil content in the root zone (fraction) measured each day. Kamal and Hatfield [48] used the equation /51/ to determine the surface resistance in Potato; and stated that the canopy resistance ( $r_c$  in  $\text{s.m}^{-1}$ ; “mean stomatal resistances of crops”), can be determined by dividing the  $r_s$  by the effective LAI as defined by other authors such as Hatfield and Allen [38] and for well watered crops,  $r_c$  can be estimated using equation /55/.

$$r_c = \frac{0.3LAI + 1.2}{LAI} r_s \quad /55/$$

Kjelgaard and Stockle [54] discussed the estimation of canopy resistance ( $r_c$ ) from single-leaf resistance ( $r_L$ , equation /56/), as originally proposed by Szeicz and Long [104]:

$$r_c = \frac{r_L}{LAI_{active}} \quad /56/$$

Kamal and Hatfield [48] divided the surface resistance ( $r_s$ ) used in the P-M model into two components, and conceptualized an excess resistance ( $r_o$ ) in series with the canopy stomatal resistance. This excess resistance was linked to the structure of the crop, particularly crop height.

$$r_s = r_c + r_o \quad /57/$$

Pereira *et al.* [81] stated that the surface resistance ( $r_s$ ) is the sum of two components: one corresponding mainly to the stomatal resistance ( $r_{st}$ ), the other to the leaf boundary layer and turbulent transfer inside the canopy ( $r_{ai}$ ) (equation 58), thus, surface resistance is not a purely physiological parameter:

$$r_s = r_{st} + r_{ai} \quad /58/$$

Stomatal resistance can take values from  $80 \text{ s.m}^{-1}$  to  $90 \text{ s.m}^{-1}$  as a common range for agricultural crops, with a suggested value of  $100 \text{ s.m}^{-1}$  for most arable crops [67]. Table 1 lists mean values for various crops under well water conditions.

The  $r_L$  is strongly dependent on the time of day (basically due to the temporal nature of climatic conditions), soil moisture content and by the plant genotype. Figure 3A shows how larger differences in  $r_L$  occur, with and without drought stress,

after 9:00 am until late in the afternoon, and the most critical point is at 13:00 hours when the highest VPD occurred. For this reason, when this variable ( $r_L$ ) is not measured, appropriate parameterization is required for good water flux or ET estimation, especially under drought stress conditions. In Figure 3C, it is possible to see in a common bean genotype under drought stress conditions, lower  $r_L$  as compared with less drought resistance during several days with drought stress. Kjelgaard and Stockle [54] conceptualized the excess resistance ( $r_o$ ) as a linear function of crop height and LAI:

$$r_o = ah_c + bLAI \quad /59a/$$

Where: a and b are constants. For corn, Kjelgaard and Stockle [54] parameterized equation /59a/ as follows:

$$r_o = 16.64h_c + 0.92LAI \quad /59b/$$

Canopy resistance can also be determined from leaf or canopy temperature since it is affected by plant characteristics, e.g. Leaf area index (LAI), height, and maturity. Soil factors (available soil water-ASW, and soil solution salinity) and weather factors ( $R_n$  and wind speed) also affect the canopy resistance.

Monteith [66] showed that transpiration rate physically depends on relative changes of surface temperature and  $r_a$ , and concluded that  $r_a$  depends on the Reynolds number of the air and can be determined from wind speed, the characteristic length of the plant surface, and the kinematic viscosity of the air. An increase in  $r_c$  for Wheat was caused by a decrease in total leaf area, by an increase in the resistance of individual leaves due to senescence, or by a combination of both effects; in Sudan grass,  $r_c$  increased with plant age and a decrease in soil moisture. Van Bavel [115] studied Alfalfa throughout an irrigation cycle and found that canopy resistance increased linearly with decreasing soil water potential. Kamal and Hatfield [48] found an exponentially inverse relationship between canopy resistance and net radiation, and a linear inverse relationship between canopy resistance and available soil water.

The Drainage and Irrigation Paper-FAO 56 [5] recommended the Szeicz and Long [104] method for calculating  $r_s$  (equation /56f/), where an average of  $r_L$  for different positions within the crop canopy, weighted by LAI or  $LAI_{\text{effective}}$  is used. This method gives good results only in very rough surfaces, like forest and partial cover crops with a dry soil [67]. Alves et al. [1] concluded that  $r_s$  of dense crops cannot be obtained by simply averaging stomatal resistance ( $r_L$ ) because VPD, which is the “driving force”, is not constant within the canopy. Alves and Pereira [3] have stated “The PM model can be used to predict ET if accurate methodologies are available for determining the  $r_s$  that take into account the energy partitioning”.

In addition to the lack of  $r_s$  values for crops, questions have been raised relative to the appropriateness of using the PM model for partial or sparse canopies because the source/sink fluxes may be distributed in a non-uniform manner throughout the field [24, 32, 55,75]. Adequate parameterization of the surface resistance makes the P-M model a good estimator of ET [3,74 90,96,].

Ramirez [87] reported that the daily ET estimation with the P-M model with  $r_s$  based on  $r_L$  and  $LAI_{\text{effective}}$  gave a good estimation in two common bean genotypes with variable LAI, without and with moderate drought stress for two crop seasons (2006 and 2007).

Ramirez et al. [88] reported inverse relation between  $r_a$  and  $r_s$  and  $r_L$  in beans (*Phaseolus vulgaris* L), as well as those reported by Alves and Pereira [3] (Fig. 4), which implies that with low  $r_a$  (windy conditions), the  $r_L$  (and therefore  $r_c$ ) increases. The Alves and Pereira [3] study did not measure the  $r_L$ , rather the  $r_s$  was estimated based on micrometeorological parameters.

Disparities in the measured  $r_s$  using the P-M inverse model arise from: a) imperfect sampling of leaves and the arbitrary method of averaging leaf resistance over the whole canopy, b) from the dependence of  $r_s$  on non-stomatal factors such as evaporation from wet soil or stems, or others and c) the complex aerodynamic behaviour of canopies [68].

Lower LAI index ( $LAI < 1.0$ ) and drought stress also affect the precision in the  $r_s$  estimation [87]. Use of the  $LAI_{\text{effective}}$  when  $LAI < 1.0$  is not necessary and tends to overestimate the  $r_s$  and under-estimate the ET. Katerji and Perrier [51] found for  $LAI > 1.0$  a good agreement between measured values of evapotranspiration over alfalfa crops using the energy balance method, and values calculated with P-M equation using variable  $r_s$ . Katerji and Perrier [50] proposed to simulate  $r_s$  using the following relation:

$$\frac{r_s}{r_a} = a \frac{r^*}{r_a} + b \quad /60/$$

Where: a and b are linear coefficients that should be determined empirically,  $r^*$  ( $s.m^{-1}$ ) is a climatic resistance [52] giving by:

$$r^* = \frac{\Delta + \gamma}{\Delta \lambda} \cdot \frac{\rho C_p VPD}{(R_n - G)} \quad /61/$$

Table 2 presents values of a and b for several crops. The Penman-Monteith model is considered as a ‘single-layer’ model. Shuttleworth and Wallace [100] developed a ‘double-layer’ model, relying on the Penman-Monteith model concept to describe the latent heat flux from the canopy ( $\lambda T$ ) and from the soil ( $\lambda E$ ) as follows:

$$\lambda T = \frac{\Delta(R_n - R_{ns}) + \rho C_p \frac{VPD_o}{r_a^c}}{\Delta + \gamma \left( 1 + \frac{r_s^c}{r_a^c} \right)} \quad /62/$$

$$\lambda E = \frac{\Delta(R_{ns} - G) + \rho C_p \frac{VPD_o}{r_a^s}}{\Delta + \gamma \left( 1 + \frac{r_s^s}{r_a^s} \right)}$$

/63/

Where:  $R_{ns}$  is the absorbed net radiation at the soil surface,  $r_a^c$  is the bulk boundary layer resistance of the canopy elements within the canopy,  $r_s^c$  is the bulk stomatal resistance of the canopy,  $r_a^s$  is the aerodynamic resistance between the soil and the mean canopy height,  $r_s^s$  is the surfaces resistance of the soil and  $VPD_o$  is the vapor pressure deficit at the height of the canopy air stream.

**Table 1.** Average values of the stomatal resistance ( $r_L$ ) for several crops.

| Cover crops           | $r_L$<br>s/m | Source                                        | Cover crops                             | $r_L$<br>s/m               | Source                                                         |
|-----------------------|--------------|-----------------------------------------------|-----------------------------------------|----------------------------|----------------------------------------------------------------|
| Corn                  | 200          | Kirkham et al. [53]                           | Cassava                                 | 714<br>Between 476 to 1428 | Oguntunde [73]. This data under limited soil water conditions. |
| Sunflower             | 400          | Kirkham et al. [53]                           | Eucalyptus                              | 200-400                    | Pereira and Alves [81]                                         |
| Soybean and potato    | 350          | Kirkham et al. [53]                           | Maple                                   | 400-700                    | Pereira and Alves [81]                                         |
| Sorghum               | 300          | Kirkham et al. [53]                           | Crops-General                           | 50-320                     | Pereira and Alves [81]                                         |
| Millet                | 300          | Kirkham et al. [53]                           | Grain sorghum                           | 200                        | Pereira and Alves [81]                                         |
| Aspen                 | 400          | Pereira and Alves [81]                        | Soybean                                 | 120                        | Pereira and Alves [81]                                         |
| Maize                 | 160          | Pereira and Alves [81]                        | Barley                                  | 150-250                    | Pereira and Alves [81]                                         |
| Alfalfa               | 80           | Pereira and Alves [81]                        | Sugar beet                              | 100                        | Pereira and Alves [81]                                         |
| Clipped grass (0.15m) | 100-150      | Pereira and Alves [81]                        | Clipped & Irrigated grass (0.10-10.12m) | 75                         | Pereira and Alves [81]                                         |
| Common beans          | 170-270      | Ramirez [87]                                  | Sorghum                                 | 192                        | Stainer et al. [101]                                           |
| Corn                  | 264          | Ramirez and Harmsen (2007). Unpublished data. | Andes Tropical Forestry                 | 132                        | Ramirez and Jaramillo [89]. (Calculated)                       |
| Coffee                | 149          | Ramirez and Jaramillo [89]. (Calculated)      | Coffee                                  | 150                        | Angelocci et al. [7]                                           |
| Wheat                 | 134          | Howell et al. [42]                            | Corn                                    | 252                        | Howell et al. [42]                                             |
|                       |              |                                               | Sorghum                                 | 280                        | Howell et al. [42]                                             |

#### The Double-layer Shuttleworth-Wallace Model

The Shuttleworth-Wallace Model (S-W) assumes that there is blending of heat fluxes from the leaves and the soil in the mean canopy airflow at the height of the effective canopy source [100]. The full expression of the Shuttleworth-Wallace Model (S-W) is presented by Zhang *et al.* (2008) as follows:

$$\lambda ET = \lambda E + \lambda T = C_{SW}^S PM_{SW}^S + C_{SW}^P PM_{SW}^P \quad /64/$$

$$PM_{SW}^S = \frac{\Delta A_{SW} + [\rho C_p D - \Delta r_a^s (A_{SW} - A_{SW}^s)] / (r_a^a + r_a^s)}{\Delta + \gamma [1 + r_s^s / (r_a^a + r_a^s)]} \quad /65/$$

$$PM_{SW}^P = \frac{\Delta A_{SW} + [\rho C_p D - \Delta r_a^p A_{SW}^s] / (r_a^a + r_a^p)}{\Delta + \gamma [1 + r_s^p / (r_a^a + r_a^p)]} \quad /66/$$

$$C_{SW}^S = \frac{1}{1 + [R_{SW}^S R_{SW}^a / R_{SW}^P (R_{SW}^S + R_{SW}^a)]} \quad /67/$$



$$C_{SW}^P = \frac{1}{1 + \left[ R_{SW}^P R_{SW}^a / R_{SW}^S (R_{SW}^P + R_{SW}^a) \right]} \quad /68/$$

$$R_{SW}^S = (\Delta + \gamma) r_a^s + \gamma_s^s \quad /69/$$

In equation /70/,  $\lambda E$  is the latent heat flux of evaporation from the soil surfaces ( $W/m^2$ ),  $\lambda T$  the latent heat fluxes of transpiration from canopy ( $W/m^2$ ),  $r_s^P$  the canopy resistance (s/m),  $r_a^P$  the aerodynamic resistance of the canopy to in-canopy flow (s/m),  $r_s^S$  the soil surfaces resistance (s/m),  $r_a^a$  and  $r_a^s$  the aerodynamic resistance from the reference height to in-canopy heat exchange plane height and from there to the soil surface (s/m), respectively.  $A_{sw}$  and  $A_{SW}^s$  are the total available energy and the available energy to the soil ( $W/m^2$ ), respectively and defined in equations /70/ to /73/:

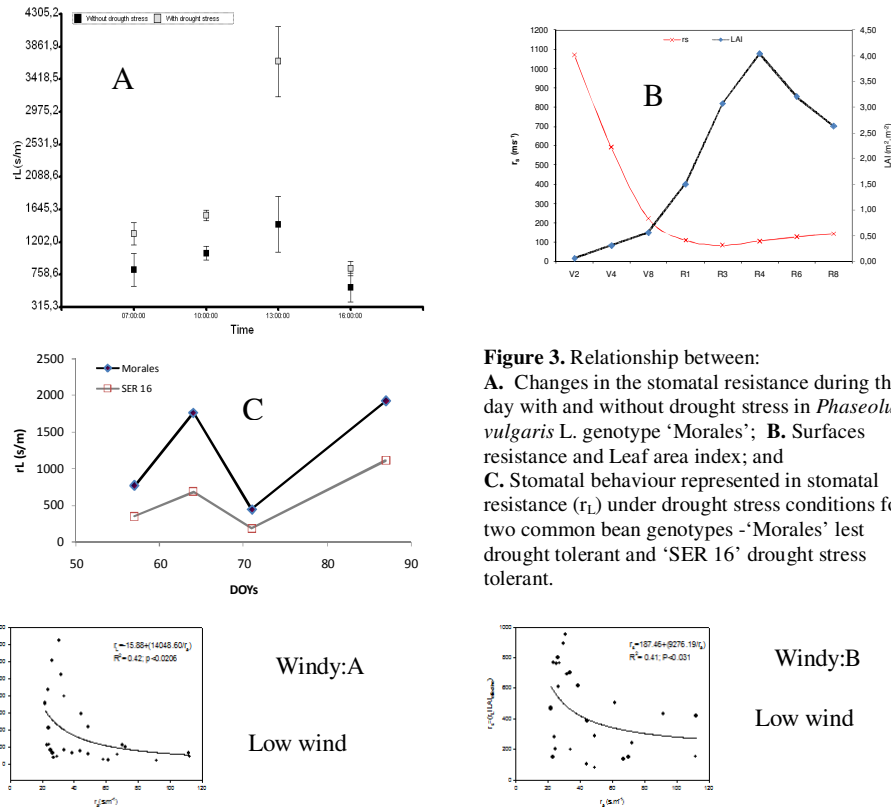
$$R_{SW}^P = (\Delta + \gamma) r_a^P + \gamma_s^P \quad /70/$$

$$Ra_{SW}^P = (\Delta + \gamma) r_a^a \quad /71/$$

$$A_{sw} = R_n - G \quad /72/$$

$$A_{SW}^s = R_{n_{SW}}^s - G \quad /73/$$

In equation /73/,  $R_{n_{SW}}^s$  is the net radiation fluxes into the soil surface ( $W/m^2$ ), and can be calculated using the Beer's law:



**Figure 3.** Relationship between: **A.** Changes in the stomatal resistance during the day with and without drought stress in *Phaseolus vulgaris* L. genotype 'Morales'; **B.** Surfaces resistance and Leaf area index; and **C.** Stomatal behaviour represented in stomatal resistance ( $r_L$ ) under drought stress conditions for two common bean genotypes - 'Morales' lest drought tolerant and 'SER 16' drought stress tolerant.

**Figure 4.** **A.** Aerodynamic resistance ( $r_a$ ) as a function of stomatal resistance ( $r_L$ ); and **B.** Aerodynamic resistance ( $r_a$ ) as a function of measured surface resistance ( $r_s = r_L / LAI_{effective}$ ) [Data from: Ramirez, [87]].

$$R_{n_{SW}}^s = R_n \cdot \exp^{(-c \cdot LAI)} \quad /74/$$

In equation /74/,  $c$  is the extinction coefficient of light attenuation (e.g.; Sene, [97] indicate  $k=0.68$  for fully grown plant,  $k=0$  for bare soil; Zhang *et al.*, [125] use 0.24 for vineyard crops). The **surfaces resistance** is calculated as follows:

$$r_s^P = \frac{r_{stmin}}{LAI_{effective} \prod_i F_i(X_i)} \quad /75/$$

Where:  $r_{st \min}$  is the minimal stomatal resistance of individual leaves under optimal conditions.  $LAI_{\text{effective}}$  is: equal to LAI for  $LAI \leq 2.0$ ;  $LAI/2$  for  $LAI \geq 4.0$  and 2 for intermediate values of LAI,  $X_i$  is a specific environmental variable, and  $F_i(X_i)$  is the stress function with  $0.0 \leq F_i(X_i) \leq 1.0$  [46].

$$F_1(S) = \left( \frac{S}{1100} \right) \left( \frac{1100 + a_1}{S + a_1} \right) \quad /76/$$

$$F_2(T) = \frac{(T - T_L)(T_H - T)^{(T_H - a_2)/(a_2 - T_L)}}{(a_2 - T_L)(T_H - a_2)^{(T_H - a_2)/(a_2 - T_L)}} \quad /77/$$

$$F_3(D) = e^{-a_3 D} \quad /78/$$

$$F_4(\theta) = \begin{cases} 1 - if \text{ } \theta \geq \theta_F \\ \frac{\theta - \theta_w}{\theta_F - \theta_w} - if \text{ } \theta_F < \theta < \theta_w \\ 0 - if \text{ } \theta \leq \theta_w \end{cases} \quad /79/$$

Where:  $S$  is the incoming photosynthetically active radiation flux ( $W/m^2$ ),  $T$  is the air temperature ( $^{\circ}C$ ),  $\theta_F$  is the soil moisture at field capacity ( $cm^3/cm^3$ ),  $\theta_w$  is the soil moisture at wilting point ( $cm^3/cm^3$ ), and  $\theta$  is the actual soil moisture in the root zone. ( $cm^3/cm^3$ ).  $T_H$  and  $T_L$  are upper and lower temperatures limits outside of which transpiration is assumed to cease ( $^{\circ}C$ ) and are set at values of 40 and  $0^{\circ}C$  [39,125]. The  $a_1 = 57.67$ ,  $a_2 = 25.78$ , and  $a_3 = 9.65$  that were determined by multi-variate optimization [125].

**Table 2.** Coefficients a and b for several crops.

| Crop                          | a     | b    | Source                                        |
|-------------------------------|-------|------|-----------------------------------------------|
| Grass                         | 0.16  | 0.0  | Katerji and Rana [52]                         |
| Tomato                        | 0.54  | 2.4  | Katerji and Rana [52]                         |
| Grain sorghum                 | 0.54  | 0.61 | Katerji and Rana [52]                         |
| Soybean                       | 0.95  | 1.55 | Katerji and Rana [52]                         |
| Sunflower                     | 0.45  | 0.2  | Katerji and Rana [52]                         |
| Sweet sorghum                 | 0.845 | 1.0  | Katerji and Rana [52]                         |
| Grass (Tropical climate)      | 0.18  | 0.0  | Gosse (1976) in Rana et al. [91]              |
| Grass (Mediterranean climate) | 0.16  | 0.0  | Rana et al. [91]                              |
| Alfalfa                       | 0.24  | 0.43 | Katerji and Perrier (1983) in Rana et al [91] |
| Sorghum                       | 0.94  | 1.1  | Rana et al. [92]                              |
| Sunflower                     | 0.53  | 1.2  | Rana et al. [92]                              |

The aerodynamic resistances [ $r_a^a$  and  $r_a^s$ ] are calculated from the vertical wind profile in the field and the eddy diffusion coefficient. Above the canopy height, the eddy diffusion coefficient ( $K$ ) is given by:

$$K = ku^*(z - d) \quad /80/$$

Where:  $u^*$  is the wind friction velocity (m/s),  $k$  is the van-Karman constant (0.41),  $z$  is the reference height (m), and  $d$  the zero plane displacement (m). The exponential decrease of the eddy diffusion coefficient ( $K$ ) through the canopy is given as follows:

$$K = k_h \cdot \exp \left[ -n \left( 1 - \frac{z}{n} \right) \right] \quad /81/$$

Where:  $k_h$  is the eddy diffusion coefficient at the top of the canopy ( $m^2/s$ ), and  $n$  is the extinction coefficient of the eddy diffusion. Zhang et al. [125] indicated that  $n = 2.5$  when  $h_c < 1$  m;  $n = 4.25$  when  $h_c > 10$  m, linear interpolation could be used for crops with  $h$  between those values.  $k_h$  is determined as follows:

$$k_h = ku^*(h_c - d) \quad /82/$$

The aerodynamic resistances  $r_a^a$  and  $r_a^s$  are obtained by integrating the eddy diffusion coefficients from the soil surface to the level of the “preferred” sink of momentum in the canopy, and from there to the reference height [125] as follows:

$$r_a^a = \frac{1}{Ku^*} \ln \left( \frac{z - d}{h_c - d} \right) + \frac{h_c}{nk_h} \left[ \exp \left[ n \left( 1 - \frac{z_0 + d}{h_c} \right) \right] - 1 \right] \quad /83/$$

$$r_a^s = \frac{h_c \exp^{(n)} \left[ \exp \left( \frac{-nz_0}{h_c} \right) - \exp \left[ -n \left( \frac{z_0 + d}{h_c} \right) \right] \right]}{nk_h} \quad /84/$$

The bulk boundary layer resistance of canopy is calculated as follows:

$$r_a^p = \frac{r_b}{2LAI} \quad /85/$$

Where:  $r_b$  is the mean boundary layer resistance (s/m) (e.g.; Brisson et al., [13], recommend use 50 s/m).

The **soil surface resistance**  $r_s^s$  is the resistance to water vapor movement from the interior to the surface of the soil, and is strongly dependent on the soil water content ( $\theta_s$ ), and is calculated using the equation /86/ defined by Anandristakis et al. [6]:

$$r_s^s = r_{s \min}^s f(\theta_s) \quad /86/$$

Where:  $\theta_s$  is soil volumetric water content ( $\text{cm}^3/\text{cm}^3$ ), and  $r_{s \min}^s$  is the minimum soil surfaces resistance, that corresponds with the soil field capacity ( $\theta_{FC}$ ) and is assumed equal to 100 s/m (e.g.; [18, 125]. The  $f(\theta_s)$  is expressed by equation /87/ defined by [125]:

$$f(\theta_s) = 2.5 \left( \frac{\theta_{FC}}{\theta_s} \right) - 1.5 \quad /87/$$

### Clumping Model

The Clumping model is based on the Shuttleworth-Wallace model; this model separates the soil surfaces into fractional areas inside and outside the influence of the canopy, and includes the fraction of canopy cover ( $f$ ). Brenner and Incoll [12] and Zhang et al. [125] expressed the model as follows:

$$\lambda E = \lambda E^s + \lambda E^{bs} + \lambda T = f(C_c^s PM_c^s + C_c^p PM_c^p) + (1-f)C_c^{bs} PM_c^{bs} \quad /88/$$

Where:  $\lambda E^s$  is the latent heat of evaporation from soil under the plant ( $\text{W}/\text{m}^2$ );  $\lambda E^{bs}$  is the latent heat of evaporation from bare soil ( $\text{W}/\text{m}^2$ );  $f$  is the fractional vegetative cover and the other terms are expressed as follows:

$$PM_c^p = \frac{\Delta A_c + \left[ \frac{(\rho C_p D - \Delta r_a^p A_c^s)}{r_a^a + r_a^p} \right]}{\Delta + \gamma \left[ 1 + \frac{r_s^p}{r_a^a + r_a^p} \right]} \quad /89/$$

$$PM_c^s = \frac{\Delta A_c + \left[ \frac{(\rho C_p D - \Delta r_a^s A_c^p)}{r_a^a + r_a^s} \right]}{\Delta + \gamma \left[ 1 + \frac{r_s^s}{r_a^a + r_a^s} \right]} \quad /90/$$

$$PM_c^{bs} = \frac{\Delta A_c^{bs} + \left[ \frac{(\rho C_p D)}{r_a^a + r_a^{bs}} \right]}{\Delta + \gamma \left[ 1 + \frac{r_s^{bs}}{r_a^a + r_a^{bs}} \right]} \quad /91/$$

$$C_c^s = \frac{R_c^{bs} R_c^p (R_c^s + R_c^a)}{[R_c^s R_c^p R_c^{bs} + (1-f)R_c^s R_c^p R_c^a + fR_c^{bs} R_c^s R_c^a + fR_c^{bs} R_c^p R_c^a]} \quad /92/$$

$$C_c^p = \frac{R_c^{bs} R_c^s (R_c^p + R_c^a)}{[R_c^s R_c^p R_c^{bs} + (1-f)R_c^s R_c^p R_c^a + fR_c^{bs} R_c^s R_c^a + fR_c^{bs} R_c^p R_c^a]} \quad /93/$$

$$C_c^{bs} = \frac{R_c^s R_c^p (R_c^{bs} + R_c^a)}{[R_c^s R_c^p R_c^{bs} + (1-f)R_c^s R_c^p R_c^a + fR_c^{bs} R_c^s R_c^a + fR_c^{bs} R_c^p R_c^a]} \quad /94/$$

$$R_c^s = (\Delta + \gamma)r_a^s + \gamma_s^s \quad /95/$$

$$R_c^p = (\Delta + \gamma)r_a^p + \gamma_s^p \quad /96/$$

$$R_c^{bs} = (\Delta + \gamma)r_a^{bs} + \gamma_s^{bs} \quad /97/$$

$$R_c^a = (\Delta + \gamma)r_a^a \quad /98/$$

Where:  $A_c^p$ ,  $A_c^s$ ,  $A_c^s$  and  $A_c^{bs}$  are energy available to evapotranspiration, to the plant, to soil under shrub and bare soil ( $W/m^2$ ) respectively,  $r_a^{bs}$  the eddy diffusion resistance from in-canopy heat exchange plane height to the soil surface (s/m),  $r_s^{bs}$  the soil surfaces resistance of bare soil (s/m). The **Available energy** for this model, the net radiation ( $R_n$ ) is divided into net radiation in the plant ( $R_n^p$ ) and the net radiation in the soil ( $R_n^s$ ). If the energy storage in the plant is assumed to be negligible, then:

$$R_{nc}^s = R_n \exp^{(-CLAI / f)} \quad /99/$$

$$R_{nc}^p = R_n - R_{nc}^s \quad /100/$$

$$A_c^s = R_{nc}^s - G^s \quad /101/$$

$$A_c^{bs} = R_{nc}^{bs} - G^{bs} \quad /102/$$

$$A_c^p = R_{nc}^p \quad /103/$$

Where:  $R_{nc}^p$  and  $R_{nc}^s$  are the radiation absorbed by the plant and the radiation by the soil ( $W/m^2$ ) respectively,  $G^s$  and  $G^{bs}$  are the soil heat flux under plant and bare soil ( $W/m^2$ ) respectively,  $C$  is the extinction coefficient of light attenuation and according to Sene [97] is equal to 0.68 for fully grown plant. The resistance for the bare soil surfaces  $r_s^{bs}$  can be calculated equally as in the S-W model, mentioned before. The aerodynamic resistance between the bare soil surface and the mean surface flow height ( $r_a^{bs}$ ) can be calculated assuming that the bare soil surface is totally unaffected by adjacent vegetation so that the aerodynamic resistance is equal to  $r_a^b$  and defined by:

$$r_a^b = \ln \frac{\left( \frac{Z_m}{Z_o} \right)^2}{k^2 U_m} \quad /104/$$

Where:  $Z_m$  is the mean surface flow height (m), and could be assumed equal to  $0.75h_c$ , and  $u_m$  is the wind speed at the  $Z_m$  (m/s). According with Zhang et al. [125], the aerodynamic resistance ( $r_a^{bs}$ ) varies between  $r_a^b$  and  $r_a^s$  as  $f$  varies from 0 to 1, and the functional relationship of this change is not known.

### Combination Model

Theoretical approaches to surface evaporation from the energy balance equation combined with sensible heat and latent heat exchange expressions give the following equation for actual evapotranspiration [81]:

$$ET = \frac{\Delta}{\Delta + \gamma} \left[ (R_n - G) + \frac{\rho C_p}{\Delta} Hu (VPD_a - VPD_s) \right] \quad /105/$$

Where:  $(R_n - G)$  = Available energy ( $MJ/m^2$ ) for the canopy consisting of net radiation,  $R_n$  and the soil heat flux,  $G$ ;  $H(u)$  = exchange coefficient (m/s) between the surface level and a reference level above the canopy but taken inside the conservative boundary sublayer;  $VPD_s$  and  $VPD_a$  (kPa) = vapor pressure deficits (VPD) for the surface level and the reference level, respectively;  $\rho$  = atmospheric density ( $kg/m^3$ );  $C_p$  = specific heat of moist air ( $J/kg^\circ C$ );  $\Delta$  = slope of the vapor pressure curve ( $Pa/^\circ C$ ); and  $\gamma$  = psychrometric constant ( $Pa/^\circ C$ ). To obtain evapotranspiration with the equation /105/, it is not an easy task to estimate  $VPD_s$ , representing the vapor pressure deficit at the evaporative surface. If  $VPD_s$  can be associated with a surface resistance term ( $r_s$ ). Therefore, ET can be calculated directly from the flux equation:

$$ET = \frac{\rho C_p}{\gamma} \frac{VPD_s}{r_s} \quad (87) \quad , \text{ and} \quad /106/$$

$$r_a = \frac{1}{Hu} \quad /107/$$

Where:  $r_a$  can be calculated using the equations discussed later in this chapter. Two main solutions can be defined for the equation /105/ using climatic data:

1. The case of full water availability corresponding to saturation at the evaporative surface. Then  $VPDs = 0$  and  $r_s$  becomes null. Equation /105/ then gives the maximum value for ET, the potential evaporation (EP), which depends only on climatic driving forces:

$$EP = \frac{\Delta(R_n - G) + \rho C_p F(u) VPD_a}{\Delta \lambda} \quad /108/$$

Where:  $F(u) = 1/r_a$ . The combination of the equations yields:

$$ET = \frac{EP}{\left(1 + \frac{\gamma}{\Delta + \gamma} \frac{r_s}{r_a}\right)} \quad /109/$$

2. The case for equilibrium between the surface and the reference levels corresponds to  $VPDs = VPD_a$ . In this case, the evapotranspiration is referred to as the equilibrium evaporation ( $E_e$ ):

$$E_e = \frac{\rho C_p VPD_a}{\gamma r_e} \quad /110/$$

Where:  $r_s$  was renamed  $r_e$ , termed the equilibrium surface resistance, indicating that the term, in this case, represents the surface resistance for equilibrium evaporation. The value for  $r_e$  depends predominately on climatic characteristics although these characteristics are influenced by  $R_n$  and  $G$  of the vegetative surface. For purposes here, the  $r_e$  term can be called the climatic resistance for the surface:

$$r_e = \frac{\rho C_p \Delta + \gamma VPD_a}{\gamma \Delta R_n - G} \quad /111/$$

EP can be estimated:

$$EP = E_e \left(1 + \frac{\gamma}{\Delta + \gamma} + \frac{r_e}{r_a}\right) \quad /112/$$

and ET can be estimated using:

$$ET = \frac{EP}{\left(1 + \frac{\gamma}{\Delta + \gamma} \frac{r_s}{r_a}\right)} \quad /113/$$

### Priestly and Taylor Model

Priestly and Taylor [84], proposed to neglect the aerodynamic term and replace the radiation term by a dimensionless coefficient ( $\alpha$ ):

$$ET = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad /114/$$

Where: ET is water flux under references conditions (well watered grass) in  $\text{mm.day}^{-1}$ ;  $R_n$  and  $G$  are net radiation and soil heat flux respectively in  $\text{mm.day}^{-1}$ ;  $\Delta$  and  $\gamma$  in  $\text{kPa.}^\circ\text{C}^{-1}$ . The term  $\alpha$  is given as 1.26 for grass field in humid weather conditions, and was adopted by Priestley and Taylor [84] for wet surfaces. However  $\alpha$  ranges from 0.7 to 1.6 for various landscape situations [26]. According with Zhang et al. [124], the term  $\alpha$  can be calculated as follows:

$$\alpha = \frac{\lambda E (\Delta + \gamma)}{\Delta (R_n - G)} = \frac{\Delta + \gamma}{\Delta (1 + \beta)} \quad /115/$$

Also the term  $\alpha$  has been estimated using an empirical equation depending on the soil moisture content and soil capacity [29,30, 124]:

$$\alpha = k \left[ 1 - \exp \left( -c \frac{\theta - d}{\theta_{fc}} \right) \right] \quad /116/$$

Where:  $k$ ,  $c$  and  $d$  are parameters of the model,  $\theta$  is the actual volumetric soil moisture content ( $\text{cm}^3.\text{cm}^{-3}$ ) and  $\theta_{fc}$  is the volumetric moisture content at field capacity ( $\text{cm}^3.\text{cm}^{-3}$ ).

### Eddy Covariance Method

The eddy covariance method is, in general, the most preferred because it provides a direct measure of the vertical turbulent flux across the mean horizontal streamlines, provided by fast sensors ( $\sim 10$  Hz) [65]. Realizing the limitation of the Thornthwaite-Holzman type of approach, Swinbank (1951) cited by Chang [19] was the first to attempt a direct measurement by the so-called eddy correlation technique. The method is based on the assumption that the vertical eddy flux can be determined by simultaneous measurements of the upward eddy velocity and the fluctuation in vapor pressure. Currently it is a routine technique for direct measurement of surfaces layer fluxes of momentum, heat, and traces gases ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{O}_3$ ) between the surfaces and the turbulent atmosphere [63].

This system recognizes that the transport of heat, moisture, and momentum in the boundary layer is governed almost entirely by turbulence. The eddy correlation method is theoretically simple using an approach to measure the turbulent fluxes of vapor and heat above the canopy surface. The eddy correlation fluxes are calculated and recorded in a 30 min or less temporal

resolution. Assuming the net lateral advection of vapor transfer is negligible, the latent heat flux (evapotranspiration) can be calculated from the covariance between the water vapor density ( $\rho_v$ ) and the vertical wind speed ( $w$ ):

$$\lambda E = \lambda \overline{w' \rho_v'} \quad /117/$$

Where:  $\lambda E$  is the latent heat flux ( $W m^{-2}$ ),  $\lambda$  is the latent heat of vaporization ( $J kg^{-1}$ ),  $\rho_v'$  is the fluctuation in the water vapor density ( $kg m^{-3}$ ), and  $w'$  is the fluctuation in the vertical wind speed ( $m s^{-1}$ ). The over bar represents the average for the period and primes indicate the deviation from the mean values during the averaging period. According to Weaver [118], the eddy correlation method depends on the relations between the direction of air movement near the land surface and properties of the atmosphere, such as temperature and humidity. The sensible heat flux can be calculated from the covariance of air temperature and the vertical wind speed.

$$H = \rho_a C_p \overline{w' T'} \quad /118/$$

Where:  $H$  = the sensible heat flux ( $W m^{-2}$ ),  $\rho_a$  the air density ( $kg m^{-3}$ ),  $C_p$  is the specific heat of moist air ( $J kg^{-1} ^\circ C^{-1}$ ) and  $T'$  = the fluctuation in the air temperature ( $^\circ C$ ).

The fine wire thermocouples (0.01 mm diameter) are not included in the eddy correlation system. The air temperature fluctuations, measured by the sonic anemometer, are corrected for air temperature fluctuations in estimation of sensible heat fluxes. The correction is for the effect of wind blowing normal to the sonic acoustic path. The simplified formula by Schotanus et al. [99] is as follows:

$$\overline{w' T'} = \overline{w' T_s'} - 0.51 (\overline{T} + 273.15) \overline{w' q'} \quad /119/$$

Where:  $\overline{w' T'}$  is rotated covariance of wind speed and sonic temperature ( $m ^\circ C s^{-1}$ ),  $T$  is air temperature ( $^\circ C$ ) and  $q$  is the specific humidity in grams of water vapor per grams of moist air.

Two types of Eddy covariance systems are used to measure the water vapor fluxes, the open path and close path. According to Anthoni et al. [8] the Open-path eddy covariance systems requires corrections for density fluctuations in the sampled air [64,119] and in general closed-path systems require incorporation of a time lag and corrections for the loss of high frequency information, due to the air being drawn through a long sampling tube [64,71]. The most common corrections in the eddy covariance system are described by Wolf et al. [121] as: i) Coordinate rotation, ii) Air density correction, and iii) Frequency-dependent signal loss.

Estimation of turbulent fluxes is highly dependent on the accuracy of the vertical wind speed measurements. Measurement of wind speed in three orthogonal directions with a sonic anemometer requires a refined orientation with respect to the natural coordinate system through mathematic coordinate rotations [103]. The vector of wind has three components ( $u$ ,  $v$ ,  $w$ ) in three coordinate directions ( $x$ ,  $y$ ,  $z$ ). The  $z$ -direction is oriented with respect to gravity, and the other two are arbitrary. Baldocchi et al. [9] provide procedures to transform the initial coordinate system to the natural coordinate system. Described in details by Sumner [103], the coordinate system is rotated by an angle  $\eta$  about the  $z$ -axis to align  $u$  into the  $x$ -direction on the  $x$ - $y$  plane, and then rotated by an angle  $\theta$  about the  $y$ -direction to align  $w$  along the  $z$ -direction. The resultant forces  $\overline{v}$  and  $\overline{w}$  are equal to zero, and  $\overline{u}$  is pointed directly to the air stream. When  $\theta$  was greater than 10 degrees, the turbulent flux data should be excluded based on the assumption that spurious turbulence was the cause of the excessive amount of the coordinate rotation:

$$\cos \theta = \frac{\sqrt{(u^2 + v^2)}}{\sqrt{(u^2 + v^2 + w^2)}} \quad /120/$$

$$\sin \theta = \frac{w}{\sqrt{(u^2 + v^2 + w^2)}} \quad /121/$$

$$\cos \eta = \frac{u}{\sqrt{(u^2 + v^2)}} \quad /122/$$

$$\sin \eta = \frac{v}{\sqrt{(u^2 + v^2)}} \quad /123/$$

The latent heat and sensible heat fluxes are computed from the coordinate rotation-transformed covariance:

$$\left( \overline{w' \rho_v'} \right)_r = \overline{w' \rho_v'} \cos \theta - \overline{u' \rho_v'} \sin \theta \cos \eta - \overline{v' \rho_v'} \sin \theta \sin \eta \quad /124/$$

$$\left( \overline{w' T_s'} \right)_r = \overline{w' T_s'} \cos \theta - \overline{u' T_s'} \sin \theta \cos \eta - \overline{v' T_s'} \sin \theta \sin \eta \quad /125/$$

After the coordinate rotation, the final latent heat flux can be estimated from equation /117/ and the following correction of air density ( $C_{air}$ ) [119] and correction for oxygen ( $CO_2$ ) [107]:

$$C_{air} = \frac{\overline{\rho_v} \overline{H}}{\overline{\rho} C_p (\overline{T} + 273.15)} \lambda \quad /126/$$

$$C_{O_2} = \frac{FK_o \overline{H}}{K_w (\overline{T} + 273.15)} \lambda \quad /127/$$

Where: F is a factor used in krypton hygrometer correction that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen and is equal to  $0.229 \text{ g } ^\circ\text{C J}^{-1}$ ,  $K_o$  is the extinction coefficient of hygrometer for oxygen, estimated as  $0.0045 \text{ m}^3 \text{ g}^{-1} \text{ cm}^{-1}$ ,  $K_w$  is the extinction coefficient of hygrometer for water and is  $0.149 \text{ m}^3 \text{ g}^{-1} \text{ cm}^{-1}$ , provided the manufacturer:

With the measured four flux components from the energy balance equation, the energy balance should be closed, however, this is not practically the case. A tendency to underestimate energy and mass fluxes has been a pervasive problem with the eddy covariance technique [33]. Ham and Heilman [33] reported closure of 0.79 for prairie locations and 0.96 for forest. Ramirez and Harmsen (2007-unpublished data) closures of 0.71 for grass and 0.75 for corn.

The errors in eddy covariance methods are associated with: 1. Accuracy of the  $R_n$  and G measurements (errors are often 5 to 10%); 2. The length scale of the eddies responsible for transport; and 3. Sensor separation and inadequate sensor response (can underestimate  $\lambda E$  by 10 to 15% [33, 57]); Ham and Heilman [33] conclude “The inherent tendency to underestimate fluxes when using eddy covariance may be linked to the errors caused by sensor separation and inadequate frequency response of the sensors. The correction proposed by Massman and Lee [64] is difficult to implement for the non-specialist because they require calculation of cospectra using high-frequency (10Hz) data, and also requires experience to interpret the cospectra properly”.

The “energy balance closure” is corrected using the Bowen ratio [56] as follows:

$$H = \beta * \lambda E \quad /128/$$

$$\lambda E = R_n - G - H \quad /129/$$

Where:  $\beta$  and  $\lambda E$  are estimated from the eddy covariance system, and  $R_n$  and G are measured.

**The Massman Analytical Formulae for Spectral Corrections to Measured Momentum and Scalar Fluxes for Eddy Covariance Systems:** Massman [63] developed an analytical method for frequency response corrections, based on the procedure developed by Horst [43]. In this method  $\zeta$  is a stability factor and is defined below.

For *Stable atmospheric conditions* ( $0 < \zeta \leq 2$ ):

a. Fast-response open path system:

$$\frac{Flux_m}{Flux} = \left[ \frac{ab}{(a+1)(b+1)} \right] \left[ \frac{ab}{(a+p)(b+p)} \right] \left[ \frac{1}{(p+1)} \right] \left[ 1 - \frac{p}{(a+1)(a+p)} \right] \quad /130/$$

b. Scalar instrument with 0.1-0.3s response:

$$\frac{Flux_m}{Flux} = \left[ \frac{ab}{(a+1)(b+1)} \right] \left[ \frac{ab}{(a+p)(b+p)} \right] \left[ \frac{1}{(p+1)} \right] \left[ 1 - \frac{p}{(a+1)(a+p)} \right] \left[ \frac{1+0.9p}{1+p} \right] \quad /131/$$

Unstable atmospheric conditions ( $\zeta \leq 0$ ):

$$\frac{Flux_m}{Flux} = \left[ \frac{a^\alpha b^\alpha}{(a^\alpha+1)(b^\alpha+1)} \right] \left[ \frac{a^\alpha b^\alpha}{(a^\alpha+p^\alpha)(b^\alpha+p^\alpha)} \right] \left[ \frac{1}{(p^\alpha+1)} \right] \left[ 1 - \frac{p^\alpha}{(a^\alpha+1)(a^\alpha+p^\alpha)} \right] \quad /132/$$

Where: the subscript m refers to the measurement flux,  $a = 2\pi \int x \tau_h$ ;  $b = 2\pi \int x \tau_b$ ;  $p = 2\pi \int x \tau_c$ ; and  $\tau_h$  and  $\tau_b$  are the equivalent time constants associated with trend removal ( $\tau_h$ ) and block averaging ( $\tau_b$ ). For relatively broad co-spectra with relatively shallow peaks, such as the flat terrain neutral/stable, such as flat terrain co-spectrum:  $\alpha=0.925$ ; and for sharper, more peaked co-spectra, such as the stable terrain co-spectra:  $\alpha=0.925$  [49].

These approximations are clearly easier to employ than numerical approaches and are applicable even when fluxes are so small as to preclude the use of *in situ* methods. Nevertheless, this approach is subject to the following conditions: i) horizontally-homogeneous upwind fetch, ii) the validity of the co-spectral similarity, iii) sufficiently long averaging periods, and preferably, iv) relatively small corrections [63].

### The Infrared Surface Temperature Method

The infrared surface temperature has also been used for the estimation of the sensible heat flux (H) using the resistance model [2]:

$$H = \rho.C_p \frac{T_o - T_a}{r_a} \quad /133/$$

Where:  $\rho$  is air density ( $\text{Kg m}^{-3}$ ),  $C_p$  specific heat at constant pressure ( $\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$ ),  $T_o$  is the temperature at surface level ( $^\circ\text{C}$ ),  $T_a$  is the temperature at the reference level ( $^\circ\text{C}$ ), and  $r_a$  is the aerodynamic resistance to heat flux between the surface and the reference level ( $\text{s.m}^{-1}$ ), the latent heat flux ( $\lambda E$ ) can be computed as the residual term in the energy balance:

$$\lambda E = R_n - G - H = R_n - G - \rho.C_p \frac{T_o - T_a}{r_a} \quad /134/$$

Alves et al. [2] states that the radiative surface temperature has several drawbacks. Thermal radiation received by the instrument can originate from the leaves but also from the soil, and the measurement can be highly dependent on crop cover, inclination of radiometer and sun height and azimuth, especially in partial cover crops. The variable d is zero plane displacement

height (m),  $Z_{oM}$  and  $Z_{oH}$  are the roughness lengths (m) for momentum and heat respectively,  $k$  is the von Karman constant,  $u_z$  is the wind speed ( $\text{ms}^{-1}$ ) at the reference height  $z$  (m), and  $\psi_M$  and  $\psi_H$  are the integrated stability functions for describing the effects of the buoyancy or stability on momentum transfer and heat between the surface and the reference level.

The necessary instruments are: Wind speed and direction sensor at (0.85 and 1.46m), psychrometer at the same height that wind sensor, a net radiometer placement at 1.5 m and infrared thermometer perpendicular to the crop rows, and positioned at an angle of 60° below horizontal to view the top leaves of the plants at 0.40 m distance [2]. The sensible heat flux [H] is calculated with the flux applied to levels  $Z_1$  and  $Z_2$ :

$$H = \rho C_p \frac{T_1 - T_2}{[ra]_L^2} \quad /135/$$

Where:  $[ra]_L^2$  is the aerodynamic resistance to heat flux between the two levels, and is computed using the equation /136/:

$$[ra]_L^2 = \frac{\ln\left(\frac{Z_2 - d}{Z_1 - d}\right)}{ku^*} \quad /136/$$

Where:  $u^*$  = the friction velocity, obtained in the process of determining aerodynamic parameter [d] and  $Z_{oM}$  from the wind profile measurements.

The air temperature at the surface level ( $T_o$ ) is calculated using equation /137/. The stability conditions can be calculated using the Richardson number.

$$T_o = T_a + \frac{Hr_a}{\rho C_p} \quad /137/$$

**Fetch requirements:** The air that passes over a surface is affected by the surface's features [93]; the minimal fetch requirement is estimated based on the thickness of the internal boundary layer ( $\delta$  in m) and a roughness parameter ( $Z_o$  in m) for each genotype considering the minimal and maximal crop height during the growing season. The  $\delta$  is calculated using the equation /138/ proposed by Monteith and Unsworth [70]:

$$\delta = 0.15 L^{4/5} Z_o^{1/5} \quad /138/$$

Where:  $L$  is the distance of traverse (fetch) across a uniform surface with roughness  $Z_o$ . The  $Z_o$  for crops is approximately one order of magnitude smaller than the crop height  $h$ , and can be calculated according to Rosenberg et al. [93] as follows:

$$\log_{10} Z_o = 0.997 \log_{10} h - 0.883 \quad /139/$$

As a factor of safety, a height to fetch of 1:50 to 1:100 is usually considered adequate for studies made over agricultural crop surfaces [5, 93] but may be too conservative and difficult to achieve in practice. Alves et al. [1] obtained full profile development using a 1:48 fetch relation in Wheat and Lettuce. Heilman et al. [40] found that for Bowen-Ratio estimates a fetch 1:20 was sufficient over grass, and Ham and Heilman [32] and Frithschen and Fritschen [28] obtained similar results.

**Stability correction:** The gradient method requires a stability correction; one of the most used is the Monin-Obukhov stability factor ( $\zeta$ ) described by [17, 86, 93]:

$$\zeta = \frac{(-k \cdot z \cdot g \cdot H)}{(\rho_a \cdot C_p \cdot T_a \cdot u^{*3})} \quad /140/$$

Where:  $k$  is von Karman's constant,  $z$  is height of wind and air temperature measurements (m),  $g$  is the gravitational constant ( $9.8 \text{ m.s}^{-2}$ ),  $H = \beta \cdot \lambda E$ ,  $T_a$  is air temperature ( $^{\circ}\text{K}$ ),  $u^*$  is the friction velocity given by Kjelgaard et al. [55] without the stability correction factor:

$$u^* = \frac{k \cdot u_z}{\ln\left(\frac{z - d + Z_{om}}{Z_{om}}\right)} \quad /141/$$

A flux with a negative sign for  $\zeta$  indicates unstable conditions and should be excluded. For fluxes under unstable conditions the  $\lambda E$  is greater than  $R_n$  [Figure 5a]; When the fluxes with negative  $\zeta$  are excluded,  $\lambda E$  is lower than  $R_n$  [Figure 5b]. Payero et al. [77] indicated that fluxes with incorrect sign and  $\beta \approx -1$  should not be considered when estimating the energy balance components by the energy balance Bowen ratio method. The negative  $\zeta$  corresponds to negative  $\beta$  [Figure 6].

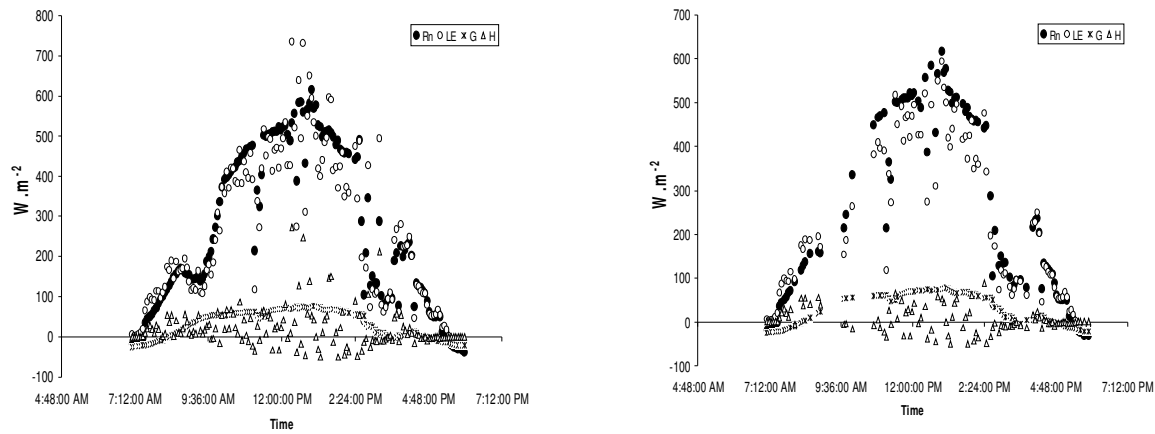
The Richardson number ( $Ri$ ) is represented by the equation /45/, also is well known as stability factor [2, 110] and represent the ratio of the buoyancy – “thermal effect” to “mechanical –wind shear” (Prueger and Kustas, [86]. Negative values indicate instability conditions where surfaces heating enhances buoyancy effects, and positive  $Ri$  values indicate a stable conditions where temperature near the surfaces are cooler than away from the surfaces.

## SUMMARY

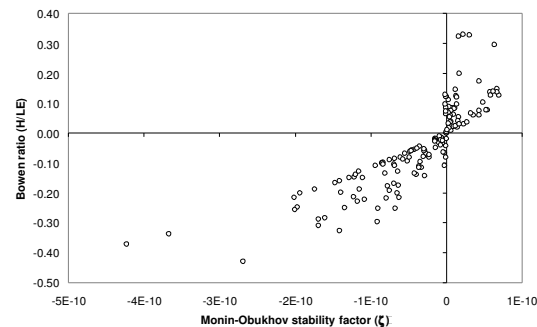
Water vapor flux in agroecosystems is the second largest component in the hydrological cycle. Water vapor flux from vegetation to the atmosphere is a widely studied variable throughout the world, due to its applicability in various disciplines such as



hydrology, climatology, and agricultural science. Evapotranspiration is important to calculate the water requirement for crops, to make climatic characterizations and for water management. The estimation of evapotranspiration from vegetated areas is a basic tool to compute water balances and to estimate water availability and also to estimate agroclimatic and hydrologic indices. During the last sixty years various methods and models to measure the water flux in agroecosystems have been developed. The aim of this chapter has been to provide a review of mass balance methods and models, application of the two steps model and direct transpiration measurement techniques. This chapter provides a revision of these methods and models with special application to crops and covered areas.



**Figure 5.** Energy balance components measured by Bowen ratio method in grass: **A.** without stability correction and **B.** with stability correction.



**Figure 6.** Relationship between Bowen ratio ( $\beta$ ) and the Monin-Obukhov stability factor.

## KEYWORDS

Aerodynamic resistance  
Calibration  
Clumping model  
Combination model  
Crop coefficients  
Cumulative growing degree days  
Drainage Lysimeter  
Eddy covariance method  
Energy balances.  
Evapotranspiration  
Fetch requirements  
Fluxes  
Humidity and temperature method  
Latent heat fluxes  
Leaf area index [LAI]  
Micrometeorological method  
Pristley - Taylor model  
Resistances  
Sensible heat flux  
Shuttleworth-Wallace model

Soil heat flux  
Stability correction  
Stomatic resistance  
Surfaces resistance  
The Bowen ratio energy balance  
The infrared surface temperature method  
The Penman-Monteith reference evapotranspiration method  
The Penman-Monteith general evapotranspiration method  
Water stress coefficient  
Water vapor deficit  
Water vapor flux  
Weighing lysimeter

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## Chapter 7

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#### INTRODUCTION

Artificial neural networks are much easier to set-up than many of the statistical models, such as regression (with only a small amount of time an ANN can be set-up; with learning and practice they can provide better results, since it is more of an art to setting one up, than a science). Most of the research on the application of ANN in agriculture science has been done in the last decade, mainly in the area of yield prediction, spatial modeling, and spatial-temporal forecasting. This chapter will introduce the basic concepts about neural network. Also the work done on the application of ANN in agriculture research will be reviewed. The application of ANN in agriculture research using real data will be presented.

#### ARTIFICIAL NEURAL NETWORK (ANN) MODELING

Artificial neural networks (ANN) are among the newest signal-processing technologies in the engineer's toolbox. The field is highly interdisciplinary, but our approach will restrict to the engineering perspective. In engineering, neural networks serve two important functions: as pattern classifiers and as nonlinear adaptive filters. This chapter will provide a brief overview of the theory, learning rules, and applications of the most important neural network models. Definitions and Style of Computation an Artificial Neural Network is an adaptive, most often nonlinear system that learns to perform a function (an input/output map) from data. Adaptive means that the system parameters are changed during operation, normally called the training phase. After the training phase the Artificial Neural Network parameters are fixed, and the system is deployed to solve the problem at hand (the testing phase). The Artificial Neural Network is built with a systematic step-by-step procedure to optimize a performance criterion or to follow some implicit internal constraint, which is commonly referred to as the learning rule.

The input/output training data are fundamental in neural network technology, because they convey the necessary information to "discover" the optimal operating point. The nonlinear nature of the neural network processing elements (PEs) provides the system with lots of flexibility to achieve practically any desired input/output map, i.e., some Artificial Neural Networks are universal mappers. There is a style in neural computation that is worth describing.

An input is presented to the neural network and a corresponding desired or target response set at the output (when this is the case the training is called supervised). An error is composed from the difference between the desired response and the system output. This error information is fed back to the system and adjusts the system parameters in a systematic fashion (the learning rule). The process is repeated until the performance is acceptable. It is clear from this description that the performance hinges heavily on the data. If one does not have data that cover a significant portion of the operating conditions or if they are noisy, then neural network technology is probably not the right solution. On the other hand, if there is plenty of data and the problem is poorly understood to derive an approximate model, then neural network technology is a good choice. This operating procedure should be contrasted with the traditional engineering design, made of exhaustive subsystem specifications and intercommunication protocols. In artificial neural networks, the designer chooses the network topology, the performance function, the learning rule, and the criterion to stop the training phase, but the system automatically adjusts the parameters. So, it is difficult to bring a priori information into the design, and when the system does not work properly it is also hard to incrementally refine the solution. But ANN-based solutions are extremely efficient in terms of development time and resources, and in many difficult problems artificial neural networks provide performance that is difficult to match with other technologies. Denker indicated that "artificial neural networks are the second best way to implement a solution" motivated by the simplicity of their design and because of their universality, only shadowed by the traditional design obtained by studying the physics of the problem. At present, artificial neural networks are emerging as the technology of choice for many applications, such as pattern recognition, prediction, system identification, and control.

#### THE BIOLOGICAL MODEL

Artificial neural networks emerged after the introduction of simplified neurons. These neurons were presented as models of biological neurons and as conceptual components for circuits that could perform computational tasks. The basic model of the neuron is founded upon the functionality of a biological neuron. "Neurons are the basic signaling units of the nervous system" and "each neuron is a discrete cell whose several processes arise from its cell body".

The neuron has four main regions to its structure: The cell body, or soma, has two offshoots from it, the dendrites, and the axon, which end in presynaptic terminals. The cell body is the heart of the cell, containing the nucleus and maintaining protein synthesis. A neuron may have many dendrites, which branch out in a treelike structure, and receive signals from other neurons. A neuron usually only has one axon which grows out from a part of the cell body called the axon hillock. The axon conducts electric signals generated at the axon hillock down its length.

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<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

These electric signals are called action potentials. The other end of the axon may split into several branches, which end in a presynaptic terminal. Action potentials are the electric signals that neurons use to convey information to the brain. All these signals are identical. Therefore, the brain determines what type of information is being received based on the path that the signal took. The brain analyzes the patterns of signals being sent and from that information it can interpret the type of information being received. Myelin is the fatty tissue that surrounds and insulates the axon. Often short axons do not need this insulation. There are un-insulated parts of the axon. These areas are called Nodes of Ranvier. At these nodes, the signal traveling down the axon is regenerated. This ensures that the signal traveling down the axon travels fast and remains constant (i.e. very short propagation delay and no weakening of the signal). The synapse is the area of contact between two neurons. The neurons do not actually physically touch. They are separated by the synaptic cleft, and electric signals are sent through chemical interaction. The neuron sending the signal is called the presynaptic cell and the neuron receiving the signal is called the postsynaptic cell. The signals are generated by the membrane potential, which is based on the differences in concentration of sodium and potassium ions inside and outside the cell membrane. Neurons can be classified by their number of processes (or appendages), or by their function. If they are classified by the number of processes, they fall into three categories. Uni-polar neurons have a single process (dendrites and axon are located on the same stem), and are most common in invertebrates. In bipolar neurons, the dendrite and axon are the neuron's two separate processes. Bipolar neurons have a subclass called pseudo-bipolar neurons, which are used to send sensory information to the spinal cord. Finally, multi-polar neurons are most common in mammals. Examples of these neurons are spinal motor neurons, pyramidal cells and Purkinje cells (in the cerebellum). If classified by function, neurons again fall into three separate categories. The first group is sensory, or afferent, neurons, which provide information for perception and motor coordination. The second group provides information (or instructions) to muscles and glands and is therefore called motor neurons. The last group, interneuronal, contains all other neurons and has two subclasses. One group called relay or projection interneurons have long axons and connect different parts of the brain. The other group called local interneurons are only used in local circuits.

## THE NEURAL NETWORK MODEL

Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between the elements. Commonly neural networks are adjusted, or trained, so that a particular input leads to a specific target output.

Neural networks use a complex combination of weights and functions to convert input variables into an output (the prediction). The Multi-Layer Perceptron (MLP) consists of a system of simple processing interconnected elements called neurons, cells or nodes. Each of the various inputs to the network is multiplied by a connection weight. These products are simply summed, fed through a transfer function to generate a result, and then output. This is a gradient-descent algorithm that is normally used to train a MLP network. Errors in the output of this procedure are assumed to be due to all processing element and connections, and these errors are reduced by propagating the output error backward to the connections in the previous layers.

Feed forward ANN models comprise a system of neurons, which are arranged in successive layers, namely input and output layers in addition to one or more hidden layers. The neurons in each layer are connected to the neurons in the subsequent layer by a weight  $w$ , which may be adjusted during training. A data pattern comprising the values  $x_i$  presented at the input layer  $i$ , is propagated forward through the network towards the hidden layer  $j$ . Each hidden neuron receives the weighted outputs  $w_{ji} x_i$ , from the neurons in the previous layer. These are summed to produce a net value ( $NET_j$ ), which is then transformed to an output value upon the application of an activation function.

A typical three-layer feed-forward ANN consists of three layers namely input, hidden and output layers. Input layer neurons are  $x_1, x_2, x_3, \dots, x_n$ ; hidden layer neurons are  $h_1, h_2, h_3, \dots, h_n$ ; and finally output layer neurons are  $o_1, o_2, o_3, \dots, o_n$ .

A neuron consists of multiple inputs and single output. The sum of inputs and their weights lead to a summation operation as,

$$NET_j = \sum W_{ij} X_i \quad /1/$$

Where:  $W_{ij}$  is established weight,  $X_i$  is input value and  $NET_j$  is input value and  $NET_j$  is input to a node in a layer  $j$ .

The output of a neuron is decided by an activation function. There are number of activation functions that can be used in ANNs such as step, sigmoid, threshold, linear etc. The logistic sigmoid function,  $f(x)$ , commonly used, can be formulated mathematically as:

$$f(x) = 1/[1+\exp(-x)]$$

$$OUTPUT_j = f(NET_j) = 1/[1+\exp(-NET_j)] \quad /2/$$

When creating a functional model of the biological neuron, there are three basic components. First, the synapses of the neuron are modeled as weights. The strength of the connection between an input and a neuron is noted by the value of the weight. Negative weight values reflect inhibitory connections, while positive values designate excitatory connections. The next two components model the actual activity within the neuron cell. An adder sums up all the inputs modified by their respective weights. This activity is referred to as linear combination. Finally, an activation function controls the amplitude of the output of the neuron. An acceptable range of output is usually between 0 and 1, or -1 and 1. Mathematically, this process is described in the Figure 1. From this model the interval activity of the neuron is shown below:

$$v_k = \sum_{j=1}^p w_{kj} x_j$$

/3/

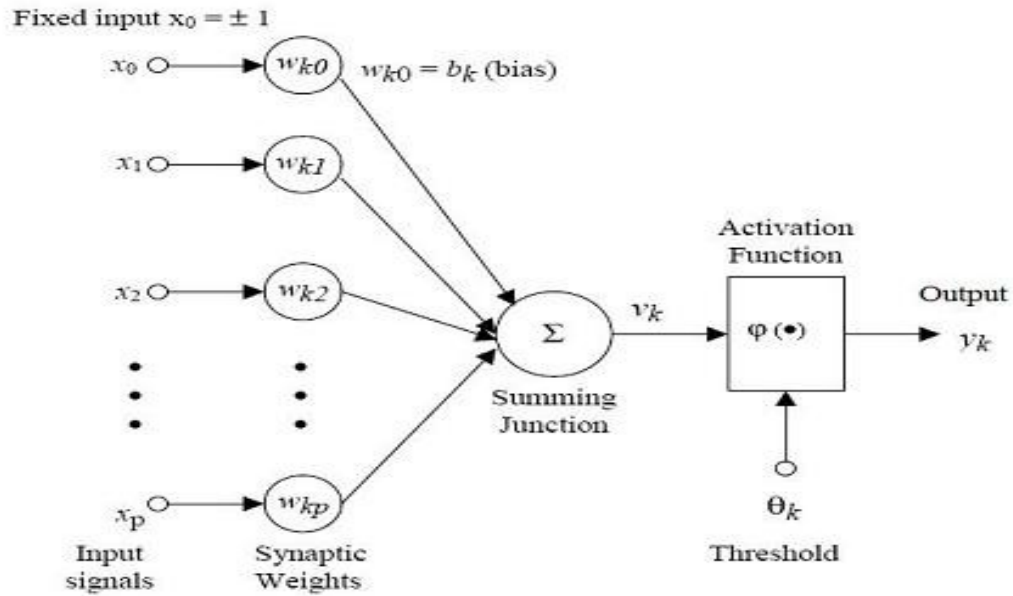
The output of the neuron,  $y_k$ , is therefore be the outcome of some activation function on the value of  $v_k$ .

#### Activation functions

As mentioned previously, the activation function acts as a squashing function, such that the output of a neuron in a neural network is between certain values (usually 0 and 1, or -1 and 1). In general, there are three types of activation functions, denoted by  $\Phi(\cdot)$ . First, there is the Threshold Function which takes on a value of 0 if the summed input is less than a certain threshold value ( $v$ ), and the value 1 if the summed input is greater than or equal to the threshold value.

$$\phi(v) = \begin{cases} 1 & \text{if } v \geq 0 \\ 0 & \text{if } v < 0 \end{cases}$$

/4/



**Figure 1.** The mathematical process.

Secondly, there is the Piecewise-Linear function. This function again can take on the values of 0 or 1, but can also take on values between that depending on the amplification factor in a certain region of linear operation.

$$\phi(v) = \begin{cases} 1 & v \geq \frac{1}{2} \\ v & -\frac{1}{2} > v > \frac{1}{2} \\ 0 & v \leq -\frac{1}{2} \end{cases}$$

/5/

Thirdly, there is the sigmoid function [Figure 2]. This function can range between 0 and 1, but it is also sometimes useful to use the -1 to 1 range. An example of the sigmoid function is the hyperbolic tangent function.

$$\phi(v) = \tanh\left(\frac{v}{2}\right) = \frac{1 - \exp(-v)}{1 + \exp(-v)}$$

/6/

The artificial neural networks which we describe are all variations on the parallel distributed processing (PDP) idea. The architecture of each neural network is based on very similar building blocks which perform the processing. In this chapter we

first discuss these processing units and discuss different neural network topologies. Learning strategies as a basis for an adaptive system.

## NEURAL NETWORK TOPOLOGIES

In the previous section, we have discussed the properties of the basic processing unit in an artificial neural network. This section focuses on the pattern of connections between the units and the propagation of data. As for this pattern of connections, the main distinction we can make is between:

- **Feed-forward neural networks**, where the data flow from input to output units is strictly feed forward. The data processing can extend over multiple (layers of) units, but no feedback connections are present, that is, connections extending from outputs of units to inputs of units in the same layer or previous layers.
- **Recurrent neural networks** that do contain feedback connections. Contrary to feed-forward networks, the dynamical properties of the network are important. In some cases, the activation values of the units undergo a relaxation process such that the neural network will evolve to a stable state in which these activations do not change anymore. In other applications, the change of the activation values of the output neurons is significant, so that the dynamical behavior constitutes the output of the neural network.

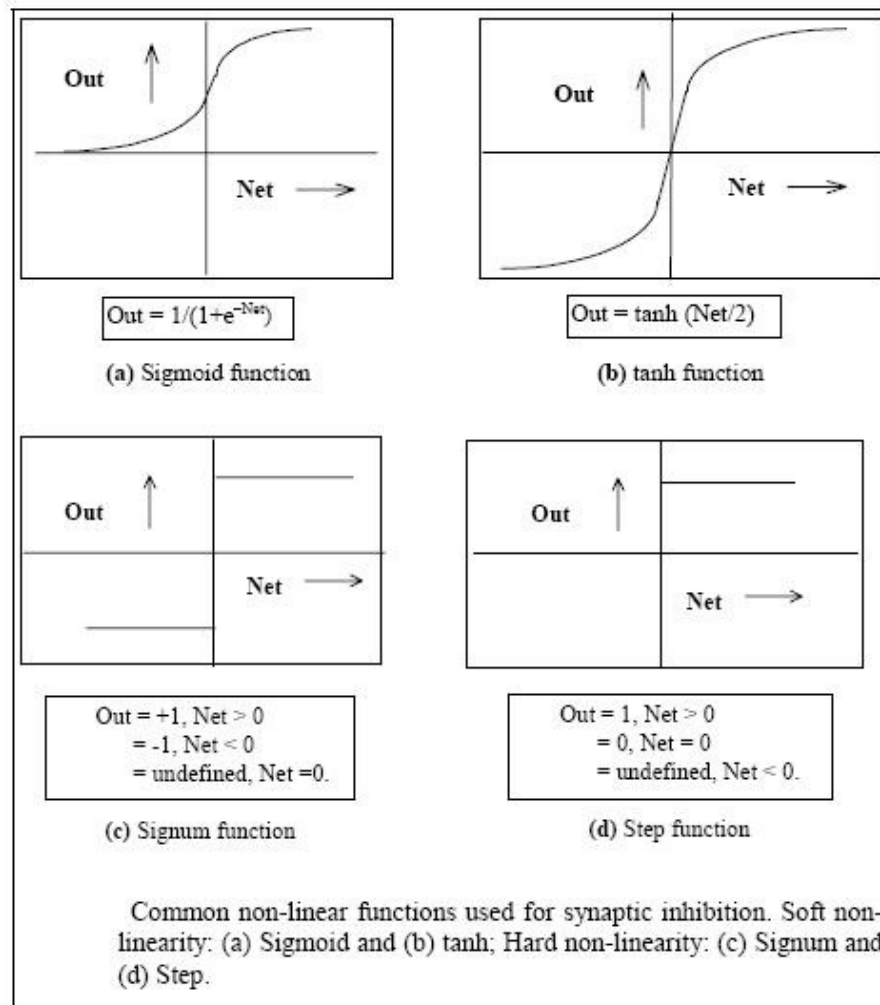


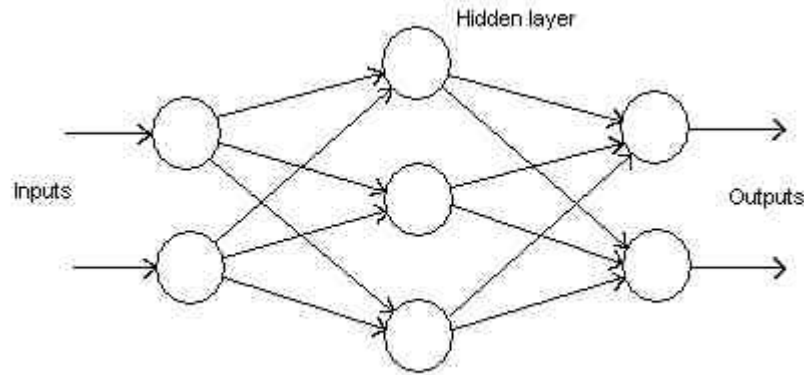
Figure 2. Common non-linear functions for synaptic inhibition.

### The Feed-Forward Neural Network Models

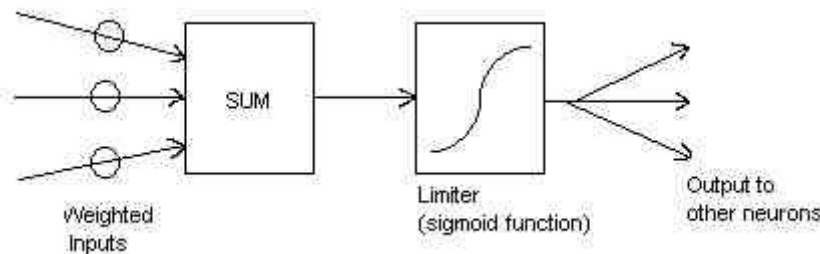
If we consider the human brain to be the 'ultimate' neural network, then ideally we would like to build a device, which imitates the brain's functions. However, because of limits in our technology, we must settle for a much simpler design. The obvious approach is to design a small electronic device, which has a transfer function similar to a biological neuron, and then connect each neuron to many other neurons, using RLC networks to imitate the dendrites, axons, and synapses. This type of electronic model is still rather complex to implement, and we may have difficulty 'teaching' the network to do anything useful. Further constraints are needed to make the design more manageable. First, we change the connectivity between the neurons so that they are in distinct layers, such that each neuron in one layer is connected to every neuron in the next layer. Further, we define that

signals flow only in one direction across the network, and we simplify the neuron and synapse design to behave as analog comparators being driven by the other neurons through simple resistors. We now have a feed-forward neural network model that may actually be practical to build and use.

As shown in Figures 3 and 4, the network functions as follows: Each neuron receives a signal from the neurons in the previous layer, and each of those signals is multiplied by a separate weight value. The weighted inputs are summed, and passed through a limiting function which scales the output to a fixed range of values. The output of the limiter is then broadcast to all of the neurons in the next layer. So, to use the network to solve a problem, we apply the input values to the inputs of the first layer, allow the signals to propagate through the network, and read the output values.



**Figure 3.** A Generalized neural network.



**Figure 4.** The structure of a neuron.

Stimulation is applied to the inputs of the first layer, and signals propagate through the middle (hidden) layer(s) to the output layer. Each link between neurons has a unique weighting value. Inputs from one or more previous neurons are individually weighted, then summed. The result is non-linearly scaled between 0 and +1, and the output value is passed on to the neurons in the next layer.

Since the real uniqueness or 'intelligence' of the network exists in the values of the weights between neurons, we need a method of adjusting the weights to solve a particular problem. For this type of network, the most common learning algorithm is called Back Propagation (BP). A BP network learns by example, that is, we must provide a learning set that consists of some input examples and the known-correct output for each case. So, we use these input-output examples to show the network what type of behavior is expected, and the BP algorithm allows the network to adapt. The BP learning process works in small iterative steps: one of the example cases is applied to the network, and the network produces some output based on the current state of its synaptic weights (initially, the output will be random). This output is compared to the known-good output, and a mean-squared error signal is calculated. The error value is then propagated backwards through the network, and small changes are made to the weights in each layer. The weight changes are calculated to reduce the error signal for the case in question. The whole process is repeated for each of the example cases, then back to the first case again, and so on. The cycle is repeated until the overall error value drops below some pre-determined threshold. At this point we say that the network has learned the problem "well enough" - the network will never exactly learn the ideal function, but rather it will asymptotically approach the ideal function.

### Multi-layer Feed Forward Networks

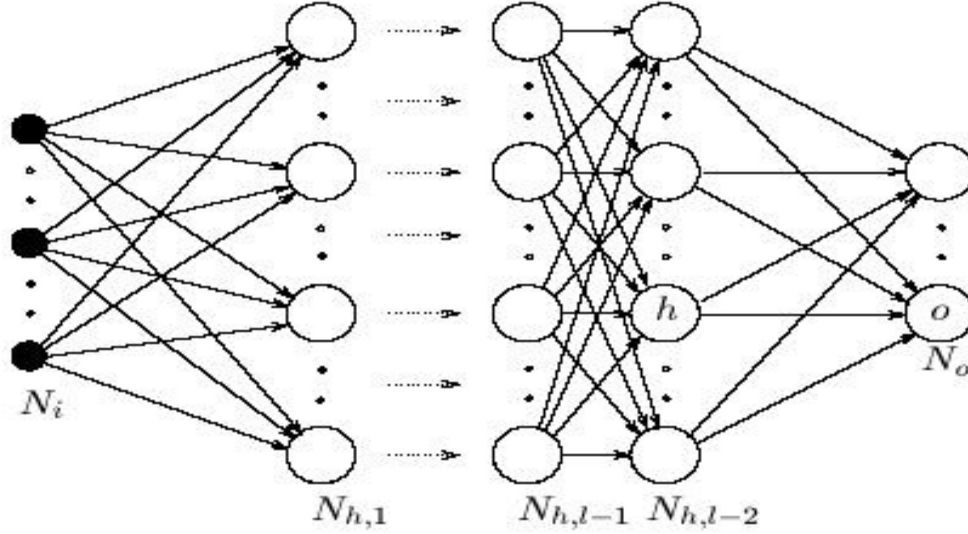
A single-layer network has severe restrictions: the class of tasks that can be accomplished is very limited. In this chapter we will focus on feed-forward networks with layers of processing units. A two layer feed-forward network can overcome many restrictions, but did not present a solution to the problem of how to adjust the weights from input to hidden units. The errors for the units of the hidden layer are determined by back-propagating the errors of the units of the output layer. For this reason the method is often called the back-propagation learning rule. Back-propagation can also be considered as a generalization of the delta rule for non-linear activation functions and multilayer networks.

### Multi-layer feed-forward network algorithm

A feed-forward network has a layered structure. Each layer consists of units which receive their input from units from a layer directly below and send their output to units in a layer directly above the unit. There are no connections within a layer. The  $N_i$  inputs are fed into the first layer of  $N_{h,1}$  hidden units. The input units are merely 'fan-out' units; no processing takes place in these units. The activation of a hidden unit is a function  $\mathcal{F}_k$  of the weighted inputs plus a bias, as given in in equation below.

$$y_k(t+1) = \mathcal{F}_k(s_k(t)) = \mathcal{F}_k \left( \sum_j w_{jk}(t) y_j(t) + \theta_k(t) \right) \quad /7/$$

The output of the hidden units is distributed over the next layer of  $N_{h,2}$  hidden units, until the last layer of hidden units, of which the outputs are fed into a layer of  $N_o$  output units [Figure 5].



**Figure 5.** The output of hidden units in multi-layer feed-forward network algorithm.

Although back-propagation can be applied to networks with any number of layers, just as for networks with binary units it has been shown that only one layer of hidden units sufficient to approximate any function with finitely many discontinuities to arbitrary precision, provided the activation functions of the hidden units are non-linear (the universal approximation theorem). In most applications a feed-forward network with a single layer of hidden units is used with a sigmoid activation function for the units.

### DELTA LEARNING RULE

Since we are now using units with nonlinear activation functions, we have to generalize the delta rule: The activation is a differentiable function of the total input, given by

$$s_k^p = \sum_j w_{jk} y_j^p + \theta_k. \quad \text{Where: } y_k^p = \mathcal{F}(s_k^p), \quad /8/$$

To get the correct generalization of the delta rule, we must set:

$$\Delta_p w_{jk} = -\gamma \frac{\partial E^p}{\partial w_{jk}}. \quad /9/$$

The error measure  $[E_p]$  is defined as the total quadratic error for pattern  $p$  at the output units:

$$E^p = \frac{1}{2} \sum_{o=1}^{N_o} (d_o^p - y_o^p)^2, \quad /10/$$

Where:  $d_o^p$  is the desired output for unit  $o$  when pattern  $p$  is clamped. We further set the equation /11/ for summed squared error.

$$E = \sum_p E^p \quad /11/$$



We can write:

$$\frac{\partial E^p}{\partial w_{jk}} = \frac{\partial E^p}{\partial s_k^p} \frac{\partial s_k^p}{\partial w_{jk}}. \quad /12/$$

$$s_k^p = \sum_j w_{jk} y_j^p + \theta_k.$$

In equation /12/, the second factor is defined as:

$$\frac{\partial s_k^p}{\partial w_{jk}} = y_j^p. \quad /13a/$$

$$\delta_k^p = -\frac{\partial E^p}{\partial s_k^p}, \quad /13b/$$

From equations /11/ to /13/, we will get an update rule which is equivalent to the delta rule as described above, resulting in a gradient descent on the error surface if we make the weight changes according to equation /14/:

$$\Delta_p w_{jk} = \gamma \delta_k^p y_j^p. \quad /14/$$

The procedure involves finding out what  $\delta_k^p$  should be for each unit  $k$  in the network. The equation /14/ is a simple recursive computation of these  $\delta$ 's which can be implemented by propagating error signals backward through the network.

To compute  $\delta_k^p$  we apply the chain rule to write this partial derivative as the product of two factors, one factor reflecting the change in error as a function of the output of the unit and one reacting the change in the output as a function of changes in the input. Thus, we have:

$$\delta_k^p = -\frac{\partial E^p}{\partial s_k^p} = -\frac{\partial E^p}{\partial y_k^p} \frac{\partial y_k^p}{\partial s_k^p}. \quad /15/$$

Now, we shall compute the second factor as follows:

$$y_k^p = \mathcal{F}(s_k^p), \quad /16/$$

$$\frac{\partial y_k^p}{\partial s_k^p} = \mathcal{F}'(s_k^p), \quad /17/$$

The equation /17/ is the same result as we obtained with the standard delta rule. Substituting this and equation /18/ in equation /15/, we get equation /19/ for any output unit  $o$ :

$$\delta_k^p = -\frac{\partial E^p}{\partial s_k^p} = -\frac{\partial E^p}{\partial y_k^p} \frac{\partial y_k^p}{\partial s_k^p}. \quad /18/$$

$$\delta_o^p = (d_o^p - y_o^p) \mathcal{F}_o'(s_o^p) \quad /19/$$

Secondly, if  $k$  is not an output unit but a hidden unit  $k = h$ , we do not readily know the contribution of the unit to the output error of the network. However, the error measure can be written as a function of the net inputs from hidden to output layer;  $E_p = E_p(s_{p1}, s_{p2}, \dots, s_{pj}, \dots)$  and we use the chain rule to write equation /20/:

$$\frac{\partial E^p}{\partial y_h^p} = \sum_{o=1}^{N_o} \frac{\partial E^p}{\partial s_o^p} \frac{\partial s_o^p}{\partial y_h^p} = \sum_{o=1}^{N_o} \frac{\partial E^p}{\partial s_o^p} \frac{\partial}{\partial y_h^p} \sum_{j=1}^{N_h} w_{ko} y_j^p = \sum_{o=1}^{N_o} \frac{\partial E^p}{\partial s_o^p} w_{ho} = -\sum_{o=1}^{N_o} \delta_o^p w_{ho}. \quad /20/$$

From equations /15/ and /20/, we get:

$$\delta_h^p = \mathcal{F}'(s_h^p) \sum_{o=1}^{N_o} \delta_o^p w_{ho}. \quad /21/$$

Equations /15/ and /21/ give a recursive procedure for computing the  $\delta$ 's for all units in the network, which are then used to compute the weight changes according to equation. This procedure constitutes the generalized delta rule for a feed-forward network of non-linear units.

### Understanding Back-Propagation Networks

The equations /21/ may be mathematically correct, but what do they actually mean? Is there a way of understanding back-propagation other than reciting the necessary equations? The answer is, of course, yes. In fact, the whole back-propagation process is intuitively very clear. What happens in the above equations is the following:

When a learning pattern is clamped, the activation values are propagated to the output units, and the actual network output is compared with the desired output values, we usually end up with an error in each of the output units. Let's call this error  $e_o$  for a particular output unit  $o$ . We have to bring  $e_o$  to zero. The simplest method to do this is the greedy method: we strive to change the connections in the neural network in such a way that, next time around, the error  $[e_o]$  will be zero for this particular pattern. We know from the delta rule that, in order to reduce an error, we have to adapt its incoming weights according to:

$$\Delta w_{ho} = (d_o - y_o)y_h. \quad /22/$$

This is step one. However, this is not enough: when we only apply this rule, the weights from input to hidden units are never changed, and we do not have the full representational power of the feed-forward network as promised by the universal approximation theorem. In order to adapt the weights from input to hidden units, we again want to apply the delta rule. In this case, however, we do not have a value for  $\delta$  for the hidden units. This is solved by the chain rule which does the following: distribute the error of an output unit  $o$  to all the hidden units that is it connected to, weighted by this connection. Differently put, a hidden unit  $h$  receives a delta from each output unit  $o$  equal to the delta of that output unit weighted with (= multiplied by) the weight of the connection between those units.

The application of the generalized delta rule thus involves two phases: During the first phase the input  $x$  is presented and propagated forward through the network to compute the output values  $[y_o]$  for each output unit. This output is compared with its desired value  $d_o$ , resulting in an error signal  $\delta_o$  for each output unit. The second phase involves a backward pass through the network during which the error signal is passed to each unit in the network and appropriate weight changes are calculated.

### Weight Adjustments With Sigmoid Activation Function

- The weight of a connection is adjusted by an amount proportional to the product of an error signal  $\delta$ , on the unit  $k$  receiving the input and the output of the unit  $j$  sending this signal along the connection:

$$\Delta_p w_{jk} = \gamma \delta_k^p y_j^p. \quad /23/$$

- If the unit is an output unit, the error signal is given by:

$$\delta_o^p = (d_o^p - y_o^p) \mathcal{F}'(s_o^p). \quad /24/$$

- Take as the activation function  $\mathcal{F}$  the 'sigmoid' function as defined:

$$y^p = \mathcal{F}(s^p) = \frac{1}{1 + e^{-s^p}}. \quad /25/$$

In this case the derivative is equal to:

$$\begin{aligned} \mathcal{F}'(s^p) &= \frac{\partial}{\partial s^p} \frac{1}{1 + e^{-s^p}} \\ &= \frac{1}{(1 + e^{-s^p})^2} (-e^{-s^p}) \\ &= \frac{1}{(1 + e^{-s^p})} \frac{e^{-s^p}}{(1 + e^{-s^p})} \\ &= y^p (1 - y^p). \end{aligned} \quad /26/$$

Such that the error signal for an output unit can be written as:

$$\delta_o^p = (d_o^p - y_o^p) y_o^p (1 - y_o^p). \quad /27/$$

- The error signal for a hidden unit is determined recursively in terms of error signals of the units to which it directly connects and the weights of those connections. For the sigmoid activation function:

$$\delta_h^p = \mathcal{F}'(s_h^p) \sum_{o=1}^{N_o} \delta_o^p w_{ho} = y_h^p (1 - y_h^p) \sum_{o=1}^{N_o} \delta_o^p w_{ho}.$$

/28/

### Learning rate and momentum

The learning procedure requires that the change in weight is proportional to:  $\partial E^p / \partial w$ .

True gradient descent requires that infinitesimal steps are taken. The constant of proportionality is the learning rate. For practical purposes we choose a learning rate that is as large as possible without leading to oscillation. One way to avoid oscillation at large, is to make the change in weight dependent of the past weight change by adding a momentum term:

$$\Delta w_{jk}(t+1) = \gamma \delta_k^p y_j^p + \alpha \Delta w_{jk}(t),$$

/29/

Where: t indexes the presentation number and F is a constant which determines the effect of the previous weight change.

Although, theoretically, the back-propagation algorithm performs gradient descent on the total error only if the weights are adjusted after the full set of learning patterns has been presented, more often than not the learning rule is applied to each pattern separately, i.e., a pattern p is applied,  $E_p$  is calculated, and the weights are adapted ( $p = 1, 2, \dots, P$ ). There exists empirical indication that this results in faster convergence. Care has to be taken, however, with the order in which the patterns are taught. For example, when using the same sequence over and over again the network may become focused on the first few patterns. This problem can be overcome by using a permuted training method.

The back propagation learning algorithm is applied to multi-layered feed-forward networks consisting of processing element with continuous and differentiable activation functions. Given a training set of input-output pairs, the algorithm provides a procedure for changing the weights in a back-propagation learning algorithm to classify the given input patterns correctly. The basis for this weight update algorithm is simply the gradient descent method as used for simple perceptron with differentiable neurons.

For a given input-output pair, the back propagation algorithm performs two phases of data flow. First, the input pattern is propagated from the input layer to the output layer, and as a result of this forward flow of data, it produces an actual output. Then the error signals resulting from the difference between output pattern and an actual output are back-propagated from the output layer to the previous layers for them to update their weights. The type of neural network used in this study is three-layer back-propagation network, consisting of an input layer, a hidden layer and an output layer. The learning algorithm used in this present research work *Levenberg-Marquardt* back-propagation of MATLAB Neural Network Tool Box (version 7.4, 2007). The transfer function selected for the layers will be sigmoid, for the hidden layer and linear for the output layer.

### Training and Testing of Neural Networks

A neural network has to be configured such that the application of a set of inputs produces (either 'direct' or via a relaxation process) the desired set of outputs. Various methods to set the strengths of the connections exist. One way is to set the weights explicitly, using a priori knowledge. Another way is to 'train' the neural network by feeding it teaching patterns and letting it change its weights according to some learning rule. We can categorize the learning situations in two distinct sorts. These are:

- **Supervised learning** or Associative learning [Figure 6] in which the network is trained by providing it with input and matching output patterns. These input-output pairs can be provided by an external teacher, or by the system which contains the neural network (self-supervised).

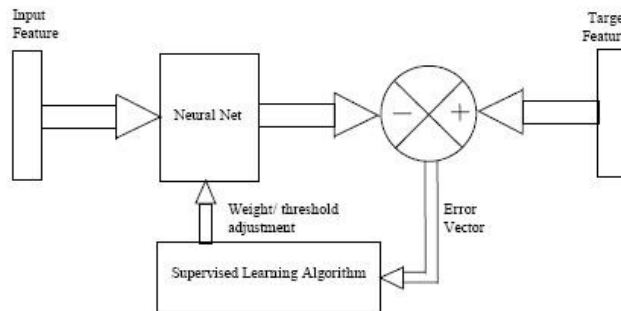


Figure 6. Training the networks with supervised learning.

- **Unsupervised learning** or Self-organization in which an (output) unit is trained to respond to clusters of pattern within the input. In this paradigm the system is supposed to discover statistically salient features of the input population. Unlike the supervised learning paradigm, there is no a priori set of categories into which the patterns are to be classified; rather the system must develop its own representation of the input stimuli.

- **Reinforcement Learning** This type of learning may be considered as an intermediate form of the above two types of learning. Here the learning machine does some action on the environment and gets a feedback response from the environment. The learning system grades its action good (rewarding) or bad (punishable) based on the environmental response and accordingly adjusts its parameters. Generally, parameter adjustment is continued until an equilibrium state occurs, following which there will be no more changes in its parameters. The self-organizing neural learning may be categorized under this type of learning.

### **Neural Network Training and ANN Model Description**

A multi-layer neural network consists of a number of interconnected nodes arranged into layers where each node (neuron) operates as a simple processing element. Each node in the network is interconnected with all nodes in the preceding and following layers. There are no interconnections within nodes of the same layer. The number of layers and the number of nodes by layer represent the network architecture. The input layer serves as an entry for the vector of input data presented to the network where each node corresponds to one explanatory variable (input). The output layer represents the output data (target). All layers between the input and output layers are referred to hidden layers.

The input ( $I_j$ ) to a node ( $j$ ) is the weighted sum (using  $w_{ij}$ ) of the outputs ( $O_i$ ) from the nodes of the preceding layer ( $i$ ). This sum is then passed through an activation function ( $f$ ) to produce the node's output ( $O_j$ ) within the range of the activation function. The activation function is usually a sigmoid or hyperbolic tangent, which is a nonlinear function with an asymptotic behavior. In our case, we used the hyperbolic tangent sigmoid function. The interconnecting weight values are adjusted and updated during the training phase to achieve minimal overall training error between the desired and calculated output vectors. All data should be rescaled to ensure they receive equal attention during the training process. In this study, data were rescaled to the interval  $[-1, 1]$ .

All parameters in neural network (weight and biases) can be denoted by the vector:

$$\underline{w} \in W \subset R^P \quad /30/$$

Where:  $P$  is the total number of parameters of the network. Training a neural network involves selecting the 'best' set of network parameters ( $\underline{w}$ ) that minimize a training error estimator. The error estimator used here was the sum squared error (SSE). Preliminary, training explored how possible architectures performed when training with different training algorithms. Next, the best combination of network architecture and training algorithm was selected. Finally the chosen combination was further tested and trained to obtain the best generalization capacity. The training methodology used was back propagation training algorithm.

While back propagation with gradient decent technique is a steepest descent algorithm, the Levenberg – Marquardt algorithm is an approximation to Newton's method. The minimization algorithm used was the Levenberg – Marquardt algorithm. In back propagation algorithm, the vector of the network parameters ( $\underline{w}$ ) is updated in each epoch (training step) using,

$$\underline{W}_{k+1} = \underline{W}_k - \alpha_k \underline{M}_k \underline{g}_k \quad /31/$$

Where:  $\alpha$  = learning rate;  $g$  = gradient of the error functions;  $M$  = approximation of the inverse of the Hessian matrix. This matrix is positive definite in order to ensure the descent. All quantities are for the  $k^{th}$  iteration. In the *Levenberg-Marquardt* algorithm, the inverse of the Hessian matrix approximated by:

$$[\epsilon \cdot I + J - J^T]^{-1} \quad /32/$$

where,  $\epsilon$  = small quantity;  $I$  = identity matrix;  $J$  = Jacobian matrix ( $J_{ij}$ ) with:

$$J_{ij} = \frac{\delta e_j}{\delta w_i} \quad /33/$$

Where:  $e_j$  is the error ( $y_j - t_j$ ) from the target value. A crucial point in the back propagation algorithm is the chose of the learning rate ( $\alpha$ ), which minimizes the error of the nest step (epoch). In the large majority of the works in the literature a fixed value of the learning rate is used during the training of the neural network.

### **Model Architecture**

The best neural network architecture can only be determined experimentally for each particular application. According to de Villiers and Barnard (3), ANN models with one hidden layer can approximate any continuous function. Thus, in this study, model architecture of one hidden layer was used. The number of nodes in the hidden layer(s) should be large enough to ensure a sufficient number of degrees of freedom for the network function and small enough to minimize the risk of loss of the network's generalization ability. Furthermore, it's important to note that a useless increase of the neural network size will lead to a significant increase in training and running time. As recommended by Maier and Dandy (2001), the node number upper limit in the hidden layer(s) was fixed as follows:

$$N^{Hl} = \min (2N^I + 1; N^{TR} / N^I + 1) \quad /34/$$

Where:  $N^{Hl}$  is the number of nodes in the hidden layer(s),  $N^I$  number of input nodes and  $N^{TR}$  the number of training sample.

## **PREDICTION OF DAILY PAN EVAPORATION USING NEURAL NETWORKS MODELS: INDIAN AGRICULTURE**

The evaporation is a complex and nonlinear phenomenon involving several weather factors in the hydrological process. It is the necessary components of any water balance assessments for different water resources planning, design, operation and management studies including hydrology, agronomy, horticulture, forestry, land resources, irrigation management, flood forecasting, investigation of agro-ecosystem and modeling etc. and perhaps the most difficult to estimate owing to complex

interactions between the components of the soil-water-plant-atmosphere system. Evaporation is an important variable in making the crop management decision and modeling crop response to weather conditions and climate change. It has been extensively used for estimating the potential and reference evapotranspiration of various crops (Gavin and Agnew, 5). Based on the limitations in measuring the pan evaporation research has been performed to model pan evaporation using various meteorological variables. It is therefore necessary to develop approaches to estimate the evaporation rates from other available meteorology variables, which are comparatively easier for measurements. The class A pan evaporation is direct method. Indirect method includes those that use meteorological data to estimate evaporation from other weather variables through empirically developed methodologies or artificial neural network and statistical approaches.

The investigation was carried out by the authors to develop and test the daily pan evaporation prediction models using various weather parameters as input variables with artificial neural network (ANN) and validated with the independent subset of data for five different locations in India. The measured variables included daily observations of maximum and minimum temperature, maximum and minimum relative humidity, wind speed, sunshine hours, rainfall and open pan evaporation.

In this general model (GM), model development and evaluation has been done for the five locations in India:

NRCC, Nagpur (Maharashtra)

JNKVV, Jabalpur (Madhya Pradesh)

PDKV, Akola (Maharashtra)

ICRISAT, Hyderabad (Andhra Pradesh) and

MPUAT, Udaipur (Rajasthan).

The daily data of pan evaporation and other inputs for two years was considered for model development and subsequent 1-2 years data for validation. Weather data consisting of 3305 daily records from 2002 to 2006 were used to develop the GM models of daily pan evaporation. Additional weather data of Nagpur station, which included 2139 daily records from 1996 - 2004, served as an independent evaluation data set for the performance of the models. The model plan strategy with all inputs has shown better performance than the reduced number of inputs. The General ANN models of daily pan evaporation with all available variables as inputs was the most accurate model delivering an  $R^2$  of 0.84 and a root mean square error 1.44 mm for the model development data set. The GM evaluation with Nagpur model development (NMD) data shown lowest RMSE (1.961 mm), MAE (0.038 mm) and MARE (2.30 %) and highest  $r$  (0.848),  $R^2$  (0.719) and  $d$  (0.919) with ANN GM M-1 with all input variables.

The basic aim of this research was to improve the effectiveness and operational ability of classic and sophisticated methods and discover perspectives of modern and sophisticated approaches such as artificial neural networks (ANN) for the prediction and estimation of pan evaporation. The regression models developed from meteorological data involve empirical relationships to some extent accounts for many local conditions. Therefore, most regression models gave reliable results when applied to climatic conditions similar to those for which they were developed. The correlations and regression studies between different meteorological parameters and evaporation measured from US Class A open pan evaporimeter under Indian conditions. Linear regression methods for prediction of evaporation using weather variables has been applied for decades and are well and understood (Jhajariya *et al.*, 8; Shirgure and Rajput, 16). The highest correlation was found with maximum temperature followed by wind speed. The coefficient of determination for maximum temperature, minimum temperature, wind speed and soil temperature at 5 cm depth was positively correlated. The relative humidity was negatively correlated (Khanikar and Nath 10). The pan evaporation and the meteorological parameters recorded at Jabalpur revealed that the morning relative humidity and the maximum temperature have a significant influence on the rate of evaporation (Shrivastava *et al.*, 17). There was a need for developing the model which can generalize for the diversified Indian conditions. Artificial neural network (ANN) is effective tool to model non-linear process like evaporation from open pan. Pan evaporation has been widely used as an estimate for irrigation scheduling of vegetables and horticultural crops (Shirgure *et al.*, 15).

The artificial neural networks provide better modeling flexibility than the other statistical approaches. Numerous researchers have shown applicability of multiple linear regression technique for estimating the evaporation, but very few have been seen on artificial neural networks in agricultural and hydrological processes in India. For instance multi-layered feed forward ANN with error back propagation techniques has been used for estimating evaporation (Arca *et al.*, 1; Sudheer *et al.*, 18; Ozlem and Evolkesk, 14; Keskin and Terzi, 9), evapo-transpiration (Kumar *et al.*, 11; Sudheer *et al.*, 18), soil water evaporation (Han and Felkar, 7) and various neuro-computing techniques for predicting the various atmospheric processes and parameters (Gardner and Dorling, 6). Bruton *et al.* (2) developed ANN models to estimate daily pan evaporation using measured weather variables as inputs. The measured variables included daily observations of rainfall, temperature, relative humidity, solar radiation, and wind speed. Daily pan evaporation was also estimated using multiple linear regression and compared to the results of the ANN models. The ANN models of daily pan evaporation with all available variables as a inputs was the most accurate model delivering an  $r^2$  of 0.717 and a root mean square error 1.11 mm for the independent evaluation data set. The accuracy of the models was reduced considerably when variables were eliminated to correspond to weather stations. Pan evaporation estimated with ANN models was slightly more accurate than the pan evaporation estimated with a multiple linear regression models. Sudheer *et al.* (19) investigated the prediction of Class A pan evaporation using the ANN technique. The ANN back propagation algorithm has been evaluated for its applicability for predicting evaporation from minimum climatic data. The study indicated that evaporation values could be reasonably estimated using temperature data only through the ANN technique. This would be of much use in instances where data availability is limited. These features provide neural networks the potential to model complex non-linear phenomenon like prediction of daily pan evaporation using meteorological measured variables. Observations of relative humidity, solar radiation, temperature, wind speed and evaporation for the past 22 years have been used to train and test the developed networks. Results revealed that the networks were able to well learn the events they were trained to recognize.

These encouraging results were supported by high values of coefficient of correlation and low mean square errors reaching 0.98 and 0.00015 respectively (Taher, 20). Daily pan evaporation was estimated by a suitable ANN model for the meteorological data recorded from the Automated *GroWeather* meteorological station near Lake Egirdir, Turkey (Ozlem *et al.*, 14). The ANN models were developed and validated a simulation model of the evaporation rate of a Class A evaporimeter pan located near Cartagena (Southeast Spain) (Molina Martinez *et al.* 13). Keskin and Terzi (9) studied the ANN models and proposed as an alternative approach of evaporation estimation for prediction of daily pan evaporation estimation. The comparison shows that there is better agreement between the ANN estimations and measurements of daily pan evaporation than for other model. Deswal and Mahesh Pal (4) studied an ANN based modeling and the influence of meteorological parameters on evaporation from a reservoir. The findings of the study also revealed the requirement of all input parameters considered together, instead of individual parameters taken one at a time. The highest correlation coefficient (0.960) along with lowest root mean square error (0.865) was obtained with the input combination of air temperature, wind speed, sunshine hours and mean relative humidity.

The basic objectives of this research work is to develop three layered feed forward with error back propagation neural network models to estimate daily pan evaporation values based on different meteorological data. The other objectives are to test the suitability of the artificial neural networks for modeling daily pan evaporation and to test and validate the developed ANN evaporation models for the input variables using the independent subset of data for other locations.

### Study Area and Dataset

Data were taken from agro-meteorological stations at: Nagpur (National Research Centre for Citrus, Experiment Station, lat. 21.09°N, long. 79.22°W. 311.3 m amsl), Jabalpur (Jawaharlal Nehru Agricultural University, lat. 23.10°N, long. 79.58°W, 410 m amsl), Akola (Dr. Panjabrao Deshmukh Agricultural University, lat. 20.42°N, long. 77.04°W. 309 m amsl), Hyderabad (International Crop Research Institute for Semi Arid Tropics, lat. 17.53°N, long. 78.27°W. 545 m amsl) and Udaipur (Maharana Pratap University of Agriculture and Technology, lat. 24.35 °N, long. 73.42 °W. 582 m amsl). These locations represent the dry sub-humid, sub-humid, semi-arid and arid climatic regions within the state of Maharashtra, Madhya Pradesh, Andhra Pradesh and Rajasthan. The intent was to develop a single model that could be used for any of the agro-climatic zones of India. The data were partitioned into a model development data set and an independent evaluation data set. The model development data set consisted of 607, 731, 507, 730 and 730 days of data (3305 total observations) for Nagpur, Jabalpur, Akola, Hyderabad and Udaipur respectively, from 2002 to 2006. The model development data set was further divided by randomly placing 80% of the observations in a training data set and the remainder 20 % in a testing data set. The training data set was used to develop the neural network models. The testing set was used to evaluate the accuracy of the ANN models during training in order to determine when to stop the training. Training was continued as long as the minimum goal of error of the ANN estimate of pan evaporation on was kept as 0.001. The model development data set was used to choose preferred ANN training parameters and to develop ANN models of pan evaporation based on various numbers of inputs. With this procedure, all model development and parameter selection were done with the model development data set. The Nagpur model development (NMD) data size was 2139. The model GM evaluation data set consisted of 2066 observations for Nagpur, Jabalpur, Akola, Hyderabad and Udaipur respectively, from 2004 to 2007 for the five locations. Weather variables included in the evaluation data set were the same as those in the model development data set. The evaluation data set was not used in model development in any way and was only used to assess the accuracy of the ANN models.

A three-layer back propagation ANN architecture was employed in all models. The MATLAB (Ver.7.4, 2007) software package was used to develop the ANN pan evaporation models. The data set included daily records of eight measured variables viz. maximum temperature (TMAX), minimum temperature (TMIN), maximum relative humidity (RMAX), minimum relative humidity (RMIN), wind speed (WISP), sunshine hours (SNHR), rainfall (RAIN) and pan evaporation (EPAN). The number of measurable weather variables used as inputs in the development of the ANN pan evaporation models (M-1 to M-7) was varied with emphasis placed on investigating models with reduced numbers of inputs, based on positive and negative effects of the parameters on evaporation process. Seven model strategies (combination of variable inputs) to be evaluated in this study is shown in Table 1.

Modeling strategy in M-1 included all seven available daily weather input variables. Model strategy M-2 considered the effect of removing rainfall from the variables in modeling strategy M-1 creating the situation of non-rainy period evaporation process. Model strategy M-3 considered removing sunshine hours and inclusion of rainfall creating the weather with rainy season and without sunshine hours. The effect of absence of maximum and minimum relative humidity in the evaporation process is tested in model strategy M-4. This is like without humidity days. In modeling plan M-5 the maximum and minimum temperature as well as relative humidity was as variables, modeling the situation with temperature and humidity. Modeling strategy M-6 included maximum temperature, wind speed and sunshine hours as input variables. The model M-7 included maximum temperature and wind speed as the only observed weather values.

### Model Architecture

The best neural network architecture according to de Villiers and Barnard (3), ANN models with one hidden layer can approximate any continuous function. Thus, in this study, model architecture of one hidden layer was used. The number of nodes in the hidden layer(s) should be large enough to ensure a sufficient number of degrees of freedom for the network function and small enough to minimize the risk of loss of the network's generalization ability. Furthermore, it's important to note that a useless increase of the neural network size will lead to a significant increase in training and running time. As recommended by Maier and Dandy (12), the node number upper limit in the hidden layer(s) was fixed as follows:

$$N^H = \min (2N^I + 1; N^{TR} / N^I + 1)$$

**Table 1.** The modeling strategies in development of ANN pan evaporation models.

| Variables | Modeling strategies |     |     |     |     |     |     |
|-----------|---------------------|-----|-----|-----|-----|-----|-----|
|           | M-1                 | M-2 | M-3 | M-4 | M-5 | M-6 | M-7 |
| TMAX      | √                   | √   | √   | √   | √   | √   | √   |
| TMIN      | √                   | √   | √   | √   | √   | -   | -   |
| RMAX      | √                   | √   | √   | -   | √   | -   | -   |
| RMIN      | √                   | √   | √   | -   | √   | -   | -   |
| WISP      | √                   | √   | √   | √   | -   | √   | √   |
| SNHR      | √                   | √   | -   | √   | -   | √   | -   |
| RAIN      | √                   | -   | √   | √   | -   | -   | -   |

√ - indicates the inclusion of the variable in neural network modeling

Where:  $N^H$  is the number of nodes in the hidden layer(s),  $N^I$  number of input nodes and  $N^{TR}$  the number of training sample. The number of hidden nodes is therefore taken from 5 to 20 as the inputs vary from seven in model M-1 to two in model M-7. The number of training samples is large. So, the ratio of the training samples to training parameters is large and  $2N^I+1$  is minimum number of hidden nodes of the networks. The accuracy increase with increasing the nodes, but the generalization ability of the model goes down. So, the optimization of nodes is done with minimum squared and absolute error. The final GM models were developed with 15 hidden nodes, which gave minimum errors. The developed model evaluation was done with the help of the Nagpur model development dataset and GM evaluation dataset. The number of records used for evaluation is 484 for NRCC, Nagpur; 487 for JNKVV, Jabalpur; 365 each for PDKV, Akola, ICRISAT, Hyderabad and MPUAT, Udaipur.

#### ANN modeling software source code program using MATLAB

The neural network utility file was edited in MATLAB (version 7.4, 2007) source code program. The main GUI consisting of all the input variables selection, input data source file, network options, training and testing functions, setting the data for training, evaluation, plotting the predicted values and saving the network is created and run in MATLAB software. The mainframe is executed by running the MainGUI.mat file in MATLAB program. The Graphical User Interface (GUI) appears by changing the directory option, which gives the details of the ANN modeling selections. The program displays the title, the input variables to be selected by making the tick marks on/off. The source data input file (.csv) is browsed for the training, testing and evaluation. The variables were selected according to the model plan M-1 to M-7 for developing and evaluating the ANN models. The ANN model architecture is three layered feed forward with error back propagation. Which is most commonly used neural network for the prediction of the non-linear process like prediction of pan evaporation. The number of hidden nodes selection is done from 5 to 20. The transfer function from input to hidden layer is logistic sigmoid and from hidden layer to output layer is linear (as the output is one i.e. EPAN). The training function is *Levenberg-Marquardt*, which is most common and accurate is selected.

The performance functions for training and testing the networks used are MAE (mean absolute error) and MSE (mean squared error). The learning rate, which decides the accuracy of the training is used for optimization are 0.1, 0.3, 0.5 and 0.7. The momentum of the training the network, which gives the speed of the training varied from 0.1, 0.3, 0.5, 0.7 and 0.9. The various combinations of hidden nodes, learning rate and momentum is done to arrive at optimum combinations to give less error. The network iterations (epochs) were kept at 1000. The ANN model development and evaluation with saved model plans is done as follows. The mainframe of the ANN modeling with MATLAB is shown in Figure 7. The GUI.mat file is opened in MATLAB software. The model development input data file (saved in .csv format) is browsed to the main GUI frame. The hidden nodes, training and transfer functions are selected. The model is generated on clicking the button **Generate model**. This generated model is displayed in command window of the MATLAB program. This gives the network architecture, input, hidden and output layer weights and bias weights. The generated ANN model is trained by clicking on the **Train model** option. Training is undertaken by setting the percentage training, testing and validation values as 80 %, 20 % and 100 % respectively. The network training process is displayed on the screen with minimum error in comparison with the set 0.001goal. The program gives the graphical output with set goal value. The model when gives the minimum value of MSE/MAE is saved as a model with particular identification name. The GM models (GM) were saved in the name as GM 15 M-1 to GM 15 M-7. This also indicates the General model with 15 hidden nodes, 0.1 learning rate and momentum each and for the model plans.

These saved models were used for validation of the same data on screen or the other source data of the independent locations. This was done by selecting the source file and clicking on the button **Evaluate model** on mainframe of the program. The saved neural network model was used for evaluation of new input file, which is browsed in evaluation module of the mainframe. The output of the pan evaporation is predicted in command window of the MATLAB program. The same is copied and used for estimating the model performance like RMSE, MAE, MARE, r,  $R^2$  and d. The graphical output of the training, testing and validation of the network as well as the plotting of the observed and ANN predicted EPAN is displayed on the desktop, which was saved for the comparison of the different ANN model plans. In this way model plans M-1 to M-7 of the General model was developed and evaluated with five different locations in India, as shown in this section.

#### Evaluation of Performance Parameters for the Model

The ANN model development and evaluation using the independent datasets of various locations was done with help of the MATLAB source code program and the datasets concerned. The developed and evaluated models were verified with the squared and absolute statistics of different performance functions. Mean squared error (MSE), Root mean squared error (RMSE), Mean

absolute relative error (MARE), Correlation coefficient (r) and coefficient of determination ( $R^2$ ) are used as model development as well as evaluation criteria's. Based on these criteria's the superiority of the model is judged. The  $R^2$  measures the degree to which two variables are linearly related. MSE and MARE provide different types of information about the predictive capabilities of the model. The MSE and RMSE measures the goodness of fit relevant to high evaporation values, whereas the MARE yields a more balanced perspective of the goodness of fit at moderate evaporation. In addition an index of agreement (d) between the observed and predicted values was calculated.

**MainGUI**

## EVAPORATION MODELING USING ARTIFICIAL NEURAL NETWORKS

Select Excel Files For Input Data :

**Select Variables**

| Select                              | Variable | Parameter                 | Abbreviation | Units  |
|-------------------------------------|----------|---------------------------|--------------|--------|
| <input checked="" type="checkbox"/> | X1       | Maximum temperature       | TMAX         | oC     |
| <input checked="" type="checkbox"/> | X2       | Minimum temperature       | TMIN         | oC     |
| <input checked="" type="checkbox"/> | X3       | Maximum relative humidity | RMAX         | %      |
| <input checked="" type="checkbox"/> | X4       | Minimum relative humidity | RMIN         | %      |
| <input checked="" type="checkbox"/> | X5       | Wind speed                | WISP         | kmph   |
| <input checked="" type="checkbox"/> | X6       | Sunshine hours            | SNHR         | hrs    |
| <input checked="" type="checkbox"/> | X7       | Rainfall                  | RAIN         | mm     |
| <input checked="" type="checkbox"/> | X8       | Evaporation (Pan)         | EPAN         | mm/day |

**Select Model**

Select Model Type :

No Of Hidden Nodes :

Transfer Functions :

Training Function :

Performance Functions :

Learning Rate :

Momentum :

Epochs :

Select Excel Files :

Select Excel Files :

**Figure 7.** The Graphical User Interface (GUI) of ANN modeling for EPAN prediction.

### General Model Development

The General model (GM) is developed using daily records of the weather inputs from Nagpur, Jabalpur; Akola; Hyderabad and Udaipur. The program in MATLAB codes is opened and run for the main frame of the ANN modeling. The main frame which helped in selecting the input data file, selecting the input variables, number of the hidden nodes, training, learning and transfer functions, learning rate and momentum. The model input file which is saved in spreadsheet (with csv format) is browsed and selected. The number of hidden nodes, learning rate and momentum is kept as 15, 0.1 and 0.1 respectively, as it has shown optimum parameters. The training function is back propagation with *Levenberg-Marquardt* algorithm and transfer function is logistic sigmoid. The number of iterations (epochs) were kept 1000. The network performance functions are kept as MAE and MSE. The goal set for testing the neural networks was 0.001 (0.1 %). The data was set to train, test and validate in the ratios of 80 %, 20 % and 100 % respectively. The training network figure for lowest MSE / MAE is also saved. The process of training the network was repeated many times and when the MSE/MAE was shown minimum the ultimate network is saved in .mat file with some name. Like this GM models with 15 hidden nodes and 0.1 learning rate and 0.1 momentum were saved optimally in the names of GM15 M-1 to GM15 M-7. The ANN General models M-1 to M-7 has input layer and bias weights. The input weights, layer weights and bias weights of these ANN models are explored in window of the MATLAB program and saved.



## RESULTS AND DISCUSSION

The model development data set was used to determine preferred values for number of hidden nodes, learning rate, and momentum. Data for all five sites were included to obtain the best model parameters, as well as all 7 input parameters. The ANN parameters for learning rate and momentum have values which are typically less than one. Learning rate and momentum combinations using 0.1, 0.3, 0.5, and 0.9 were tested with hidden node numbers ranging from 5 to 20. The training data were used for training and the testing data were used to determine when to stop training. The accuracy of the model on the model development data set (training data and testing data) was then determined. In the initial experimentation, it was found that the accuracy of the models was reduced for number of hidden nodes above 15, and Learning rate and momentum below 0.1. Otherwise, there was little variation in accuracy for the various combinations of parameters. The accuracy was higher for 15 hidden nodes, a learning rate of 0.1 and a momentum of 0.1. Experimentation was performed due to the limited effect of the ANN parameters on model accuracy. The accuracies of the models in feed forward mode for the development and evaluation data sets are shown in Table 2. The results for the evaluation data set provide an independent evaluation of the prediction accuracy of the models.

### Error Statistics of General model (GM) Development

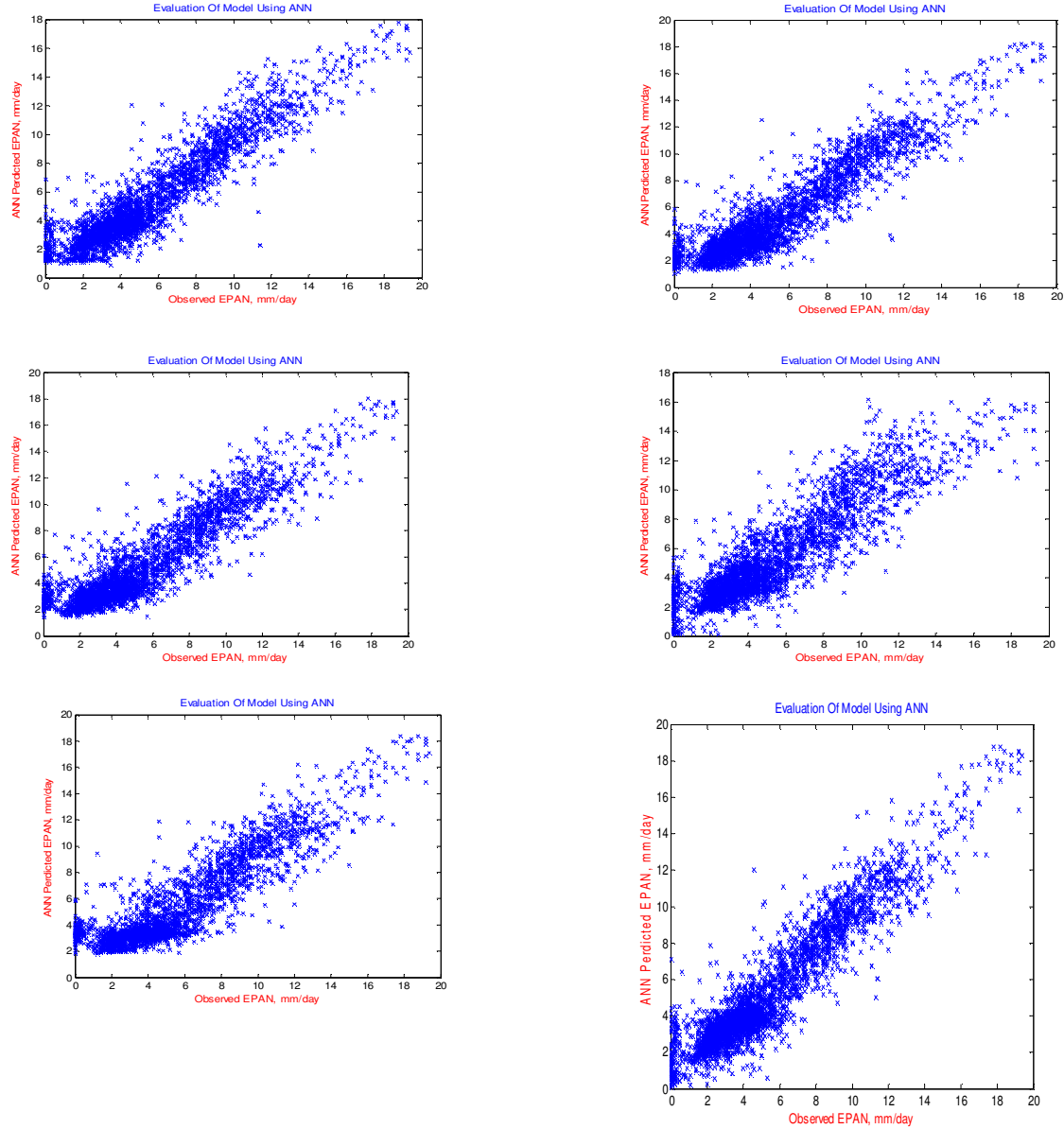
The ANN General model development data shows that the RMSE, MAE and MARE is increased and  $r$ ,  $R^2$  and  $d$  is decreased when the input variables were sequentially removed from seven variables in M-1 to two variables in M-7. The lowest RMSE (1.439 mm), MAE (0.0207 mm) and MARE (0.915 %) and highest  $r$  (0.916),  $R^2$  (0.839) and  $d$  (0.956) was observed with GM M-1 model, in which all the input variable are taken into consideration. In model M-2, where all the six input variables excluding RAIN was considered in ANN model has also shown lower RMSE, MAE and MARE and higher  $r$ ,  $R^2$  and  $d$ . The RMSE, MAE and MARE was 1.478 mm, 0.0218 mm and 1.076 %, which is slightly more than the model M-1, but not a significant difference exists. The  $r$ ,  $R^2$  and  $d$  in model M-2 is 0.911, 0.831 and 0.953 respectively. These values are less than the values of model M-1. The RMSE, MAE and MARE of GM M-3 model are higher and  $r$ ,  $R^2$  and  $d$  are lower as compared to ANN model M-1 and M-2. This is mainly due to the replacement of sunshine hours input of model M-2 with RAIN variable. This indicates that the performance of all variables without SNHR (but with RAIN variable) shows higher RMSE, MAE and MARE and lower  $r$ ,  $R^2$  and  $d$  as compared to model M-2. The RMSE, MAE and MARE of model M-3 are 1.559 mm, 0.024 mm and 1.362 % respectively. The  $r$ ,  $R^2$  and  $d$  of model M-3 are 0.901, 0.812 and 0.947 respectively. The error statistics of model GM M-4 in which the relative humidity (RMAX and RMIN) are not the input variables. The RMSE, MAE and MARE of model M-4 is 1.625 mm, 0.026 mm and 1.506 %, which is higher than the models M-1, M-2 and M-3. The  $r$ ,  $R^2$  and  $d$  of M-4 is 0.892, 0.796 and 0.942 respectively and these values are higher than model M-1 M-2 and M-3. It is mainly due to the absence of RMAX and RMIN input variables and have higher negative correlation with the pan evaporation. Although five variables are there in model M-4, but the important variables i.e. RMAX and RMIN are not considered for modeling has shown more error.

The model M-5 performance is better than the model M-4. The RMSE, MAE and MARE in model M-5 is increased to 1.685 mm, 0.0284 mm and 1.549 % from 1.625 mm, 0.026 mm and 1.50 % in model M-4. The  $r$ ,  $R^2$  and  $d$  is also decreased to 0.883, 0.78 and 0.935 in model M-5 as compared to model M-4. The input variables are TMAX, WISP and SNHR in model M-6. The RMSE, MAE and MARE of model M-6 is 1.702 mm, 0.0289 mm and 1.996 % respectively. The  $r$ ,  $R^2$  and  $d$  of model M-6 was 0.88, 0.776 and 0.935 which are lower as compared to M-5 and higher than model M-7. The RMSE, MAE and MARE is increased to 1.759 mm, 0.0309 mm and 2.52 % in GM model M-7, in which only TMAX and WISP are the input variables of the model. The  $r$ ,  $R^2$  and  $d$  were also lowest in model M-7 as compared to M-1 to M-6. The  $r$ ,  $R^2$  and  $d$  in model M-7 were 0.872, 0.76 and 0.929 respectively. The evaluation of general model development is graphically presented [Figure 8].

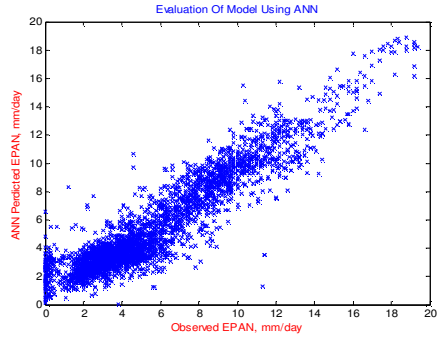
### General Model Evaluation with Nagpur Model Development (NMD) Dataset

The Nagpur model development (NMD) data from April, 1996 to March, 2004 (2139 observations) was used for evaluating the ANN General model with M-1 to M-7 model strategies. The optimum number of hidden nodes, learning rate and momentum for General model (GM) is 15, 0.1 and 0.1 respectively. The trained ANN models M-1 to M-7 with minimum error reaching towards the goal. Each saved model architecture indicates the input variables, hidden layers and number of nodes in it, biases, input, hidden and output layer weights, bias weights. The corresponding model output values of the predicted EPAN as used for evaluation of these developed models. The output resulted from the ANN models at minimum MSE / MAE was compared with observed EPAN and the various model evaluation parameters were analyzed to decide the best predictive model for pan evaporation. The absolute and squared statistics of the ANN models is tabulated and presented in Table 2. ANN General model evaluation using Nagpur model development data shows that the RMSE, MAE and MARE is increased and  $r$ ,  $R^2$  and  $d$  is decreased when the input variables were sequentially removed from seven inputs in model M-1 to six inputs in model M-2 and M-3. The lowest RMSE (1.961 mm), MAE (0.038 mm) and MARE (2.30 %) and highest  $r$  (0.848),  $R^2$  (0.719) and  $d$  (0.919) was observed with GM M-1 model, in which all the input variables are taken into consideration. However, in model M-2 and M-3, where six input variables are considered in GM modeling has also shown lower RMSE, MAE and MARE and higher  $r$ ,  $R^2$  and  $d$ . This shows that the GM model generalization capacity is better when tested with Nagpur model development data. The RMSE, MAE and MARE in model plan M-2 was 1.973 mm, 0.0389 mm and 2.49 %, which is slightly more than the model M-1. The  $r$ ,  $R^2$  and  $d$  in model M-2 is 0.845, 0.715 and 0.917 respectively. These values are also less to the values of model M-1. The RMSE, MAE and MARE of GM M-3 model are higher and  $r$ ,  $R^2$  and  $d$  are lower as compared to model M-1 and M-2. This is mainly due to the replacement of sunshine hours input of model M-2 with RAIN variable. This indicates that the performance of all variables without SNHR (but with RAIN variable) shows higher RMSE, MAE and MARE and lower  $r$ ,  $R^2$  and  $d$  as compared to model M-

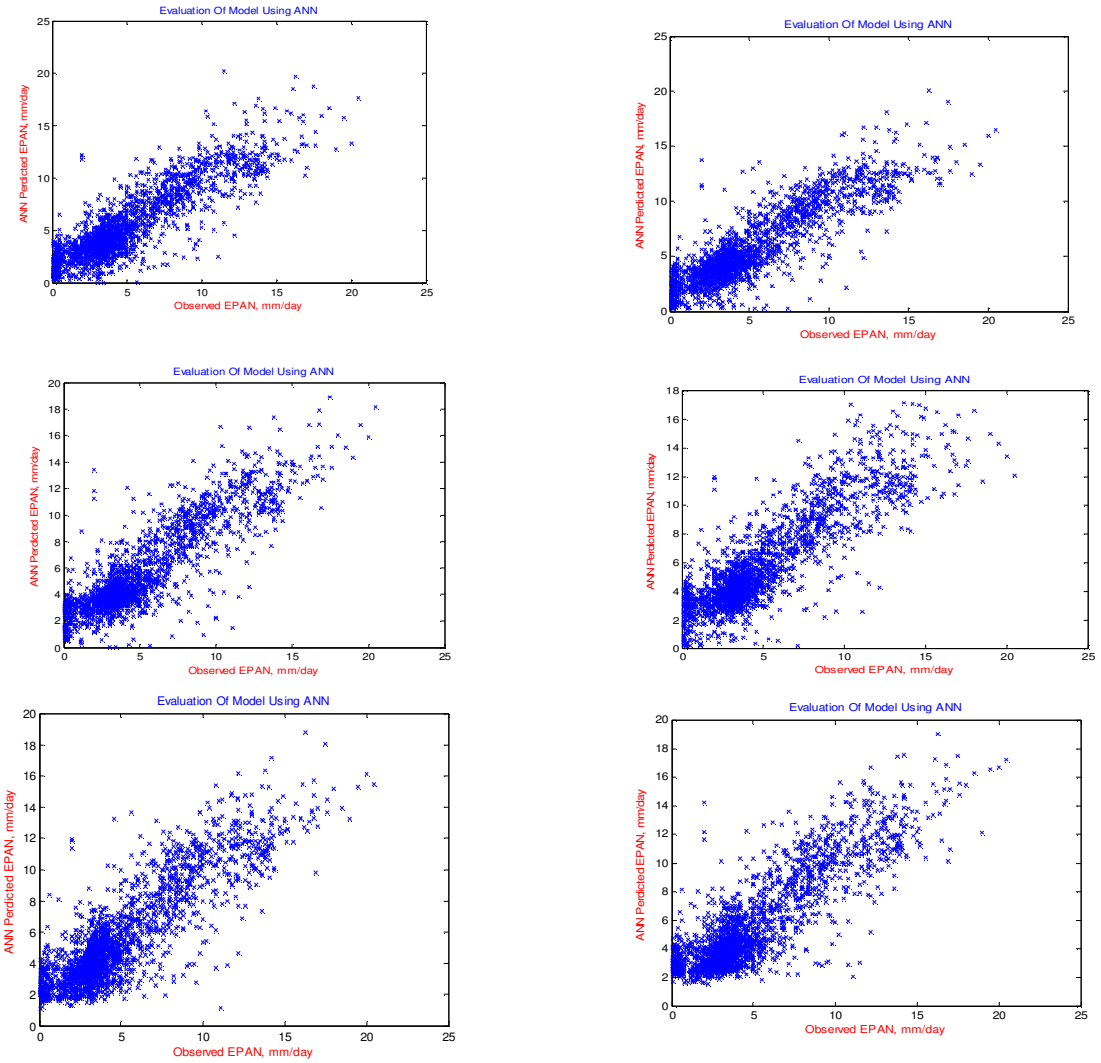
2. The RMSE, MAE and MARE of model M-3 are 1.984 mm, 0.0394 mm and 2.86 % respectively. The  $r$ ,  $R^2$  and  $d$  of model M-3 are 0.844, 0.712 and 0.915 respectively. The error statistics of model GM M-4 in which the relative humidity (RMAX and RMIN) are not the input variables. The RMSE, MAE and MARE of model M-4 is 2.081 mm, 0.0433 mm and 3.27 %, which is higher than the models M-1, M-2 and M-3. The  $r$ ,  $R^2$  and  $d$  of M-4 is 0.826, 0.683 and 0.906 respectively and these values are higher than model M-3. It is mainly due to the absence of RMAX and RMIN input variables and have higher negative correlation with the pan evaporation.



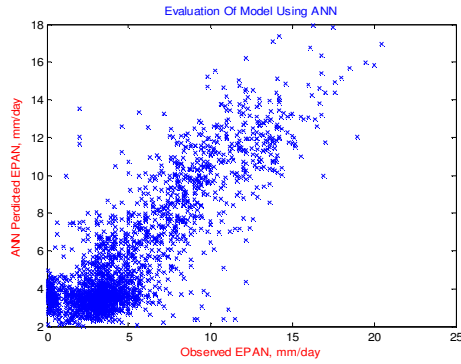
**Figure 8a.** Observed and predicted EPAN with General models (GM M1- M7) development data.



**Figure 8b.** Observed and predicted EPAN with General models (GM M1- M7) development data.



**Figure 9a.** ANN Models evaluation with Nagpur model development data (NMD).



**Figure 9b.** ANN Models evaluation with Nagpur model development data (NMD).

**Table 2.** RMSE, coefficient of determination ( $R^2$ ) and index of agreement ( $d$ ) of ANN General model development and evaluation dataset.

| ANN<br>GM<br>models | GM model development |       |      | GM model evaluation with NMD data |       |      |
|---------------------|----------------------|-------|------|-----------------------------------|-------|------|
|                     | RMSE<br>mm/d         | $R^2$ | $d$  | RMSE<br>mm/d                      | $R^2$ | $d$  |
| GM M-1              | 1.44                 | 0.84  | 0.95 | 1.96                              | 0.72  | 0.92 |
| GM M-2              | 1.48                 | 0.83  | 0.95 | 1.97                              | 0.71  | 0.91 |
| GM M-3              | 1.56                 | 0.81  | 0.94 | 1.98                              | 0.71  | 0.91 |
| GM M-4              | 1.62                 | 0.79  | 0.94 | 2.08                              | 0.68  | 0.90 |
| GM M-5              | 1.68                 | 0.78  | 0.93 | 2.06                              | 0.69  | 0.91 |
| GM M-6              | 1.70                 | 0.77  | 0.93 | 2.12                              | 0.67  | 0.90 |
| GM M-7              | 1.76                 | 0.76  | 0.92 | 2.11                              | 0.67  | 0.90 |

The model M-5 performance is better than the model M-4. The RMSE, MAE and MARE in model M-5 is reduced to 2.061 mm, 0.0425 mm and 3.24 % from 2.081 mm, 0.0433 mm and 3.27 % in model M-4. The  $r$ ,  $R^2$  and  $d$  is also increased to 0.830, 0.689 and 0.910 in model M-5 as compared to model M-4. The model M-5, in which four input variables is assumed to be one of the better models with minimum number of input variables. The input variables are TMAX, WISP and SNHR in model M-6. The RMSE, MAE and MARE of model M-6 is 2.127 mm, 0.0453 mm and 4.24 % respectively. The  $r$ ,  $R^2$  and  $d$  of model M-6 was 0.818, 0.669 and 0.904, which are lower as compared to M-5. The RMSE, MAE and MARE is decreased to 2.111 mm, 0.0445 mm and 5.01 % in GM model M-7, in which only TMAX and WISP are the input variables of the model. The  $r$ ,  $R^2$  and  $d$  was also slightly higher in model M-7 as compared to M-6. The  $r$ ,  $R^2$  and  $d$  in model M-7 is 0.821, 0.674 and 0.902 respectively. The evaluation of General models using Nagpur model development data with ANN model M-1 to M-7 are graphically presented [Figure 9]. These results indicated that maximum temperature and relative humidity observations were very beneficial in accurate estimation of pan evaporation, when compared to any other single variable.

## SUMMARY

The three layered feed forward neural network with back propagation prediction method that uses Artificial Intelligence (AI) to model the daily pan evaporation was developed and evaluated using independent datasets. From these research results, it is concluded that the constructed ANN models successfully identifies the evaporation process and accurately predict the pan evaporation in a next time step. Three layered feed forward neural networks with error back propagation was found suitable for modeling the evaporation. Once the network is trained, with a satisfactory amount of input data, it can accurately predict the daily pan evaporation. The network architectures performed better with one hidden layer and 15 hidden nodes ( $2^{n+1}$ ) for GM modeling problems. Single hidden layer performed good for both the models. The *Levenberg Marquardt* minimization training function gave the best network training results when used in the back propagation algorithms. While evaluating the data the model plan strategy with all inputs has shown better performance than the reduced number of inputs. The daily pan evaporation is estimated for the five locations using three layer feed forward neural network with error back propagation. Seven model strategies with combinations of input variables to develop the ANN models of pan evaporation were developed. Strategy M-1, which includes all 7 input variables, had the highest accuracy. This ANN model had an  $R^2$  of 0.78 and an RMSE of 1.61 mm on the independent GM evaluation data set. The models evaluation with Nagpur model development (NMD) dataset had an  $R^2$  of 0.72 and an RMSE of 1.96 mm. The ANN model has a strong correlation with observed pan evaporation. Differences between the ANN model prediction and observed pan evaporation do not appear to be biased as the observation of pan evaporation changes.

## KEYWORDS

Artificial Neural Network

Coefficient of determination  
Correlation coefficient  
Dr. Panjabrao Deshmukh Agricultural University, Akola  
Epochs  
Error back propagation algorithm  
Evaporation  
Evaporation modeling  
Evapotranspiration  
Feed forward neural networks  
Hidden layer  
Hydrological processes  
Hydrology  
Index of agreement  
India  
Indian Agriculture  
Input variables  
Input weights  
International Crop Research Institute for Semiarid Tropics, Hyderabad  
Jawaharlal Nehru Agricultural University, Jabalpur  
Land water resources  
Layer weight  
Learning function  
Learning rate  
*Levenberg Marquardt* minimization  
Linear regression methods  
Linear regression model  
Logistic sigmoid function  
Maharana Pratap University Agricultural and Technology, Udaipur  
MATLAB software  
Maximum relative humidity  
Maximum temperature  
Mean absolute error  
Mean absolute relative error  
Mean square error  
Minimum relative humidity  
Minimum temperature  
Model evaluation  
Model architecture  
Model development  
Model strategies  
Model validation  
Modeling criteria  
Momentum  
Multi-layer perceptron  
Multi-layered feed forward ANN  
Multiple linear regression  
National Research Centre for Citrus, Nagpur  
Network function  
Neural network  
Non- linear regression models  
Observed values  
Output variable  
Pan evaporation  
Predicted values  
Prediction of pan evaporation  
Rainfall  
Root mean square error  
Soil water evaporation  
Sunshine hours  
The class 'A' pan evaporimeter  
Training function  
Water management

Water resources planning and management  
Weather forecasting  
Wind speed

# **BIBLIOGRAPHY**

Refer to the bibliography for the literature cited.

## Chapter 8

### Evapotranspiration for Cypress and Pine Forests: Florida – USA<sup>1,2</sup>

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#### INTRODUCTION

The importance of evapotranspiration [ET] in the hydrologic cycle has long been recognized; in central Florida, evapotranspiration is second only to precipitation in magnitude. Of the approximately 1,320 millimeters (mm) of mean annual rainfall in central Florida, 680 to 1,220 mm have been estimated to return to the atmosphere as evapotranspiration [44, 49]. Despite the importance of evapotranspiration in the hydrologic cycle, the magnitude, seasonal and diurnal distributions, and relation to environmental variables of evapotranspiration remain relatively unknown. Uncertainty in evapotranspiration from non-agricultural vegetation is particularly apparent. The mixed cypress wetland and pine flat wood forest cover examined in the present investigation is common in central Florida, as are the fires that burned much of the forest during the study. Accurate estimates of evapotranspiration from commonly occurring land covers are fundamental to the quantitative understanding necessary for prudent management of Florida's water resources.

The eddy correlation method (or eddy covariance method) has been used successfully to directly measure evapotranspiration in Florida by Bidlake and others [1993, 3]; Knowles [1996, 22]; and Sumner [1996, 44]. This micrometeorological method offers several advantages to alternative water-budget approaches (lysimeter or regional water budget) by providing more areal integration and less site disruption than lysimeters, by eliminating the need to estimate other terms of a water budget (precipitation, deep percolation, runoff, and storage), and by allowing relatively fine temporal resolution (less than 1 hour).

Evapotranspiration can be estimated by using evapotranspiration models. These models also provide insight into the relative importance of individual environmental variables in the evapotranspiration process. The Priestley-Taylor model [34] for evaporation from a wet surface (potential evapotranspiration) was modified to allow for non-potential conditions [13], and has successfully simulated evapotranspiration in the Florida environment (22, 44, 15).

<sup>1</sup> David M. Sumner, PhD, Hydrologist, United States Geological Survey, Florida Water Science Center, 12703 Research Parkway, Orlando – FL – 32826, USA. Phone: 407-803-5518, Email: <dmsumner@usgs.gov>. The author gratefully extends his appreciation to Catherine Lowenstein and her staff at the Tiger Bay State Forest for providing assistance during this study. The contributions of Timothy Curran and Jerome Kelly of the USGS in construction and maintenance of the evapotranspiration station are gratefully acknowledged.

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<sup>2</sup> Numbers in parentheses indicate the references in the bibliography.

The U.S. Geological Survey (USGS), in cooperation with the St. Johns River Water Management District and the County of Volusia, began a 4-year study in 1996 to estimate the temporal pattern of evapotranspiration in the Tiger Bay watershed, Volusia County, Fla., a forested watershed, and to develop a quantitative description of the effect of environmental variability on evapotranspiration from forested areas in Florida. This analysis can provide guidance in the estimation of evapotranspiration and the description of the relation between the environment and evapotranspiration in other areas with similar environmental characteristics. During the study period, the watershed experienced a severe drought and natural fires, which provided the opportunity to study the effects of such extreme events on the evapotranspiration process.

This chapter presents daily estimates of evapotranspiration during a 2-year period from a forested watershed (Tiger Bay, Volusia County, Fla.), which was subjected to natural fires, and provides evaluations of the causal relations between the environment and evapotranspiration. Measurements were made on a nearly continuous basis from January 1998 through December 1999 at an evapotranspiration station just outside the watershed, using eddy correlation and meteorological instrumentation. An evapotranspiration model based on the Priestley-Taylor equation was used to estimate evapotranspiration for burned and unburned areas and to quantify the relation between evapotranspiration and the environment. A water budget of the watershed was constructed to assess the validity of the eddy correlation-measured evapotranspiration totals for the 2-year period.

### Description of the Study Area

The study area is the approximately 7,500-hectare Tiger Bay watershed within Volusia County, Fla. (Figure 1). The watershed was almost completely forested in January 1998, but was subjected to extensive burning and logging during the study period. The watershed characteristics are typical of many areas within the lower coastal plain of the southeastern United States - nearly flat, slowly draining land with a vegetative cover consisting primarily of pine flat wood uplands interspersed within cypress wetlands. The northern part of the watershed mostly is within the 9,500-hectare Tiger Bay State Forest; the southern part of the watershed primarily is privately owned land used for timber production. The watershed is within the relatively flat Talbott Terrace physiographic area [37]. More than 90 percent of the watershed is at an altitude of 11 to 13 meters (m). Small variations in local topography result in areal variations in hydroperiod. A low-lying wetland can be inundated much of the year, whereas an adjacent upland, less than a few tens of centimeters (cm) elevated above the wetland, may only occasionally or never exhibit standing water. Most of the surface runoff from the watershed is through inter-connected wetlands [36].

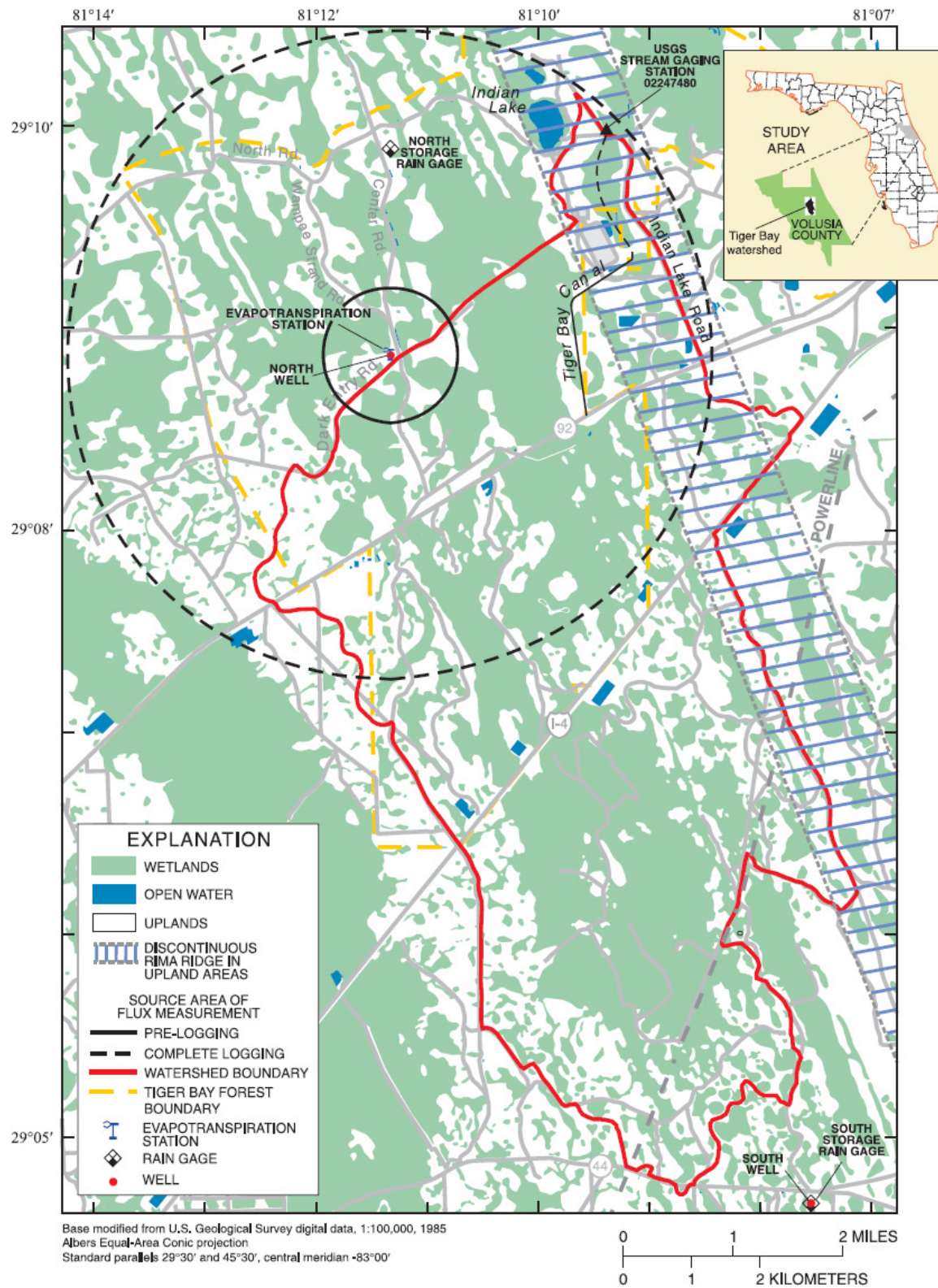
More than 95 percent of the watershed is forested. Two tree species dominate the forest cover in the watershed: slash pine (evergreen) and pond cypress (deciduous; leaves drop in November-December with regrowth in March-April). The distribution of vegetation in the vicinity of the evapotranspiration station is shown in Figure 2.

Vegetation in the watershed reflects the variation in hydroperiod [40]. Wetlands are dominated by pond cypress (*Taxodium ascendens*), with lesser amounts of other wetland tree species including blackgum (*Nyssa biflora*), loblolly bay (*Gordonia lasianthus*), and red maple (*Acer rubrum*). The understory of wetlands consists of a wide variety of plants including leather fern (*Acrostichum danaeifolium*), marsh fern (*Thelypteris palustris*), cinnamon fern (*Osmunda cinnamomea*), swamp lily (*Crinum americanum*), maidencane (*Panicum hemitomon*), red root (*Lachnanthes caroliniana*), hooded pitcher plant (*Sarracenia minor*), St. John's Wort (*Hypericum fasciculatum*), yellow colic root (*Aletris lutea*), pipewort (*Eriocaulon decangulare*), and white-topped sedge (*Rhynchospora colorata*). Water level varies from about 0.3 m above land surface to as much as 1 m below land surface in low-lying areas, although these areas are inundated more than 50 percent of the time [40].

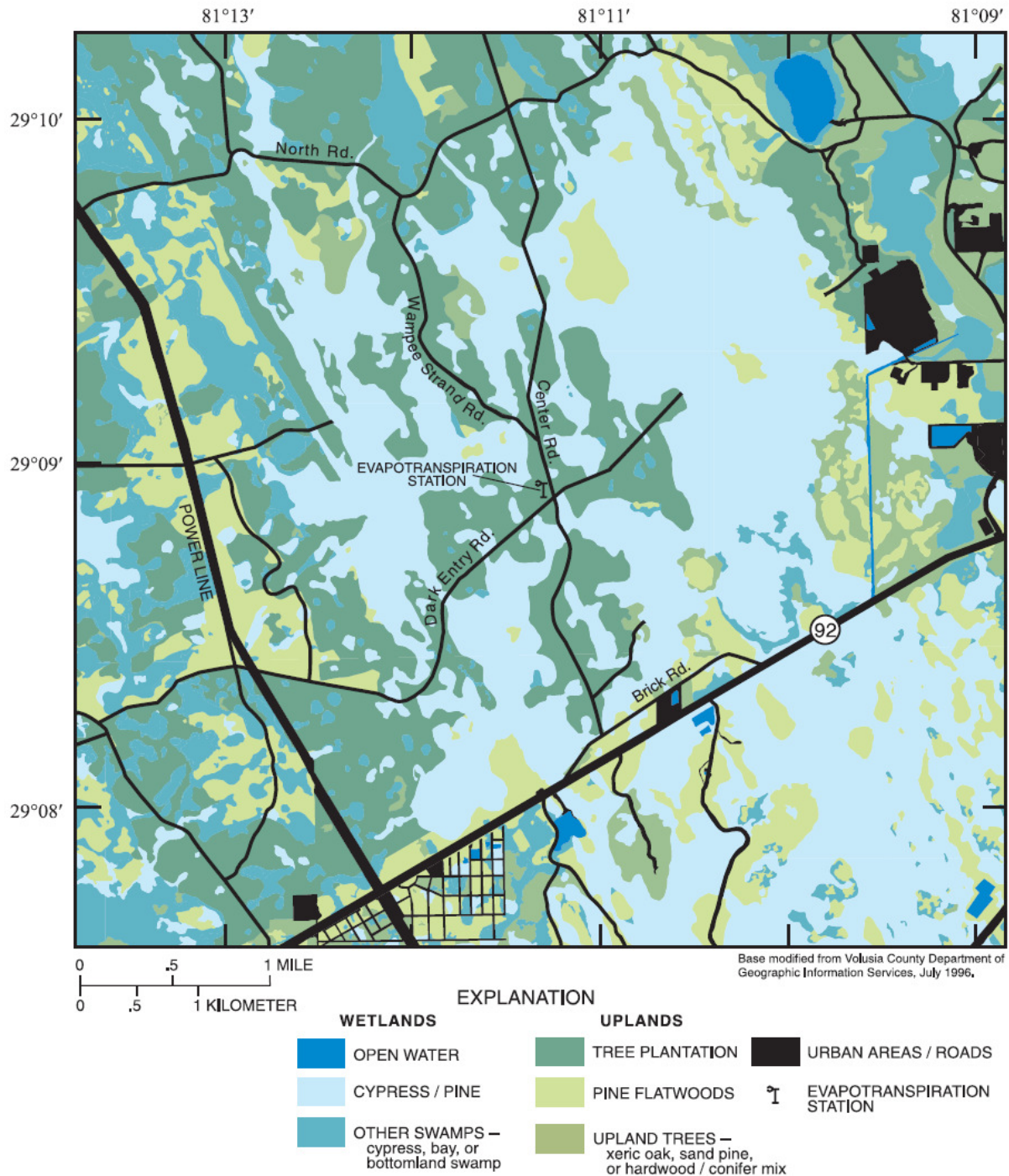
Uplands generally are either slash pine tree (*Pinus elliotii*) plantations or naturally seeded pine flatwoods (primarily slash pine with some longleaf pine (*Pinus palustris*)). These areas have an understory including saw palmetto (*Serenoa repens*), gallberry (*Ilex glabra*), wax myrtle (*Myrica cerifera*), red root (*Lachnanthes caroliniana*), and broomsedge (*Andropogon virginicus*). Understory vegetation in the pine plantations is control-burned about every 3 years. Water level varies from about 0.1 m above land surface to as much as 2 m below land surface in uplands; however, water levels are always greater than 2 m below land surface in the small part of the uplands within the Rima Ridge (Figure 1). The Rima Ridge consists of discontinuous remnants of terrace deposits parallel to the present-day coastline [37]. Vegetation on the ridge areas includes sand live oak (*Quercus geminata*) and sand pine (*Pinus clausa*). Most of the limited urbanization within the Tiger Bay watershed is on the Rima Ridge.

Brush fires burned extensively throughout peninsular Florida during spring 1998 as a result of a severe drought. A high-pressure system remained stationary over the State, blocking the normal pattern of convective thunderstorms [48]. During the 3-month period, April-June, National Oceanic and Atmospheric Administration (NOAA) stations at Daytona Beach and DeLand recorded about 10 and 30 percent of long-term, average precipitation, respectively. Brush fires, ignited by lightning strikes, began in Volusia County on June 19, 1998, and continued until rainfall resumed in late June and early July, burning about 55,000 hectares (one-fifth of the County) and about 40 percent of the watershed (Figure 3). Although areas of both wetlands and uplands were burned during the June-July fires, a comparison of Figures 1 and 3 reveals that upland areas were burned more extensively than wetland areas. Re-growth of understory vegetation occurred rapidly after the fires ceased and the rains began. Emergent growth of red root (*Lachnanthes caroliniana*) in burned areas was particularly evident. Some trees were killed by the fire, whereas other burned trees were merely damaged and exhibited leaf regrowth soon after the fire (Figure 4). Large-scale harvesting of insect-infested, fire-damaged trees (both living and dead trees) occurred during the months following the fires. Of the approximately 4,800 hectares that burned within the 9,500-hectare Tiger Bay State Forest, about 3,200 hectares were logged (Catherine Lowenstein, Tiger Bay State Forest, oral communication, 2000).





**Figure 1.** Location of Tiger Bay watershed.



**Figure 2.** Distribution of vegetation in vicinity of evapotranspiration station.

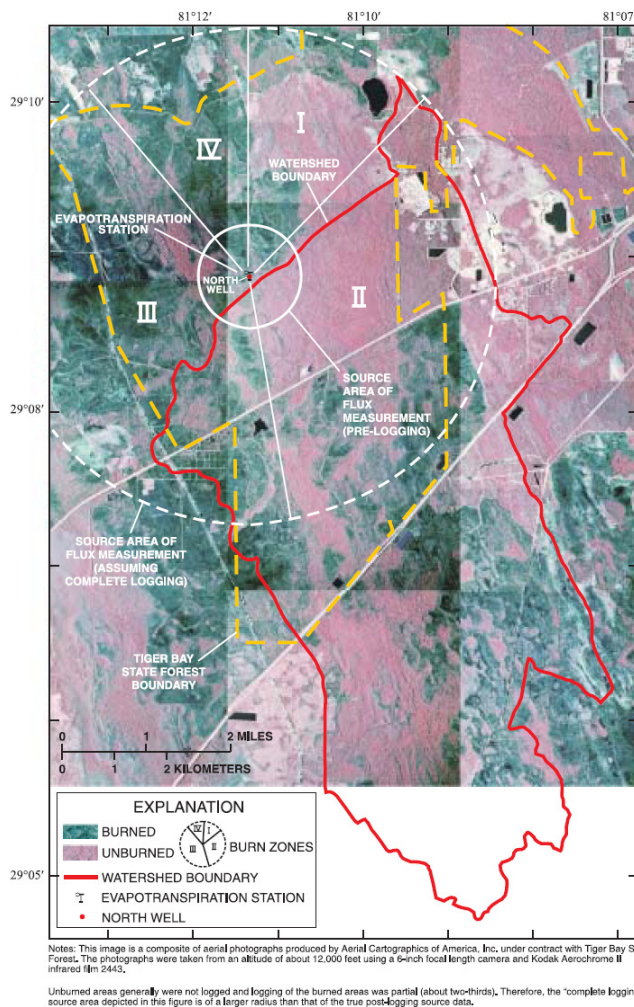
Fires moved from west-to-east through the area of the evapotranspiration station on June 25, 1998. Damaged trees in the vicinity of the evapotranspiration station were logged during November-December 1998.

The two dominant soil groups of the watershed also reflect the areal variation in hydroperiod and vegetation [2]. Wetlands tend to be underlain by organic soils (hyperthermic family of Terric Medisaprists) of the Samsula-Terra Ceia-Tomoka group, that are very poorly drained. The uplands tend to be underlain by poorly drained soils (sandy, siliceous, hyperthermic family of Ultic Haplaquods) of the Pomona-Wauchula group that have a dark, organic-stained subsoil underlain by loamy material.

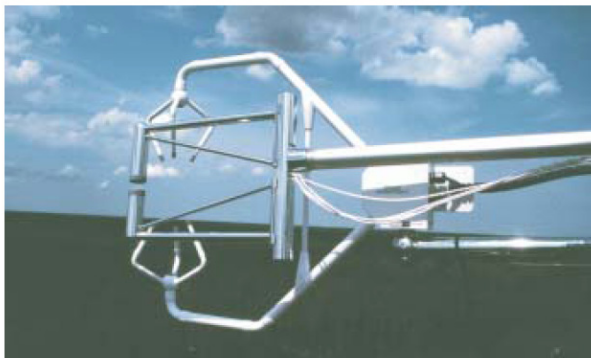
The climate of central Florida is humid subtropical and is characterized by a warm, wet season (June-September) and a mild, relatively dry season (October-May). During the dry season, precipitation commonly is associated with frontal systems.



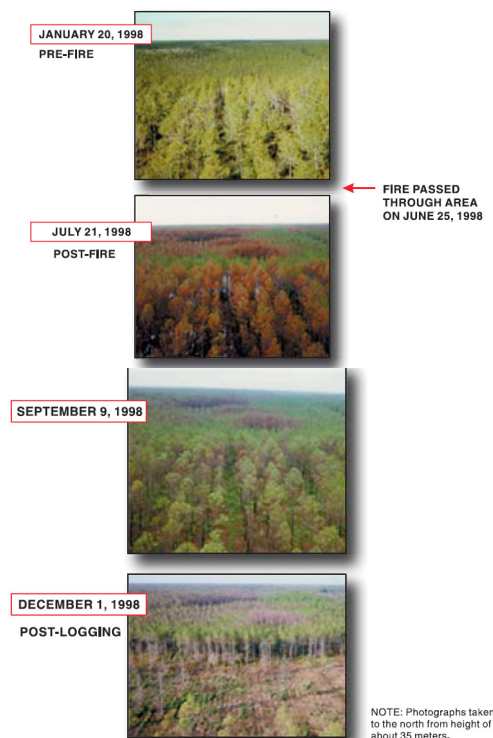
Rainfall averages about 1,350 mm/yr in Volusia County [37]. More than 50 percent of the annual rainfall generally occurs during the wet season when diurnal thunderstorm activity is common. Mean air temperature in the study area is about 21 °C, ranging from occasional winter temperatures below 0°C to summer temperatures approaching 35°C. Diurnal temperature variations average about 12°C.



**Figure 3.** Infrared photograph (July 7, 1998) of vicinity of evapotranspiration station showing area burned during fires of June 1998.



**Figure 5.** Krypton hygrometer (foreground) and sonic anemometer (background) mounted at top of tower at evapotranspiration station.



**Figure 4.** Photographic times series of vegetation in vicinity of evapotranspiration station



**Figure 6.** Evapotranspiration station being serviced by hydrologic technician.

**Table 1.** Study instrumentation [CSI, Campbell Scientific, Inc.; REBS, Radiation and Energy Balance Systems, Inc.; RMY, R. M. Young, Inc.; TE, Texas Electronics, Inc.]. **Note:** Negative height is depth below land surface.

| Type of measurement                       | Instrument                                                                                                             | Height(s) above land surface (meters) |
|-------------------------------------------|------------------------------------------------------------------------------------------------------------------------|---------------------------------------|
| Evapotranspiration                        | CSI eddy correlation system including Model CSAT3 three-dimensional sonic anemometer and Model KH20 krypton hygrometer | 36.5                                  |
| Air temperature/relative humidity         | CSI Model HMP35C temperature and relative humidity probe                                                               | 1.5, 9.1, 18.3, and 35                |
| Net radiation                             | REBS Model Q-7.1 net radiometer                                                                                        | 35                                    |
| Wind speed/direction                      | RMY Model 05305-5 Wind Monitor-AQ                                                                                      | 35                                    |
| Photosynthetically active radiation (PAR) | LI-COR, Inc. Model LI190SB quantum sensor                                                                              | 35                                    |
| Soil moisture                             | CSI Model CS615 water content reflectometer                                                                            | 0 to -.3                              |
| Precipitation                             | TE Model 525 tipping bucket rain gage and NovaLynx Model 260-2520 forester's (storage) rain gages (2)                  | 18.3 (tipping bucket) and 1 (storage) |
| Water level in well                       | Druck, Inc. Model PDCR950 pressure transducer                                                                          | -2                                    |
| Datalogging                               | CSI Model 10X and Model 21X dataloggers; 12 volt deep-cycle batteries (2); 20 watt solar panels (2)                    | 0 to 1                                |

Rainfall to the watershed leaves the basin as runoff, evapotranspiration, or deep leakage from the surficial aquifer system to the underlying Upper Floridan aquifer [21, 33]. Intermittent runoff gaged at Tiger Bay canal along the northern edge of the watershed (Figure 1) averaged 0.47 cubic meters per second ( $\text{m}^3/\text{s}$ ) or about 200 millimeters per year ( $\text{mm}/\text{yr}$ ) from 1978 to 1999 [53]. Evapotranspiration has been estimated to average about 990  $\text{mm}/\text{yr}$  over Volusia County [37] and about 890  $\text{mm}/\text{yr}$  in the Tiger Bay watershed [7]. Previous researchers have documented relatively small differences in the annual evapotranspiration rates from the two primary land covers. Bidlake and others [1993, 3] estimated annual cypress evapotranspiration (970  $\text{mm}$ ) to be only 8.5 percent less than that from pine flatwoods (1,060  $\text{mm}$ ), based on studies conducted in Sarasota and Pasco Counties, Fla. Liu [1996, 24] estimated average annual evapotranspiration from both covers to be 1,080  $\text{mm}$ , based on a study conducted in Alachua County, Fla.

The hydraulic head in the surficial aquifer system within the watershed generally is above that of the underlying Upper Floridan aquifer. Consequently, water leaks downward from the surficial aquifer system, through the intermediate confining unit, to the Upper Floridan aquifer. Deep leakage was estimated (based on ground-water flow simulations) to have been about 56  $\text{mm}/\text{yr}$  prior to ground-water development, but in 1995, the rate was estimated to have doubled to 112  $\text{mm}/\text{yr}$ , as a result of lowering the hydraulic head in the Upper Floridan aquifer by pumping (Stan Williams, St. Johns River Water Management District, oral communication, 2000).

## METHODS AND MATERIALS: MEASUREMENT AND SIMULATION OF EVAPOTRANSPIRATION

Evapotranspiration was measured at a site just outside the study area (Figure 1) using the eddy correlation method in a manner similar to that described by Sumner [1996, 44]. The site chosen for the evapotranspiration station was within an 18.3-m-tall, 30-year-old pine plantation (Figure 2). Eddy correlation instrumentation was mounted on a 36.5-m-tall Rohn 45G communications-type tower at the site (Figures 5 and 6), and data were collected for a 2-year period from January 1, 1998, to December 31, 1999. Other meteorological instrumentation also was deployed on or around the tower to collect data for evapotranspiration modeling and to provide ancillary data for the eddy correlation analysis. Instrumentation used in the study is described in Table 1. Measured daily values of evapotranspiration were used to calibrate evapotranspiration models (modified Priestley-Taylor). Evapotranspiration was estimated for burned and unburned areas using the calibrated evapotranspiration models. A water budget for the watershed over the study period was constructed based on measured or estimated values of precipitation, evapotranspiration, runoff, leakage, and storage.

### Measurement of Evapotranspiration

#### Eddy-Correlation Method

The eddy correlation method [9, 45] was used to measure two components of the energy budget of the plant canopy: latent and sensible heat fluxes. Latent heat flux ( $\lambda E$ ) is the energy removed from the canopy in the liquid-to-vapor phase change of water, and is the product of the heat of vaporization of water ( $\lambda$ ) and the evapotranspiration rate ( $E$ ). Sensible heat ( $H$ ) is the heat energy removed from the canopy as a result of a temperature gradient between the canopy and the air.

Both latent and sensible heat fluxes are transported by turbulent eddies in the air. Turbulence is generated by a combination of frictional and convective forces. The energy available to generate turbulent fluxes of vapor and heat is equal to the net radiation ( $R_n$ ) minus the sum of the heat flux into the soil surface ( $G$ ) and the change in storage ( $S$ ) of energy in the biomass and air. The energy involved in fixation of carbon dioxide usually is negligible [5]. Net radiation is the difference between incoming radiation (shortwave solar radiation and long wave atmospheric radiation) and outgoing radiation (reflected shortwave and long-wave radiation; and emitted long wave canopy radiation). Energy is transported to and from the base of the canopy by conduction through the soil.

Assuming that net horizontal advection of energy is negligible, the energy-budget equation, for a control volume extending from land surface to a height  $z_s$  at which the turbulent fluxes are measured, is given in equation /1/:

$$R_n - G - S = H + \lambda E \quad /1/$$

$$E = \overline{w\rho_v} = \overline{(\bar{w} + w')(\bar{\rho}_v + \rho'_v)} \quad /2/$$

$$E = \overline{\bar{w}\bar{\rho}_v} + \overline{w'\rho'_v} + \overline{w'\bar{\rho}_v} + \overline{\bar{w}\rho'_v} \quad /3/$$

$$\overline{w'\rho'_v} = \text{covariance}(w, \rho_v) \quad /4/$$

In the energy-budget equation /1/: The left side of equation /1/ represents the available energy and the right side represents the turbulent flux of energy;  $R_n$  is net radiation to or from plant canopy, in watts per square meter;  $G$  is soil heat flux at land surface, in watts per square meter;  $S$  is change in storage of energy in the biomass and air, in watts per square meter;  $H$  is sensible heat flux at height  $z_s$  above land surface, in watts per square meter;  $\lambda E$  is latent heat flux at height  $z_s$  above land surface, in watts per square meter. The sign convention is such that  $R_n$  and  $G$  are positive downwards; and  $H$  and  $\lambda E$  are positive upwards.

The eddy correlation method is a conceptually simple, one-dimensional approach for measuring the turbulent fluxes of vapor and heat above a surface. For the case of vapor transport above a flat, level land- scape, the time-averaged product of measured values of vertical wind speed ( $w$ ) and vapor density ( $\rho_v$ ) is the estimated vapor flux (evapotranspiration rate) during the averaging period, assuming that the net lateral advection of vapor is negligible. Because of the insufficient accuracy of instrumentation available for measurement of actual values of wind speed and vapor density, this procedure generally is performed by monitoring the fluctuations of wind speed and vapor density about their means, rather than monitoring their actual values.

This formulation is represented in equations /2/ to /4/, where:  $E$  is evapotranspiration rate, in grams per square meter per second;  $w$  is vertical wind speed, in meters per second;  $\rho_v$  is vapor density, in grams per cubic meter; and overbars and primes indicate means over the averaging period and deviations from means, respectively.

The first term of the right side of equation /3/ is approximately zero because mass-balance considerations dictate that mean vertical wind speed perpendicular to the surface is zero; this conclusion is based on an assumption of constant air density (correction for temperature-induced air-density fluctuations is discussed later in this chapter). The second and third terms are zero based on the definition that the mean fluctuation of a variable is zero. Therefore, it is apparent from equation /4/ that vertical wind speed and vapor density must be correlated in order for the value of vapor flux to be non-zero. The turbulent eddies that transport water vapor (and sensible heat) produce fluctuations in both the direction and magnitude of vertical wind speed. The ascending eddies must on average be more moist than the descending eddies for evapotranspiration to occur, that is, upward air movement must be positively correlated with vapor density and downward air movement must be negatively correlated with vapor density.

### Source Area of Measurements

The source area for a turbulent flux measurement defines the area (upwind of measurement location) contributing to the measurement. The source area can consist of a single vegetative cover if that cover is adequately extensive. This condition is met if the given cover extends sufficiently upwind such that the atmospheric boundary layer has equilibrated with the cover from ground surface to at least the height of the instrumentation. If this condition is not met, the flux measurement is a composite of fluxes from two or more covers within the source area. The source area is defined in this report as the area contributing to 90 percent of the sensor measurement. Schuepp and others [1990, 39] provide an estimate of the source area, and the relative contributions within the source area, based on an analytical solution of a one-dimensional (upwind) diffusion equation for a uniform surface cover. In this approach, source area varies with instrument height ( $z_s$ ), zero displacement height ( $d$ ), roughness length for momentum ( $z_m$ ), and atmospheric stability. The instrument height in this study was 36.5 m. Campbell and Norman [1998, 8] proposed empirical relations based on canopy height ( $h$ ) for zero displacement height ( $d \sim 0.65h$ ) and roughness length for momentum ( $z_m \sim 0.10h$ ). Uniform canopy heights of 18.3 m (pre-logging) and 0.3 m (assuming complete logging) were assumed in this analysis. The source area estimates were made assuming mildly unstable conditions; the Obukhov stability length [6] was set equal to -10 m. The source area increases as the height of the instrument above the vegetative canopy increases and as the roughness length for momentum decreases; therefore, the extensive logging that occurred following the fires enlarged the source area. The source area for the turbulent flux measurements (Figure 7) was estimated to be within an upwind distance of about 1,000 m (pre-logging) or 4,800 m (assuming complete logging). As stated earlier, unburned areas generally were not logged and logging of the burned areas was partial (about two-thirds). Therefore, the "complete logging" source area depicted in Figure 7 is of a larger radius than that of the true post-logging source area.

The site of the evapotranspiration station was chosen such that the source area of the turbulent flux measurements would be representative of the relative mix of wetlands and uplands in the pre-fire watershed (Figure 1). Before the fire and associated logging, the source area of the turbulent flux measurement (Figure 1) consisted of: 43.7 percent upland, 56.1 percent wetland, and 0.2 percent lake. These relative fractions of wetland and upland were very close to those of the entire Tiger Bay watershed (43.8 percent upland, 55.5 percent wetland, and 0.7 percent lake) before the fires. Also, areas of wetland and upland within the pre- fire

source area were interspersed, indicating that turbulent flux measurements approximated a representative value of the composite mix of wetlands and uplands, regardless of the wind direction.

Fires within the watershed during spring 1998 changed the primary components of source area heterogeneity from wetland/upland to burned/unburned (Figure 3) and complicated interpretation of the turbulent flux measurements. Burned and unburned areas were not well-interspersed, resulting in measurements that reflected varying fractions of burned and unburned areas, depending on the wind direction. Following the fires, turbulent fluxes representative of burned areas were measured, both pre- and post-logging, when the wind was from the northwest (zone IV in Figure 3).

Turbulent fluxes representative of unburned areas were measured when the wind was from the east (zone II) throughout the study period. The absence of near-station burning in zone II, and therefore a lack of subsequent near-station logging in this zone, resulted in a consistently small (radius of 1,000 m), and unburned, source area throughout the study period when the wind was from zone II. Turbulent fluxes representative of burned areas were measured following the fires and prior to logging when the wind was from the northeast (zone I). With the expansion of the source area associated with logging, however, the post-logging turbulent flux measurements were representative of a composite of burned and unburned areas when the wind was from zone I. Examination of the estimated [39] cumulative fractional contribution to the turbulent flux measurement as a function of upwind distance from the measurement (Figure 7) provided information to approximate the relative degree of burned/unburned area compositing. Based on this approach, an estimate was made that post-logging turbulent flux measurements made when the wind was from zone I reflected a surface cover that was 75 percent burned and 25 percent unburned. Burned and unburned areas within zone III were relatively well interspersed and in approximately equal relative amounts following the fires. Therefore, post-fire turbulent fluxes measured when the wind was from zone III were assumed to reflect a surface cover that was 50 percent burned and 50 percent unburned. Estimates of the relative contribution (as a function of wind direction and status of the surface cover) of burned vegetation to the measured turbulent flux signal are summarized in Table 2. These estimates were used to develop weighting coefficients indicative of the fraction of the turbulent flux measurement for a given day that reflected burned vegetation, which is further discussed later in this chapter.

### Instrumentation

Instrumentation capable of high-frequency resolution must be used in an application of the eddy correlation method because of the relatively high frequency of the turbulent eddies that transport water vapor. Instrumentation included a three-axis sonic anemometer and a krypton hygrometer to measure variations in wind speed and vapor density, respectively (Figure 5). The sonic anemometer relies on three pairs of sonic transducers to detect wind-induced changes in the transit time of emitted sound waves and to infer fluctuations in wind speed in three orthogonal directions. The measurement path length between transducer pairs is 10.0 cm (vertical) and 5.8 cm (horizontal); the transducer path angle from the horizontal is 60 degrees. In contrast to some sonic anemometers used previously [44], the transducers of this improved anemometer are not permanently destroyed by exposure to moisture, and thus are suitable for long-term deployment. Operation of the anemometer used in this study ceases when moisture on the transducers disrupts the sonic signal, but recommences upon drying of the transducers.

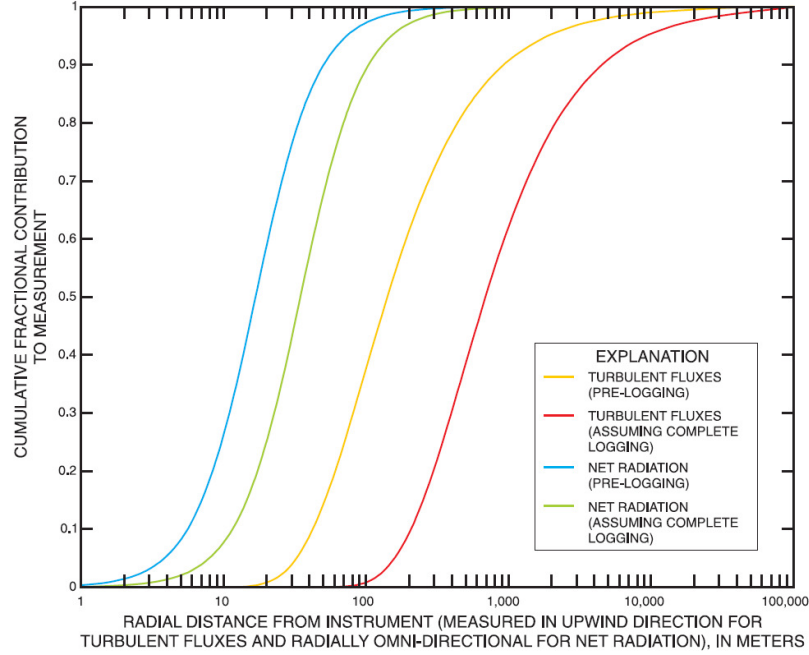
The hygrometer relies on the attenuation of ultra-violet radiation, emitted from a source tube, by water vapor in the air along the 1-cm path to the detector tube. The instrument path line was laterally displaced 10 cm from the midpoint of the sonic transducer path lines. Hygrometer voltage output is proportional to the attenuated radiation signal, and fluctuations in this signal can be related to fluctuations in vapor density by Beer's Law [59]. Similar to the anemometer, the hygrometer ceases data collection when moisture obscures the windows on the source or detector tubes. Also, the tube windows become "scaled" with exposure to the atmosphere, resulting in a loss of signal strength. The hygrometer is designed such that vapor density fluctuations are accurately measured in spite of variable signal strength; however, if signal strength declines to near-zero values, the fluctuations cannot be discerned. Periodic cleaning of the windows (performed monthly in this study) with a cotton swab and distilled water restored the signal strength. Eddy correlation instrument-sampling frequency was 8 Hertz with 30 - minute averaging periods. The eddy correlation instrumentation was placed about 18.2 m above the tree canopy (Figure 6). Data were processed and stored in a data logger near ground-level.

To be representative of the surface cover, flux measurements must be made in the inertial sublayer, where vertical flux is constant with height and lateral variations in vertical flux are negligible [28]. Measurements made in the underlying roughness sublayer can reflect individual roughness elements (for example, individual trees or gaps between trees), rather than the composite surface cover. Garrat [1980, 14] defines the lower boundary of the inertial sublayer to be at a height such that the difference of this height and the zero displacement height ( $d$ ) is much greater than the roughness length for momentum ( $z_m$ ). Employing Campbell and Norman's [1998, 8] empirical relations and assuming that "much greater than" implies greater by a factor of ten (10), leads to an instrument height ( $z_s$ ) requirement of  $z_s > [1.65 * h]$ . A factor of about 2 was used in this chapter as a conservative measure. As a conservative measure, the instrument height (36.5 m) used in this chapter was about twice canopy height.

### Calculation of Turbulent Fluxes

Latent heat flux [See equation /5/] was estimated based on a modified form of equation /4/. In equation /5/:  $\lambda E$  is latent heat flux, in watts per square meter;  $\lambda$  is latent heat of vaporization of water, estimated as a function of temperature [43], in joules per gram;  $\rho$  is air density that is estimated as a function of air temperature, total air pressure, and vapor pressure [28], in grams per cubic meter;  $H$  is sensible heat flux, in watts per square meter;  $C_p$  is specific heat capacity of air, estimated as a function of temperature and relative humidity [43], in joules per gram per degree Celsius;  $T_a$  is air temperature, in degrees Celsius;  $F$  is a

factor that accounts for molecular weights of air and atmospheric abundance of oxygen, and is equal to 0.229 gram-degree Celsius per joule;  $K_o$  is an extinction coefficient of hygrometer for oxygen, estimated as 0.0045 cubic meters per gram per centimeter [46];  $K_w$  is an extinction coefficient of hygrometer for water, equal to the manufacturer-calibrated value, in cubic meters per gram per centimeter; and overbars and primes indicate means over the averaging period and deviations from the means, respectively. The second and third terms of the right side of equation /5/ account for temperature-induced fluctuations in air density [58] and for the sensitivity of the hygrometer to oxygen [45], respectively.



**Figure 7.** Radial extent of source areas of turbulent flux and net radiation measurements.

**Table 2.** Relative fraction of burned vegetation sensed by eddy correlation instrumentation [The sector is in degrees measured clockwise from north (Figure 3);  $g_i$  is the fractional contribution of burned area within burn zone  $i$  to the measured latent heat flux when wind direction is from burn zone  $i$ ]

| Burn zone $i$ | Sector     | $g_i$    |                           |              |
|---------------|------------|----------|---------------------------|--------------|
|               |            | Pre-fire | Post-fire/<br>pre-logging | Post-logging |
| I             | 0 to 45    | 0.0      | 1.0                       | 0.75         |
| II            | 45 to 170  | .0       | 0                         | 0            |
| III           | 170 to 320 | .0       | 0.5                       | .5           |
| IV            | 320 to 360 | .0       | 1                         | 1            |

Similarly to vapor transport, sensible heat can be estimated by using equation /6/. The sonic anemometer is capable of measuring “sonic” temperature based on the dependence of the speed of sound on this variable [19, 20]. Schotanus and others [1983, 38] related the sonic sensible heat based on measurement of sonic temperature fluctuations to the true sensible heat given in equation /6/. Those researchers included a correction, for the effect of wind blowing normal to the sonic acoustic path that has been incorporated directly into the anemometer measurement by the manufacturer (Swiatek, E., 1998. Campbell Scientific, Inc., written communication), leading to a simplified form of the Schotanus and others [1983, 38] formulation given in equation /7/.

In equation /7/:  $T_s$  is the sonic temperature, in degrees Celsius; and  $q$  is specific humidity, in grams of water vapor per grams of moist air. Fleagle and Businger [1980, 12] defined the specific humidity  $[q]$  in equation /8/, based on the relation between specific humidity and vapor density.

In equation /8/:  $\rho_v$  is vapor density, in grams per cubic meter. Equation /7/ can be expressed in terms of fluctuations in the hygrometer-measured water vapor density rather than fluctuations in specific humidity as shown in equation /9/. In equation /9/:  $R_d$  is the gas constant for dry air ( $= 0.28704$  joules per degree Celsius per gram); and  $P_a$  is atmospheric pressure, in pascals (assumed to remain constant at 100.7 kilopascals at top of tower at about 48 meters above sea level).



$$\lambda E = \lambda \left( \overline{w'p'_v} + \frac{\rho_v H}{\rho C_p (T_a + 273.15)} + \frac{FK_o H}{K_w (T_a + 273.15)} \right) \quad /5/$$

$$H = \rho C_p \overline{w' T'_a} \quad /6/$$

$$\overline{w' T'_a} = \overline{w' T'_s} - 0.51 \overline{(T_a + 273.15)} \overline{w' q'} \quad /7/$$

$$q \approx \frac{\rho_v R_d (T_a + 273.15)}{P_a} \quad /8/$$

$$\overline{w' T'_a} = \frac{\overline{(T_a + 273.15)}}{\overline{(T_s + 273.15)}} (\overline{w' T'_s} - 0.51 R_d \overline{(T_a + 273.15)^2} \overline{w' \rho'_v} / P_a) \quad /9/$$

$$(\overline{w' c'})_r = \overline{w' c'} \cos \theta - \overline{u' c'} \sin \theta \cos \eta - \overline{v' c'} \sin \theta \sin \eta \quad /10/$$

$$\cos \theta = \frac{\sqrt{(u^2 + v^2)}}{\sqrt{(u^2 + v^2 + w^2)}} \quad /11/$$

$$\sin \theta = \frac{w}{\sqrt{(u^2 + v^2 + w^2)}} \quad /12/$$

$$\cos \eta = \frac{u}{\sqrt{(u^2 + v^2)}} \quad /13/$$

$$\sin \eta = \frac{v}{\sqrt{(u^2 + v^2)}} \quad /14/$$

Estimation of turbulent fluxes (equations /5/ and /6/) relies on an accurate measurement of velocity fluctuations perpendicular to the lateral airstream. The study area is relatively flat and level, indicating that the air stream is approximately perpendicular to gravity and the sonic anemometer was oriented with respect to gravity with a bubble level. Measurement of wind speed in three orthogonal directions with the sonic anemometer allows for a more refined orientation of the collected data with the natural coordinate system through mathematical coordinate rotations. The magnitudes of the coordinate rotations are determined by the components of the wind vector in each 30-minute averaging period.

The wind vector is composed of three time-averaged components (u, v, w) in three initial coordinate directions (x, y, z). Using a bubble level, direction z initially was approximately oriented with respect to gravity, and the other two directions were arbitrary. Tanner and Thurtell [1969, 47] and Baldocchi and others [1988, 1] outline a procedure in which measurements made in the initial coordinate system are transformed into values consistent with the natural coordinate system. First, the coordinate system is rotated by an angle  $\eta$  about the z-axis to align u along a transformed x-direction on the x-y plane. Next, rotation by an angle  $\theta$  is performed about the y-direction to align w along a transformed z-direction. These rotations result in a natural coordinate system with mean values of wind speed along the transformed y and z axes equal to zero and the mean airstream pointed directly along the transformed x axis.

The coordinate rotation-transformed covariances needed to compute turbulent fluxes are described in equation /10/. Where:

$(\overline{w' c'})_r$  = is the rotated covariance;

$c'$  = is the fluctuation in either vapor density ( $\rho_v$ ) or virtual temperature ( $T_s$ ); and

$\overline{w' c'}$ ,  $\overline{u' c'}$ , and  $\overline{v' c'}$  = are covariances measured in the original coordinate system;

The  $[\cos \theta]$ ,  $[\sin \theta]$ ,  $[\sin \eta]$ , and  $[\cos \eta]$  are defined in equations /11/ to /14/, respectively.

The presence of the tower and the anemometer produced spurious turbulence which possibly impacted measured velocity fluctuations, particularly when the wind was from the tower-side of the sensor. Turbulent flux data for which the inferred mis-leveling angle  $\theta$  was greater than 10 degrees were excluded based on the assumption that spurious turbulence was the cause of the excessive amount of coordinate rotation.

### Consistency of Measurements with Energy Budget

Previous investigators [29, 23, 3, 17, 44, 50, 15] have described a recurring problem with the eddy correlation method: A common discrepancy of the measured latent and sensible heat fluxes with the energy-budget equation (Equation /1/). The usual case is that measured turbulent fluxes ( $H + \lambda E$ ) are less than the measured available energy ( $R_n - S$ ). Bidlake et al. [1993, 3] accounted for only 49 and 80 percent of the measured available energy with measured turbulent fluxes ( $H + \lambda E$ ) at cypress swamp and pine flat-



wood sites, respectively. Turbulent fluxes measured above a coniferous forest by Lee and Black [1993, 23] accounted for only 83 percent of available energy. Several researchers [29, 17, 15] have shown that the eddy correlation method performs best in windy conditions (relatively high friction velocity,  $u^*$ ). Friction velocity is directly proportional to wind speed, but also incorporated rates the frictional effects of the plant canopy and land surface on the wind and the effects of atmospheric stability [8]. Friction velocity can be computed with three dimensional sonic anemometer measurements of velocity fluctuations as [43] shown in equation /15/.

Goulden and others [1996, 17] concluded that eddy correlation-measured values of carbon flux from a forest were underestimated when  $u^*$  was less than 0.17 m/s. German [2000, 15] noted that at  $u^*$  greater than 0.3 m/s, little discrepancy existed between measured available energy and measured turbulent fluxes. Possible explanations for the observed discrepancy between the measured turbulent fluxes and the measured available energy include: a sensor frequency response that is insufficient to capture high-frequency eddies; an averaging period insufficient to capture low-frequency eddies, resulting in a non-zero mean wind speed perpendicular to the airstream; drift in the absolute values of anemometer and hygrometer measurements resulting in statistical non-stationarity within the averaging period; lateral advection of energy; and overestimation of available energy. Lateral advection of energy is not a likely explanation because most of the studies reporting underestimation of turbulent fluxes were conducted at sites with adequately extensive surface covers. Measurement of the soil heat flux and storage terms of the available energy can be problematic, given the difficulty in making representative measurements of these terms; however, the turbulent flux underestimation occurs even with a daily composite of fluxes (in which case these terms generally are negligible).

Likewise, overestimation of net radiation seems unlikely, given the relative simplicity and laboratory calibration of net radiometers. For these reasons, it was assumed in this study that the available energy was accurately measured and that any error in energy-budget closure was associated with errors in measurement of turbulent fluxes. Moore [1976, 29] also noticed an underestimation of turbulent fluxes and suggested that this under-estimation would likely apply equally to each of the turbulent fluxes (sensible and latent heat flux), leading to the conclusion that the ratio of the fluxes can be measured adequately. This assumption seems reasonable, given that the same turbulent eddies transport both sensible and latent heat, and therefore, any eddies that are missed by the instrumentation because of anemometer response or averaging period would have a proportionally equal effect on both turbulent fluxes. German [2000, 15] provided empirical support for this assumption at a saw-grass site in south Florida where simultaneous measurement of the ratio of fluxes was based on two approaches: the eddy correlation method (using instrumentation identical to that used in the present study) and the measurement of temperature and vapor pressure differentials between vertically separated sensors [4]. These independent approaches for estimating the ratio of turbulent fluxes were in reasonable agreement during the daylight hours when evapotranspiration predominated. Assuming that the ratio of turbulent fluxes is adequately measured by the eddy correlation method, the energy budget equation (Equation /1/), along with turbulent fluxes ( $H$  and  $\lambda E$ ) measured using the standard eddy correlation technique, can be used to produce corrected ( $H_{cor}$  and  $\lambda E_{cor}$ ) turbulent fluxes in an energy-budget variant of the eddy correlation method, as shown in equation /16/. As shown below, we get equation /19/ for  $H_{cor}$  after introducing the Bowen ratio [Equation /17/].

$$u^* = \sqrt{\overline{u'w'}^2 + \overline{v'w'}^2} \quad /15/$$

$$R_n - G - S = H_{cor} + \lambda E_{cor} = \lambda E_{cor}(1 + B) \quad /16/$$

$$\text{Bowen ratio:} \quad /17/$$

$$B = \frac{H}{\lambda E}$$

$$\text{Rearranging equation /16/, we get:} \quad /18/$$

$$\lambda E_{cor} = \frac{R_n - G - S}{1 + B}$$

$$\text{Combining equations /17/ and /18/:} \quad /19/$$

$$H_{cor} = R_n - G - S - \lambda E_{cor}$$

Instrumentation was installed at the evapotranspiration station to provide estimates of soil heat flux ( $G$ ) and changes in stored energy ( $S$ ) in the biomass and air. Soil heat flux at a depth of 8 cm was measured at two representative locations using soil heat-flux plates. An estimate of the soil heat flux at land surface was computed based on the estimated change in stored energy in the soil above the heat flux plates. The changes in stored energy in the soil above the heat flux plates were estimated based on thermocouple-measured changes in soil temperature and estimates of soil heat capacity. The estimates of soil heat capacity were based on mineralogy, soil bulk density, and soil moisture content. Soil moisture content was measured using time-domain reflectometry (TDR) probes placed within the upper 8 cm of soil. Thermocouples were installed at multiple locations within the trunks of representative trees to allow for estimation of changes in storage of energy within the biomass. Estimates of biomass density (based on tree surveys) and biomass heat capacity (available from previous studies) also are required for calculation of changes in biomass stored energy. Changes in storage of energy in the air generally are small in comparison with soil heat flux and biomass heat storage, but were estimated based on measurement of the temperature and relative humidity profile below the turbulent flux sensors. With the exception of the temperature and relative humidity sensors, all of the instrumentation intended to provide data to estimate soil heat flux and changes in stored energy was destroyed by earth-moving equipment used to construct a fire break around the evapotranspiration station a few hours before a fire passed through the area of the station.

Energy generally enters the soil surface and is stored in the biomass and air during the day and released at night. It was assumed that soil heat flux and changes in energy storage in the biomass and air were negligible over a diurnal cycle. This facilitated the evaluation of equations /18/ and /19/, using daily composites of terms in these equations. This approach allowed for neglect of those terms of the energy budget that were not measured as a result of fire-damaged instrumentation.

During periods of rapid temperature changes (for example, cold front passage), however, the net soil heat flux and the net change in energy stored in the biomass and air over a diurnal cycle may not be negligible. As mentioned previously, problems such as scaling of hygrometer windows, moisture on anemometer or hygrometer, or excessive coordinate rotation can result in missing 30-minute turbulent flux data. These data must be estimated prior to construction of daily composites of turbulent fluxes. In the present study, regression analysis of measured turbulent flux data and photosynthetically active radiation (PAR) was used to estimate unmeasured values of turbulent fluxes. These regression-estimated values of turbulent fluxes are not as reliable as measured values. Therefore, the fraction of daily-composited turbulent flux data derived from regression estimates was limited to 25 percent (up to 6 hours per day). The procedure outlined above for culling, estimating, and compositing 30-minute turbulent flux data still resulted in missing values for some days.

### Simulation of Evapotranspiration

An evapotranspiration model was developed for estimating daily values of evapotranspiration representative of both burned and unburned areas. Post-fire measurements of evapotranspiration generally reflected a composite of evapotranspiration from burned and unburned vegetation. A model was developed that reflected the mixture of source area characteristics and allowed calculation of the evapotranspiration from each source area.

### Evapotranspiration Models

The eddy correlation instrumentation can have extended periods of inoperation, as discussed previously. However, more robust meteorological and hydrologic instrumentation (sensors for measurement of net radiation, air temperature, relative humidity, PAR, wind speed, soil moisture, and water-table depth) can provide nearly uninterrupted data collection. Evapotranspiration models, calibrated to measured turbulent flux data and based on continuous meteorological and hydrologic data, can provide continuous estimates of evapotranspiration. Evapotranspiration models also can provide insight into the cause-and-effect relation between the environment and evapotranspiration.

Physics-based evapotranspiration models generally rely on the work of Penman [1948, 32], who developed an equation for evaporation from wet surfaces based on energy budget and aerodynamic principles. Penman equation has been used to estimate evapotranspiration from well-watered, dense agricultural crops (reference or potential evapotranspiration). In Penman's equation, the transport of latent and sensible heat fluxes from a "big leaf" to the sensor height is subject to an aerodynamic resistance. The big leaf assumption implies that the plant canopy can be conceptualized as a single source of both latent and sensible heat at a given height and temperature. Inherent in the Penman approach is the assumption of a net one-dimensional, vertical transport of vapor and heat from the canopy. The Penman equation is shown in equation /20/.

$$\lambda E = \frac{\Delta(R_n - G - S) + \frac{\rho C_p(e_s - e)}{r_h}}{\Delta + \gamma} \quad /20/$$

$$\lambda E = \frac{\Delta(R_n - S)}{\Delta + \gamma} \quad /21/$$

$$\lambda E = \alpha \frac{\Delta(R_n - S)}{\Delta + \gamma} \quad /22/$$

$$\lambda E = (1 - w_b)\lambda E_u + w_b\lambda E_b \quad /23/$$

In equation /20/:  $\lambda E$  is latent heat flux, in watts per square meter;  $\Delta$  is slope of the saturation vapor-pressure curve, in kilopascals per degree Celsius;  $G$  is soil heat flux at land surface, in watts per square meter;  $S$  is change in storage of energy in the biomass and air, in watts per square meter;  $C_p$  is specific heat capacity of the air, in joules per gram per degree Celsius;  $e_s$  is saturation vapor pressure, in kilopascals;  $e$  is vapor pressure, in kilopascals;  $r_h$  is aerodynamic resistance, in seconds per meter; and  $\gamma$  is the psychrometric constant = approximately 0.067 kilopascals per degree Celsius, but varying slightly with atmospheric pressure and temperature. The first term is known as the energy term; the second term is known as the aerodynamic term. The equation /21/ [Priestley and Taylor (1972)] is simplification of the Penman equation for the case of saturated atmosphere ( $e = e_s$ ), for which the aerodynamic term is zero.

However, Priestley and Taylor [1972, 34] noted that empirical evidence suggests that evaporation from extensive wet surfaces is greater than this amount, presumably because the atmosphere generally does not attain saturation. Therefore, the Priestley-Taylor coefficient [ $\alpha$ , equation /22/] was introduced as an empirical correction to the theoretical expression [equation 21]. This formulation assumes that the energy and aerodynamic terms of the Penman equation are proportional to each other. The value of  $\alpha$  has been estimated to be 1.26, which indicates that under potential evapotranspiration conditions, the aerodynamic term of the Penman equation is about 21 percent of the total latent heat flux. Eichinger and others (1996) have shown that the empirical value of  $\alpha$  has a theoretical basis: A nearly constant value of  $\alpha$  is expected under the existing range of Earth-atmospheric conditions.

Previous studies (13, 41, 44) have applied a modified form of the Priestley-Taylor equation. The approach in these studies relaxes the Penman assumption of a free-water surface or a dense, well-watered canopy by allowing  $\alpha$  to be less than 1.26 and to vary as a function of environmental factors. The Penman-Monteith equation [27] is a more theoretically rigorous generalization of the Penman equation that also accounts for a relaxation of these Penman assumptions. However, Stannard [1993, 41] noted that the modified Priestley-Taylor approach to simulation of observed evapotranspiration rates was superior to the Penman-Monteith approach for a sparsely vegetated site in the semi-arid rangeland of Colorado. Similarly, Sumner [1996, 44] noted that the modified Priestley-Taylor approach performed better than did that of Penman-Monteith for a site of herbaceous, successional vegetation in central Florida. Therefore, the modified Priestley-Taylor approach was chosen for the present investigation.

### Partitioning of Measured Evapotranspiration

An evapotranspiration model (daily resolution) was developed to partition the measured evapotranspiration into two components characteristic of the primary types of surface cover (burned and unburned) of the watershed during the study period. As mentioned previously, upland areas were more likely to have been burned during the June-July 1998 fires than wetland areas. Therefore, to some extent, the model results also reflect the variation between upland and wetland evapotranspiration. The model was of the form, as shown in equation /23/, where:  $\lambda E$  is measured latent heat flux at the station, in watts per square meter;  $w_b$  is the fraction of the measured latent heat flux originating from burned areas, dimensionless;  $\lambda E_u$  is latent heat flux from unburned areas, in watts per square meter; and  $\lambda E_b$  is latent heat flux from burned areas, in watts per square meter.

$$w_b = \frac{IV}{\sum_{i=I} g_i f_i} \quad /24/$$

$$f_i = \frac{\sum_{k=1}^{48} PAR_k \delta_i(\Psi_k)}{\sum_{k=1}^{48} PAR_k} \quad /25/$$

The weighting coefficient ( $w_b$ ) for a given day must incorporate the spatial distribution of surface cover types near the point of flux measurement (Figure 3 and Table 2), the changing (upwind) source area for the measurement associated with changes in wind direction, and the diurnal changes in evapotranspiration. If the relative fraction of burned surface cover in the upwind source area remained constant for a given day (that is, the wind direction remained from a given zone of a relatively uniform mixture of surface cover types),  $w_b$  would be simply the fraction of burned surface cover within the zone. Also, if evapotranspiration from each surface cover type remained constant during a given day,  $w_b$  would be simply the time-weighted average of the fraction of burned surface cover within the upwind source areas. However, intra-day changes in source area composition, associated with changes in wind direction, and the strong diurnal cycle in evapotranspiration had to be considered during computation of day-by-day values of  $w_b$ . For example, suppose that the wind were from the west during the night and from the east during the day. In this situation, the measured daily evapotranspiration would be much more representative of the surface cover to the east because daytime evapotranspiration generally is much higher than nighttime evapotranspiration. Strong diurnal biases in wind direction [Figure 8] exist in the study area, which can lead to situations such as that described. Therefore, weighting coefficients must reflect these diurnal patterns in evapotranspiration.

The diurnal pattern of evapotranspiration during a given day generally is strongly correlated with the diurnal pattern of incoming radiation, as can be inferred from the Priestley-Taylor equation (equation /22/) or seen empirically [44].  $PAR$  was used as a surrogate for the factors that produce intra-day variations in evapotranspiration for both surface cover types. Nighttime  $PAR$  is equal to zero, implying that only daytime winds from a given zone are assumed to contribute to the measured latent heat flux for a given day. Other factors (such as variations in air temperature) that contribute to the diurnal pattern of evapotranspiration were considered minor, compared to the effect of  $PAR$ , and were not considered in the determination of weights for use in the equation /23/. The computation for the day-by-day values of  $w_b$  is derived in Appendix I at the end of this chapter and is shown in equation /24/, where:  $g_i$  is the fractional contribution of burned area within burn zone  $i$  to the measured latent heat flux when wind direction is from burn zone  $i$  (See Table 2);  $i$  is an index for the burn zones (Figure 3); and  $f_i$  is the  $PAR$ -weighted fraction of the day that wind direction is from burn zone  $i$  and is computed using equation /25/.

In equation /25/:  $k$  is an index for the 48 measurements of 30-minute averages within a given day;  $\delta_i(\Psi_k)$  is a binary function equal to 1, if  $\Psi_k$  is within burn zone  $i$  and otherwise equals 0;  $PAR_k$  is the measured  $PAR$  for time period  $k$  within a given day; and  $\Psi_k$  is the wind direction for time period  $k$  within a given day.

In the evapotranspiration model (equation /23/): Both  $\lambda E_u$  and  $\lambda E_b$  are simulated by the modified Priestley-Taylor equation (equation /22/) with individual Priestley-Taylor  $\alpha$  functions. The  $\alpha$  function for  $\lambda E_u$  was assumed to remain unchanged throughout the 2-year study period; however, the  $\alpha$  function for  $\lambda E_b$  was divided into multiple time periods to reflect the radical change in surface cover of the burned areas following the fire, logging, and regrowth of vegetation. The measurements of average, daily evapotranspiration provided a standard with which to calibrate the Priestley-Taylor evapotranspiration model. Calibration of the Priestley-Taylor model involved quantification of the functional relations between the Priestley-Taylor's  $\alpha$  and environmental variables. This quantification was achieved through identification of the form of the functional relation (trial-and-error approach) and estimation of the parameters of that relation (regression analysis) that produced optimal correspondence between measured and simulated values of latent heat flux.

The form of the calibrated model (equation /23/) allowed for evapotranspiration to be estimated for any mix of burned and unburned areas through appropriate specification of  $w_b$ . Daily values of evapotranspiration for burned and unburned areas were estimated with  $w_b$  equal to 1 and 0, respectively. Evapotranspiration from the watershed was estimated with  $w_b$  equal to 0 and 0.4 (burned fraction of watershed) prior to and following the fires, respectively. The potential evapotranspiration from the watershed was estimated with similar weighting, but with a Priestley-Taylor  $\alpha$  equal to a constant value of 1.26.

### Measurement of Environmental Variables

Meteorological, hydrologic, and vegetative data were collected in the study area for several reasons: (1) as ancillary data required by the energy- budget variant of the eddy correlation method, (2) as independent variables within the evapotranspiration model, and (3) to construct a water budget for the Tiger Bay watershed. Meteorological variables monitored included net radiation, air temperature, relative humidity, wind speed, and *PAR*. These data were recorded by data loggers at 15-second intervals, using instrumentation summarized in Table 1, and the resulting 30-minute means were stored.

Two net radiometers, each deployed at a height of 35 m, provided redundant measurements of net radiation at the evapotranspiration station. Measured values of net radiation were corrected for wind-speed effects as suggested by the instrument manual for the Radiation and Energy Balance Systems, Inc., Model Q-7.1 net radiometer. In late 1999, missing net radiation data necessitated an estimate of net radiation based on a regression of *PAR* and net radiation. *PAR* consists of that part of incoming solar radiation that is used in plant photosynthesis and is highly correlated with incoming solar radiation. Based on data collected during 1993 - 1994 in Orange County - Florida, solar radiation (in watts per square meter) can be approximated (standard error of estimate = 11 watts per square meter) as 0.49 times *PAR* (in micromoles per second per square meter).

The source area of the net radiation measurement was estimated by using the approach of Reifsnyder [1967, 35] and Stannard [1994, 42]. The measurement of net radiation had a much smaller source area than the turbulent flux measurement (Figure 7). About 90 percent of the source area for the net radiometers was within a radial distance of 55 m (pre-logging) or 110 m (post- logging). Therefore, the source area for the net radiometer in the near- vicinity of the evapotranspiration station was one of the following: (1) pine plantation (pre-logging), (2) burned pine plantation (post-fire, but pre-logging), or (3) clear-cut, with understory regrowth (post-logging). Other covers also existed within the watershed, primarily wetlands and unburned pine lands. Lacking net radiation measurements over more than one cover, the assumption was made that net radiation measured at the unburned pine plantation was representative of all unburned surface covers. The period of record prior to the fire (the initial 175 days of 1998) was used to develop a regression-based predictor of net radiation as a function of *PAR*. This relation was used to estimate net radiation in unburned areas following the burning of the area around the evapotranspiration station. The net radiation measured at the evapotranspiration station following burning was assumed to be representative of all burned areas. Logging of the burned area near the evapotranspiration station occurred during a period of extensive logging through- out the watershed. Some error is introduced to the estimation of net radiation over burned areas because the logging was not simultaneous for all burned areas and because the logging over burned areas was not complete (as mentioned previously, two-thirds of the burned forest within Tiger Bay State Forest was logged). Estimates of daily net radiation for burned and unburned areas were composited as shown in equation /26/ into a value consistent with the turbulent flux measurements (equations /18/ and /19/) using the weighting coefficient ( $w_b$ ) previously defined (equation /24/).

$$R_n = (1 - w_b)R_{nu} + w_b R_{nb} \quad /26/$$

$$NDVI = \frac{NIR - Vis}{NIR + Vis} \quad /27/$$

In equation /26/:  $R_n$  is composited net radiation, in watts per square meter;  $R_{nu}$  is net radiation for unburned areas, in watts per square meter; and  $R_{nb}$  is net radiation for burned areas, in watts per square meter.

A regression between post-logging, daily values of net radiation and *PAR* was used to estimate net radiation from burned and logged surfaces during the latter part of 1999 after net radiometer domes were damaged, perhaps by birds. Vegetation within the study area was mapped previously by Volusia County Department of Geographic Information Systems (1996a, 56; 1996b, 57] and Simonds and others [1980, 40]. Post-fire, infrared, aerial photographs were used to identify the areal distribution of burned vegetation in the watershed.

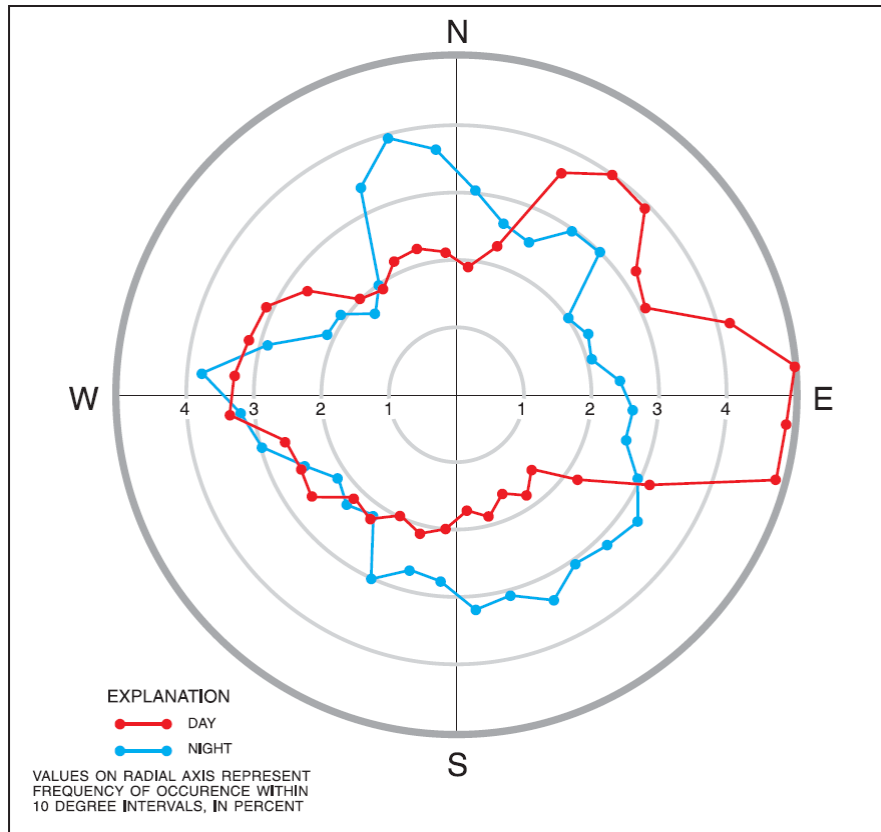


Figure 8. Wind direction frequency pattern at location of evapotranspiration station.

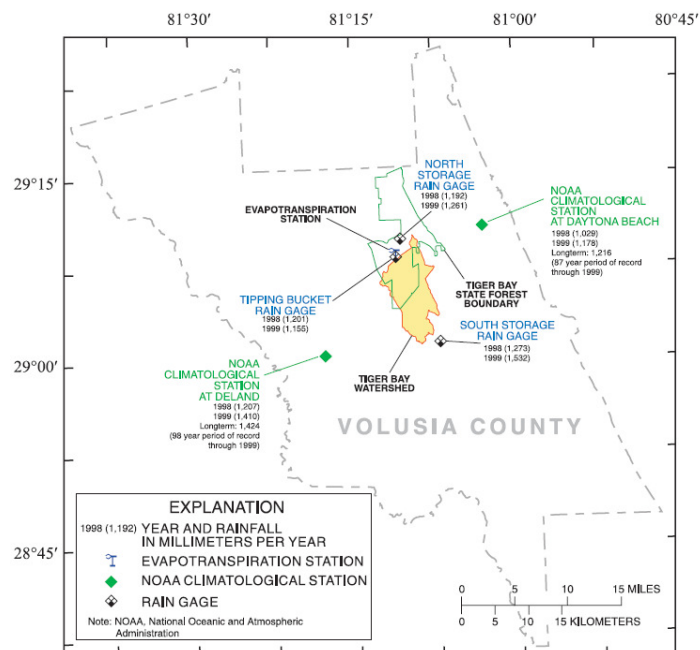


Figure 9. Location of rain gages in vicinity of Tiger Bay watershed.

Temporal variations in vegetation were documented with monthly photographs taken from the tower at the evapotranspiration station and with normalized difference vegetation index (NDVI) data. NDVI data were provided by the USGS Earth Resources Observation Systems (EROS) Data Center through analysis of the Advanced Very High Resolution Radiometer

(AVHRR) data [11, 52, 54] from operational National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. NDVI is defined in equation /27, where: NIR is near-infrared reflectance measured in AVHRR band 2 (725 - 1100 nanometers); and Vis is visible reflectance measured in AVHRR band 1 (580 - 680 nanometers).

NDVI is highly correlated with the density of living, leafy vegetation. The physical basis for this correlation is the sharp contrast in the absorptivity of visible and near-infrared radiation by leaves, which absorb approximately 85 percent of incident visible radiation, but only 15 percent of near-infrared radiation [8]. Other ground covers (dead plant material, soil, and water) do not exhibit this extreme spectral differential in absorption. The AVHRR-computed NDVI data are provided at 2-week and 1-kilometer (km) by 1-km resolution. For the present study, NDVI data, within a 3-km by 3-km square and approximately centered on the location of the evapotranspiration station, were composited to quantify temporal trends in the density of living, leafy vegetation in the vicinity of the turbulent flux measurements during the study period.

Air temperature and relative humidity were monitored at the evapotranspiration station at heights of 1.5, 9.1, 18.3, and 35 m. The slope of the saturation vapor pressure curve (a function of air temperature) and vapor pressure deficit were computed in the manner of Lowe [1977, 25] using the average of air temperature and relative humidity values measured at these four heights. A propeller-type anemometer to monitor wind speed and direction and an upward-facing quantum sensor to measure incoming *PAR* were deployed at a height of 35 m at the evapotranspiration station.

Hydrologic variables that were monitored included precipitation, water-table depth, stream discharge, and soil moisture. Precipitation records were obtained from a tipping bucket rain gage mounted at a height of about 18.3 m at the evapotranspiration station and from two storage rain gages installed in forest clearings and monitored weekly (Figure 9). Spatial variability in annual rainfall can be substantial within Volusia County, based on the long-term NOAA stations at DeLand and Daytona Beach (Figure 9). The Daytona Beach area, on average, receives about 15 percent less annual rainfall than does the DeLand area [30, 31]. The uncertainty associated with the rainfall distribution between these two stations precluded the use of both stations for estimation of rainfall to the Tiger Bay watershed during the study period. Rather, the rainfall totals from the two storage rain gages located near the watershed were averaged to provide estimates of rainfall to the watershed. Tipping bucket rain gages can underestimate rainfall, particularly during high-intensity events; therefore, the tipping bucket gage monitored at the evapotranspiration station was used primarily to provide a high-resolution description of the temporal rainfall pattern, and the storage rain gages were used primarily to estimate cumulative rainfall.

Water-table depth was monitored at two surficial- aquifer system wells at opposite ends of the watershed. Water-level measurements were obtained at 30-minute intervals using a pressure transducer in the north well (USGS site identification number 290813081111801), located at the evapotranspiration station. The south well (USGS site identification number 290119081074001), at the location of the south storage rain gage (Figure 1), was measured weekly using an electric tape. Although the two wells monitored were located at opposite ends of the watershed (Figure 1), both wells were within similar upland settings. Although the water-table depth in wet- land areas would be expected to be less than that measured in upland wells, water levels are expected to change at the same rate in the low relief environment of this watershed. Therefore, changes in the measured upland water-table depths can be regarded as indicators of changes in the representative water-table depth of the watershed.

Daily values of stream discharge for the only surface-water outflow from the Tiger Bay watershed, Tiger Bay canal near Daytona Beach (Figure 1; USGS station number 02247480), were obtained from the USGS database (U.S. Geological Survey, 1998a, 1999a, and 2000). Soil moisture at two representative locations at the evapotranspiration station was monitored using time-domain reflectometry (TDR) probes installed to provide an averaged volumetric soil moisture content within the upper 30 cm of the soil. Soil moisture measurements were made and recorded on the data logger every 30 minutes. The TDR probes were damaged by a fire in late June 1998, but were replaced in early August 1998. The soil moisture measurements made at the evapotranspiration station probably are indicative of only the uplands; wetlands commonly are inundated at times when shallow upland soils are not.

## RESULTS AND DISCUSSION: EVAPOTRANSPIRATION MEASUREMENT AND SIMULATION

Most (73 percent) of the 30-minute resolution eddy correlation measurements made during the 2-year study period were acceptable and could be used to develop an evapotranspiration model to estimate missing data and to discern the effects of environmental variables on evapotranspiration. Unacceptable measurements resulted from failure of the krypton hygrometer or sonic anemometer, or because of excessive (more than 10 degrees) coordinate rotation in the post-processing "leveling" of the anemometer data. Unacceptable data were most extensive in the evening and early-morning hours (Figure 10) because dew formation on the sensors during these times of day was common. This diurnal pattern of missing data was fortunate because turbulent fluxes are expected to be relatively small during the evening and early morning, when solar radiation is low. Missing data were estimated based on linear regression between the turbulent fluxes and *PAR* (Figures 11 and 12). Because *PAR* is zero at night, this approach assigned constant values of latent and sensible heat flux to missing night time data. The assumed constant value of night time latent heat flux assigned to missing data was 9.04 watts per square meter (Figure 11). This value generally was small relative to daytime values of latent heat flux, and therefore, not significantly inconsistent with the assumption of negligible nighttime latent heat flux inherent in the development of weighting coefficients (equations /23/ to /25/). Examples of measured and *PAR*-estimated turbulent fluxes are shown for a period in late February 1998 in Figure 13.

Turbulent flux data exhibited pronounced diurnal patterns. The average diurnal pattern of turbulent fluxes and *PAR* (Figure 14) indicates that the vast majority of evapotranspiration occurs in daytime, driven by incoming solar radiation. During

average daytime conditions, both latent and sensible heat flux are upward, with most of the available energy partitioned to latent heat flux. At night, the land or canopy surface cools below air temperature, producing a reversal in the direction of sensible heat flux (Figure 14). Although the average, nighttime latent heat flux is upward (Figure 14), dew formation (downward latent heat flux) commonly occurs.

The relation between net radiation and *PAR* varied as a result of the fire, logging, and regrowth. Regressions between daily values of net radiation and *PAR* are shown in Figure 15 for three periods: pre-fire, post-fire/pre-logging, and post-logging. The measured and estimated values of daily net radiation for burned and unburned areas are shown in Figure 16. Measured values of *PAR*, a quantity highly correlated with incoming solar radiation, are shown in Figure 17. The strong seasonality of net radiation evident in figure 16 was a consequence of the yearly solar cycle, which produces a sinusoidal input of solar radiation to the upper atmosphere. Deviations from the sinusoidal pattern (such as during September-October 1999) were largely the result of cloudy conditions that produced periods of low *PAR*. The cloudy and rainy period immediately after the fire resulted in relatively low values of *PAR* and low estimated values of net radiation in unburned areas. The measured (burned) net radiation, however, was relatively high, indicating that the surface reflectance of burned areas decreased markedly after the fire blackened much of the landscape. The measured net radiation for burned areas was about 20 percent higher than the estimated net radiation for unburned areas in the 6 months following the June 1998 fire. With the regrowth of vegetation, reflectance gradually increased to near pre-fire values in the post-logging period, and the differences between values of net radiation for burned and unburned areas were less distinct.

As described previously, daily composites of measured turbulent fluxes were constructed with the restriction that no more than 6 hours of data for a given day could be missing and subject to estimation using the gross *PAR*-based relations (Figures 11 and 12). This restriction limited the number of acceptable daily values of measured turbulent fluxes to 449 during the 2-year (730 days) study period. Only a small amount of the total turbulent flux (5.6 and 5.1 percent for latent and sensible heat flux, respectively) comprising the acceptable daily values was estimated by the *PAR*-based relation. As expected from previous studies, the available energy tended to be greater (measured turbulent fluxes accounted for only about 84.7 percent of estimated available energy) than the turbulent fluxes derived from the standard eddy correlation method (Figure 18), and the energy-budget closure tended to improve with increasing friction velocity (Figure 19). The measured turbulent fluxes generally accounted for estimated available energy at friction velocity values greater than about 0.6 m/s. The acceptable daily values of turbulent fluxes, computed by both the standard eddy correlation method (equations /5/ and /6/) and the energy- budget variant of the eddy correlation method (equations /18/ and /19/), are presented in Figures 20 and 21.

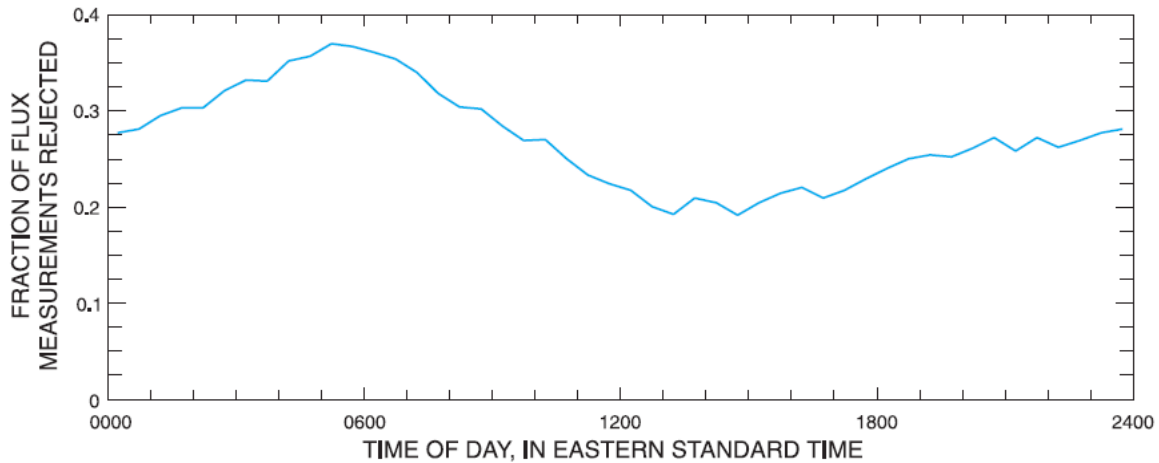
These values represent the fluxes measured at the evapotranspiration station, and therefore, represent varying proportions of burned and unburned source areas. The relative proportions varied widely following the fire (Figure 22), with values ranging from those that were almost completely representative of unburned areas ( $w_b = 0$ ) to those with 80 percent representative of burned areas ( $w_b = 0.8$ ).

As a consequence of the previously mentioned discrepancy between available energy and measured turbulent fluxes, the standard eddy correlation method produced turbulent flux values that were, on average, only 84.7 percent of those produced by the energy-budget variant.

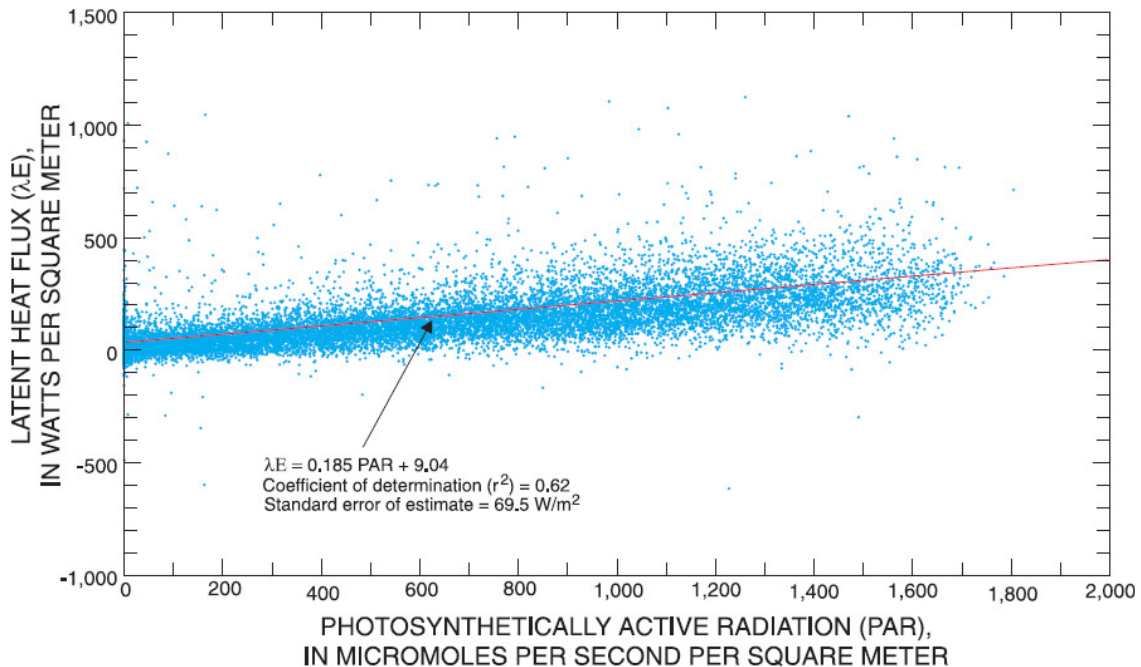
### Calibration of Evapotranspiration Model

Calibration of the evapotranspiration model was essentially a process of determining the best functional form of the modified Priestley-Taylor coefficient,  $\alpha$ . The environmental variables considered as possible predictors of Priestley-Taylor's  $\alpha$  (equation /22/) included: water-table depth, soil moisture, *PAR*, air temperature, vapor-pressure deficit, daily rainfall, NDVI, and wind speed. Of these variables, only water-table depth, soil moisture, and *PAR* were identified as significant determinants of Priestley-Taylor's  $\alpha$ . Soil moisture was highly correlated with water-table depth (Figure 23), and therefore, one of these variables can be excluded from the  $\alpha$  function to avoid redundancy. To enhance the transfer value of this study, water-table depth was retained as a variable in the  $\alpha$  function, and soil moisture was eliminated, because water-level data are more commonly available than soil moisture data. In other environmental settings, such as areas with a relatively deep water table or coarse-textured soils, the water table may be hydraulically de-coupled from the shallow soil moisture much of the time, and a different functional representation of  $\alpha$  than was used in this study would be appropriate.

Priestley-Taylor's  $\alpha$  was initially simulated with a three-part model incorporating the three different surface covers: (1) unburned areas; (2) post-fire/pre- logging, burned areas (June 25 to December 16, 1998); and (3) post-logging, burned areas (December 17, 1998, to December 31, 1999). The time divisions for the burned areas grossly approximated the observed variation in NDVI over the study period (Figure 24). The effects of the fire and transient regrowth of vegetation (Figure 4) on NDVI were evident (Figure 24). In the almost 6 months prior to the fire (January 1-June 24, 1998), NDVI maintained a relatively constant value of about 0.5. NDVI sharply declined at the time of the fire, but recovered within 4 months to a value of about 0.4, which was maintained throughout the remainder of the study. As a simplification, the effect of the transient aspect of vegetative regrowth within the 4-month recovery period was not incorporated into the model for  $\alpha$ . Instead, the function of  $\alpha$  for this recovery period, as for all time periods, was a function solely of water-table depth and *PAR*.



**Figure 10.** Diurnal pattern of rejected flux measurements.



**Figure 11.** Relation between measured 30-minute averages of photosynthetically active radiation (PAR) and latent heat flux ( $\lambda E$ ).

Surprisingly, the annual pattern of leaf growth and drop for the deciduous cypress trees within the watershed was not apparent in values of NDVI, perhaps because of the exposure of understory vegetation following leaf drop. Simulations that attempted to use NDVI directly as an explanatory variable for variations in evapotranspiration were unsuccessful. This failure is perhaps related to erratic variations in NDVI (Figure 24), which are a product of sensor and data registration limitations (Kevin Gallo, NOAA, written communication, 2001).

An analysis of error in the preliminary model showed a seasonal pattern in the residuals (difference of measured and simulated latent heat fluxes) within the post-logging period (Figure 25). Measured evapotranspiration generally was overestimated in the early part of this period and underestimated in the late part of the period. The bias was apparently unrelated to changes in green leaf density, based on the relatively constant value of NDVI following logging (Figure 24). Possible explanations for the model bias include factors not clearly identified by NDVI: phenological changes associated with maturation or seasonality of plants that emerged after the fire or successional changes in composition of the plant community within burned areas. To reflect the apparent change in system function during the post-logging period, this period was further subdivided into an early period (December 17, 1998 through April 22, 1999) and a late period (April 23 through December 31, 1999). This subdivision of the post-logging period resulted in an improved model (standard error of estimate = 9.67 watts per square meter), compared to the model with a single post-logging period (standard error of estimate = 10.82 watts per square meter) and reduced the seasonal bias in residuals (Figure 25).



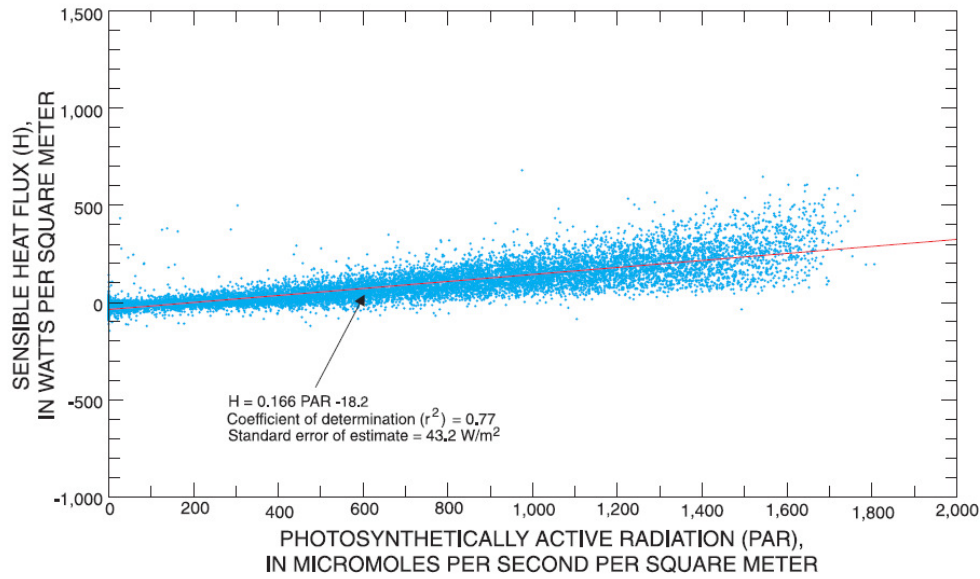


Figure 12. Relation between measured 30-minute averages of photosynthetically active radiation (PAR) and sensible heat flux (H).

The general form of  $\alpha$  was identical for all surface covers (equation /28/), although model parameter values varied with surface cover (Table 3):

$$\alpha_j = C_{1j}h_{wt} + C_{2j}PAR + C_{3j}$$

/28/

In equation /28/:  $\alpha_j$  is the Priestley-Taylor coefficient for the  $j$ th surface cover;  $j$  is an index denoting the surface cover;  $j = 1$  (unburned areas);  $j = 2$  (burned areas during post-fire/pre-logging period;  $j = 3$  (burned areas during initial post-logging period); and  $j = 4$  (burned areas during final post-logging period);  $C_{1j}$ ,  $C_{2j}$ , and  $C_{3j}$  are empirical parameters that are estimated through regression, within the context of equations /22/ to /25/; and  $h_{wt}$  is water table depth below a reference level placed at the highest water level measured (0.11 meters above land surface) at the evapotranspiration station (uplands environment) during the study period, in meters.  $h_{wt}$  is constrained to be greater than zero.

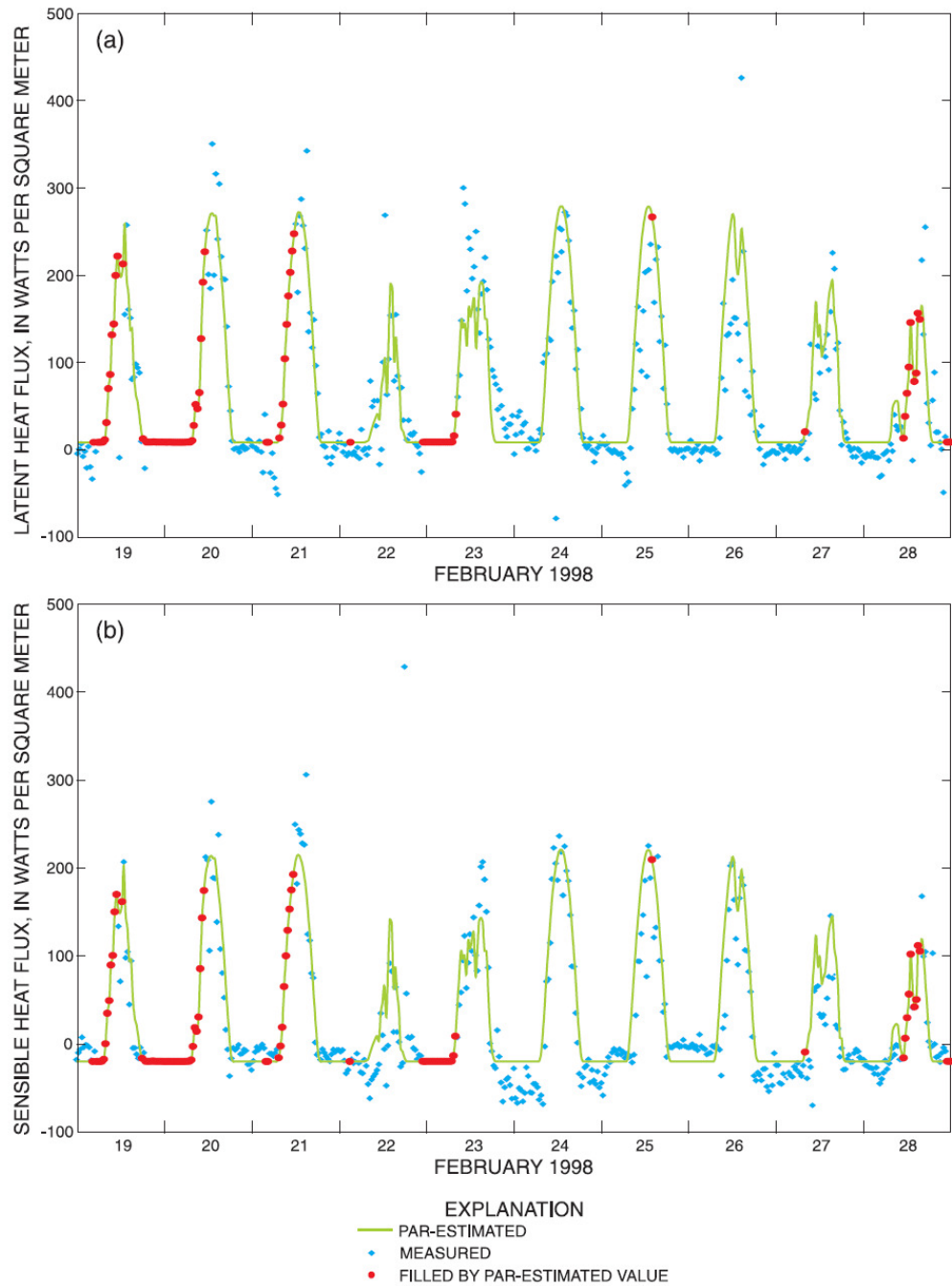
Regressions to estimate the model parameters within eq. 28 were designed to minimize the sum of squares of error residuals between measured and simulated latent heat fluxes. Measured latent heat flux was used as the dependent variable of the regression; the right side of eq. 22 contained the independent variables, as well as the unknown parameter ( $C_{1j}$ ,  $C_{2j}$ , and  $C_{3j}$ ; and  $j = 1$  to 4). The values of  $\lambda E_u$  and  $\lambda E_b$  were estimated with equation /22/, using the appropriate values of net radiation ( $R_{nu}$  and  $R_{nb}$  of equation /26/ for  $\lambda E_u$  and  $\lambda E_b$ , respectively), and equation /28/. The variable  $w_b$  was estimated with the equations /24/ and /25/.

The form of  $\alpha$  used in this study is similar to that used by German [2000, 15] for south Florida wetlands, where water level and incoming solar radiation were the sole determinants of  $\alpha$ . In the study by German, however, the form of  $\alpha$  involved both first and second order terms of incoming solar radiation. In this study, addition of the second-order PAR term added negligible improvement to simulation of evapotranspiration.

A comparison between simulated and measured values of latent heat flux is shown in Figure 26 and regression statistics are shown in Table 3. The model exhibited little temporal bias (Figure 25), even in the post-fire/pre-logging period when substantial transient changes (re-growth) in vegetative cover occurred in the burned areas. The lack of significant temporal bias supports the utilization of the particular discretization of time used in the model. More than 95 percent of the values of latent heat flux were within 25 percent of the measured values.

### Application of Evapotranspiration Model

The calibrated evapotranspiration model (equations /22/ and /23/, with  $\alpha$  values given by equation /28/ and regression-derived parameters given in Table 3) described in the previous section was used to estimate average, daily values of evapotranspiration for both burned and unburned areas of the watershed during the 2-year study period. The model also provided a quantitative framework to examine the relation between evapotranspiration and the environment. The input variables for the model included daily values of net radiation (Figure 16), PAR (Figure 17), water-table depth at the evapotranspiration station (Figure 27), and air temperature (Figure 28).



**Figure 13.** Measured and photosynthetically active radiation (PAR)-estimated values of (a) latent heat flux and (b) sensible heat flux during 10-day period in late February 1998.

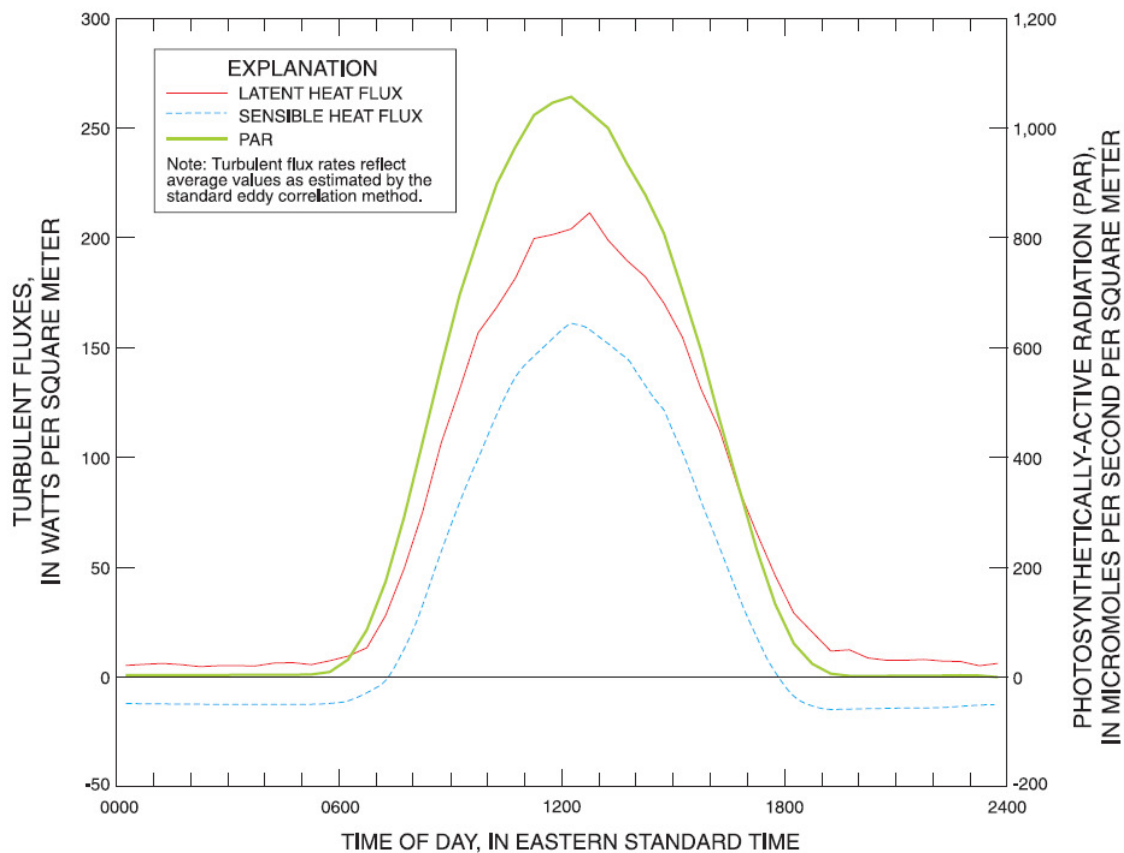


Figure 14. Average diurnal pattern of energy fluxes and photosynthetically active radiation (PAR).

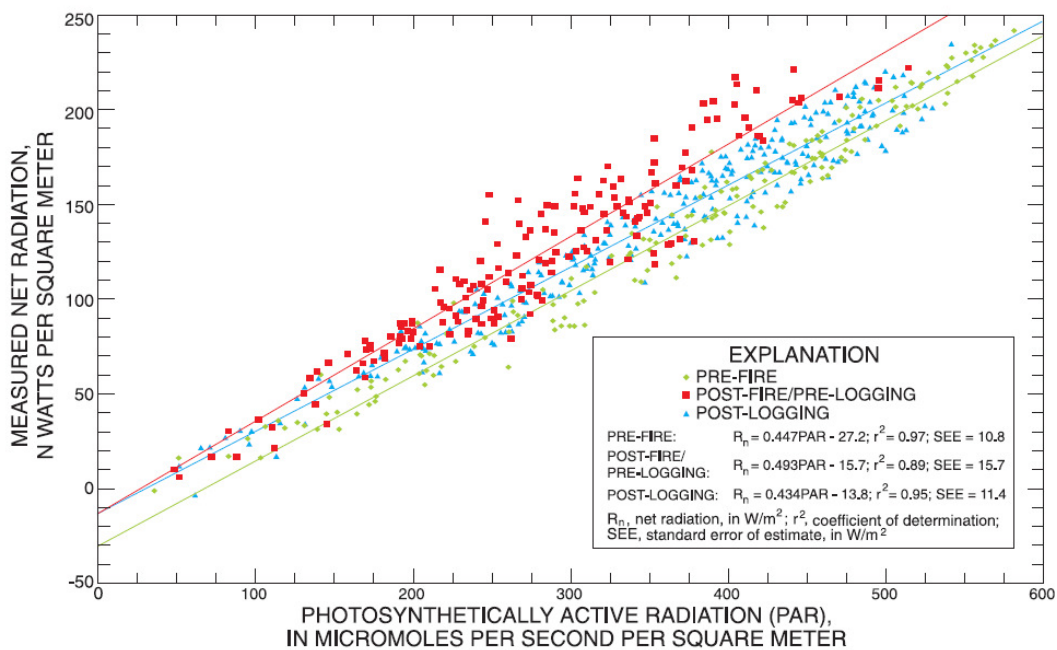


Figure 15. Relation between daily values of measured net radiation and photosynthetically active radiation (PAR).

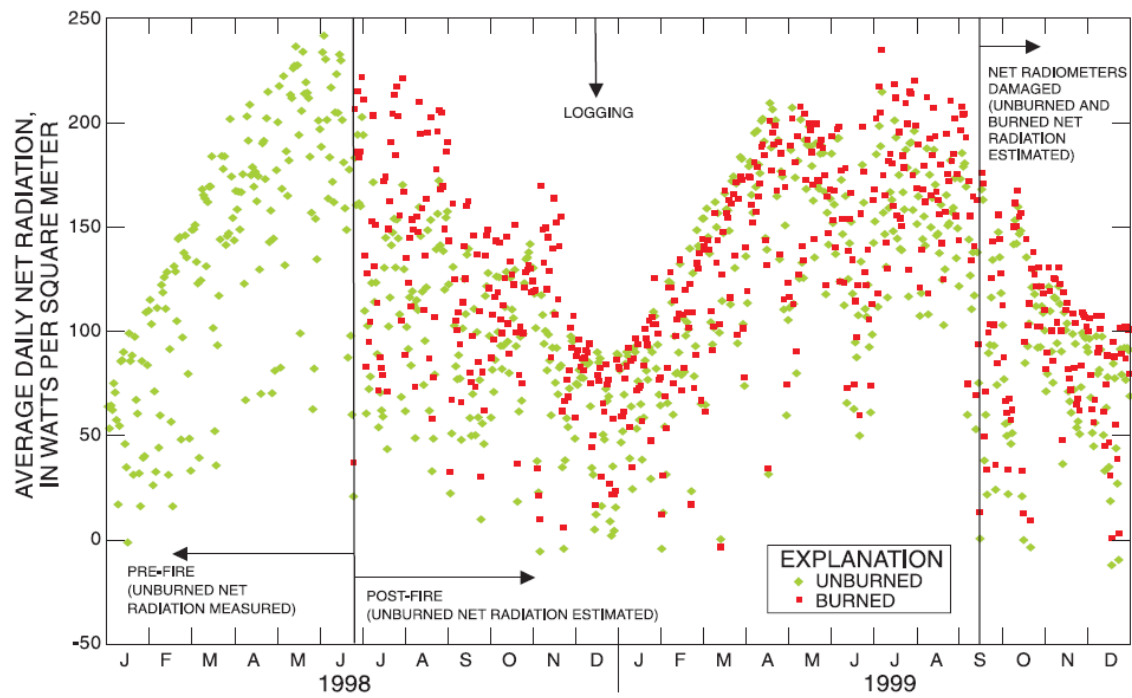


Figure 16. Average daily net radiation for burned and unburned areas.

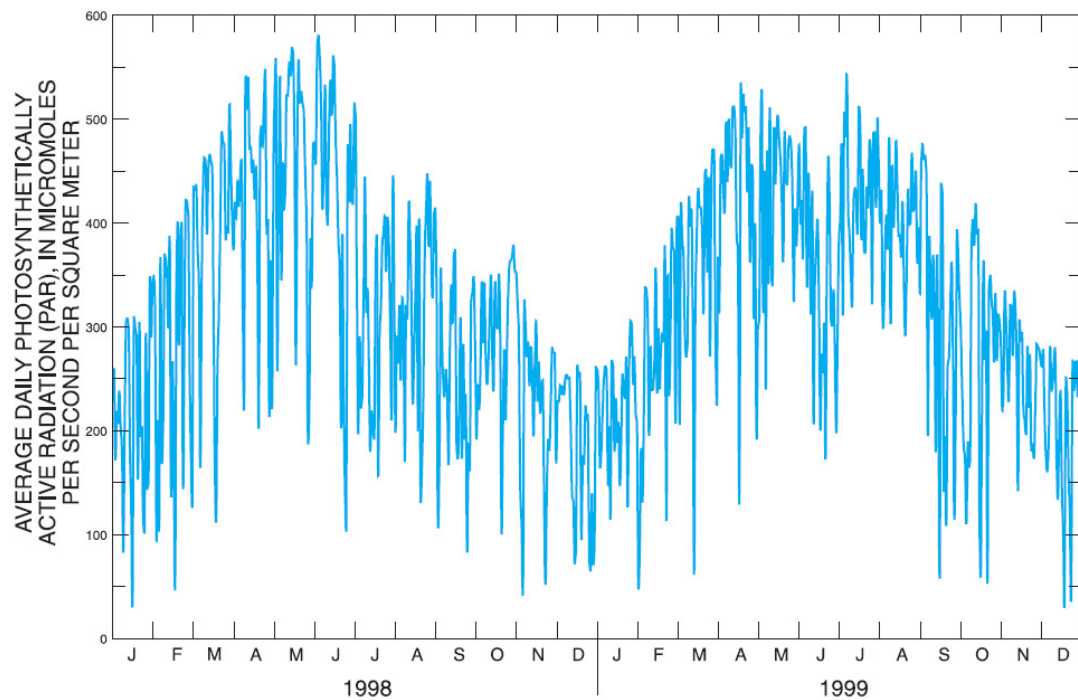


Figure 17. Average daily photosynthetically active radiation (PAR).

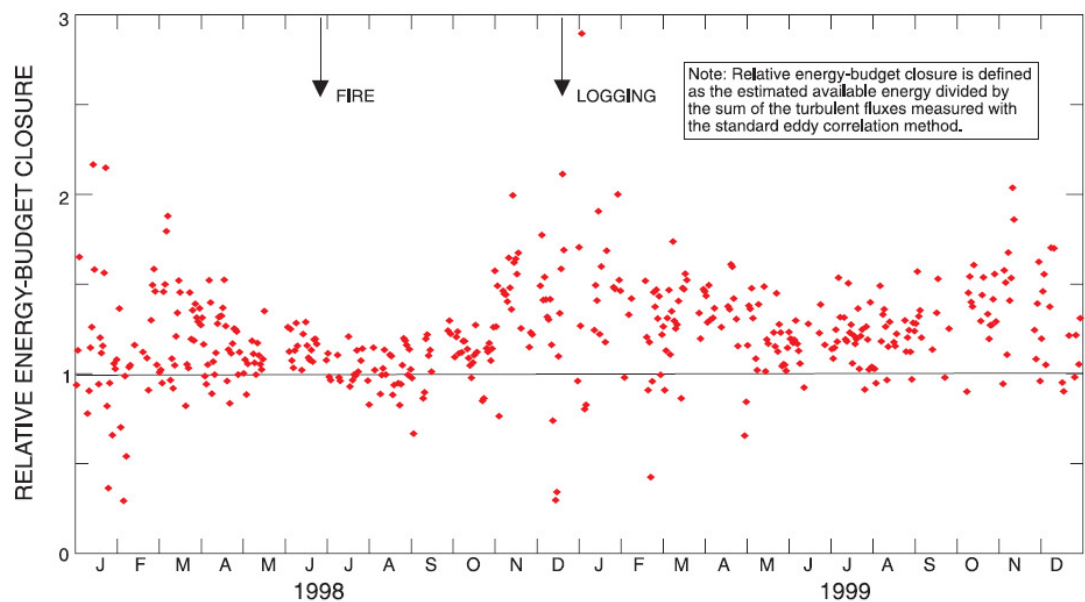


Figure 18. Temporal distribution of daily relative energy-budget closure.

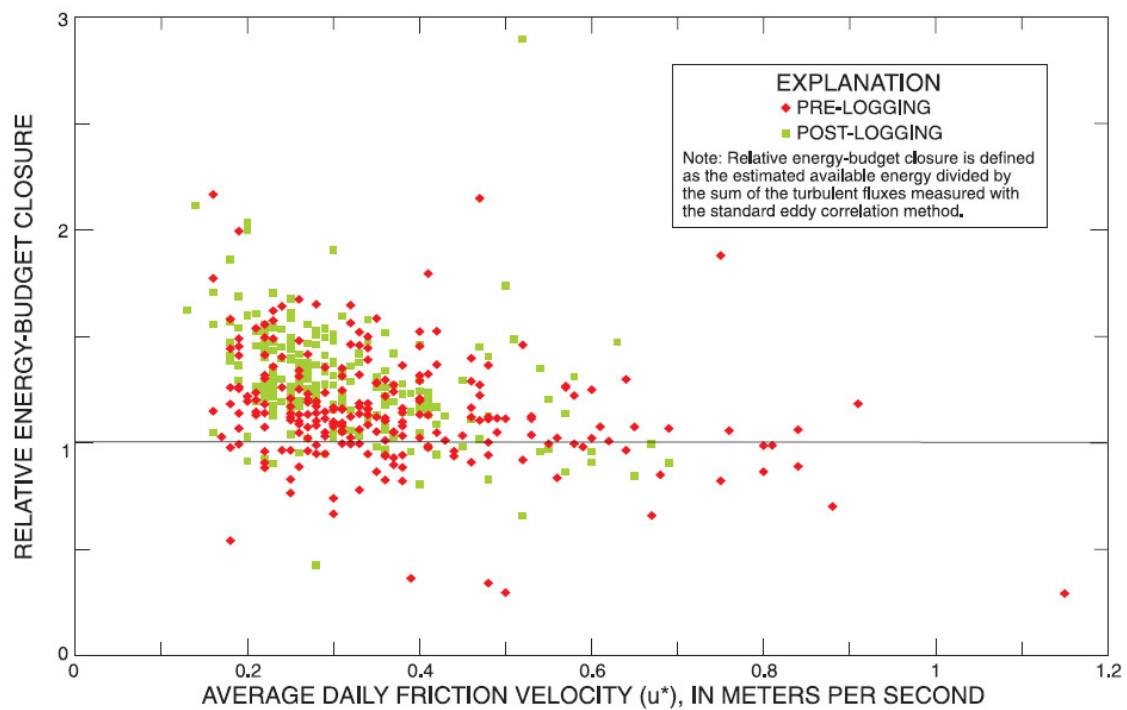
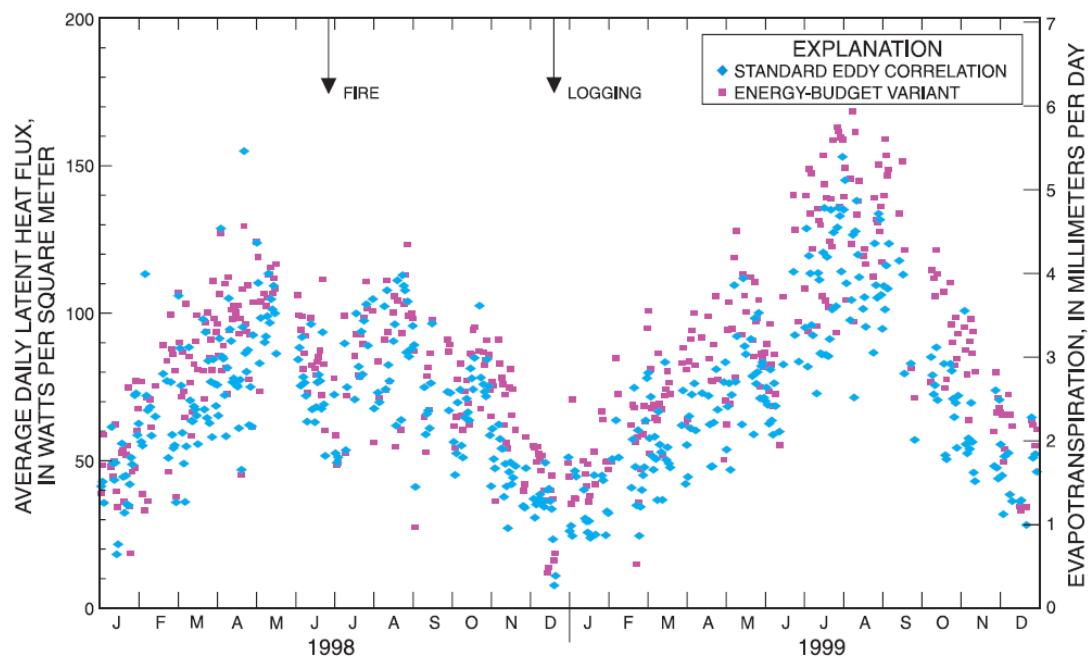
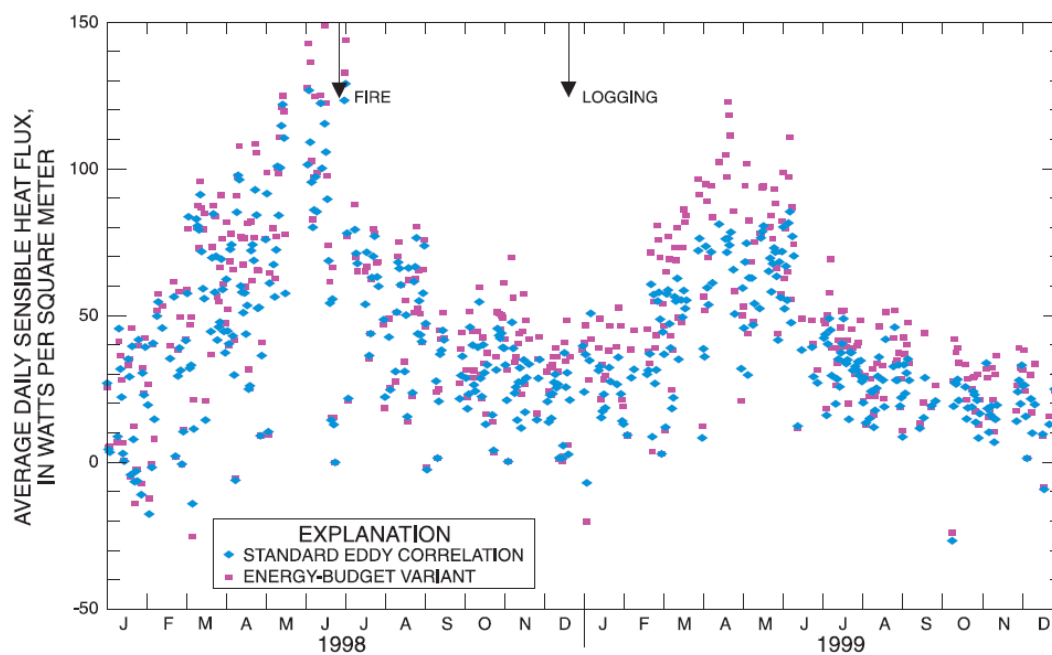


Figure 19. Relation between daily energy-budget closure and average daily friction velocity.

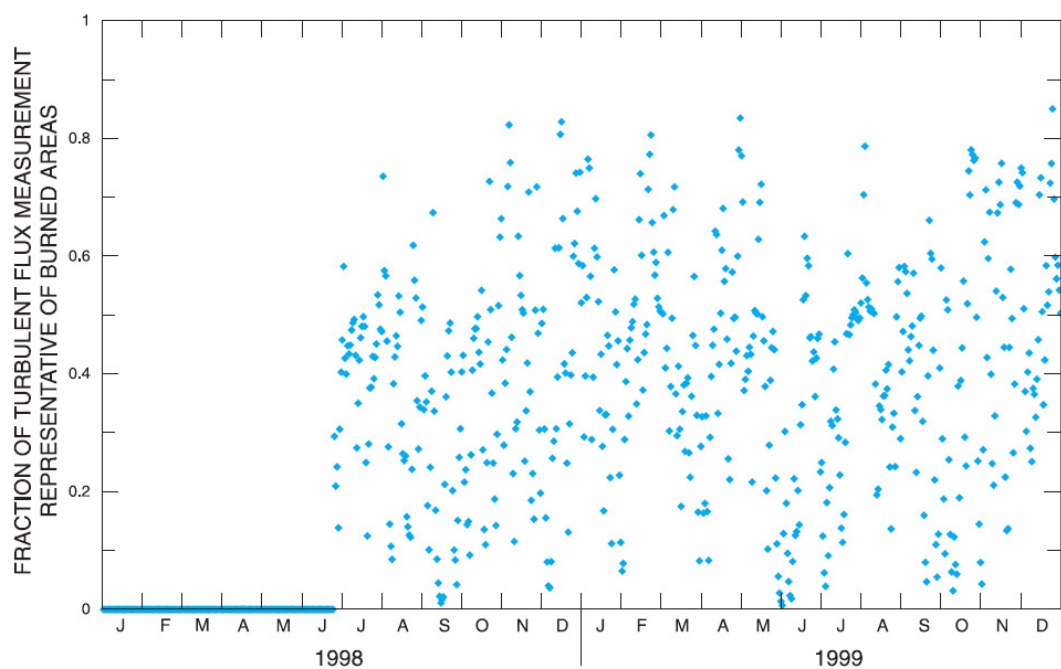


**Figure 20.** Average daily latent heat flux measured by the eddy correlation method and the energy-budget variant.

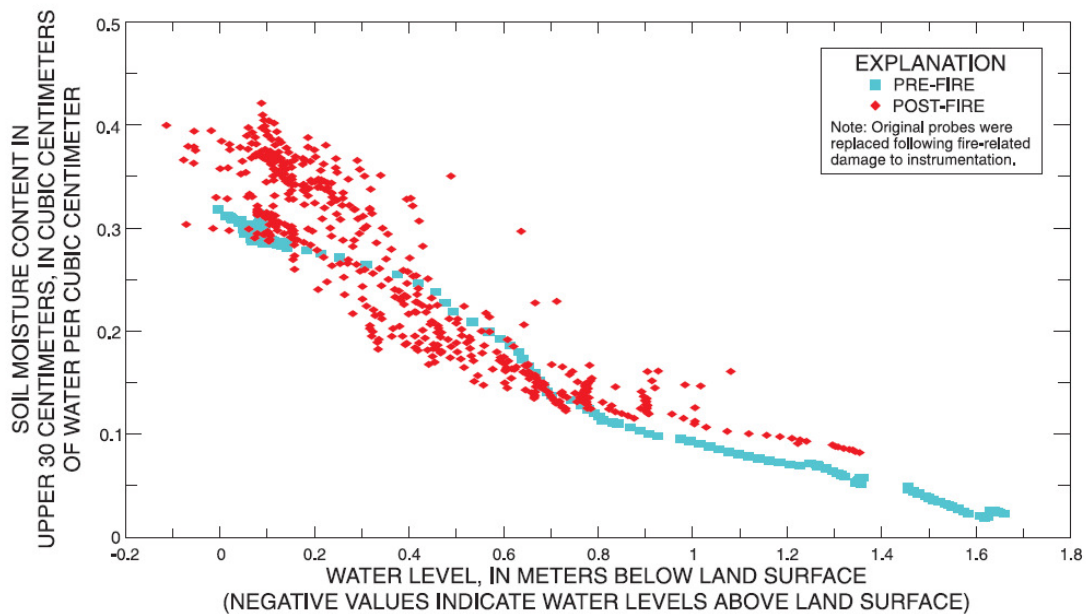


**Figure 21.** Average daily sensible heat flux measured by the eddy correlation method and the energy-budget variant.

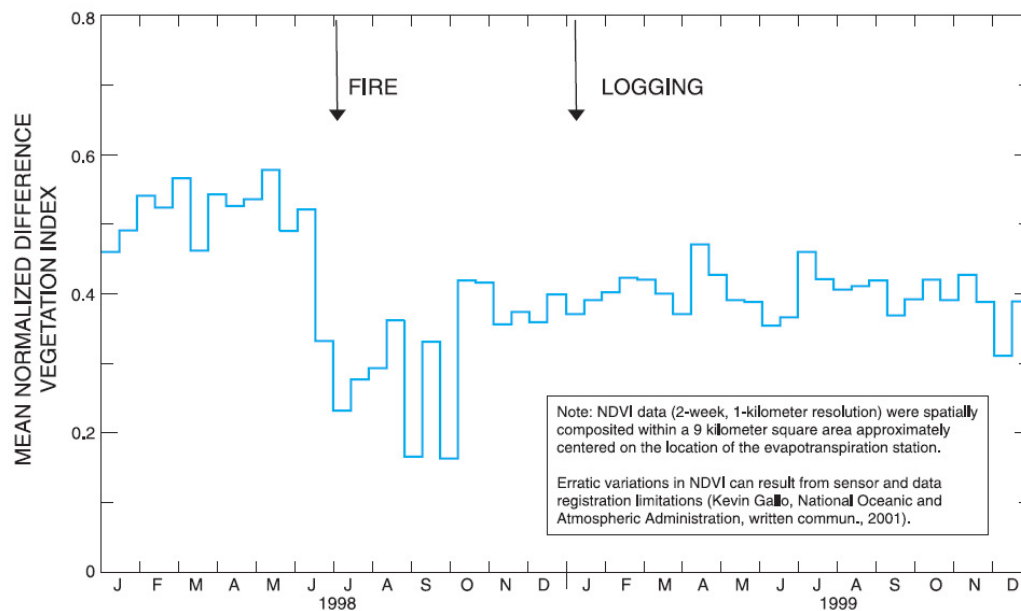




**Figure 22.** Daily values of fraction of burned fraction of turbulent flux measurement.

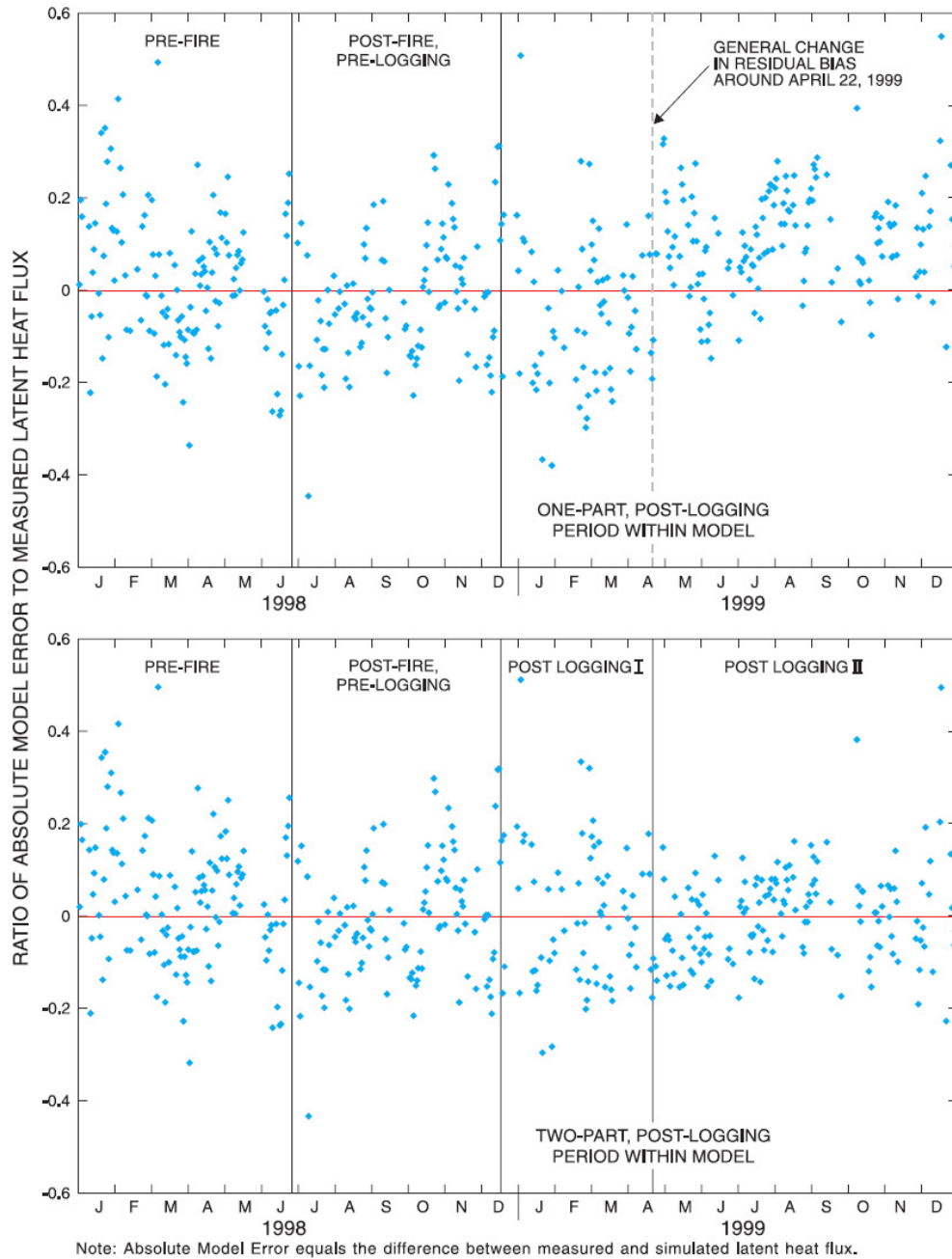


**Figure 23.** Relation between soil moisture content and water level.





actual and potential evapotranspiration showed strong seasonal patterns and day-to-day variability (Figures 29 and 30). Actual evapotranspiration from the watershed averaged only 72 percent of potential evapotranspiration.



**Figure 25.** Temporal variability in relative error of evapotranspiration model.

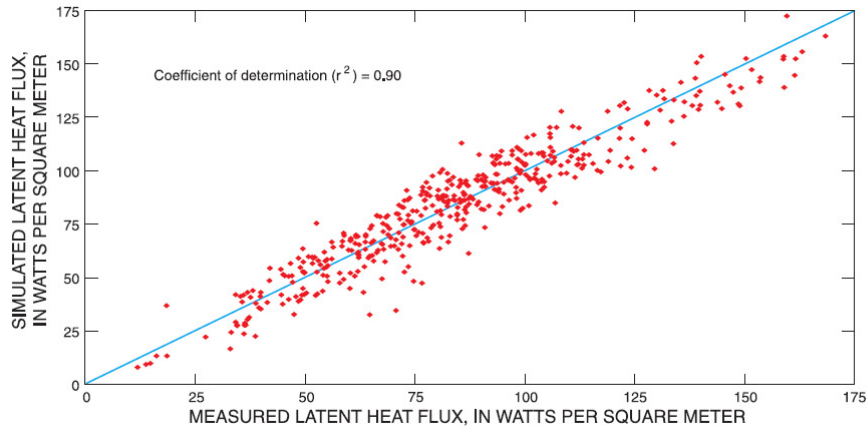


Figure 26. Comparison of simulated and measured values of daily latent heat flux.

The effect of the extreme drought period in spring 1998 (Figure 27) on turbulent fluxes was substantial (Figures 29, 31, and 32). Turbulent fluxes usually emulate the general sinusoidal, seasonal pattern of solar radiation and air temperature [22, 44, 15]. The usual sinusoidal pattern of latent heat flux was truncated in spring 1998 (Figure 29) because of a lack of available moisture (Figures 27 and 33). The drought-induced reduction in latent heat flux was compensated by an increase in sensible heat flux (Figure 31) with an associated increase in the Bowen ratio. Comparison of the Bowen ratio (Figure 32) with the water-table and soil moisture records (Figures 27 and 33) indicates that the moisture status of the watershed has a major role in the partitioning of the available energy. Relative evapotranspiration is a ratio of actual to potential evapotranspiration and was computed as  $\alpha / 1.26$ ; and it decreased from about 1 in the early, wet part of 1998 to less than 0.50 during the drought (Figure 34). After the drought ended in late June and early July 1998 and water levels quickly returned to near land surface, evapotranspiration increased sharply. The evapotranspiration rate, however, averaged only about 60 percent of the potential rate in the burned areas, as compared to about 90 percent in the unburned areas. This discrepancy can be explained as a result of fire damage to vegetation.

Potential evapotranspiration rates for burned and unburned areas were similar (Figure 30), although actual evapotranspiration rates for the two areas were quite distinct from each other (Figure 29). The relation between actual and potential evapotranspiration was not a simple constant multiplier (for example, a crop factor), but rather was time-varying as a function of water-table depth, PAR, and surface cover (Figure 34). Relative evapotranspiration exceeded a value of 1 at times, probably as a result of experimental error, as well as the approximate and empirically derived nature of the assumed potential value of 1.26 for  $\alpha$ . The potential evapotranspiration rates (Figure 30) did not strongly reflect either the drought or surface burning and logging, as does the actual evapotranspiration.

Within the framework of the calibrated model, variations in the environmental variables contained in  $\alpha$  (water-table depth and PAR) reduce actual evapotranspiration below potential evapotranspiration for a given surface cover. The evapotranspiration model indicated that relative evapotranspiration decreased as the depth to the water table increased (Figure 35). The range of water-table depths prevalent during the study period was slightly above land surface to about 1.75 m below land surface. Presumably, at some water-table depth greater than 1.75 m, relative evapotranspiration would reach an asymptotic constant value as vegetation becomes unable to access moisture below the water table. The rate of decline of relative evapotranspiration with water-table depth was greater for the post-logging period than for the pre-logging period. This result is perhaps a manifestation of the replacement of many deep-rooted trees by shallow-rooted understory vegetation following the fires. Shallow-rooted plants would be less able to tap into deep soil moisture or the water table than would deep-rooted vegetation.

Water-table depth has been considered an important predictor of evapotranspiration in hydrologic analysis [49], but little empirical evidence has been available to define the relation between these two environmental variables. The USGS modular finite-difference ground-water flow model (MODFLOW) simulates relative evapotranspiration as a unique, piece-wise, linear function of water-table depth, where evapotranspiration declines from a potential rate when the water table is at or above land surface to zero at the "extinction depth" [26]. Contrary to the MODFLOW conceptualization of evapotranspiration, this study indicates that the variation in relative evapotranspiration is explained not only by water-table depth, but also by PAR. Relative evapotranspiration decreased with increasing PAR (Figure 36), with the exception of the late post-logging period, which showed a slight increase in relative evapotranspiration with increasing PAR. This observation perhaps can be explained by assumptions within the Priestley-Taylor formulation that the energy and aerodynamic terms of the Penman equation are proportional to each other. Under non-potential conditions, these two terms might deviate from the assumption of proportionality, but in such a manner that can be "corrected" through a functional relation between the multiplier  $\alpha$  and a term (PAR) strongly correlated with the energy term.

Within the model developed in this study, net radiation and air temperature do not directly affect the Priestley-Taylor  $\alpha$  and relative evapotranspiration, although net radiation has an indirect effect through the correlation of this variable with PAR. These variables, however, are important in the determination of evapotranspiration, as can be seen in equation /22/. Evapotranspiration is directly proportional to  $[\Delta / (\Delta + \gamma)]$ , a term that is a function of temperature (Figure 37).

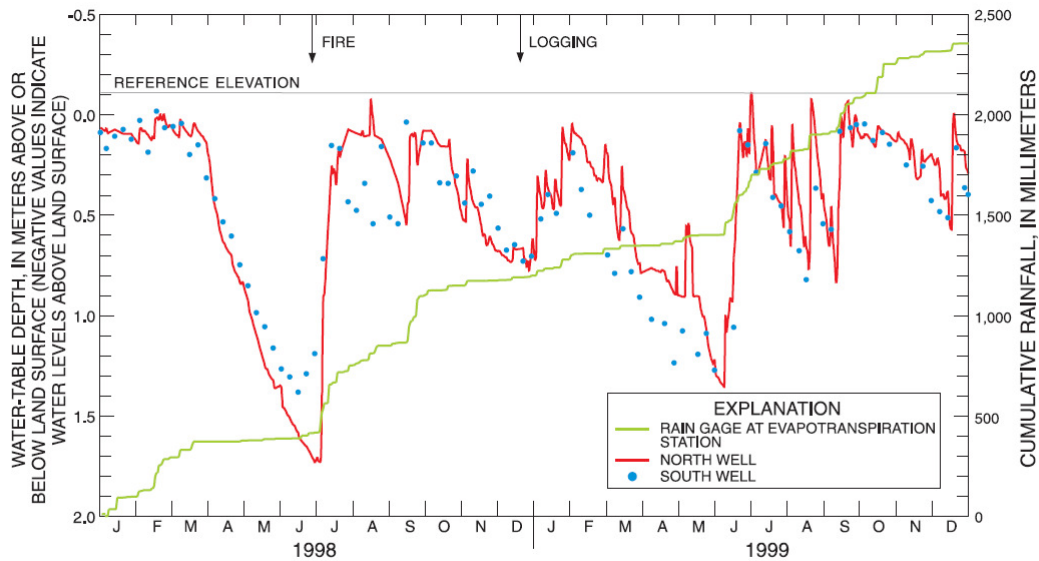


Figure 27. Water-table depth and cumulative rainfall.

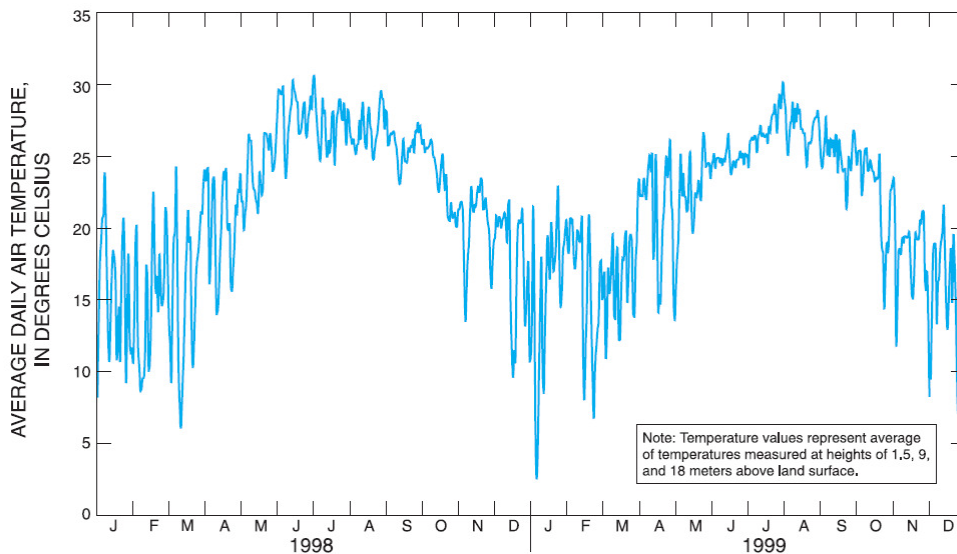


Figure 28. Average daily air temperature.

For example, a change in air temperature from 20 to 30 degrees Celsius will produce about a 14-percent increase in evapotranspiration, assuming the environment is otherwise unchanged. The relation of net radiation and evapotranspiration is one of direct proportionality. Net radiation displayed dramatic temporal variations, both day-to-day (as a result of variations in cloud cover) and seasonally (Figure 16), making this variable the most important determinant of evapotranspiration. This conclusion is supported by a sensitivity analysis (Table 4) based on perturbing each environmental variable of the evapotranspiration model by an amount equal to the observed standard deviation of the daily values of that variable. All unperturbed variables were assumed equal to mean values. This analysis indicated that variations in net radiation explained the greatest amount of the variation in evapotranspiration. Variations in *PAR*, closely correlated with net radiation, explained a large amount of the variation in evapotranspiration prior to logging, but explained little of the variation after logging. Evapotranspiration was moderately sensitive to variations in air temperature. Variations in water-table depth explained a moderate amount of the variation in evapotranspiration prior to the fire; however, evapotranspiration became more sensitive to variations in water-table depth after logging.

The model developed in this study is subject to several qualifications. The form of the equation developed for  $\alpha$  was empirical, rather than physics-based, and was simply designed to reproduce measured values of evapotranspiration as accurately as possible. The correlation between environmental variables complicates a unique determination of parameters.

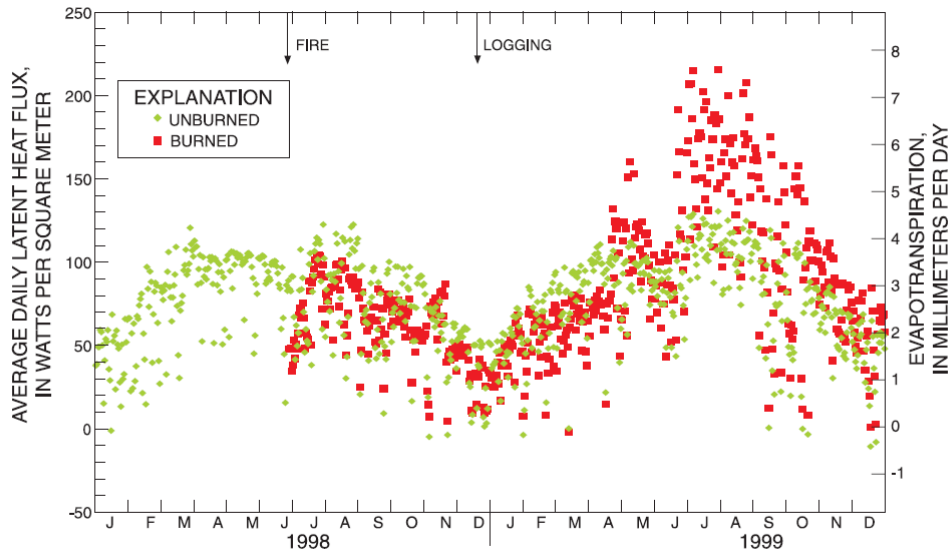


Figure 29. Average daily latent heat flux and evapotranspiration.

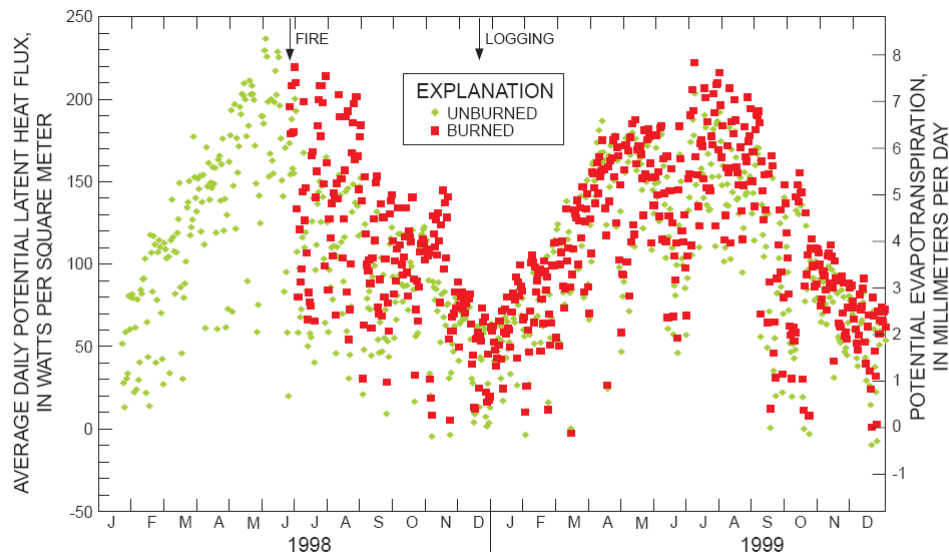


Figure 30. Average daily potential latent heat flux and potential evapotranspiration.

The model was developed for a limited range of environmental conditions, and therefore, extrapolation of the model to conditions not encountered in this study should be done with caution. The measured (upland) water-table depth at the evapotranspiration station, used as an independent variable in the model, explained some of the variation in evapotranspiration from the mixed upland/wetland watershed. However, water-table depth is not uniform within the watershed and, in particular, water-table depth in wetland areas usually is less than in upland areas. Therefore, caution should be used in applying the model to estimate evapotranspiration based on water-table depth measurements made at other locations in the watershed. For these reasons, the evapotranspiration model described in this report should be viewed as a general guide, rather than as a definitive description of the relation of evapotranspiration to environmental variables. The fact that the model successfully ( $r^2 = 0.90$ ) reproduced 449 daily measurements of site evapotranspiration over a wide range of seasonal and surface-cover values lends credence to the ability of the model to estimate evapotranspiration at the site.

### Water Budget

Construction of a water budget for the Tiger Bay watershed serves to provide a tool for watershed management and for assessing the integrity of the eddy correlation evapotranspiration measurements. The water budget for the watershed is given in equation /29/, where:  $P$  is precipitation, in millimeters per year;  $ET$  is evapotranspiration, in millimeters per year;  $R$  is runoff, in millimeters per

year;  $L$  is leakage to the Upper Floridan aquifer, in millimeters per year; and  $\Delta S$  is rate of change in storage, in millimeters per year.

$$P - (ET + R + L - \Delta S) = 0$$

/29/

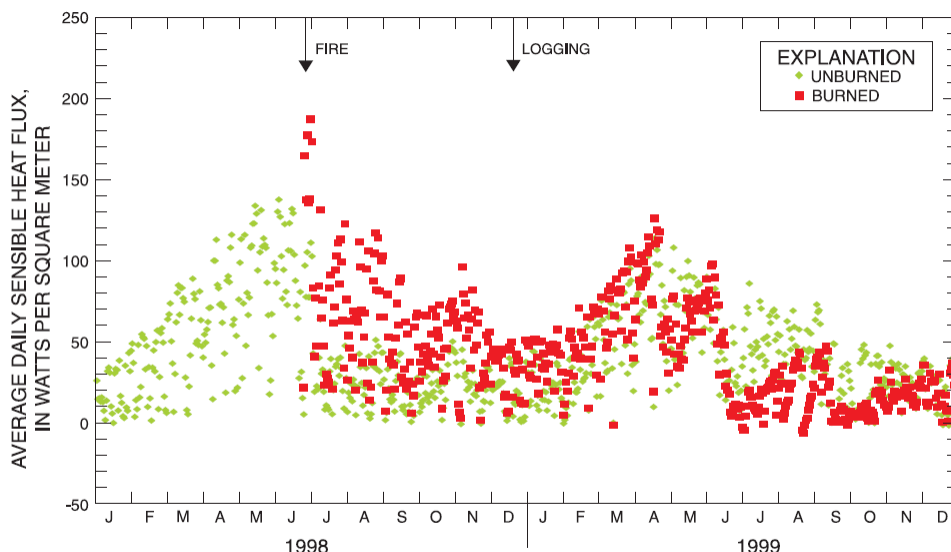


Figure 31. Average daily sensible heat flux.

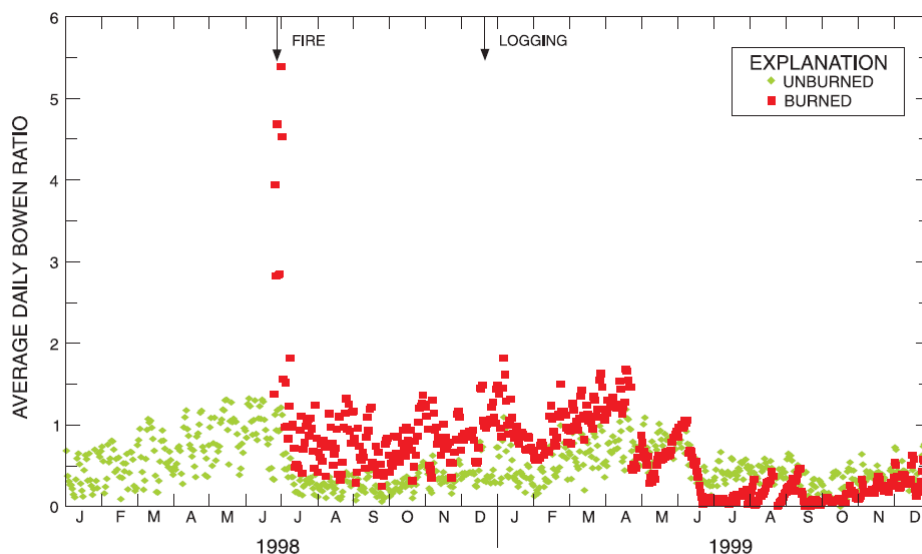


Figure 32. Average daily Bowen ratio.

A water budget for the Tiger Bay watershed during the 1998-1999 study period is shown in Table 5 and Figure 38. Precipitation (Figures 9 and 27), evapotranspiration (Figure 29), and runoff (Figure 39) were measured or obtained as described previously in this chapter. The estimated value of deep leakage to the Upper Floridan aquifer (112 mm/yr) during 1995 (Stan Williams, St. Johns River Water Management District, oral communication, 2000) also was assumed to be appropriate for the study period (1998-99). The rate of change in water- shed storage over the study period was not directly measured, but was estimated as the water-budget residual. The water budget (Tables 5 and 6; Figure 38) indicated that about 76 percent of watershed rainfall was lost as evapotranspiration during the 2-year study. The ratio of evapotranspiration to rainfall was remarkably stable from year-to-year (74 percent in 1998 and 77 percent in 1999). This stability occurred despite the very different environmental conditions prevailing during the study. Rainfall was a more consistent predictor of evapotranspiration than was potential evapotranspiration. The relative evapotranspiration varied rather greatly (67 percent in 1998 to 77 percent in 1999).

Runoff removed about 18 percent of the rainfall during the study period, but this percentage varied widely from year-to-year (29 percent in 1998 and 8 percent in 1999) as shown in Figure 39. The runoff for 1998 was over three times that of 1999,

despite the greater rainfall in 1999. This disparity can be explained largely by the antecedent water-table conditions for individual rain periods (Figure 27).

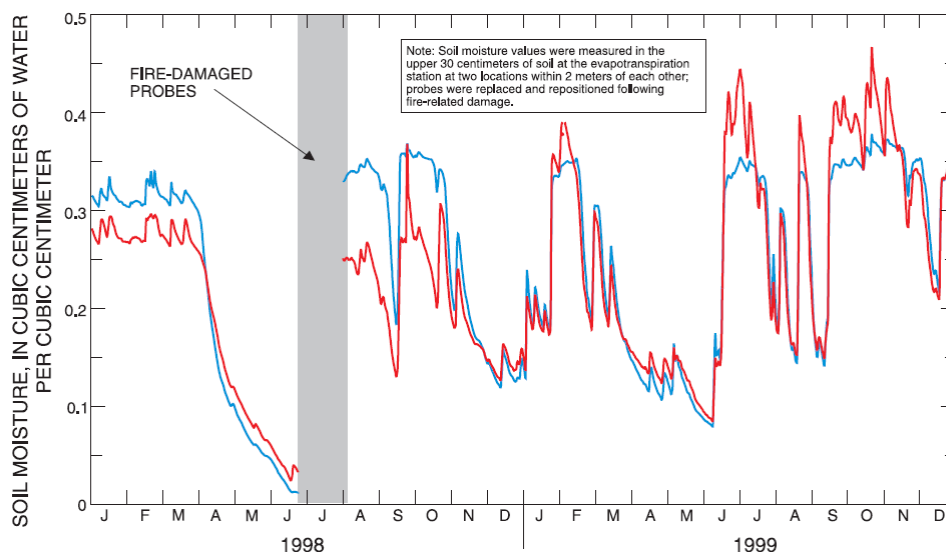


Figure 33. Shallow, volumetric soil moisture at evapotranspiration station.

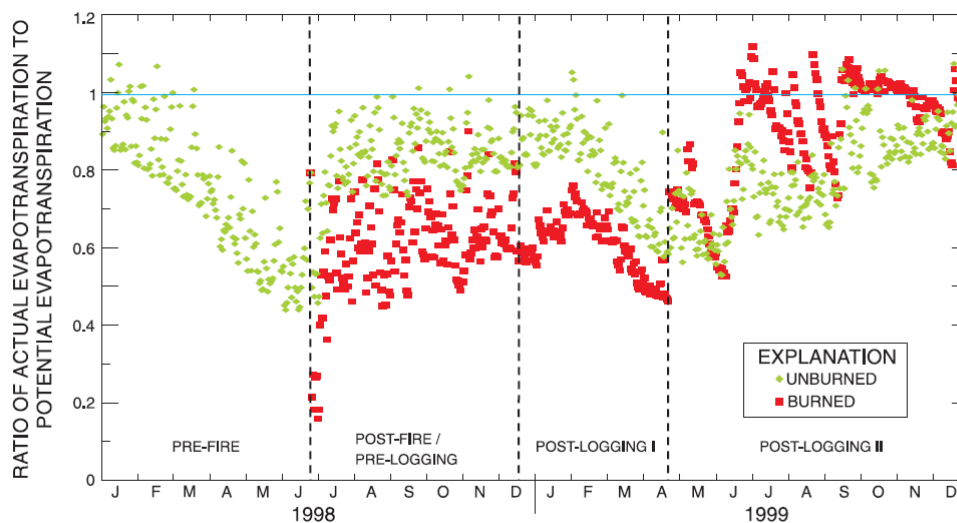


Figure 34. Temporal variability of daily values of relative evapotranspiration.

A relatively large fraction of precipitation in 1998 occurred when the water-table depth was shallow, leading to relatively high rejection of infiltration and subsequent runoff. Additionally, the temporal distribution of precipitation affects the amount of watershed runoff. Runoff is maximized following short, but intense, rainfall during which the infiltration capacity of the soil is exceeded. This phenomenon may explain the disparate runoff responses in July 1998 (very intense rainfall and significant runoff) and June-July 1999 (less intense rainfall and no runoff). This disparity was noted despite similar total amounts of precipitation with similar antecedent water-table conditions for each of the two periods. An alternative explanation may be that the soils became hydrophobic as a result of the fire, contributing to relatively more runoff in July 1998. Also, seasonal or fire-related variations in evapotranspiration can result in variations in the amount of precipitation available as runoff. Deep leakage was a relatively small fraction of the rainfall (about 9 percent), although this water-budget term could increase (at the expense of runoff and evapotranspiration) if continued development of the Upper Floridan aquifer in the area increases the hydraulic gradient between the surficial aquifer system and the underlying Upper Floridan aquifer.



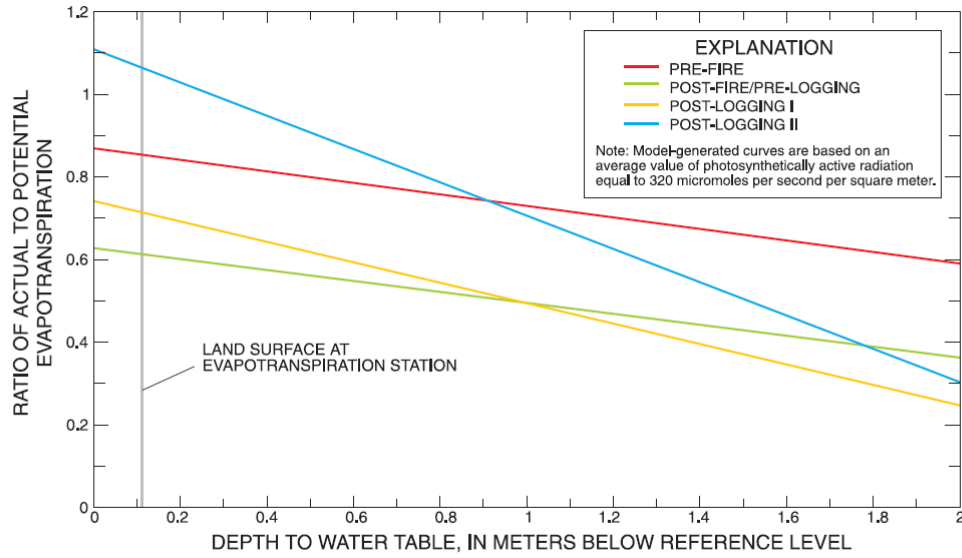


Figure 35. Relation between relative evapotranspiration and depth to water table.

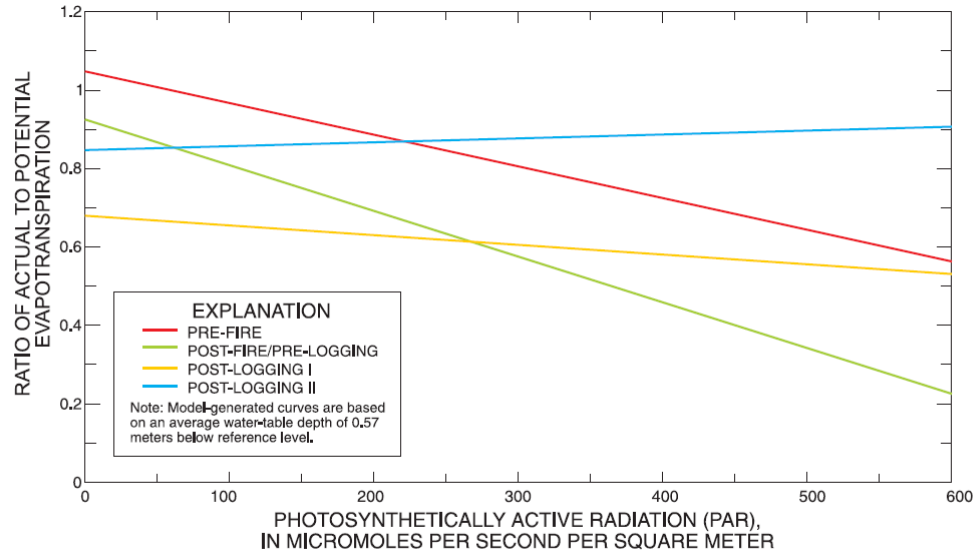


Figure 36. Relation between relative evapotranspiration and photosynthetically active radiation (PAR).

The consistency of the water-budget terms can be expressed by the absolute and relative water-budget closures as shown in equations /31/ and /32/, where:  $C_a$  is absolute water-budget closure, in millimeters per year;  $C_r$  is relative water budget closure, in percent; and  $P$ ,  $ET$ ,  $R$ ,  $L$ , and  $\Delta S$  are the same as defined in equation /29/.

$$C_a = P - (ET + R + L + \Delta S) \quad /30/$$

$$C_r = \frac{100 C_a}{P} \quad /31/$$

Watershed storage ( $\Delta S$ ) was an unmeasured quantity within the water budget. Therefore, evaluation of water-budget closure was facilitated by the judicious choice of a time period when negligible change in storage occurred within the watershed. Based on the measured water levels in the watershed (Figure 27), the time period from March 3, 1998, through September 23, 1999, was selected as an interval when change in watershed storage could be assumed to be zero.

**Table 4.** Sensitivity of evapotranspiration models to environmental variables

[Values are computed using each of four evapotranspiration models; mean and standard deviation values are representative of daily values during the 2-year period of record, with the exception of net radiation for which these values are representative of 1999. ET is evapotranspiration rate, in millimeters per day (mm/d);  $ET(\bar{x}) = 2.92, 2.19, 2.38$ , and  $3.49$  mm/d for the unburned, post-fire/pre-logging, post-logging I, and post-logging II models, respectively. Percent change (+) is defined as  $100(ET(\bar{x} + \sigma) - ET(\bar{x})) / ET(\bar{x})$ ; percent change (-) is defined as  $100(ET(\bar{x} - \sigma) - ET(\bar{x})) / ET(\bar{x})$ .  $R_n$  is net radiation, in watts per square meter ( $W/m^2$ ); PAR is photosynthetically active radiation, in micromoles per square meter per second ( $\mu moles/m^2/s$ );  $T_a$  is air temperature, in degrees Celsius;  $h_{wt}$  is water-table depth below reference point, in meters (m)]

| Environmental variable (x) | Mean ( $\bar{x}$ ) | Standard deviation ( $\sigma$ ) |
|----------------------------|--------------------|---------------------------------|
| $R_n$ (unburned)           | 118.3              | 50.0                            |
| $R_n$ (burned)             | 127.6              | 49.6                            |
| PAR                        | 320.0              | 118.3                           |
| $T_a$                      | 21.3               | 5.4                             |
| $h_{wt}$                   | .57                | .42                             |

| Unburned model             |                        |                        |                    |                    |
|----------------------------|------------------------|------------------------|--------------------|--------------------|
| Environmental variable (x) | $ET(\bar{x} + \sigma)$ | $ET(\bar{x} - \sigma)$ | Percent change (+) | Percent change (-) |
| $R_n$ (unburned)           | 4.15                   | 1.69                   | 42                 | -42                |
| PAR                        | 2.58                   | 3.27                   | -12                | 12                 |
| $T_a$                      | 3.16                   | 2.64                   | 8                  | -10                |
| $h_{wt}$                   | 2.71                   | 3.14                   | -7                 | 7                  |

| Post-fire/pre-logging model |                        |                        |                    |                    |
|-----------------------------|------------------------|------------------------|--------------------|--------------------|
| Environmental variable (x)  | $ET(\bar{x} + \sigma)$ | $ET(\bar{x} - \sigma)$ | Percent change (+) | Percent change (-) |
| $R_n$ (burned)              | 3.05                   | 1.33                   | 39                 | -39                |
| PAR                         | 1.64                   | 2.74                   | -25                | 25                 |
| $T_a$                       | 2.37                   | 1.98                   | 8                  | -10                |
| $h_{wt}$                    | 1.97                   | 2.41                   | -10                | 10                 |

| Post-logging I model       |                        |                        |                    |                    |
|----------------------------|------------------------|------------------------|--------------------|--------------------|
| Environmental variable (x) | $ET(\bar{x} + \sigma)$ | $ET(\bar{x} - \sigma)$ | Percent change (+) | Percent change (-) |
| $R_n$ (burned)             | 3.32                   | 1.45                   | 39                 | -39                |
| PAR                        | 2.26                   | 2.50                   | -5                 | 5                  |
| $T_a$                      | 2.58                   | 2.15                   | 8                  | -10                |
| $h_{wt}$                   | 1.97                   | 2.80                   | -17                | 17                 |

| Post-logging II model      |                          |                          |                    |                    |
|----------------------------|--------------------------|--------------------------|--------------------|--------------------|
| Environmental variable (x) | $ET(\bar{x}_i + \sigma)$ | $ET(\bar{x}_i - \sigma)$ | Percent change (+) | Percent change (-) |
| $R_n$ (burned)             | 4.86                     | 2.12                     | 39                 | -39                |
| PAR                        | 3.53                     | 3.44                     | 1                  | -1                 |
| $T_a$                      | 3.78                     | 3.15                     | 8                  | -10                |
| $h_{wt}$                   | 2.8                      | 4.16                     | -19                | 19                 |

The beginning and ending of this interval occurred at times when temporal changes in water level were relatively slight, implying that the water levels measured at the two monitor wells at the beginning and ending dates of the interval were probably representative of the watershed. The absolute value of the measured rate of change in water level was less than 6 mm/yr at both monitor wells over this 570-day interval.

Based on measured or estimated values of  $P$  (1,245 mm/yr),  $ET$  (1,048 mm/yr),  $R$  (132 mm/yr), and  $L$  (112 mm/yr), the absolute and relative water-budget closures were [- 47] mm/yr and 3.8 percent, respectively. The consistency of these independently measured water-budget terms provides support for, but not confirmation of, the reliability of the measured evapotranspiration. Compensating errors among water-budget terms or compensating errors within the temporal pattern of estimated evapotranspiration also could produce a consistent water budget.

Evapotranspiration was estimated during the present study using an energy-budget variant (equation /18/) of the eddy correlation method, rather than the standard eddy correlation method (equation /5/). The water-budget analysis provided an independent means to evaluate the relative accuracies of the two eddy correlation methods. The standard method produced turbulent flux estimates that were, on average, about 84.7 percent of those produced by the energy-budget variant. Applying this fraction to

**Table 5.** Water budget of Tiger Bay watershed

[ $P$  is the precipitation (average of north and south storage rain gages (fig. 1)), in millimeters per year (mm/yr);  $ET$  is the evapotranspiration (energy-budget variant of eddy correlation method), in mm/yr;  $R$  is the runoff from watershed at Tiger Bay canal, in mm/yr;  $L$  is the estimated (1995) leakage to the Upper Floridan aquifer, in mm/yr (Stan Williams, St. Johns River Water Management District, oral commun., 2000);  $\Delta S$  is the rate of change in watershed storage estimated as a water-budget residual, in mm/yr]

| Year    | P     | ET    | R   | L   | $\Delta S$ |
|---------|-------|-------|-----|-----|------------|
| 1998    | 1,233 | 916   | 357 | 112 | -152       |
| 1999    | 1,396 | 1,070 | 114 | 112 | 100        |
| 1998-99 | 1,315 | 993   | 236 | 112 | -26        |

**Table 6.** Potential evapotranspiration and relative rates of annual water-budget terms for Tiger Bay watershed

[ $PET$  is the potential evapotranspiration, in mm/yr;  $ET$  is the evapotranspiration (energy-budget variant of eddy correlation method), in millimeters per year (mm/yr);  $P$  is the precipitation (average of the north and south storage rain gages), in mm/yr;  $R$  is the runoff from watershed at Tiger Bay canal, in mm/yr; and  $L$  is the estimated (1995) leakage to the Upper Floridan aquifer, in mm/yr (Stan Williams, St. Johns River Water Management District, oral commun., 2000)]

| Year    | PET   | $\frac{ET}{PET}$ | $\frac{ET}{P}$ | $\frac{R}{P}$ | $\frac{L}{P}$ |
|---------|-------|------------------|----------------|---------------|---------------|
| 1998    | 1,356 | 0.67             | 0.74           | 0.29          | 0.09          |
| 1999    | 1,391 | .77              | .77            | .08           | .08           |
| 1998-99 | 1,374 | .72              | .76            | .18           | .09           |

**Table 7.** Average rate of change in water-table depth at monitor wells

[ $\Delta h_{North}$  is the rate of change in water-table depth at the evapotranspiration station, in millimeters per year (mm/yr);  $\Delta h_{South}$  is the rate of change in water-table depth at the south storage rain gage, in mm/yr;  $\Delta h_{avg}$  is the average rate of change in water-table depth ( $(\Delta h_{North} + \Delta h_{South}) / 2$ ), in mm/yr]

| Year    | $\Delta h_{North}$ | $\Delta h_{South}$ | $\Delta h_{avg}$ |
|---------|--------------------|--------------------|------------------|
| 1998    | -660               | -616               | -638             |
| 1999    | +432               | +308               | +370             |
| 1998-99 | -114               | -154               | -134             |



the evapotranspiration total for the water budget period from March 3, 1998, to September 23, 1999, the absolute and the relative budget closures corresponding to the standard eddy correlation method are 113 mm/yr and 9.1 percent, respectively. These closure values are greater than the values reported for the energy-budget variant, consistent with the assumption that the energy-budget variant was more accurate than the standard eddy correlation method.

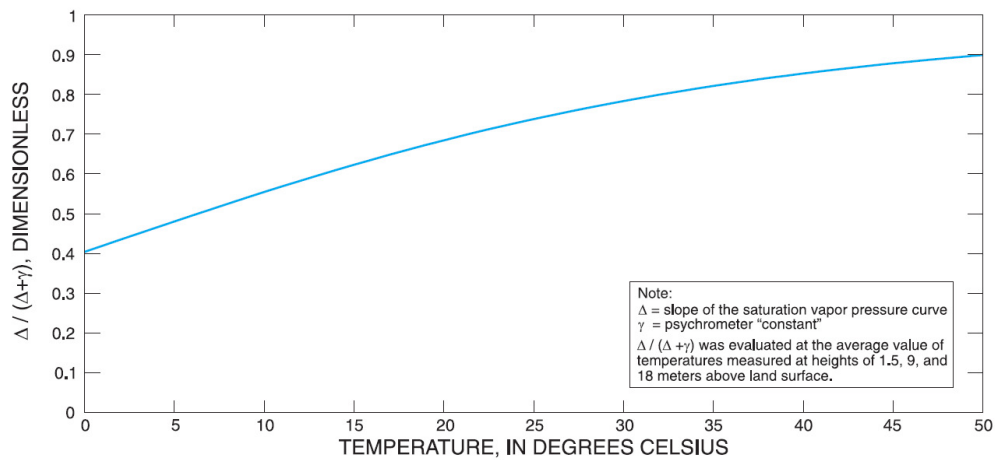


Figure 37. The Priestley-Taylor variable  $\Delta / (\Delta + \gamma)$  as a function of temperature.

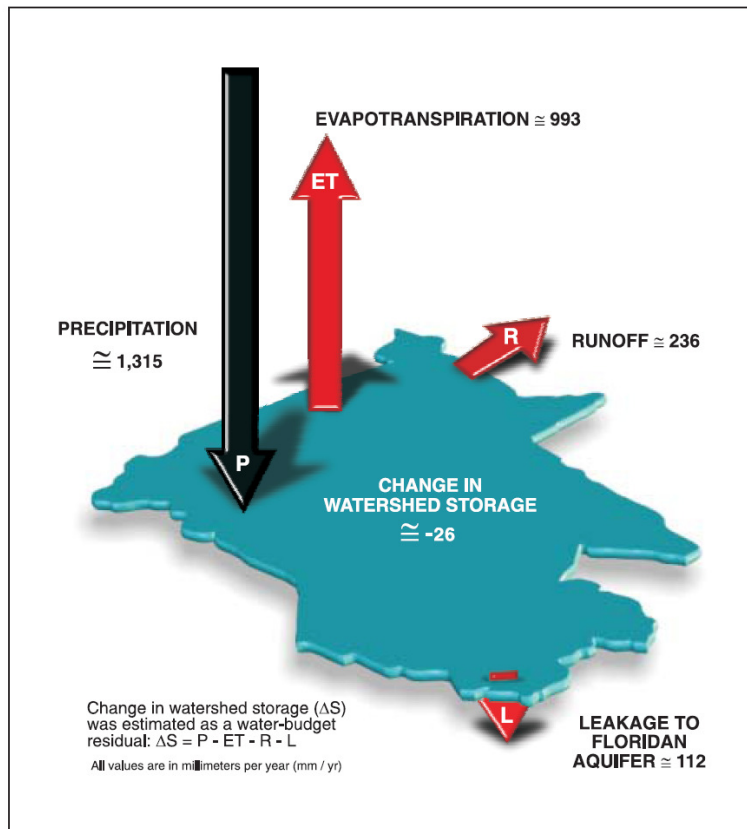
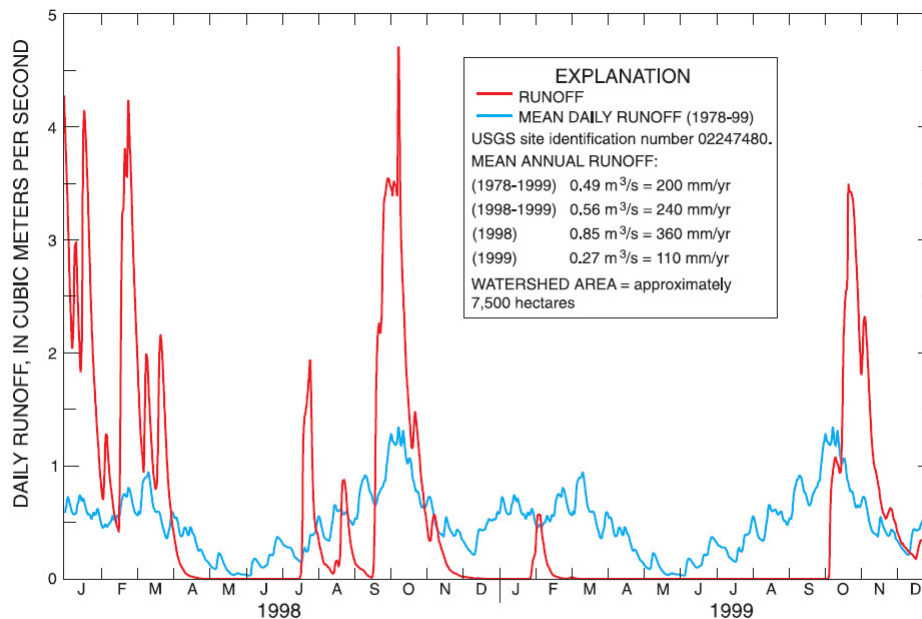


Figure 38. Water budget for Tiger Bay watershed during calendar years 1998 - 99.

**Table 8.** Comparison of estimates of specific yield based on evapotranspiration estimated with the energy-budget variant and with the standard eddy correlation method

[ $\Delta S$  is the rate of change in watershed storage computed as a residual of the water budget ( $\Delta S = P - (ET + R + L)$ ), in millimeters per year (mm/yr);  $P$  is the average watershed precipitation, in mm/yr; evapotranspiration ( $ET$ ) estimated by the standard variant of the eddy correlation method is approximated as 84.7 percent of that estimated (table 5) by the energy-budget variant of the eddy correlation method;  $R$  is the average watershed runoff, in mm/yr;  $L$  is the estimated (1995) leakage to the Upper Floridan aquifer, in mm/yr (Stan Williams, St. Johns River Water Management District, oral commun., 2000).  $S_y$  is specific yield ( $\Delta S / \Delta h_{avg}$ ), dimensionless; and  $\Delta h_{avg}$  is the estimated, average rate of change in water-table depth, in mm/yr (table 7)]

| Year    | Energy-budget variant |       | Standard method |       |
|---------|-----------------------|-------|-----------------|-------|
|         | $\Delta S$            | $S_y$ | $\Delta S$      | $S_y$ |
| 1998    | -152                  | 0.24  | -12             | 0.02  |
| 1999    | 100                   | .27   | 268             | .71   |
| 1998-99 | -26                   | .19   | 126             | -.94  |



**Figure 39.** Runoff from Tiger Bay watershed.

Additional support for the assumption that the energy-budget variant was preferable to the standard eddy correlation method could be discerned from a residual analysis that assumed that precipitation, leakage, runoff, and evapotranspiration were accurately measured and that a lack of water-budget closure can be explained solely by the residual-calculated storage term. The specific yield representative of the watershed was then computed as the rate of change of watershed storage divided by a representative rate of change in water level within the watershed. The specific yield, estimated in this manner, was evaluated for credibility as a means of identifying the preferred variant of the eddy correlation method. Specific yield is defined as the volume of water yielded per unit area per unit change in water level. Specific yield can range from near zero if the capillary fringe intersects land surface [16] to near unity for standing water. The specific yield of sandy soils (such as those in the uplands) ranges from 0.10 to 0.35 [18]. In this analysis, the representative rate of change in water-table depth for the watershed was assumed equal to the average rate of change in water-table depth at the two upland monitor wells (Table 7). As mentioned previously, upland and wetland water levels are expected to change at the same rate in the low relief environment of this watershed.

Results of the residual analysis, using evapotranspiration estimated by both approaches, are shown in table 8. The energy-budget variant of the eddy correlation method produced specific yield estimates (0.24 in 1998, 0.27 in 1999, and 0.19 in 1998-99) that were somewhat consistent between each of the three time periods and were within the range of possible values. The standard eddy correlation method produced estimates of specific yield that were inconsistent between each of the three time periods and were unreasonable (0.02 in 1998, 0.71 in 1999, and -0.94 in 1998-99). The residual analysis of water budgets further supports the assumption that the energy-budget variant of the eddy correlation method is more accurate than the standard method.

**Based on this research, followings can be concluded:** A 2-year (1998-99) study was conducted to estimate evapotranspiration [ET] from a forested watershed (Tiger Bay, Volusia County, Florida), which was subjected to natural fires, and to evaluate the causal relations between the environment and ET. The watershed characteristics are typical of many areas within the lower coastal plain of the southeastern United States - nearly flat, slowly draining land with a vegetative cover consisting primarily of pine flat wood uplands interspersed within cypress wetlands. Drought-induced fires in spring 1998 burned about 40 percent of the watershed and most of the burned area was logged in late-fall 1998. ET was measured using eddy correlation sensors placed on a tower 36.5-meter (m) high within an 18.3-m-high forest. About 27 percent of the 30-minute eddy correlation data were missing as a result of either inoperation of the sensors related to scaling of the hygrometer windows, collection of rainfall or dew on the sensors, or spurious turbulence created by the sensor mounting arm and the attached tower. These missing data generally occurred during periods (evening to early morning) when ET was relatively low. Linear relations between photosynthetically active radiation (PAR) and the fluxes of ET and sensible heat were used to estimate missing 30-minute values. Data were composited into daily values if the turbulent fluxes for more than 18 hours of a given day were directly measured, rather than being estimated with the PAR-based relation. Daily values for which more than 6 hours of data were missing were considered non-measured. This procedure resulted in 449 measurements of daily ET over the 2-year (730-day) period. An energy-budget variant of the standard eddy correlation method that accounts for the common underestimation of ET by the standard method was computed.

Following the fires, the daily measurements of ET were a composite of rates representative of burned and unburned areas of the watershed. The fraction of a given daily measurement derived from burned areas was estimated based on the diurnal pattern of wind direction and PAR for that day and on the transpiration station. The daily values of ET were used to calibrate a Priestley-Taylor model. The model was used to estimate ET for burned and unburned areas and to identify and quantify the environmental controls on ET.

The ET model successfully ( $r^2 = 0.90$ ) reproduced daily measurements of site ET over a wide range of environmental conditions, giving credence to the ability of the model to estimate ET at the site. Estimation of ET from the watershed was based on an area-weighted composite of estimated values for burned and unburned areas. Annual ET from the watershed was 916 and 1,070 millimeters (mm) for 1998 and 1999, respectively, and averaged 993 mm. These values are comparable to those reported by previous researchers. ET has been estimated to average about 990 millimeters per year (mm/yr) over Volusia County [37] and to average about 890 mm/yr in the Tiger Bay watershed [7]. Bidlake and others [1993, 3] estimated annual cypress ET (970 mm) to be only 8.5 percent less than that of pine flat woods (1,060 mm) based on studies conducted in Sarasota and Pasco Counties, Florida. Liu [1996, 24] estimated average, annual ET of both cypress and pine flatwoods to be 1,080 mm based on a study in Alachua County, Florida.

The extensive burning and logging that occurred during the study produced a landscape that was not typical of forested areas of Florida. The estimated ET from unburned areas can be considered more representative of typical forest cover. Annual ET from unburned areas was 937 and 999 mm for 1998 and 1999, respectively, and averaged 968 mm. ET from burned areas for the 10-month period after the fire (July 1998-April 1999) averaged about 17 percent less than that from unburned areas and, for the following 8-month period (May-December 1999), averaged about 31 percent higher than from unburned areas. During the 554-day period after the fire, the average ET for burned areas (1,043 mm/yr) averaged 8.6 percent higher than that for unburned areas (960 mm/yr). Both actual and potential ET showed strong seasonal patterns and day-to-day variability. Actual ET from the watershed averaged only 72 percent of potential ET. ET declined from near potential rates in the wet conditions of January 1998 to less than 50 percent of potential ET after the fire and at the peak of the drought in June 1998. After the drought ended in early July 1998 and water levels returned to near land surface, ET increased sharply. The ET rate, however, was only about 60 percent of the potential rate in the burned areas, as compared to about 90 percent of the potential rate in the unburned areas. This discrepancy can be explained as a result of fire damage to vegetation. Beginning in spring 1999, ET from burned areas increased sharply relative to unburned areas, sometimes exceeding unburned ET by almost 100 percent. Possible explanations for the dramatic increase in ET from burned areas are not clear at this time, but may include phenological changes associated with maturation or seasonality of plants that emerged after the fire or successional changes in composition of plant community within burned areas.

Within the framework of the Priestley-Taylor model developed during this study, variations in daily ET were the result of variations in: surface cover, net radiation, PAR, air temperature, and water-table depth. Potential ET depended solely on net radiation and air temperature and increased as each of these variables increased. The extent to which potential ET was approached was determined by the Priestley-Taylor coefficient  $\alpha$ . In this study, Priestley-Taylor  $\alpha$  was a linear function of water-table depth and PAR. Unique parameters within the  $\alpha$  function were estimated for each of four surface covers or time periods: unburned; burned, but unlogged; and both burned and logged (early post-logging and late post-logging). The ET model indicated that relative ET (the ratio of actual to potential ET) decreased as the depth to the water table increased. The rate of decline of relative ET with water-table depth was greater for the post-logging period than for the pre-logging period, perhaps indicative of the replacement of many deeply rooted trees by shallow-rooted understory vegetation following the fires. Shallow-rooted plants

would be less able to tap into deep soil moisture or the water table than deep-rooted trees. Relative ET decreased with increasing PAR, with the exception of the late post-logging period, which showed a slight increase in relative ET with increasing PAR.

A water budget for the watershed supported the validity of the estimates of ET produced with the energy-budget variant of the eddy correlation method. Independent estimates of average rates of rainfall (1,245 mm/yr), runoff (132 mm/yr), deep leakage (112 mm/yr), as well as ET (1,048 mm/yr) were compiled for a 570-day period over which the change in watershed storage was negligible. Water-budget closure was 47 mm/yr or 3.8 percent of rainfall, indicating good consistency between the estimated ET and estimates of the other terms of the water budget. Estimates of ET produced by the standard eddy correlation method were relatively inconsistent with the water budget (water-budget closure was 113 mm/yr or 9.1 percent of rainfall), indicating that the energy- budget variant is superior to the standard eddy correlation method. Specific yield was estimated based on estimated changes in watershed storage and water level. The change in watershed storage was estimated as a residual of the water budget. Specific yield values produced using ET estimated by the energy-bud- get variant of the eddy correlation method were reasonable and relatively consistent from year-to-year (0.19 to 0.27). However, specific yield values based on ET estimated by the standard eddy correlation method were unreasonable and inconsistent from year-to-year (-0.94 to 0.72). These results further support the premise that the energy - budget variant is more accurate than the standard eddy correlation method.

ET rates were about 74 and 77 percent of rainfall for 1998 and 1999, respectively, relatively constant considering the variability in surface cover and rainfall patterns between the 2 years. Potential ET was less consistent as an indicator of actual ET; ET was 67 and 77 percent of potential ET for years 1998 and 1999, respectively.

## SUMMARY

Daily values of evapotranspiration [ET] from a watershed in Volusia County, Florida, were estimated for a 2-year period (January 1998 through December 1999) by using an energy-budget variant of the eddy correlation method and a Priestley- Taylor model. The watershed consisted primarily of pine flat wood uplands interspersed within cypress wetlands. A drought-induced fire in spring 1998 burned about 40 percent of the watershed, most of which was subsequently logged. The model reproduced the 449 measured values of ET reasonably well ( $r^2 = 0.90$ ) over a wide range of seasonal and surface-cover conditions. Annual ET from the water- shed was estimated to be 916 millimeters (36 inches) for 1998 and 1,070 millimeters (42 inches) for 1999. ET declined from near potential rates in the wet conditions of January 1998 to less than 50 percent of potential ET after the fire and at the peak of the drought in June 1998. After the drought ended in early July 1998 and water levels returned to near land-surface, ET increased sharply; however, the ET rate was only about 60 percent of the potential rate in the burned areas, compared to about 90 percent of the potential rate in the unburned areas. This discrepancy can be explained as a result of fire damage to vegetation. Beginning in spring 1999, ET from burned areas increased sharply relative to unburned areas, sometimes exceeding unburned ET by almost 100 percent. Possible explanations for the dramatic increase in ET from burned areas could include phenological changes associated with maturation or seasonality of plants that emerged after the fire or successional changes in composition of plant community within burned areas.

Variations in daily ET are primarily the result of variations in surface cover, net radiation, photosynthetically active radiation (PAR), air temperature, and water-table depth. A water budget for the watershed supports the validity of the daily measurements and estimates of ET. A water budget constructed using independent estimates of average rates of rainfall, runoff, and deep leakage, as well as ET, was consistent within 3.8 percent. An alternative water budget constructed using ET estimated by the standard eddy correlation method was consistent only within 9.1 percent. This result indicates that the standard eddy correlation method is not as accurate as the energy-budget variant.

## KEYWORDS

Aerodynamic resistance  
Anemometer  
Aquifer  
Atmospheric pressure  
Big leaf assumption  
Bowen ratio  
Bowen ratio energy-budget variant (of eddy covariance method)  
Cypress  
Eddy covariance  
Eddy covariance method  
Energy-budget closure  
Energy-budget variant  
Evaporation  
Evaporative fraction  
Evapotranspiration  
evapotranspiration, Potential  
evapotranspiration, Reference  
Fire  
Florida

Florida Pinelands  
 Floridan aquifer  
 Hargreaves equation  
 Hygrometer  
 Inertial sublayer  
 Insect defoliation  
 Latent heat flux  
 National Centers for Environmental Prediction (NCEP)  
 Net radiation  
 North American Regional Reanalysis (NARR)  
 PAR  
 Penman equation  
 Penman-Monteith equation  
 Photosynthetically active radiation (PAR)  
 Pinelands  
 Precipitation  
 Priestley-Taylor equation  
 Residual energy-budget variant  
 Residual energy-budget variant (of eddy covariance method)  
 Roughness sublayer  
 Runoff  
 Sensible heat flux  
 Soil moisture  
 Source area  
 Source area (eddy covariance)  
 Time-domain reflectometry (TDR)  
 Turbulent fluxes  
 United States Geological Survey  
 Uplands  
 USGS  
 Vapor flux  
 Water balance  
 Wetlands

## BIBLIOGRAPHY

Refer to the bibliography for the literature cited.

## APPENDIX –I

### Derivation of Equation /24/ for $w_b$ in This Chapter.

The assumptions inherent in the weighting scheme used in equations /23/ through /25/ can be seen through derivation of equation /24/ for  $w_b$ . The latent heat flux measured by the eddy correlation sensors and derived from burned surface covers over a given day of 48 measurements is given by:

$$\lambda E_{bm} = \sum_i g_i \frac{1}{48} \sum_k \lambda E_{bk} \delta_i(\psi_k) \quad /A1/$$

Where:  $\lambda E_{bm}$  is daily latent heat flux derived from burned surface covers and measured by the flux sensors, in watts per square meter;  $g_i$  is fractional contribution of burned area within burn zone i to the measured latent heat flux when wind direction is from burn zone i;  $\lambda E_{bk}$  is latent heat flux from burned surface covers for time step k, in watts per square meter;  $\delta_i(\psi_k)$  is a binary function equal to 1 if  $\psi_k$  is within burn zone i and otherwise equals 0; and the index i is incremented from zone I to IV, and the index k is incremented from 1 to 48.

By definition, the expression in equation A1 is equal to the second term of the right side of equation /23/. Setting these two expressions equal and assuming that the high-resolution latent heat flux measurements for burned surfaces are directly proportional to photosynthetically active radiation (PAR), and therefore, that the daily resolution latent heat flux for burned surfaces are directly proportional to average daily PAR:

$$w_b(\overline{aPAR}) = \frac{1}{48} \sum_i g_i \sum_k (aPAR_k) \delta_i(\psi_k), \quad /A2/$$

Where:  $w_b$  is the fraction of the measured latent heat flux originating from burned areas, dimensionless; and overbars represent daily average values and the variable  $a$  is the constant of proportionality between latent heat flux and PAR. Solving equation /A2/, for  $w_b$ :

$$w_b = \frac{\frac{1}{48} \sum_i g_i \sum_k (aPAR_k) \delta_i(\psi_k)}{aPAR} \quad /A3/$$

$$w_b = \frac{\frac{1}{48} \sum_i g_i \sum_k (aPAR_k) \delta_i(\psi_k)}{a \frac{1}{n} \sum_k PAR_k} \quad /A4/$$

$$w_b = \frac{\sum_i g_i \sum_k PAR_k \delta_i(\psi_k)}{\sum_k PAR_k} \quad /A5/$$

Equation /A5/ is identical to equation /24/. The constant of proportionality  $a$  can change from day-to-day as environmental conditions (for example, water level, air temperature, and green leaf density) change and, in fact, as shown in equation /A5/,  $w_b$  is independent of the particular value of the constant. An equivalent expression, equal to  $[1 - w_b]$ , can be derived for the weight applied to daily latent heat flux from unburned surfaces. The constant of proportionality between unburned latent heat flux and PAR can be different than that between burned latent heat flux and PAR.

It is interesting to note that the use of measured high-resolution  $\lambda E$ , rather than PAR, as a means of adjusting the weights for the combination of changing source area composition and diurnal variations in evapotranspiration (ET) (equation /25/), produces excessive weighting towards zones with high-ET surface covers. This observation can be illustrated best by an example. Suppose, for a given day, the wind direction were from a lake (high ET) before solar noon and from a desert (near-zero ET) after solar noon. In this case, the appropriate weighting for each surface cover, within an equation of the form of equation /23/, would be 0.5 and the average, measured ET for the day would be about one-half that of the lake. However, weighting by the fraction of ET measured from each zone would lead to a weight of near 1.0 for the lake zone and 0.0 for the desert zone, leading to a model for lake evaporation that would produce underestimates of true lake evaporation.

## APPENDIX – II

Mathematical equations for Evapotranspiration from a Cypress and Pine forest Subjected to Natural Fires, Volusia County, Florida – USA, 1998-99 [U.S. GEOLOGICAL SURVEY Water-Resources Investigations Report 01-4245]

|                                                                                                                                        |      |                                                                                           |      |
|----------------------------------------------------------------------------------------------------------------------------------------|------|-------------------------------------------------------------------------------------------|------|
| $R_n - G - S = H + \lambda E$                                                                                                          | /1/  | Combining equations /17/ and /18/:                                                        | /19/ |
| $E = \overline{w\rho_v} = \overline{(\bar{w} + w')(\bar{\rho}_v + \rho'_v)}$                                                           | /2/  | $H_{cor} = R_n - G - S - \lambda E_{cor}$                                                 |      |
| $E = \overline{(\bar{w}\rho_v + \bar{w}\rho'_v + w'\rho_v + w'\rho'_v)}$                                                               | /3/  | $\lambda E = \frac{\Delta(R_n - G - S) + \frac{\rho C_p(e_s - e)}{r_h}}{\Delta + \gamma}$ | /20/ |
| $\overline{w'\rho'_v} = \text{covariance}(w, \rho_v)$                                                                                  | /4/  | $\lambda E = \frac{\Delta(R_n - S)}{\Delta + \gamma}$                                     | /21/ |
| $\lambda E = \lambda \left( \overline{w'\rho'_v} + \frac{\rho_v H}{\rho C_p(T_a + 273.15)} + \frac{FK_o H}{K_w(T_a + 273.15)} \right)$ | /5/  | $\lambda E = \alpha \frac{\Delta(R_n - S)}{\Delta + \gamma}$                              | /22/ |
| $H = \rho C_p \overline{w'T'_a}$                                                                                                       | /6/  | $\lambda E = (1 - w_b)\lambda E_u + w_b\lambda E_b$                                       | /23/ |
| $\overline{w'T'_a} = \overline{w'T'_s} - 0.51 \overline{(T_a + 273.15)} \overline{w'q'}$                                               | /7/  | $w_b = \frac{IV}{\sum_{i=1} g_i f_i}$                                                     | /24/ |
| $q \approx \frac{\rho_v R_d(T_a + 273.15)}{P_a}$                                                                                       | /8/  | $f_i = \frac{\sum_{k=1}^{48} PAR_k \delta_i(\psi_k)}{\sum_{k=1}^{48} PAR_k}$              | /25/ |
| $\overline{w'T'_a} = \frac{(T_a + 273.15)}{(T_s + 273.15)} (\overline{w'T'_s} - 0.51 R_d(T_a + 273.15)^2 \overline{w'\rho'_v} / P_a)$  | /9/  | $R_n = (1 - w_b)R_{nu} + w_b R_{nb}$                                                      | /26/ |
| $(\overline{w'c'})_r = \overline{w'c'} \cos \theta - \overline{u'c'} \sin \theta \cos \eta - \overline{v'c'} \sin \theta \sin \eta$    | /10/ | $NDVI = \frac{NIR - Vis}{NIR + Vis}$                                                      | /27/ |
| $\cos \theta = \frac{\sqrt{(u^2 + v^2)}}{\sqrt{(u^2 + v^2 + w^2)}}$                                                                    | /11/ | $\alpha_j = C_{1j} h_{wt} + C_{2j} PAR + C_{3j}$                                          | /28/ |
| $\sin \theta = \frac{w}{\sqrt{(u^2 + v^2 + w^2)}}$                                                                                     | /12/ | $P - (ET + R + L - \Delta S) = 0$                                                         | /29/ |
| $\cos \eta = \frac{u}{\sqrt{(u^2 + v^2)}}$                                                                                             | /13/ | $C_a = P - (ET + R + L + \Delta S)$                                                       | /30/ |

$$\sin \eta = \frac{v}{\sqrt{(u^2 + v^2)}} \quad /14/$$

$$C_r = \frac{100C_a}{P} \quad /31/$$

$$u^* = \sqrt{\sqrt{u'w'^2 + v'w'^2}} \quad /15/$$

$$R_n - G - S = H_{cor} + \lambda E_{cor} = \lambda E_{cor} (1 + B) \quad /16/$$

$$\text{Bowen ratio (B)} : \quad B = \frac{H}{\lambda E} \quad /17/$$

$$\text{Rearranging equation /16/:} \quad \lambda E_{cor} = \frac{R_n - G - S}{1 + B} \quad /18/$$

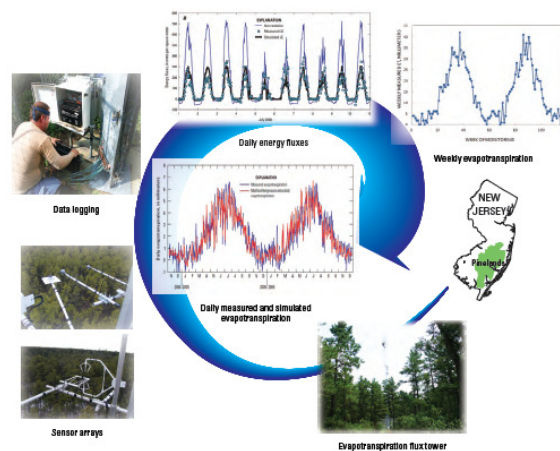
## Part II: Applications



## Chapter 9

### Evapotranspiration for Pinelands in New Jersey – U.S.A.<sup>1,2</sup>

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<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

## INTRODUCTION

Water budgets are fundamental to the understanding of hydrologic systems. If the various components of the water budget can be quantified, including inflows, outflows, and changes in stored water, then a more complete understanding and evaluation of a hydrologic system becomes possible. In the New Jersey Pinelands area (Figure 1), wetlands and aquatic habitats are supported by discharge from the Kirkwood - Cohansey aquifer system, and detailed water budgets of the area are needed in order to develop a quantitative understanding of aquifer-wetland-stream interactions at the watershed scale. As described by Rhodehamel [50], groundwater flow in the Pinelands is initiated as aquifer recharge, primarily in upland areas, and follows regional and local subsurface flow paths, with local flow paths terminating as aquifer discharge to wetlands and streams. Temporal variations in recharge affect aquifer interactions with wetlands and streams, as demonstrated by investigations in the New Jersey Pinelands by Modica [41] and Walker et al. [66]. Quantification of aquifer recharge on a seasonal basis, therefore, is needed to understand the dynamics of aquifer interactions with wetlands and streams.

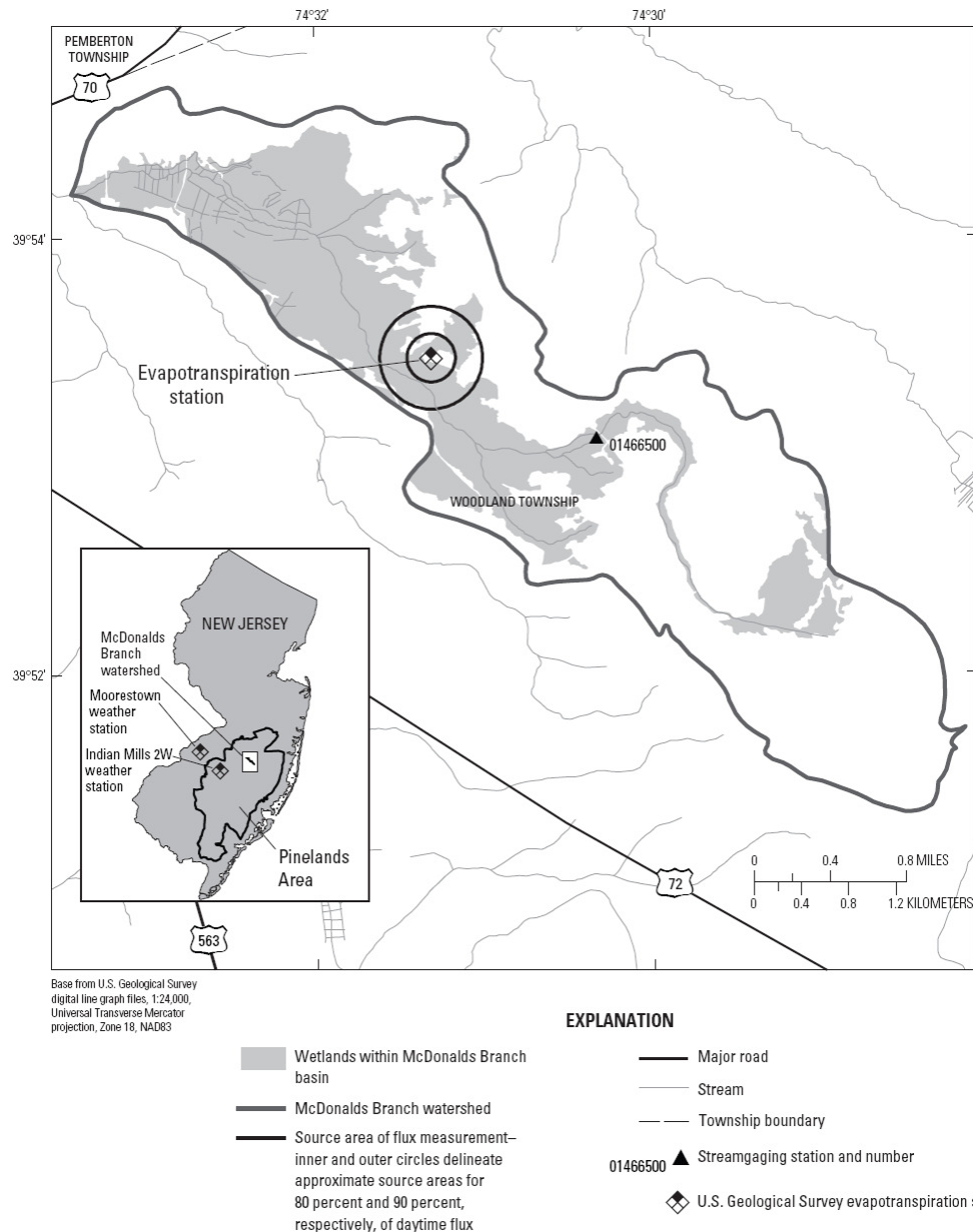
Evapotranspiration (ET) is an important component of the hydrologic budget in the Pinelands, and ET variability exerts considerable control over the amount of water available seasonally for aquifer recharge. On an average annual basis, ET from the Pinelands has been estimated to exceed recent Statewide public water use in New Jersey by more than a factor of two [based on data presented by Rhodehamel, [50]; and Hutson et al., [30]. In spite of its significance, the seasonal variability of ET and the relations between ET and other environmental factors in this ecologically important region are poorly quantified. Methods for direct measurement of ET have been developed [17, 60] and used in a number of settings [44, 58, 55]. Estimating seasonally variable ET rates for specific time periods at the watershed scale in the Pinelands requires site-specific data. The U.S. Geological Survey (USGS) conducted a study of ET in the Pinelands, in cooperation with the New Jersey Pinelands Commission, to quantify the temporal variability of ET and to examine relations between ET and environmental variables as part of the Kirkwood-Cohansey Project [48]. During November 10, 2004 through February 20, 2007, ET was monitored above a wetland forest canopy in the McDonalds Branch basin in Burlington County, New Jersey (See Figure 1). Meteorological and eddy-covariance sensors were deployed on a 24.5-meter (m) tower, and groundwater levels and soil moisture at the site were also monitored. Three models were evaluated for their utility in simulating ET, and a time series of weekly ET rates was developed for the measurement period.

This chapter presents the results of an ET study at the wet- land forest site in the Pinelands area. The chapter also includes: An explanation of the methods used, an analysis of the flux source area, measured ET rates, relation of these rates to environmental variables, a comparison of wetland ET with ET measured in upland areas in the Pinelands, and a comparison of ET measured during the 27-month monitoring period to ET simulated using selected models. The results of this study can be used in conjunction with information on other components of the water budget to develop an understanding of temporal variations in water exchange among different compartments of the Pinelands hydrologic system. Results can also be extended to formulate approaches for estimating ET in the Pinelands during other time periods using commonly measured environmental variables. Values for ET are shown in figures and are listed in tables. This chapter can serve as a guideline for similar studies in other locations worldwide.

### Current Status of Research

ET in the New Jersey Pinelands has been the subject of published investigations for more than 115 years. The following summary of previous investigations provides context for the present study. Determination of ET played a key role in early water-supply planning in the region.

Vermeule [64] approximated monthly and annual ET for southern New Jersey watersheds on the basis of calculations made using empirical relations between precipitation and runoff in other East Coast watersheds. These calculations were used to estimate the safe yield for Joseph Wharton's 1891 proposal to divert flow from more than 1,191 square kilometers of "the great pine belt" of southern New Jersey and deliver it to the cities of Camden and Philadelphia [13]. Wood [73] quantified interception (the amount of rain or snow stored on leaves and branches and eventually evaporated back to the atmosphere), an important component of the hydrologic cycle that contributes to evapotranspiration, in an oak-pine forest in the Pinelands. A number of studies were conducted during the 1950s and 1960s to understand the effects of forest management practices on water resources in the Pinelands as part of a research initiative referred to as the "Pine Region Hydrological Research Project" [8]; related research continued into the 1970s. Lull and Axley [39] studied ET in different upland vegetative communities in the Pinelands by measuring soil moisture changes, but significant differences were not found among the communities. Barksdale [6] concluded that ET in the lower Delaware River Basin accounted for about 50 percent of precipitation. Rhodehamel [50] found this 50-percent value applicable to the Pinelands area and estimated the mean annual ET rate in the Pinelands on the basis of the long-term difference between precipitation and runoff to be 572 millimeters per year (mm/yr), or about 50 percent of precipitation. Rhodehamel [51] found reasonable agreement between this ET rate and estimated ET rates from other investigations in the Pinelands and vicinity. Summer ET rates in hardwood-dominated and cedar-dominated wetlands in the Pinelands were estimated from water-table fluctuations, and no differences in the ET rates of these communities were detected [2, 9]. ET rates in lowland shrub communities were found to be lower than those of lowland tree communities [9]. ET rates were shown to be greater in lowland (wetland) areas of the Pinelands, where water is more available to plants, than in upland areas [4]. Ballard [3] examined these differences in an energy flux context and concluded that in wetland tree areas, the net summer loss of groundwater discharge through ET was 250 millimeters (mm).



**Figure 1.** Location of McDonalds Branch basin, selected weather stations, and evapotranspiration station, Pinelands area, New Jersey.

ET has been estimated as part of water-supply and availability studies in the New Jersey Coastal Plain. Mean ET rates in the major drainage areas of the New Jersey Coastal Plain were estimated by Vowinkel and Foster [65] as the long-term difference between mean precipitation and mean runoff. Estimates of ET (presented as “water loss”) for basins partly within the Pinelands ranged from 414 to 653 mm/yr [65]. More detailed examinations of water budgets that include ET in selected drainage areas that are within the New Jersey Coastal Plain and at least partly within the Pinelands are presented in a series of reports by Watt and Johnson [67], Johnson and Barringer [32], Watt and others [68], Johnson and Watt [31], Watt and others [69], and Gordon [25]. Although the methods used to estimate ET in these studies vary somewhat, the ET estimates were all based on the concept of water-budget closure and are, therefore, consistent with estimates of other water-budget components. The ET estimates from the previously mentioned series of reports range from 563 to 658 mm/yr. As part of the Kirkwood - Cohansey Project, the USGS assessed hydrologic conditions in three basins in the Pinelands during 2004–2006, including the McDonalds Branch basin where the present ET study site is located [66]. Results of the hydrologic assessment of the McDonalds Branch basin include estimates of water-budget components that can be used to evaluate the veracity of ET measurements presented in

this report. Other recent investigations have examined the physiological responses of a variety of Pinelands shrub and tree species to hydrologic stress, fire, and insect defoliation.

As part of their research on carbon and fire dynamics in the Pinelands, Clark and others [14,16] measured ET flux using an eddy covariance method at an oak - dominated upland site and two pine-dominated upland sites in the Pinelands. They observed that ET at the oak-dominated upland site was slightly greater in summer and lower in winter than ET at the pitch pine-dominated upland site and that ET averaged 51 to 62 percent of annual precipitation at the sites when they were undisturbed. Additional flux monitoring demonstrated the effects of fire and insect defoliation on ET and water-use efficiency at the three sites; annual ET at one of the defoliated sites was as low as 419 mm/year, 37 percent of incident precipitation [16]. When all years were considered, maximum seasonal leaf area index at these sites explained 82 and 80 percent of the variation in daily ET during the summer at the oak- and pine - dominated sites, respectively. Results of the study by Clark and others [16] indicate that gypsy moth defoliation disturbance in 2007 may have resulted in a temporary increase in aquifer recharge of approximately 7 percent in upland forests throughout the Pinelands. Schäfer [52] examined changes in stomatal conductance in response to drought, defoliation, and mortality in an upland oak/pine forest in the Pinelands. Drought caused reductions in canopy-level conductance, and corresponding reductions in ET, with the magnitude of the effect varying by species.

## METHODS AND MATERIAL: MEASUREMENT AND SIMULATION OF EVAPOTRANSPIRATION

Evapotranspiration (ET) was measured at a site within McDonalds Branch basin (Figure 1) using the eddy-covariance method [17, 5, 60]. The site chosen for the ET station is within a pitch-pine lowland stand. Canopy vegetation at the site is dominated by *Pinus rigida* (pitch pine) that reaches a maximum height of about 15 m. Understory vegetation is dominated by *Gaylussacia frondosa* (dangleberry), *Kalmia angustifolia* (sheep laurel), *Eubotrys racemosa* (fetterbush), and *Xerophyllum asphdeloides* (turkeybeard). Vegetation types in nearby areas of cedar swamp are dominated by *Chamaecyparis thyroides* (Atlantic white cedar) and *Sphagnum spp* (sphagnum moss); nearby areas of hardwood swamp are dominated by *Acer rubrum* (red maple) and *Nyssa silvatica* (blackgum). Depth to the water table at the site fluctuates between about 0.5 to 1.5 meters (m) below land surface although parts of the surrounding area exhibit standing water during wet periods. The site of the ET station is adjacent to one of the vegetation plots used by Laidig and others [35,36] to develop models for predicting the distribution of wetland vegetation on the basis of hydrologic conditions. Eddy-covariance instrumentation was deployed on a 24.5 m tall Rohn 45G communications - type tower at the site (Figure 2), and 30-minute data were collected for an 833-day period from November 10, 2004, to February 20, 2007. Other meteorological and hydrologic instrumentation also was deployed on or around the tower to collect data for ET models and to provide ancillary data for the eddy-covariance analysis. The instrumentation used in the study is described in Table 1. Measured values of ET were used to calibrate ET models or for comparison with model results.

### Measurement of Evapotranspiration

Evapotranspiration can be measured above a forest canopy by using a variety of methods. The method selected for this study is the eddy-covariance method. List of symbols in this chapter are given at the end of this chapter. Appendix - I indicates all equations that are used in this chapter.

#### The Eddy Covariance Method

The eddy-covariance method [17, 60] was used to measure two components of the energy budget of the plant canopy: latent and sensible heat fluxes. Latent heat flux ( $\lambda E$ ) is the energy removed from the canopy in the liquid-to-vapor phase change of water and is the product of the heat of vaporization of water ( $l$ ) and the ET rate ( $E$ ). Sensible heat flux ( $H$ ) is the heat energy removed from/added to the canopy as a result of convective transport along a temperature gradient between the canopy and the air. Both latent and sensible heat fluxes are transported by turbulent eddies in the air that are generated by a combination of frictional and convective forces. The energy available to generate turbulent fluxes of vapor and heat is equal to the net radiation ( $R_n$ ) less the sum of the heat flux into the soil surface ( $G$ ) and the change in storage ( $S$ ) of energy in the biomass, air, and any standing water.

The energy involved in fixation of carbon dioxide is usually negligible[10]. Net radiation is the difference between incoming radiation (short- wave solar radiation and long wave atmospheric radiation) and outgoing radiation (reflected shortwave and surface-emitted long wave radiation). Energy is transported to and from the base of the canopy by conduction through the soil. Assuming that net horizontal advection of energy is negligible, the energy-budget is described in equation /1/, for a control volume extending from land surface to a height  $z_s$  at which the turbulent fluxes are measured. <sub>s</sub>

$$R_n - G - S = H + \lambda E \quad /1/$$

$$E = \overline{w\rho_v} = \overline{(\bar{w} + w')(\bar{\rho}_v + \rho_v')} \quad /2/$$

$$E = \overline{\bar{w}\rho_v} + \overline{\bar{w}\rho_v'} + \overline{w'\rho_v} + \overline{w'\rho_v'} \quad /3/$$

$$\overline{w'\rho_v'} = \text{covariance}(w, \rho_v) \quad /4/$$

In equation /1/: The left-hand side of equation /1/ represents the available energy and the right-hand side represents the turbulent fluxes;  $R_n$  is net radiation to/from plant canopy, in watts per square meter;  $G$  is soil heat flux at land surface, in watts per square meter;  $S$  is change in storage of energy in the biomass, air, and in any standing water, in watts per square meter;  $H$  is sensible heat flux at height  $z_s$  above land surface, in watts per square meter;  $\lambda E$  is latent heat flux at height  $z_s$  above land surface,



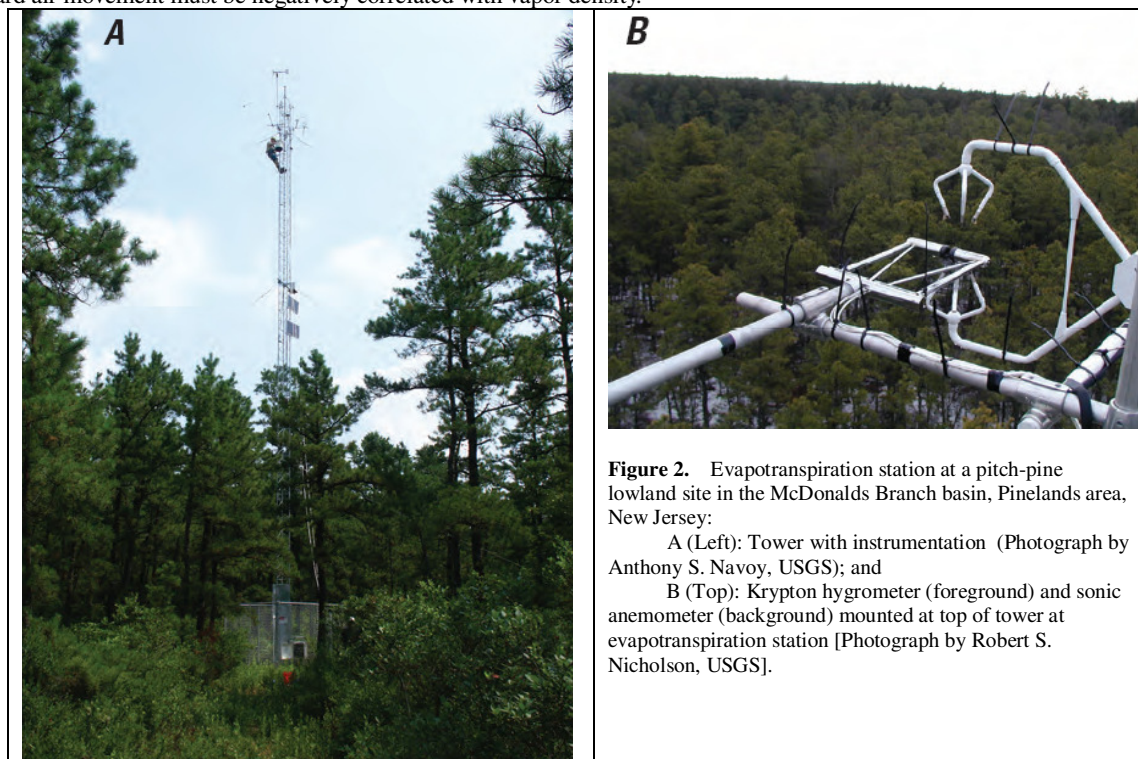
in watts per square meter; and the sign convention is such that  $R_n$  and  $G$  are positive downwards and  $H$  and  $\lambda E$  are positive upwards.

The eddy-covariance method is a conceptually simple, one-dimensional approach for measuring the turbulent fluxes of vapor and heat above a surface. For the case of vapor transport above a flat, level landscape, the time-averaged product of measured values of vertical wind speed ( $w$ ) and vapor density ( $\rho_v$ ) is the estimated vapor flux (ET rate) during the averaging period, assuming that the net lateral advection of vapor is negligible. Because of the insufficient accuracy of instrumentation available for measurement of actual values of wind speed and vapor density, this procedure generally is performed by monitoring the fluctuations of wind speed and vapor density about their means, rather than monitoring their actual values. This formulation is represented in equations /2/ to /4/ above and the variables in these equations are defined below:

- $E$  Evapotranspiration rate, in grams per square meter per second;
- $w$  Vertical wind speed, in meters per second;
- $\rho_v$  Vapor density, in grams per cubic meter; and

Over-bars and primes indicate means over the averaging period and deviations from means, respectively.

The first term of equation /3/ is approximately zero because mass-balance considerations dictate that mean vertical wind speed perpendicular to the surface is zero; this conclusion is based on an assumption of constant air density (correction for air-density fluctuations are noted later in this report). The second and third terms are zero based on the definition that the mean fluctuation of a variable is zero. Therefore, it is apparent from equation /4/ that vertical wind speed and vapor density have to be correlated for a non-zero vapor flux to exist. The turbulent eddies that transport water vapor (and sensible heat) produce fluctuations in both the direction and magnitude of vertical wind speed. The ascending eddies must on average be moister than the descending eddies for ET to occur; that is, upward air movement has to be positively correlated with vapor density, and downward air movement must be negatively correlated with vapor density.



**Figure 2.** Evapotranspiration station at a pitch-pine lowland site in the McDonalds Branch basin, Pinelands area, New Jersey:

A (Left): Tower with instrumentation (Photograph by Anthony S. Navoy, USGS); and

B (Top): Krypton hygrometer (foreground) and sonic anemometer (background) mounted at top of tower at evapotranspiration station [Photograph by Robert S. Nicholson, USGS].

### Source Area of Measurements

The source area for a turbulent flux measurement is defined as the area (upwind of the measurement location) contributing to the measurement. The source area can consist of a single vegetative cover if that cover is adequately extensive.

This condition is met if the given cover extends sufficiently far upwind such that the atmospheric boundary layer has equilibrated with the cover from ground surface to at least the height of the instrumentation. If this condition is not met, the flux measurement is a composite of fluxes from two or more covers within the source area.

Schuepp and others [54] provide an estimate of the source area for turbulent flux measurements and the relative contributions within the source area on the basis of an analytical solution of a one-dimensional (upwind) diffusion equation for a uniform surface cover. In this approach, source area varies with instrument height ( $z_c$ ), zero displacement height ( $d$ ), roughness length for momentum ( $z_m$ ), and atmospheric stability. The instrument height for the turbulent flux measurements in this study was 22.1 m. Campbell and Norman [12] proposed empirical relations for zero displacement height ( $d \sim 0.65 \cdot h$ ) and roughness length for momentum ( $z_m \sim 0.10 \cdot h$ ), where  $h$  is the canopy height. A uniform canopy height of 15 m was assumed in this analysis. The source area estimates were made assuming mildly unstable conditions typical of daytime conditions when heat and vapor fluxes

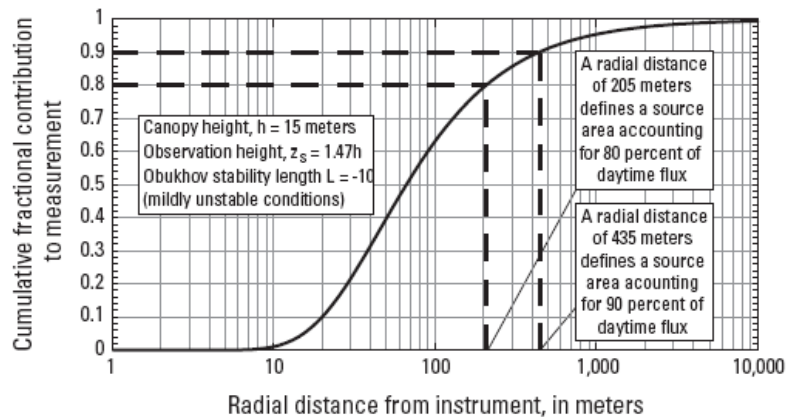
are highest; the Obukhov stability length [11] was set equal to [-10 m]. About 80 percent and 90 percent of the source area for the daytime turbulent flux measurements were estimated to be within upwind distances of about 205 and 435 m, respectively, as shown in Figures 1 and 3.

**Table 1.** Description of the instrumentation in this chapter.

CSI, Campbell Scientific, Inc.;  
HS, Hydrological Services Pty Ltd;  
REBS, Radiation and Energy Balance Systems, Inc.;  
RMY, R.M. Young, Inc.;

**NOTE:** Number of instruments listed in parentheses; psi, pounds per square inch; negative height is depth below land surface.

| Characteristics                   | Instrumentation                                                                                                           | Height above land surface (meters) |
|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------|------------------------------------|
| Evapotranspiration                | CSI eddy-covariance system including Model CSAT3 three-dimensional sonic anemometer and Model KH20 krypton hygrometer (1) | 22.1                               |
| Air temperature/relative humidity | CSI Model HMP45 temperature and relative humidity probe (1)                                                               | 22.3                               |
| Solar radiation                   | LI-COR, Inc., Model LI200 pyranometer (1)                                                                                 | 22                                 |
| Net radiation                     | REBS Model Q-7.1 net radiometers (2)                                                                                      | 22                                 |
| Soil moisture                     | CSI Model CS615 Water content reflectometer (1)                                                                           | 0 – [-0.3]                         |
| Precipitation                     | HS Model TB3 tipping bucket rain gage (1)                                                                                 | 14.2                               |
| Water level in well               | In-Situ Model MiniTROLL 5 pounds per square inch pressure sensor and data logger unit (1)                                 | [-2]                               |
| Wind speed and direction          | RMY Model 05305VM Wind Monitor (1)                                                                                        | 24.7                               |
| Data logging                      | CSI Model 10X data loggers (2);<br>12-volt 100 amp-hour deep-cycle batteries (2);<br>50 watt solar panels (2)             | 0–1<br>0–1 and<br>10–13            |



**Figure 3.** Radial extent of source area for daytime turbulent flux measurements: Produced using the method of Schuepp and others [54].

The source area during the generally more stable nighttime conditions could extend considerably further, but turbulent fluxes are relatively small in the absence of sunlight. The source area is forested throughout, but includes wetlands with pitch pine and cedar swamps and uplands covered by oak and pine (Figure 1). Because the measured turbulent fluxes are representative of upwind land covers, the vegetative composition of the source area will change with varying wind direction. For example, wind directions ranging clockwise from southeast to west would provide flux measurements almost exclusively representative of forested wetland; other wind directions provide flux measurements representative of varying mixtures of wetland and upland forests. In this chapter, discrepancies between measured ET and simulated ET from models that are invariant with wind direction are examined as a function of wind direction. This comparison shows the degree to which differences in ET between the two forest communities can be discerned with the available measurements.

## Instrumentation

Instrumentation capable of high-frequency resolution is used in applications of the eddy-covariance method because of the relatively high frequency of the turbulent eddies that transport water vapor. Instrumentation included a three-axis sonic anemometer and a krypton hygrometer to measure variations in wind speed and vapor density, respectively (Figure 2; Table 2).

The sonic anemometer relies on three pairs of sonic transducers to detect wind-induced changes in the transit time of emitted sound waves and to infer fluctuations in wind speed in three orthogonal directions. The measurement path length between transducer pairs is 10.00 cm (vertical) and 5.8 cm (horizontal); and the transducer path angle from the horizontal is 60 degrees. In contrast to some sonic anemometers used previously [58], the transducers of this improved anemometer are not permanently destroyed by exposure to moisture and thus are suitable for long-term deployment. Operation of the anemometer used in this study ceases when moisture on the transducer disrupts the sonic signal but recommences upon drying of the transducers.

The hygrometer relies on the attenuation of ultraviolet radiation, emitted from a source tube, by water vapor in the air along the 1-cm path to the detector tube. The instrument path line was laterally displaced 10 cm from the midpoint of the sonic-transducer path lines (Figure 2B). Hygrometer volt- age output is proportional to the attenuated radiation signal, and fluctuations in this signal can be related to fluctuations in vapor density by Beer's Law [71].

Similar to the anemometer, the hygrometer ceases data collection when moisture obscures the windows on the source or detector tubes. Also, the tube windows become "scaled" with exposure to the atmosphere, resulting in a loss of signal strength. The hygrometer is designed such that vapor density fluctuations are accurately measured in spite of variable signal strength; however, if signal strength declines to near-zero values, the fluctuations cannot be discerned. Periodic cleaning of the sensor windows (performed monthly in this study) with a cotton swab and distilled water restores signal strength. Eddy-covariance instrument-sampling frequency was 8 Hertz (Hz) with 30-minute averaging periods. The eddy-covariance instrumentation was placed about 7.1 m above the tree canopy. The 8-Hz data were processed into 30-minute composites and stored in a data logger near ground level.

Flux measurements are made in the constant-flux inertial sub-layer, in which lateral variations in vertical flux are negligible, to be representative of the surface cover. Measurements made in the underlying roughness sub-layer can reflect individual roughness elements (for example, individual trees or gaps between trees) rather than the composite surface cover [43]. Garratt [23] defines the lower boundary of the inertial sublayer to occur where the difference of the instrument height ( $z_c$ ) and the zero displacement height ( $d$ ) is much greater than the roughness length for momentum ( $z_m$ ). Employing the empirical relations of Campbell and Norman [12] for zero displacement height and roughness length for momentum, and assuming that "much greater than" implies greater by a factor of eight, leads to an instrument height requirement of  $z_c$  greater than  $[1.45^*h]$ . A factor of about 1.47 was used in this chapter.

### Calculation of Turbulent Fluxes

Latent heat flux was estimated using equation /5/, which is a modified form of equation /4/.

Latent heat flux: /5/

$$\lambda E = \lambda \left( (1 + \mu\sigma) \overline{(w' \rho'_v)} + \frac{\rho_v H}{\rho C_p (T_a + 273.15)} \right) + \frac{FK_o H}{K_w (T_a + 273.15)}$$

Sensible heat: /6/

$$H = \rho C_p \overline{w' T'_a}$$

$$\overline{w' T'_a} = \overline{w' T'_s} - 0.51 \overline{(T_a + 273.15)} \overline{w' q'} \quad /7/$$

The variables in equation /5/ are defined as:  $\lambda E$  is latent heat flux, in watts per square meter;  $\lambda$  is latent heat of vaporization of water, estimated as a function of temperature [57], in joules per gram;  $\mu$  is ratio of molecular weight of air to molecular weight of water;  $\sigma$  is ratio of vapor density ( $\rho_v$ ) to air density ( $\rho$ );  $\rho$  is air density, estimated as a function of air temperature, total air pressure, and vapor pressure [43], in grams per cubic meter;  $H$  is sensible heat flux, in watts per square meter;  $C_p$  is specific heat capacity of air, estimated as a function of temperature and relative humidity [57], in joules per gram per degree Celsius;  $T_a$  is air temperature, in degrees Celsius;  $F$  is a factor that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen, equal to 0.229 gram- degree Celsius per joule;  $K_o$  is extinction coefficient of hygrometer for oxygen, estimated as  $[-0.0045]$  cubic meters per gram per centimeter [61];  $K_w$  is extinction coefficient of hygrometer for water, equal to the manufacturer-calibrated value, in cubic meters per gram per centimeter; and overbars and primes indicate means over the averaging period and deviations from the means, respectively.

The  $(1 + \mu\sigma)$  multiplier and the second term of the right-hand side of equation /5/ account for temperature-induced fluctuations in air density [70], and the third term accounts for the sensitivity of the hygrometer to oxygen [60]. Similar to vapor transport, sensible heat can be estimated by using equation /6/. The sonic anemometer is capable of measuring "sonic" temperature on the basis of the dependence of the speed of sound on this variable [33, 34]. Schotanus and others [53] related the sonic sensible heat, based on measurement of sonic temperature fluctuations, to the true sensible heat given in equation /6/. Those researchers included a correction for the effect of wind blowing normal to the sonic acoustic path that has been

incorporated directly into the anemometer measurement by the manufacturer (E. Swiatek, Campbell Scientific, Inc., written communication, 1998), leading to a simplified form of the Schotanus and others [53] formulation given in equation /7/. The variables in equation /7/ are defined as:  $T_s$  is a sonic temperature, in degrees Celsius; and  $q$  is a specific humidity, in grams of water vapor per gram of moist air.

On the basis of the relation between specific humidity and vapor density, Fleagle and Businger [19] defined specific humidity ( $q$ ) in equation /8/, where:  $R_d$  is the gas constant for dry air (0.28704 joules per degree Celsius per gram) and  $P_a$  is atmospheric pressure, in pascals (assumed to remain constant at 100.5 Kilopascals at top of tower about 58 meters above sea level).

$$q \approx \frac{\rho_v R_d (T_a + 273.15)}{P_a} \quad /8/$$

$$\overline{w'T_a'} = \frac{\overline{(T_a + 273.15)}}{\overline{(T_s + 273.15)}} (\overline{w'T_s'} - 0.51 R_d \overline{(T_a + 273.15)^2} \overline{w'\rho_v'} / P_a) \quad /9/$$

Equation /7/ can be expressed in terms of fluctuations in the hygrometer-measured water vapor density rather than fluctuations in specific humidity as shown in equation /9/ above. Estimation of turbulent fluxes (equation /5/ and /6/) relies on an accurate measurement of velocity fluctuations perpendicular to the lateral airstream. The study area is relatively flat and level, indicating that the airstream is approximately perpendicular to gravity and the sonic anemometer was oriented with respect to gravity with a bubble level. Measurement of wind speed in three orthogonal directions with the sonic anemometer used in this investigation allowed for a more refined orientation of the collected data with the natural coordinate system through mathematical coordinate rotations. The magnitude of the coordinate rotations are determined by the components of the wind vector in each 30-minute averaging period. The wind vector is composed of three time-averaged components ( $u$ ,  $v$ ,  $w$ ) in the three coordinate directions ( $x$ ,  $y$ ,  $z$ ). Direction  $z$  initially was approximately oriented vertically (with respect to gravity) and the other two directions were arbitrary. Tanner and Thurtell [62] and Baldocchi and others [5] outline a procedure in which measurements made in the initial coordinate system are transformed into values consistent with the natural coordinate system. First, the coordinate system is rotated by an angle  $\eta$  about the  $z$ -axis to align  $u$  into the  $x$ -direction on the  $x$ - $y$  plane. Next, rotation by an angle  $\theta$  is performed about the  $y$ -direction to align  $w$  along the  $z$ -direction. These rotations force  $v$  and  $w$  equal to zero; therefore,  $u$  is pointed directly into the airstream. A third rotation is sometimes used in complex situations (such as a curving airstream around a mountain) to force  $v$  and  $w$  equal to zero, although Baldocchi and others [5] indicate that two rotations generally are adequate, and two rotations were used in the current study.

### Consistency of Measurements with Energy Budget

Previous investigators [44, 37, 7, 26, 58, 63, 24, 21] have described a recurring problem with the eddy-covariance method: a frequent discrepancy of the measured latent and sensible heat fluxes with the energy-budget equation (equation /1/). The usual case is that measured turbulent fluxes ( $H + \lambda E$ ) are less than the measured available energy ( $R_n - G - S$ ). Turbulent fluxes measured above a coniferous forest by Lee and Black [37] accounted for only 83 percent of available energy. Possible explanations for the observed discrepancy in the measured turbulent fluxes include a sensor frequency response that is insufficient to capture high-frequency eddies; an averaging period insufficient to capture low-frequency eddies; drift in the absolute values of anemometer and hygrometer measurements, resulting in statistical non-stationarity within the averaging period; lateral advection of energy; a discrepancy in the measurement points for the wind and vapor density sensors; and overestimation of available energy. Several researchers [44, 26, 24] have shown that the eddy-covariance method obtains better energy-budget closure in windy conditions than during calm conditions.

Twine and others [63] performed an experiment using multiple models of eddy-covariance sensors and net radiometers to measure energy fluxes from a grassland and observed a systematic energy closure discrepancy (turbulent fluxes less than available energy) of 10 to 30 percent. Their conclusion was that eddy-covariance measurements should be adjusted for energy-budget closure. Two common alternatives to adjust turbulent flux measurements for energy-budget closure are to (1) preserve the Bowen ratio or (2) preserve the measured sensible heat flux. Twine and others [63] indicate a preference for the Bowen ratio approach but state that “the method for obtaining closure appears to be less important than assuring that eddy-covariance measurements are consistent with conservation of energy.” The Bowen ratio alternative assumes that the ratio of turbulent fluxes is adequately measured by the eddy-covariance method. The energy-budget equation (eq. 1), along with turbulent fluxes ( $H$  and  $\lambda E$ ) measured using the standard eddy-covariance method are used to produce corrected ( $H_{BREB}$  and  $\lambda E_{BREB}$ ) turbulent fluxes in this “Bowen ratio energy-budget variant” of the eddy-covariance method as indicated in equations /10/ to /12/. On the basis of equation /12/, this variant fails when the Bowen ratio is close to [-1] and the denominator approaches zero. The second alternative for adjustment of fluxes for energy-budget closure used in this study assumes that the sensible heat flux measured by the standard eddy-covariance method is correct but that latent heat flux is underestimated. Therefore, the corrected latent heat flux is computed as a residual of the energy budget (equation /1/). This “residual energy-budget” variant of the eddy-covariance method is shown in equation /14/.

$$R_n - G - S = H_{BREB} + \lambda E_{BREB} = \lambda E_{BREB} (1 + B) \quad /10/$$



Bowen ratio: /11/

$$B = \frac{H}{\lambda E}$$

Rearranging equation /10/: /12/

$$\lambda E_{BREQ} = \frac{R_n - G - S}{1 + B}$$

Combine equations /11/ and /12/; and rearranging: /13/

$$H_{BREQ} = R_n - G - S - \lambda E_{BREQ}$$

“Residual energy- budget” variant: /14/

$$\lambda E_{REQ} = R_n - G - S - H$$

Energy generally enters the soil surface and (or) any standing water and is stored in the biomass and air during the day and released at night. Implementation of equations /10/ to /14/ was facilitated by using daily composites of terms in these equations and assuming that soil heat flux and changes in energy storage in the biomass, air, and any standing water were negligible at this site over a diurnal cycle. Therefore, although eddy-covariance flux measurements were made at 30-minute resolution, only daily or coarser ET estimates incorporate energy-budget closure considerations. Use of a daily compositing interval of flux values in this study allowed for neglect of those terms of the energy budget that were not measured (soil heat flux and biomass/air/standing water energy storage). However, during periods of rapid temperature changes (for example, cold front passage), the net soil heat flux and the net change in energy stored in the biomass/air/ standing water over a diurnal cycle may not be negligible.

As mentioned previously, missing 30-minute turbulent flux data can result from scaling of hygrometer windows and from moisture on the anemometer or hygrometer. These data need to be estimated prior to construction of daily composites of turbulent fluxes. In the present study, regression analysis of measured 30-minute turbulent flux and net radiation data was used to estimate unmeasured values of 30-minute turbulent fluxes. Additionally, both  $H$  and  $\lambda E$  were set to zero during periods of rainfall when rainwater on eddy-covariance and net radiation sensors resulted in missing or corrupted data. An assumption of negligible turbulent fluxes during rainfall events was considered reasonable because of the cloudy and, therefore, low net radiation conditions generally prevalent during rain.

### Simulation of Evapotranspiration

Several models were evaluated for their utility in estimating ET. The eddy-covariance instrumentation can have extended periods of non-operation, as discussed previously. However, more robust meteorological and hydrologic instrumentation (sensors for measurement of net radiation, air temperature, relative humidity, solar radiation, wind speed, soil moisture, and water-table depth) provide nearly uninterrupted data. ET models, calibrated to measured turbulent flux data and based on continuous meteorological and hydrologic data, can be used to fill gaps in measured data, providing continuous estimates of ET. Additionally ET models can provide insight into the cause-and-effect relation between the environment and ET: Relationships among water-table depth, soil moisture, and ET. Finally, some ET models can provide estimates of maximum (potential or reference) ET under conditions of optimal moisture availability.

Measurement of ET using the eddy-covariance method is resource intensive, so it is practical to use the results of short-term studies to develop and verify ET models that can then be used to estimate ET for other time periods and to understand the cause and effect nature of evaporative processes. The utility of different models is related to the model assumptions or the data used by the models. For example, results of a model that is indifferent to wind direction can be compared with measurements to help determine if ET is related to wind direction. A model that requires only temperature data can be used to estimate historical variability in ET using readily available long-term temperature records. This section describes the description of the three ET models explored.

### Priestley-Taylor Equation

Physics-based ET models generally rely on the work of Penman [47], who developed an equation for evaporation from wet surfaces that is based on energy budget and aerodynamic principles. That equation has been applied to estimate ET from well-watered, dense agricultural crops (reference or potential ET). In Penman's equation, the transport of latent and sensible heat fluxes from a “big leaf” to the sensor height is subject to an aerodynamic resistance. The “big leaf” assumption implies that the plant canopy can be conceptualized as a single source of both latent and sensible heat at a given height and temperature. Inherent in the Penman approach is the assumption of a net one-dimensional, vertical transport of vapor and heat from the canopy. The Penman equation is described by equation /15/. In equation /15/: The first term is known as the energy term; the second term is known as the aerodynamic term;  $\Delta$  is slope of the saturation vapor-pressure curve, in kilopascals per degree Celsius;  $e_s$  is saturation vapor pressure, in kilopascals;  $e$  is vapor pressure, in kilopascals;  $\gamma$  is the psychrometric “constant”, equal to approximately 0.067 kilopascals per degree Celsius but varying slightly with atmospheric pressure and temperature;  $r_h$  is aerodynamic resistance, in seconds per meter; and other terms are as previously defined.

Penman equation:

/15/

$$\lambda E = \frac{\Delta(R_n - S) + \frac{\rho C_p (e_s - e)}{r_h}}{\Delta + \gamma}$$

Priestley and Taylor (1972) for  $e_s = e$  [For saturated atmosphere]:

/16/

$$\lambda E = \frac{\Delta(R_n - S)}{\Delta + \gamma}$$

After introducing “Priestley-Taylor coefficient,  $\alpha$ ” in equation /16/, we

/17/

$$\lambda E = \alpha \frac{\Delta(R_n - S)}{\Delta + \gamma}$$

get:

Priestley and Taylor [49] proposed a simplification of the Penman equation for the case of saturated atmosphere ( $e_s = e$ ), for which the aerodynamic term is zero, yielding equation /16/ above. However, Priestley and Taylor [49] noted that empirical evidence indicates that evaporation from extensive wet surfaces is greater than this amount, presumably because the atmosphere generally does not attain saturation. Therefore, the Priestley-Taylor coefficient,  $\alpha$ , was introduced as an empirical correction to the theoretical expression, giving us equation /17/.

This formulation assumes that the energy and aerodynamic terms of the Penman equation are proportional to each other. The value of  $\alpha$  has been estimated to be 1.26, which indicates that under potential ET conditions, where there is no moisture limitation, the aerodynamic term of the Penman equation is about 21 percent of the total latent heat flux. Eichinger and others [18] have shown that the empirical value of  $\alpha$  has a theoretical basis; a nearly constant value of  $\alpha$  is expected under the existing range of Earth-atmospheric conditions. Previous studies [20, 55, 58] have applied a modified form of the Priestley-Taylor equation. The approach in these studies relaxes the Penman assumption of a free-water surface or a dense, well-watered canopy by allowing  $\alpha$  to be less than 1.26 and to vary as a function of environmental factors. The Penman-Monteith equation [42] is a more theoretically rigorous generalization of the Penman equation that also accounts for a relaxation of the Penman assumptions. However, Stannard [55] noted that the modified Priestley-Taylor approach to simulation of observed ET rates was superior to the Penman-Monteith approach for a sparsely vegetated site in the semi-arid rangeland of Colorado. Similarly, Sumner [58] found the modified Priestley-Taylor approach performed better than the Penman-Monteith for a site of herbaceous, successional vegetation in central Florida. The modified Priestley-Taylor approach was evaluated in the present investigation to simulate daily ET. The selected form of  $\alpha$  as a function of environmental variables was determined in this study through trial-and-error exploratory data analysis, and the parameterization of a particular form of  $\alpha$  was determined using regression with measured daily values of ET.

### Hargreaves Equation

The Hargreaves equation [27] is widely used in agricultural studies in the United States and globally to estimate reference ET. Reference ET is defined as the evapotranspiration from an actively growing, well-watered grass or alfalfa vegetative cover of a specific height range [1]. The Hargreaves equation is appealing because of the sparse data requirements; only minimum and maximum daily air temperatures are required, and these are typically measured at most weather stations. The coefficients and form of the equation are empirical and were developed based on a comparison with ET data from precision weighing lysimeters used with grass land covers. The Hargreaves equation is based on an empirical relation between ET and the two most important explanatory variables for this term—incoming solar radiation and air temperature (equation /18/). Another empirical relation (equation /19/) is used to relate incoming solar radiation to extraterrestrial radiation and a variable highly correlated with cloud cover (daily temperature range). Combining equations /18/ and /19/, we get the Hargreaves equation /20/.

|                                      |      |
|--------------------------------------|------|
| $ET_a = aR_s(TC + b)$                | /18/ |
| $R_s = K_{RS}R_aTR^{0.50}$           | /19/ |
| $ET_a = aK_{RS}R_a(TC + b)TR^{0.50}$ | /20/ |

In equations /18/ to /20/:  $E_a$  is reference ET, in the same water evaporation units as  $R_a$  (for example, millimeters perday);  $R_s$  is incoming solar radiation on land surface, the same water evaporation units as  $ET_a$ ;  $R_a$  is extraterrestrial radiation, in the same water evaporation units as  $ET_a$ ;  $TC$  is average daily air temperature, in degrees Celsius;  $TR$  is daily temperature range, in degrees Celsius;  $a$  and  $b$  are empirical coefficients [ $a = 0.0135$  and  $b = 17.8$ ; and  $K_{RS}$  is an empirical coefficient usually estimated as 0.16 for inland areas and 0.19 for coastal areas, respectively. Hargreaves and Samani [28] suggested that the product [ $aK_{RS}$ ] in equation /20/ be set equal to 0.0023 for reference conditions.  $R_a$  can be estimated using an analytical expression of latitude and day of year [1].  $TC$  and  $TR$  are usually estimated as the average and difference of maximum and minimum daily air temperature, respectively.

In this study, a modified form of the Hargreaves equation was considered to allow for the non-reference conditions. The modification allows the empirical coefficients [ $a$  and  $b$ ] of equation /18/ to vary in a regression analysis to best replicate measured daily values of ET and incoming solar radiation. The necessary daily temperature data for these analyses were obtained from measurements at the ET station and also from nearby National Weather Service stations in New Jersey [45].

#### **North American Regional Reanalysis**

The National Centers for Environmental Prediction (NCEP) - North American Regional Reanalysis (NARR) is an effort to create a long-term set of consistent climate data for North America [40, 46]. NARR is based on a coupled approach to simulation of atmospheric and land-surface processes of energy and mass transfer that assimilates weather data. The period of record of NARR is from 1979 to 2012, and the resolution is 32 kilometers (km) and 3 hours. In the present study, NARR estimates of latent heat flux (at NARR grid centered at 39.75° N and 74.5° W) were compared to the values measured at the ET station (39.89° N and 74.52° W).

#### **Measurement of Environmental Variables**

Meteorological hydrologic and vegetative data were collected in the study area as ancillary data required by the energy-budget variant of the eddy-covariance method and as independent variables within an ET model. Meteorological variables monitored included net radiation air temperature relative humidity, wind speed, and incoming solar radiation. These data were monitored by data loggers at 15-second intervals, using instrumentation summarized in table 1; the resulting 30-minute means were stored. Two net radiometers, deployed at a height of 22 m, provided redundant measurement of net radiation at the ET station. Measured values of net radiation were corrected for wind-speed effects as instructed by the instrument manual. About 90 percent of the source area of the net radiation measurement is contained within a radius of three times the height of the sensor above the canopy [56]. Therefore, the measurement of net radiation had a much smaller source area (radius of about 21 m) than did the turbulent flux measurement (about 90 percent of source area within upwind distance of about 450 m during typical daytime conditions). The source area for measured net radiation is composed exclusively of the pitch pine lowlands/cedar swamp typical of forested wetlands in the Pinelands area.

Air temperature and relative humidity were monitored at the ET station at a height of 22.3 m. The slope of the saturation vapor pressure curve (a function of air temperature) was computed in the manner of Lowe [38], using the measured air temperature. A propeller-type anemometer to monitor wind speed and direction and an upward-facing pyranometer to measure incoming solar radiation were deployed at heights of 24.7 and 22 m, respectively, at the ET station (Table 1).

Hydrologic variables that were monitored include precipitation, water-table depth, stream discharge, and soil moisture. Precipitation records were obtained from a tipping-bucket rain gage deployed at a height of 14.2 m at the ET station. Soil moisture at a location at the ET station was monitored using a water content reflectometer probe installed to provide an averaged volumetric soil moisture content within the upper 30 cm of the soil profile. The measured soil moisture values at this single location are not necessarily representative of the watershed or of the source area of the turbulent flux measurements but are presumed to be correlated with generalized wetting and drying conditions. Soil-moisture measurements were made and recorded on the data logger every 30 minutes (Table 1).

Water levels in a shallow (3-m depth) observation well at the ET station (USGS well number 051604) were measured at 60-minute intervals using a pressure transducer and recorded. The well is situated 5 m from the ET flux tower. Stream discharge of the McDonalds Branch was measured at 15-minute intervals at an upstream site 1.4 km east of the ET station (USGS station number 01466500; Figure 1). Well-construction data, water-level and stream-discharge data collection methods, water-level data, and stream-discharge data are presented in a report by Walker and others [66].

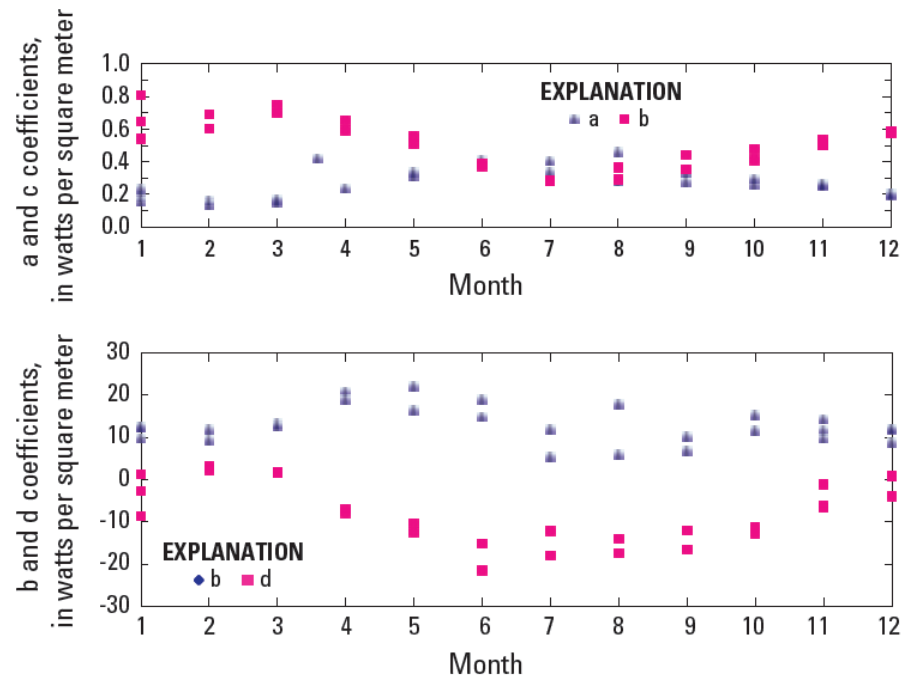
### **RESULTS AND DISCUSSION: EVAPOTRANSPIRATION MEASUREMENT AND SIMULATION**

Most (73 percent) of the 30-minute resolution eddy-covariance measurements made during the 833-day study period were acceptable and was used to develop ET models to estimate missing data and discern the effect of environmental variables on ET. Unacceptable measurements resulted from failure of the krypton hygrometer or sonic anemometer and were most extensive (81 percent of missing data) during night-time hours because dew formation at night is common in this humid climate. This diurnal pattern of missing data was less of a problem than it might appear initially because turbulent fluxes are relatively small during the evening to early-morning hours when solar radiation is zero or low, so errors associated with gap filling do not translate into substantial errors in total ET. The environmental variable that provided the best explanatory value for 30-minute turbulent flux values was net radiation; missing flux data were estimated on the basis of linear regressions between the turbulent fluxes and net radiation for each month of the study (equations /21/ and /22/). This approach reproduced measured 30-minute values of  $\lambda E$  and  $H$  with  $r^2$  values of 0.80 and 0.84, respectively, and standard errors of 34 and 46 watts per square meter ( $W/m^2$ ), respectively. The  $R_n$ -to-turbulent flux regression coefficients showed considerable consistency for a given month from year to year (Figure 4). Although 27 percent of the 30-minute turbulent flux measurements were gap filled using equations /21/ and /22/, the fraction of energy flux gap filled was small (5% of  $\lambda E$  and 7% of  $H$ , respectively) because missing data generally occurred during periods of low energy flux.

$$\lambda E = a_i R_n + b_i \quad /21/$$

$$H = c_i R_n + d_i$$

In equations /21/ and /22/:  $a_i$ ,  $b_i$ ,  $c_i$ , and  $d_i$  are coefficients for a given year-month  $i$ ;  $a_i$  and  $c_i$  are unitless;  $b_i$  and  $d_i$  are in watts per square meter. All other variables have been defined before in this chapter.

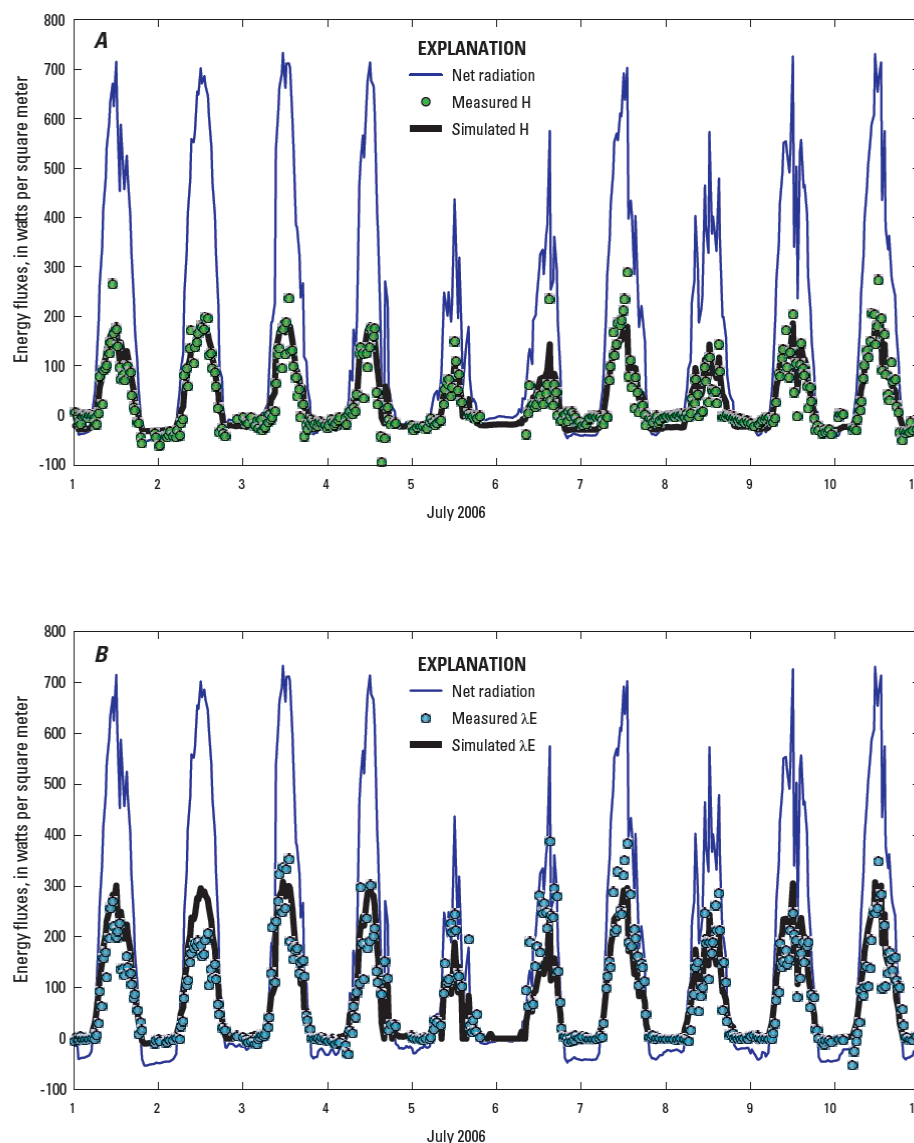


**Figure 4.** Monthly values of regression coefficients used in equations 21 and 22.

Examples of measured and regression-simulated energy fluxes are shown for July 1–10, 2006, in Figure 5. The prominence of daytime over nighttime turbulent fluxes is evident. Also, a strong correspondence between the diurnal and cloudiness-related variations in net radiation and the turbulent fluxes is apparent. The simple linear relations of equations /21/ and /22/ also reproduced the variations in measured turbulent fluxes reasonably. The mean, diurnal pattern of turbulent fluxes and net radiation (Figure 6) indicates that the vast majority of ET occurs during daytime, driven by incoming solar radiation. During average daytime conditions, both latent and sensible heat flux are upward. At night, the surface cools below air temperature, producing a reversal in the direction of sensible heat flux. Although the average, nighttime latent heat flux was slightly upward, dew formation (downward latent heat flux) commonly occurred.

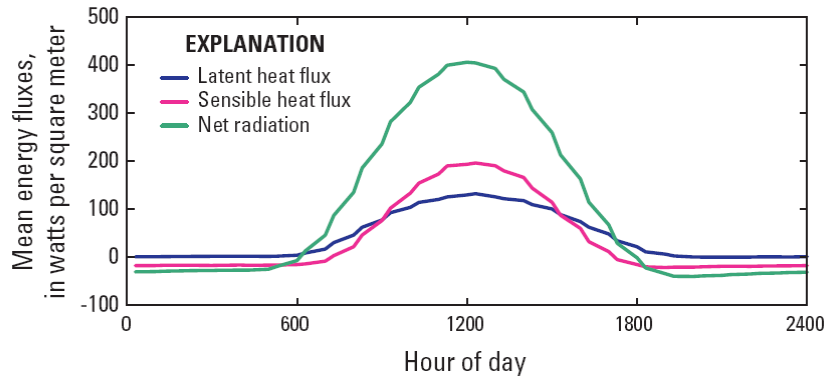
Daytime wind was predominantly from wetland source areas (Figure 1 and Figure 7). The two wind arcs most representative of uplands (350° clockwise to 20° and 90° clockwise to 120°) represent only 15 percent of measured wind directions; other wind directions were primarily representative of wetlands, although to varying degrees. From this analysis and the analysis of the source area (Figures 1 and 3), it is concluded that the source of measured evaporative flux is primarily wetlands.

Energy-budget closure of turbulent fluxes relative to net radiation was examined using weekly, gap-filled composites of the sum of  $\lambda E$  and  $H$ . As previously discussed, for this analysis, net radiation is equivalent to available energy because it has been assumed that the storage and soil heat flux energy-budget terms are negligible over daily or greater time scales. Energy-budget closure was generally better during relatively windy periods, as indicated in Figure 8. Measured and gap-filled 30-minute turbulent fluxes accounted for 77 and 83 percent of mean net radiation values of 101 and 100 W/m<sup>2</sup> for 2005 and 2006, respectively. The relatively large energy-budget discrepancy from early June 2005 to mid-October 2005 led to an exchange of krypton hygrometers on October 19, 2005, and to subsequently improved energy-budget closure.

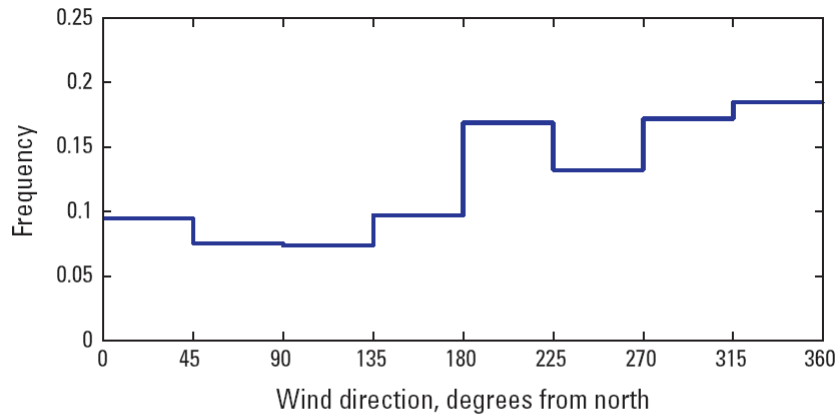


**Figure 5.** Measured and simulated energy fluxes: A, sensible heat flux and B, latent heat flux at the wetland site in the Pinelands area, New Jersey, July 1–10, 2006. (H, sensible heat flux;  $\lambda E$ , latent heat flux)

The hygrometer used in the early part of the study was returned to the manufacturer for evaluation and was diagnosed as exhibiting an unstable voltage output. For this reason, daily values of  $\lambda E$  computed using either the standard eddy-covariance method or the Bowen ratio variant are considered unreliable for the period June 1, 2005, to October 19, 2005. After the conclusion of the study, the hygrometer used subsequent to October 19, 2005, was returned to the manufacturer for evaluation and was deemed to be stable with a drift in calibration of less than 1 percent. Daily values of ET are shown in figure 9 for the standard eddy-covariance method and the Bowen ratio and residual variants, excluding the standard and Bowen ratio methods for the period in 2005 when hygrometer readings were probably not reliable. For 2006, average ET was 1.66, 2.10, and 2.25 millimeters per day (mm/d) for the standard, Bowen ratio, and residual eddy-covariance methods, respectively; this comparison was restricted to the 343 days when the Bowen ratio was not close to -1 and equation 12 did not have a denominator near zero. As indicated by Twine and others (2000), energy-budget-closure methods are preferable to the standard eddy-covariance method. The discrepancy in estimated ET between the Bowen ratio and the residual energy - budget methods averaged 7 percent in 2006 with the Bowen ratio variant producing consistently lower ET estimates than the residual variant. The residual variant was selected in this study as the final method to quantify ET and will be used from here on, primarily because of the loss of data continuity in the Bowen ratio method associated with the suspected failure of the hygrometer during June–October 2005. However, the 7 percent overestimation of ET by the residual method relative to the Bowen ratio method can serve as an estimate of possible bias or uncertainty in estimated ET related to the method of energy-budget closure.



**Figure 6.** Mean diurnal pattern of energy fluxes at the wetland site in the Pinelands area, New Jersey, 2005–06.



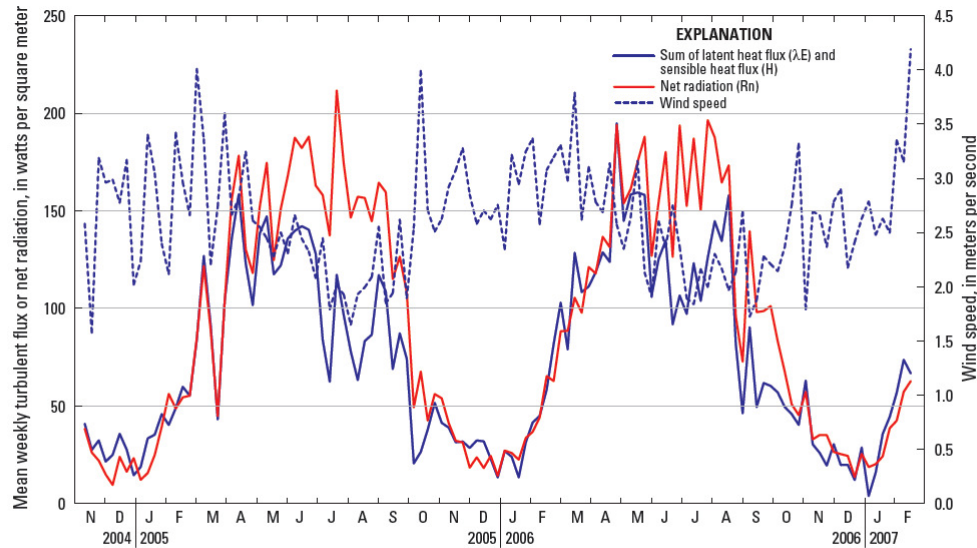
**Figure 7.** Relative frequency of measured wind direction at the wetland site in the Pinelands area, New Jersey, 2005–06.

Weekly, monthly, and 12-month totals of measured rainfall and ET estimated with the residual energy-budget variant of the eddy-covariance method are summarized in tables 2 and 3. Annual ET was a remarkably consistent fraction of annual precipitation (0.62 and 0.58 in 2005 and 2006, respectively) and of net radiation (0.62 in 2005 and 2006) as shown in table 4. An examination of long-term (1902–2011) precipitation data at the nearby National Weather Service Indian Mills weather station indicates that the study period was slightly wetter than mean annual total of 1,173 mm; annual precipitation totals at Indian Mills were 1,325 mm for 2005 and 1,396 mm for 2006, respectively. The Indian Mills precipitation totals are within 30 mm (about 2 percent) of the precipitation measured at the study site during 2005 and 2006 (table 4). Stream flow measurements during 2005–06 indicate average conditions; mean annual stream flow measured at USGS stream gaging station 01466500 (Figure 1) during 2005–06 was 0.0593 cubic meters per second (m<sup>3</sup>/s), which is nearly identical to the long-term mean annual flow of 0.0592 m<sup>3</sup>/s for the 1954–2011 period of record.

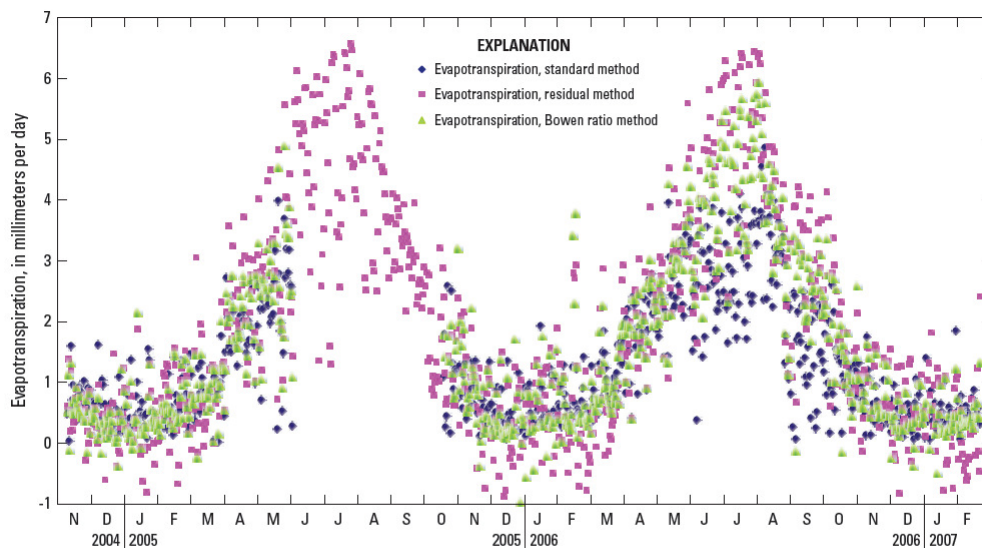
Stream flow, water-table altitude, and soil moisture all fluctuated with similar responses to precipitation and no precipitation. Soil moisture and water-table altitude were highly correlated ( $r^2=0.91$ ). Minimum and maximum ET occurred during December to February and July, respectively (Table 3). Twelve-month ET totals were in a relatively narrow range (786 to 821 mm) over the period of record compared to the range in 12-month rainfall totals (1,124 to 1,452 mm). A first-order data analysis consisting of linear regressions between several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) indicated that net radiation ( $r^2 = 0.72$ ) and air temperature ( $r^2 = 0.73$ ) were the dominant explanatory variables for daily ET. Cross correlation was noted between net radiation and air temperature ( $r^2 = 0.41$ ), and cross correlations are expected between these variables and forest phenological changes, precluding a unique determination of the role of each variable in determining ET. Variations in the evaporative fraction (ratio of latent heat flux to net radiation) indicate that air temperature is the strongest explanatory variable in the partitioning of available energy for ET (Figure 10A). The



evaporative fraction was seemingly unaffected by decreased soil moisture during the April to September 2005 and the July to August 2006 dry periods, until soil moisture fell below a critical threshold of about 0.15, and evaporative fraction decreased. When rains ended the dry period and soil moisture rose above this threshold again, the evaporative fraction recovered (Figure 10B). A similar drop in evaporative fraction during a dry period in early July 2004 was observed at a nearby upland oak-pine site and attributed to apparent stomatal closure (Kenneth Clark, U.S. Forest Service, written communication, 2010). Schäfer [52] measured a reduction in sap-flux scaled canopy conductance at the upland site during drought conditions in 2006. The observed decrease in the evaporative fraction during the extreme dry periods is an important indication that lower water availability can result in lower rates of ET.



**Figure 8.** Mean weekly values of net radiation, turbulent fluxes, and wind speed at the wetland site in the Pinelands area, New Jersey, November 2004–February 2007.



**Figure 9.** Daily evapotranspiration measured using the standard eddy-covariance method, the Bowen ratio method, and the residual energy-budget variant method, at the wetland site in the Pinelands area, New Jersey, November 2004–February 2007.

**Table 2.** Weekly measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy covariance method at the wetland site, Pinelands area, New Jersey, November 2004–February 2007.

[mm, millimeter]

| First day of week | Rainfall (mm) | Evapotranspiration (mm) | First day of week | Rainfall (mm) | Evapotranspiration (mm) |
|-------------------|---------------|-------------------------|-------------------|---------------|-------------------------|
| 11/10/2004        | 37            | 4                       | 8/31/2005         | 0             | 25                      |
| 11/17/2004        | 3             | 4                       | 9/7/2005          | 0             | 24                      |
| 11/24/2004        | 39            | 3                       | 9/14/2005         | 8             | 21                      |
| 12/1/2004         | 33            | 2                       | 9/21/2005         | 2             | 20                      |
| 12/8/2004         | 19            | 2                       | 9/28/2005         | 3             | 17                      |
| 12/15/2004        | 2             | 0                       | 10/5/2005         | 92            | 10                      |
| 12/22/2004        | 26            | 0                       | 10/12/2005        | 135           | 13                      |
| 12/29/2004        | 2             | 5                       | 10/19/2005        | 68            | 8                       |
| 1/5/2005          | 38            | 2                       | 10/26/2005        | 1             | 10                      |
| 1/12/2005         | 31            | 0                       | 11/2/2005         | 0             | 10                      |
| 1/19/2005         | 6             | 2                       | 11/9/2005         | 6             | 7                       |
| 1/26/2005         | 11            | 1                       | 11/16/2005        | 70            | 4                       |
| 2/2/2005          | 9             | 6                       | 11/23/2005        | 26            | 3                       |
| 2/9/2005          | 30            | 5                       | 11/30/2005        | 34            | 2                       |
| 2/16/2005         | 14            | 3                       | 12/7/2005         | 17            | 2                       |
| 2/23/2005         | 21            | 5                       | 12/14/2005        | 27            | 0                       |
| 3/2/2005          | 14            | 6                       | 12/21/2005        | 16            | 3                       |
| 3/9/2005          | 2             | 6                       | 12/28/2005        | 67            | 3                       |
| 3/16/2005         | 3             | 6                       | 1/4/2006          | 1             | 4                       |
| 3/23/2005         | 64            | 5                       | 1/11/2006         | 31            | 6                       |
| 3/30/2005         | 44            | 11                      | 1/18/2006         | 52            | 6                       |
| 4/6/2005          | 35            | 17                      | 1/25/2006         | 6             | 5                       |
| 4/13/2005         | 0             | 17                      | 2/1/2006          | 17            | 4                       |
| 4/20/2005         | 10            | 15                      | 2/8/2006          | 14            | 4                       |
| 4/27/2005         | 30            | 18                      | 2/15/2006         | 1             | 6                       |
| 5/4/2005          | 5             | 17                      | 2/22/2006         | 2             | 0                       |
| 5/11/2005         | 0             | 23                      | 3/1/2006          | 7             | 1                       |
| 5/18/2005         | 43            | 18                      | 3/8/2006          | 4             | 10                      |
| 5/25/2005         | 17            | 25                      | 3/15/2006         | 0             | 1                       |
| 6/1/2005          | 34            | 27                      | 3/22/2006         | 2             | 4                       |
| 6/8/2005          | 0             | 35                      | 3/29/2006         | 3             | 13                      |
| 6/15/2005         | 0             | 32                      | 4/5/2006          | 24            | 11                      |
| 6/22/2005         | 51            | 33                      | 4/12/2006         | 0             | 14                      |
| 6/29/2005         | 53            | 31                      | 4/19/2006         | 46            | 15                      |
| 7/6/2005          | 31            | 31                      | 4/26/2006         | 1             | 16                      |
| 7/13/2005         | 47            | 27                      | 5/3/2006          | 0             | 17                      |
| 7/20/2005         | 1             | 42                      | 5/10/2006         | 66            | 19                      |
| 7/27/2005         | 7             | 34                      | 5/17/2006         | 9             | 23                      |
| 8/3/2005          | 29            | 30                      | 5/24/2006         | 0             | 28                      |
| 8/10/2005         | 16            | 33                      | 5/31/2006         | 43            | 22                      |
| 8/17/2005         | 1             | 31                      | 6/7/2006          | 26            | 25                      |
| 8/24/2005         | 1             | 26                      | 6/14/2006         | 0             | 32                      |



**Table 2.** Weekly measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy covariance method at the wetland site, Pinelands area, New Jersey, November 2004–February 2007.—Continued

[mm, millimeter]

| First day of week | Rainfall (mm) | Evapotranspiration (mm) |
|-------------------|---------------|-------------------------|
| 6/21/2006         | 82            | 27                      |
| 6/28/2006         | 28            | 41                      |
| 7/5/2006          | 78            | 32                      |
| 7/12/2006         | 3             | 37                      |
| 7/19/2006         | 13            | 30                      |
| 7/26/2006         | 26            | 40                      |
| 8/2/2006          | 5             | 37                      |
| 8/9/2006          | 0             | 30                      |
| 8/16/2006         | 0             | 27                      |
| 8/23/2006         | 90            | 19                      |
| 8/30/2006         | 127           | 16                      |
| 9/6/2006          | 0             | 25                      |
| 9/13/2006         | 68            | 21                      |
| 9/20/2006         | 15            | 20                      |
| 9/27/2006         | 11            | 20                      |
| 10/4/2006         | 26            | 16                      |
| 10/11/2006        | 76            | 12                      |
| 10/18/2006        | 15            | 9                       |
| 10/25/2006        | 40            | 8                       |
| 11/1/2006         | 5             | 5                       |
| 11/8/2006         | 117           | 6                       |
| 11/15/2006        | 11            | 6                       |
| 11/22/2006        | 44            | 7                       |
| 11/29/2006        | 5             | 2                       |
| 12/6/2006         | 0             | 4                       |
| 12/13/2006        | 4             | 5                       |
| 12/20/2006        | 44            | 4                       |
| 12/27/2006        | 39            | 3                       |
| 1/3/2007          | 51            | 7                       |
| 1/10/2007         | 3             | 4                       |
| 1/17/2007         | 7             | 0                       |
| 1/24/2007         | 3             | 3                       |
| 1/31/2007         | 5             | 0                       |
| 2/7/2007          | 0             | 0                       |
| 2/14/2007         | 34            | 3                       |

**Table 3.** Monthly and 12-month measured rainfall and evapotranspiration measured using the residual energy-budget variant of the eddy-covariance method at the wetland site, Pinelands area, New Jersey, December 2004–January 2007.

[mm, millimeter; -, no data]

| Year-Month | Monthly measured evapotranspiration (mm) | 12-month moving sum evapotranspiration (mm) | Monthly measured rainfall (mm) | 12-month moving sum rainfall (mm) |
|------------|------------------------------------------|---------------------------------------------|--------------------------------|-----------------------------------|
| 04-Dec     | 7                                        | -                                           | 79                             | -                                 |
| 05-Jan     | 7                                        | -                                           | 88                             | -                                 |
| 05-Feb     | 18                                       | -                                           | 60                             | -                                 |
| 05-Mar     | 27                                       | -                                           | 97                             | -                                 |
| 05-Apr     | 66                                       | -                                           | 111                            | -                                 |
| 05-May     | 94                                       | -                                           | 73                             | -                                 |
| 05-June    | 133                                      | -                                           | 115                            | -                                 |
| 05-July    | 148                                      | -                                           | 108                            | -                                 |
| 05-Aug     | 134                                      | -                                           | 48                             | -                                 |
| 05-Sep     | 94                                       | -                                           | 13                             | -                                 |
| 05-Oct     | 49                                       | -                                           | 296                            | -                                 |
| 05-Nov     | 27                                       | 804                                         | 120                            | 1,208                             |
| 05-Dec     | 8                                        | 805                                         | 96                             | 1,225                             |
| 06-Jan     | 22                                       | 821                                         | 136                            | 1,273                             |
| 06-Feb     | 14                                       | 816                                         | 33                             | 1,245                             |
| 06-Mar     | 24                                       | 814                                         | 13                             | 1,161                             |
| 06-Apr     | 58                                       | 806                                         | 74                             | 1,124                             |
| 06-May     | 94                                       | 807                                         | 76                             | 1,127                             |
| 06-June    | 119                                      | 794                                         | 171                            | 1,183                             |
| 06-July    | 157                                      | 802                                         | 125                            | 1,201                             |
| 06-Aug     | 124                                      | 792                                         | 99                             | 1,252                             |
| 06-Sep     | 88                                       | 786                                         | 213                            | 1,452                             |
| 06-Oct     | 55                                       | 792                                         | 163                            | 1,319                             |
| 06-Nov     | 26                                       | 790                                         | 176                            | 1,375                             |
| 06-Dec     | 15                                       | 797                                         | 53                             | 1,332                             |
| 07-Jan     | 14                                       | 789                                         | 104                            | 1,299                             |

### Comparison of Measured Evapotranspiration at Wetland and Upland Sites

Basin-scale hydrologic analysis requires estimates of ET over large areas, and therefore, an accounting of variability in ET rates across the landscape is needed. Previous investigations have indicated a substantial difference in ET between wetlands and uplands in the Pinelands area. Plot-scale studies using lysimeters concluded that ET from wetland areas in the Pinelands is expected to be greater than ET from upland areas because wetland soils are wetter and water is more readily available for ET [3, 4]. Evaluation of this difference over larger areas is possible by comparing ET measurements collected at the wetland station with those collected at three nearby upland stations operated by the U.S. Forest Service (USFS). The locations of ET measurement stations for the wetland stand and the three upland USFS stands are shown in Figure 11. The three upland stations are located

within 14 km of the wetland station, and fluxes were monitored using eddy-covariance techniques similar to those used at the wetland station. The specific ET measurement methods used at the three upland sites are described by Clark and others [14,15,16]. The three upland forest stands are dominated by oak, pine, and mixed oak and pine, respectively. ET was measured at the upland stations during 2005–09, which included periods of disturbance by fire and insect defoliation that had a significant effect in reducing ET. Annual precipitation and ET measured at the three upland stations and the wetland station are listed in Table 4. Clark and others [15] showed that, when averaged across all upland stations for all years of measurement (2005–09), annual ET was 606 mm/yr. The average annual ET measured at the wetland station during 2005–06 (801 mm/yr) is about 32 percent higher than this upland average. When ET at the upland stations is averaged over years without disturbance (685 mm/yr), the average annual wetland ET is about 17 percent higher. As a percentage of precipitation, ET at the wetland station was higher than that of the undisturbed oak and mixed oak/pine upland stations in 2005 and was similar to that of the undisturbed oak and pine upland stations in 2006.

**Table 4.** Summary of selected characteristics measured or simulated annually and dates of spring and fall freezes at the wetland site, Pinelands area, New Jersey, 2005–06.

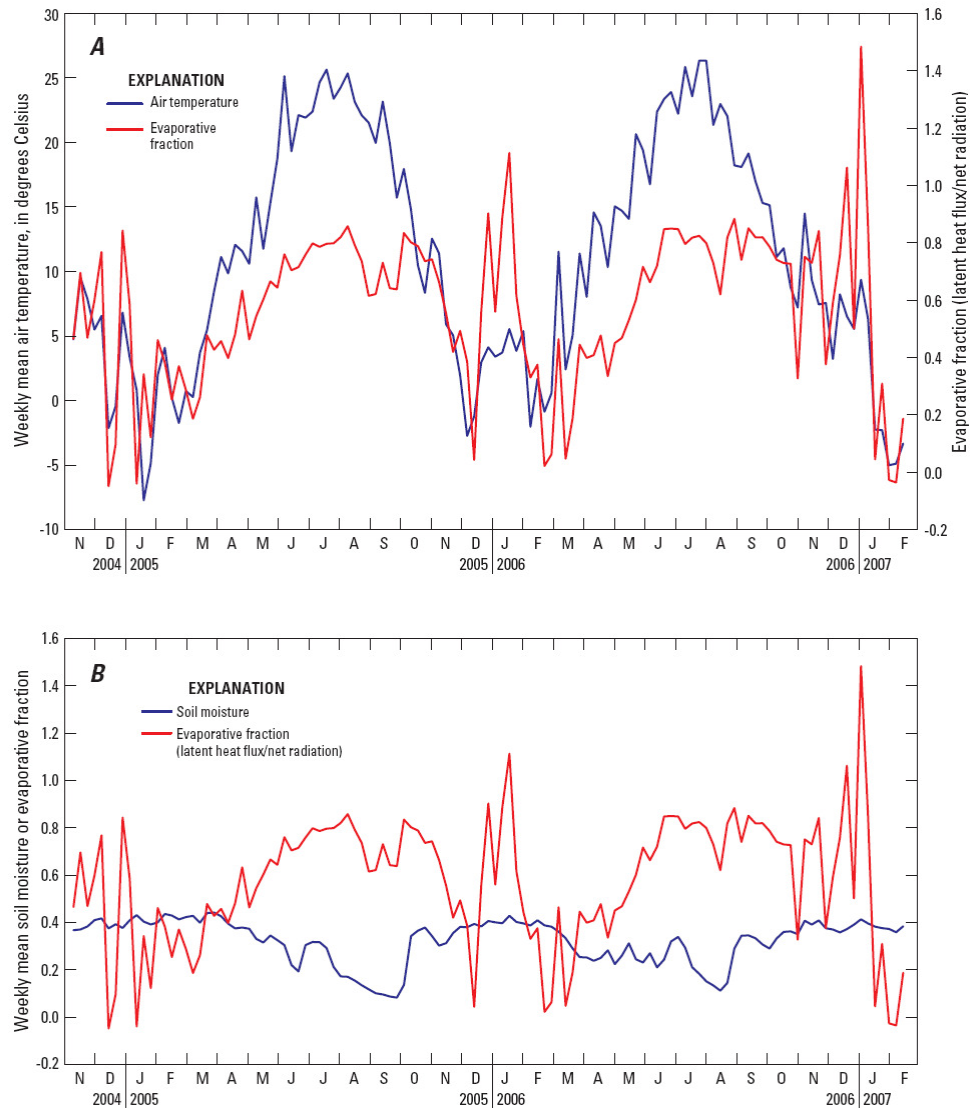
| Characteristic                                                                                       | Year 2005   | Year 2006  |
|------------------------------------------------------------------------------------------------------|-------------|------------|
| Measured evapotranspiration at McDonalds Branch ( $AET_m$ ), in millimeters                          | 805         | 797        |
| Priestley-Taylor potential evapotranspiration (PET), in millimeters                                  | 1,022       | 1,013      |
| Hargreaves reference evapotranspiration (RET), in millimeters                                        | 986         | 1,008      |
| North American Regional Reanalysis (NARR) actual evapotranspiration ( $AET_{NARR}$ ), in millimeters | 831         | 930        |
| Rainfall (R) at McDonalds Branch, in millimeters                                                     | 1,225       | 1,332      |
| Snow (S) at Indian Mills, in millimeters                                                             | 749         | 343        |
| Estimated precipitation ( $P = R + 0.1S$ ), in millimeters                                           | 1,300       | 1,366      |
| Measured latent heat flux, in watts per square meter                                                 | 63          | 62         |
| Incoming solar radiation, in watts per square meter                                                  | 159         | 163        |
| Net radiation ( $R_n$ ), in watts per square meter                                                   | 101         | 100        |
| Average daily minimum temperature, in °C                                                             | 6.64        | 7.62       |
| Average daily maximum temperature, in °C                                                             | 16.75       | 17.83      |
| Last spring freeze                                                                                   | 17-April    | 24-March   |
| First fall freeze                                                                                    | 11-November | 27-October |
| Priestley-Taylor vegetation factor ( $AET_m/PET$ )                                                   | 0.79        | 0.82       |
| Hargreaves vegetation factor ( $AET_m/RET$ )                                                         | 0.79        | 0.79       |
| Measured to NARR evapotranspiration ratio ( $AET_m/AET_{NARR}$ )                                     | 0.97        | 0.86       |
| Evapotranspiration to precipitation ratio ( $AET_m/P$ )                                              | 0.62        | 0.58       |
| Evaporative fraction (ratio of mean latent heat flux to mean net radiation)                          | 0.62        | 0.62       |

Several factors are likely contributing to differences in ET rates among different stations and among different years. These factors include water availability, dominant plant species, and leaf area. Water availability varies year to year with precipitation and evapotranspiration, and it also varies site to site with depth to the water table and other site conditions. Water availability is less variable in wetlands because the water table is close to or at land surface, whereas in uplands the water-table is deeper. Also, upland soils are more susceptible to drought conditions. Phenological and physiological differences among plant species result in different seasonal patterns of ET and different responses to stress and disturbance in the Pinelands, as described by Clark and others [15].

Leaf area is a function of several site characteristics, including plant species, successional stage, and response to disturbance (including by fire and defoliation). The results presented in Table 5 and Figure 12 indicate that inter-annual variability in wetland ET may be less than that of upland ET because the wetland sites are less susceptible to periodic drought conditions, disturbance by fire [22], and insect defoliation [29, 72]. Higher ET in wetlands is probably attributable to greater water availability and differences in canopy plant species and leaf area.

A useful approach for validating ET measurements is to use them in a watershed-scale analysis of the water budget, along with other hydrologic measurements. A balanced water budget is an indication that the various measurements are internally consistent. Walker and others [66] describe the water balance in the McDonalds Branch basin for 2005–06. The analysis includes

an estimate of basin-wide, spatially weighted ET that was based on the respective ET rates for the wetland and upland sites described previously. The analysis included a land-surface water budget and a groundwater budget. Both budgets were used to estimate aquifer recharge independently as a residual. The comparability of the independent recharge estimates for the McDonalds Branch basin indicate that the ET measurements presented in this report are reasonably consistent with other hydrologic measurements.



**Figure 10.** Relation of A, weekly mean air temperature and B, weekly mean soil moisture to evaporative fraction, at a wetland site in the Pinelands area, New Jersey, November 2004–February 2007.

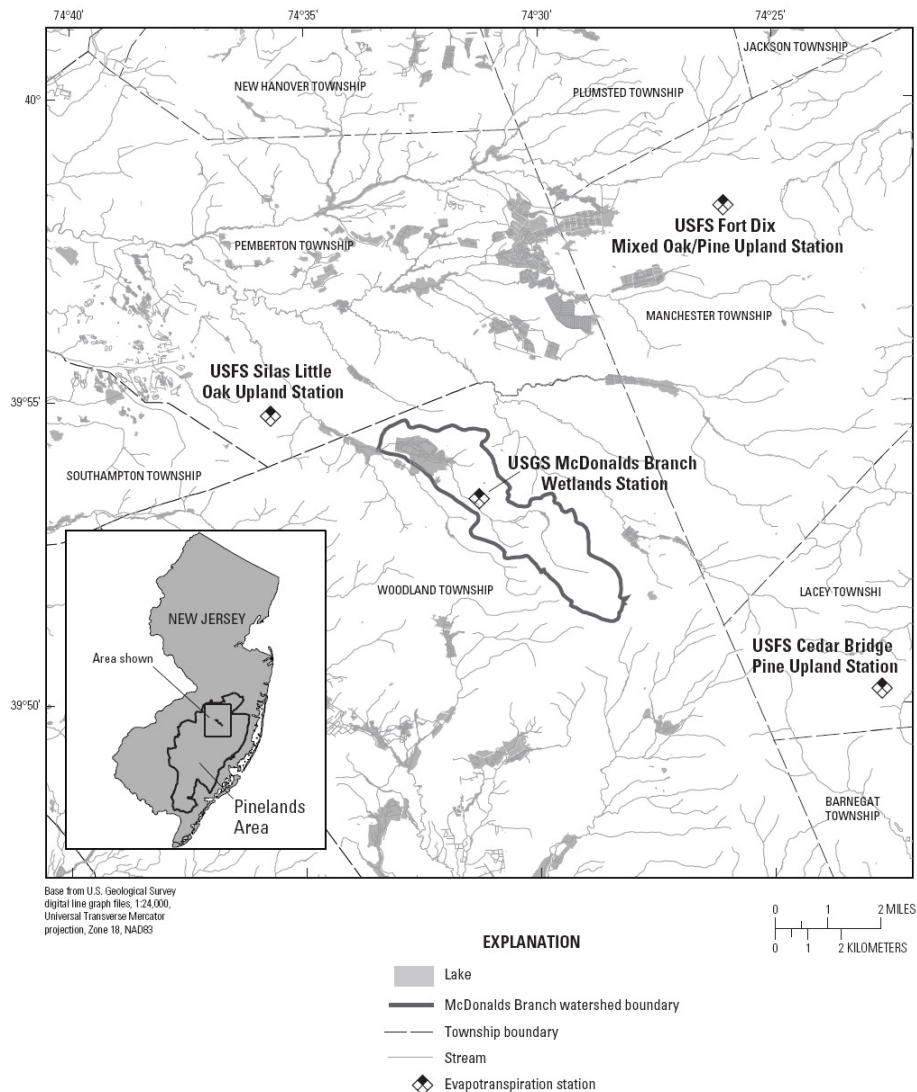
### Utility of Models to Simulate Evapotranspiration

The utility of three models (Priestley-Taylor, Hargreaves, and North American Regional Reanalysis, NARR) were evaluated through a comparison of model-simulated ET with ET measured at the wetland site using the residual energy-budget variant method. Models that successfully replicated measured ET offer the potential to transfer the results of the site measurements to other locations or to other time periods outside the study period.

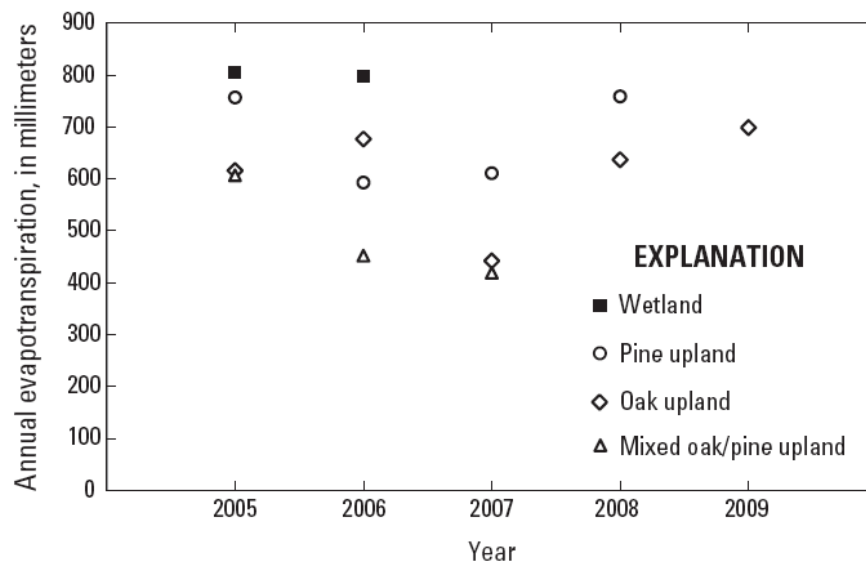
#### *Priestley-Taylor Equation*

The environmental variables considered as possible predictors of modified Priestley-Taylor  $\alpha$  included soil moisture, solar radiation, air temperature, vapor-pressure deficit, and wind speed. Exploratory data analysis revealed that the greatest explanatory value for the Priestley-Taylor  $\alpha$  was related to air temperature, followed by solar radiation, soil moisture, wind speed, and finally vapor-pressure deficit. A “Priestley-Taylor  $\alpha$  function” composed of a second order polynomial of air temperature (Figure 13) was optimized to successfully reproduce daily values of latent heat flux measured with the energy- budget residual variant ( $r^2 = 0.90$ ; standard error = 0.65 mm or 19 W/m<sup>2</sup>; and bias = 0; Table 6).

Comparison of modeled latent heat flux residuals with possible explanatory variables other than air temperature revealed little relation, supporting the use of the simple temperature-dependent Priestley-Taylor  $\alpha$  function. This function shows an increase in  $\alpha$  with air temperature, with the rate of increase decreasing with increasing air temperature. This relation for  $\alpha$  probably represents a combination of direct plant stomatal response to air temperature but also a response to phenological changes in the forest plant species that are associated with seasonal temperature changes. A comparison of residuals with vector-averaged daily mean wind direction (Figure 14) provides a means of evaluating the effects of non-homogeneous surface covers (wetlands and uplands) within the source area of the latent heat flux measurement. No obvious relation was apparent between ET residuals and wind direction that was consistent with the patterns of wetlands and uplands in the source area, indicating that wind direction, a surrogate for source areas with different vegetation, was not responsible for variability in ET not already accounted for by the temperature relation. Figure 15 shows a good relation between daily measured (energy-budget residual variant) and modified Priestley-Taylor simulated latent heat flux, without noticeable temporal bias. The simulated values of latent heat flux generally are less erratic in the winter than are the measured values; this phenomenon may be more a consequence of violation of one of the assumptions of latent heat flux measurement — negligible changes in canopy heat storage during rapid winter-time temperature changes — than an error in the model.



**Figure 11.** Location of the wetland and upland evapotranspiration measurement stations, Pinelands area, New Jersey. (USGS, U.S. Geological Survey; USFS, U.S. Forest Service)

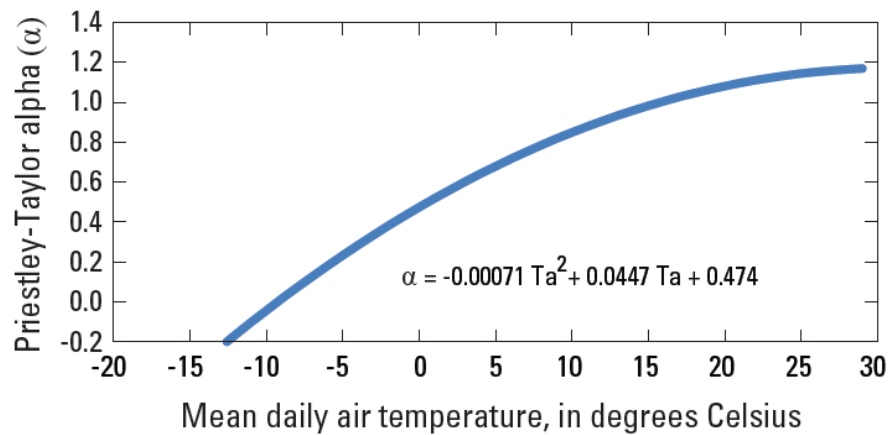


**Figure 12.** Annual evapotranspiration measured at the wetland, pine upland, oak upland, and mixed oak/pine upland sites in the Pinelands area, New Jersey, 2005–09.

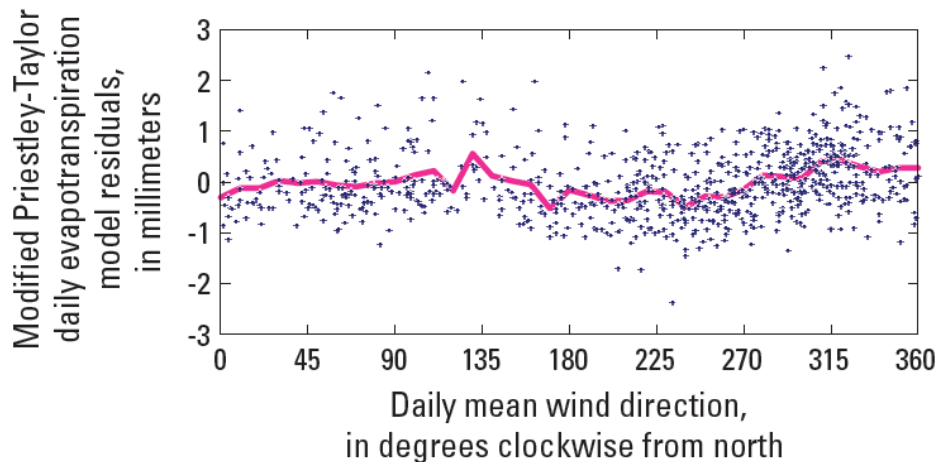
**Table 5.** Annual evapotranspiration at the wetland site and three upland forest sites, Pinelands area, New Jersey, 2005–09.

[Data for upland sites are from Clark and others (2012). mm, millimeters; ET, evapotranspiration]

| Site                 | Year | Disturbance<br>(if any) | Annual<br>precipitation<br>(mm) | Annual ET<br>(mm) | Annual ET<br>as a percentage<br>of precipitation |
|----------------------|------|-------------------------|---------------------------------|-------------------|--------------------------------------------------|
| Wetland (this study) | 2005 |                         | 1,225                           | 805               | 66                                               |
|                      | 2006 |                         | 1,332                           | 797               | 60                                               |
| Oak upland           | 2005 |                         | 1,092                           | 616               | 56                                               |
|                      | 2006 |                         | 1,108                           | 677               | 61                                               |
|                      | 2007 | Complete defoliation    | 934                             | 442               | 47                                               |
|                      | 2008 | Partial defoliation     | 936                             | 637               | 68                                               |
|                      | 2009 |                         | 1,173                           | 699               | 60                                               |
| Mixed upland         | 2005 |                         | 1,184                           | 607               | 51                                               |
|                      | 2006 | Burn and defoliation    | 1,163                           | 452               | 39                                               |
|                      | 2007 | Partial defoliation     | 1,135                           | 419               | 37                                               |
| Pine upland          | 2006 |                         | 1,230                           | 757               | 62                                               |
|                      | 2007 | Partial defoliation     | 1,052                           | 593               | 56                                               |
|                      | 2008 | Prescribed burn         | 1,163                           | 611               | 54                                               |
|                      | 2009 |                         | 1,382                           | 759               | 55                                               |



**Figure 13.** Optimized relation between Priestley-Taylor  $\alpha$  and mean daily air temperature for the wetland site in the Pinelands area, New Jersey.



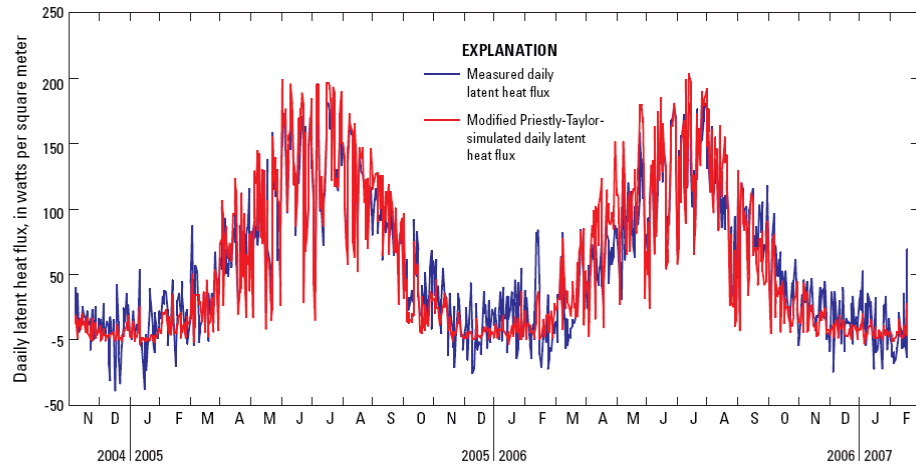
**Figure 14.** Relation of residuals using the modified Priestley-Taylor model to daily mean wind direction, wetland site, Pinelands area, New Jersey, 2004–07. Residual is simulated evapotranspiration minus measured evapotranspiration: The two wind arcs most representative of uplands are 350 degrees clockwise to 20 degrees and 90 degrees clockwise to 120 degrees. The red line is mean residual for a given wind direction.



**Table 6.** Error statistics relating evapotranspiration measured at the wetland site to evapotranspiration simulated using alternative models, Pinelands area, New Jersey.

[mm, millimeter]

| Alternative model                                                                    | Coefficient of determination ( $r^2$ ) with measured actual evapotranspiration | Root mean square error (mm/day) | Bias relative to measured evapotranspiration (mm/year) |
|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------|--------------------------------------------------------|
| Priestley-Taylor potential evapotranspiration (PET)                                  | 0.85                                                                           | 1.08                            | +216                                                   |
| Hargreaves reference evapotranspiration (RET)                                        | 0.87                                                                           | 0.85                            | +196                                                   |
| Modified Priestley-Taylor actual evapotranspiration ( $AET_{PT}$ )                   | 0.9                                                                            | 0.65                            | 0                                                      |
| Modified Hargreaves actual evapotranspiration ( $AET_{H_g}$ )                        |                                                                                |                                 |                                                        |
| McDonalds Branch wetland site                                                        | 0.89                                                                           | 0.61                            | 0                                                      |
| Indian Mills weather station                                                         | 0.84                                                                           | 0.73                            | 0                                                      |
| Moorestown weather station                                                           | 0.83                                                                           | 0.76                            | 0                                                      |
| North American Regional Reanalysis (NARR) actual evapotranspiration ( $AET_{NARR}$ ) | 0.6                                                                            | 1.21                            | +80                                                    |



**Figure 15.** Measured and modified Priestley-Taylor-simulated daily latent heat flux for the wetland site, Pinelands area, New Jersey, 2005–06.

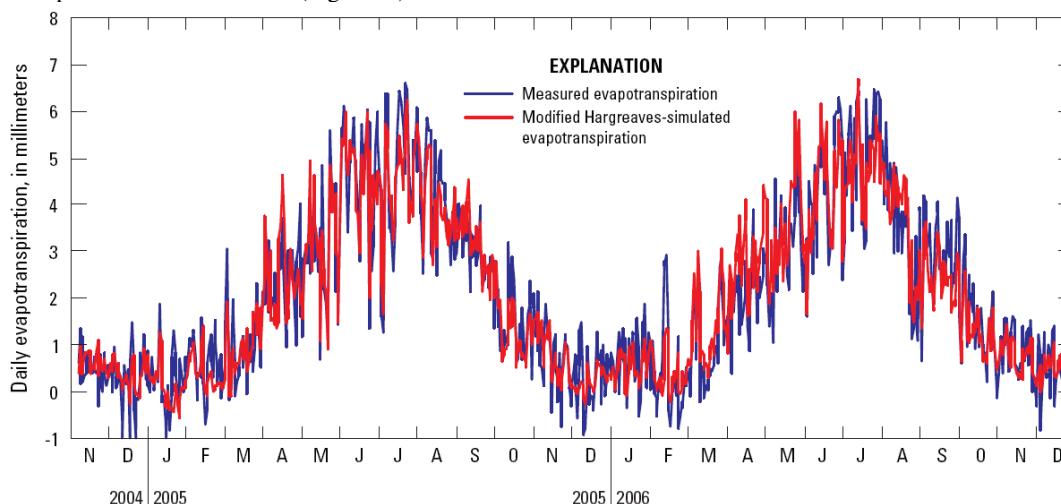
The modified Priestley-Taylor model developed in this study is subject to several qualifications. The form of the equation developed for  $\alpha$  was empirical rather than physics based and was simply designed to reproduce measured values of ET as accurately as possible. The covariance between environmental variables confounds a unique parameterization. The model was developed for a limited range of environmental conditions, and therefore, extrapolation of the model to conditions not encountered in this study are best done with caution. As noted earlier, deficit soil moisture appeared to play a role in restricting ET during particularly dry periods, but this effect was not considerable enough to be discerned clearly in the identification of the appropriate Priestley-Taylor  $\alpha$  function.

Annual measured ET at the wetland site was a relatively constant fraction of potential ET as estimated by the standard Priestley-Taylor method with an  $\alpha$  of 1.26 (0.79 and 0.82 in 2005 and 2006, respectively; Table 4). However, potential ET was highly correlated with measured ET ( $r^2 = 0.85$ ), indicating that a constant vegetation factor applied to potential ET also can replicate actual ET rather well at this wetland site, where moisture availability was not often a constraint.

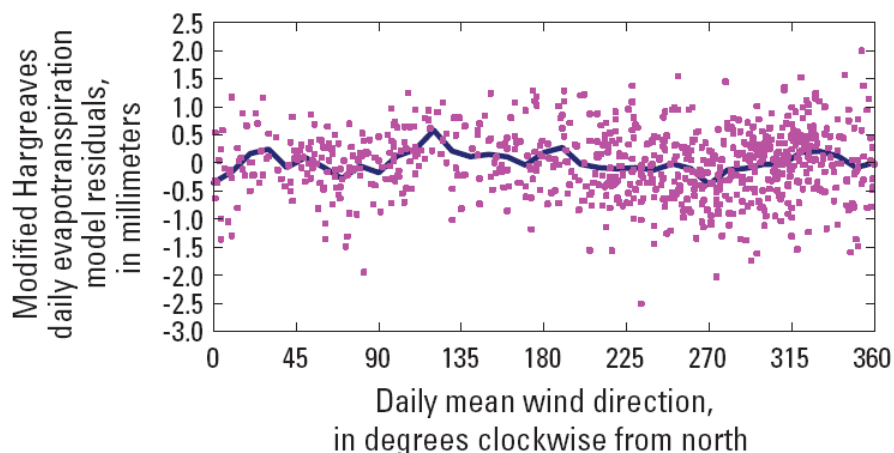
### Hargreaves Equation

The modified Hargreaves equation performed remarkably well at reproducing measured values of daily ET (Table 6; Figure 16.) with relatively low error and little temporal bias. Additionally, measurements of daily incoming solar radiation were also well replicated ( $r^2 = 0.70$ ; coefficient of variation = 31 percent; and bias = 3 percent) using the preferred value of  $K_{RS} = 0.16$  for inland areas. The values of  $a$  and  $b$  identified by the regression analysis to most closely replicate measured daily ET for each source of temperature data are shown in Table 7–7. As might be expected, use of temperature data from the ET station at the McDonalds Branch site provides better explanatory values within the modified Hargreaves equation for ET ( $r^2 = 0.89$ ; standard error = 0.61

mm/d; and bias = 0 mm/year) than does use of remote temperature data from either of the National Weather Service stations (Indian Mills and Moorestown; Table 6). However, Hargreaves models adjusted for temperature data from either of the remote temperature stations can be considered successful at ET estimation, although the models performed slightly better using values from the closer Indian Mills station ( $r^2 = 0.84$ ; standard error = 0.73 mm/d; and bias = 0 mm/year) than using values from the more distant Moorestown station ( $r^2 = 0.83$ ; standard error = 0.76 mm/d; and bias = 0 mm/year). The lower values (3.1 to 4.1) of the temperature offset parameter  $b$  in the optimized forms of the modified Hargreaves actual ET equation relative to the  $b$  value of 17.8 in the standard Hargreaves reference evapotranspiration equation imply that actual ET shows greater sensitivity to temperature at this site than does reference ET. Annual ET was a constant fraction of reference ET, as estimated by the standard Hargreaves method (0.79 in 2005 and 2006; table 4). However, daily reference ET was highly correlated ( $r^2 = 0.87$ ) with measured ET, indicating that a constant vegetation factor applied to reference ET can replicate actual ET at the wetland site rather well. Again, no obvious relation was apparent between ET residuals and wind direction that was consistent with the patterns of wetlands and uplands in the source area (Figure 17).

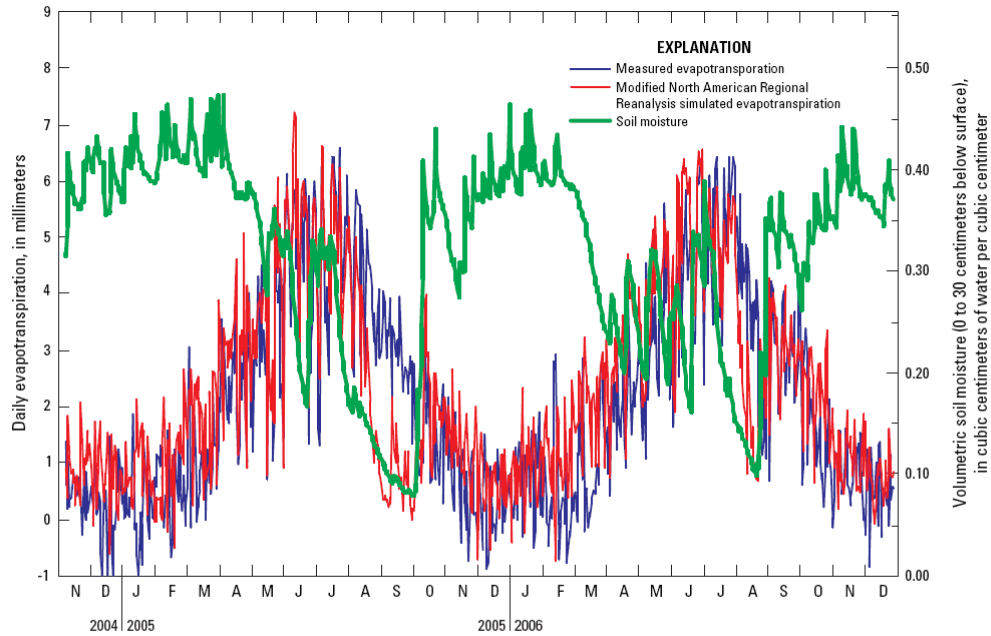


**Figure 16.** Daily measured and modified Hargreaves-simulated evapotranspiration for the wetland site, Pinelands area, New Jersey, 2005–06.



**Figure 17.** Relation of residuals using the modified Hargreaves daily evapotranspiration model to daily mean wind direction, wetland site, Pinelands area, New Jersey, 2004–07. Residual is simulated evapotranspiration minus measured evapotranspiration: The two wind arcs most representative of uplands are 350 degrees clockwise to 20 degrees and 90 degrees clockwise to 120 degrees. The blue line is mean residual for a given wind direction.





**Figure 18.** Daily measured and modified North American Regional Reanalysis simulated evapotranspiration, and volumetric soil moisture for the wetland site, Pinelands area, 2005–06.

**Table 7.** Parameters for the standard Hargreaves reference evapotranspiration equation and optimized parameters for the modified Hargreaves actual evapotranspiration equation for alternative sources of daily temperature data.

[ $a$ ,  $b$ ,  $K_{RS}$ , and  $aK_{RS}$  are empirical coefficients]

| Parameter         | Standard Hargreaves | McDonalds Branch wetland site | Moorestown weather station | Indian Mills weather station |
|-------------------|---------------------|-------------------------------|----------------------------|------------------------------|
| $a$               | 0.0148              | 0.0198                        | 0.0167                     | 0.0169                       |
| $b$               | 17.8                | 4.1                           | 3.1                        | 3.2                          |
| $K_{RS}$ (inland) | 0.16                | 0.16                          | 0.16                       | 0.16                         |
| $aK_{RS}$         | 0.0023              | 0.0032                        | 0.0027                     | 0.0027                       |

#### **North American Regional Reanalysis (NARR)**

The North American Regional Reanalysis performed relatively poorly ( $r^2 = 0.60$ ; standard error = 1.21 mm; and bias = 80 mm/year) at replicating measured values of daily ET relative to the other models considered (Table 6). In particular, NARR showed substantial under-prediction of measured ET during the dry periods (Figure 18) that occurred during August–October 2005 and in August 2006 and slight over-prediction during wetter periods. Apparently, the NARR algorithms restrict ET as a result of perceived plant moisture stress during dry periods to a degree that is excessive for the largely wetland environment of the study area. The large spatial resolution of the NARR product (32-km grid) is intended for a more regional estimate of ET than the relatively small-scale measurement described in the present study, and this discrepancy in scale can be expected to account for some of the difference between the two ET estimates. Annual measured ET totals as a fraction of NARR ET were 0.97 and 0.86 in 2005 and 2006, respectively (Table 4).

#### **Comparison and Limitations of Evapotranspiration Models**

Of the models investigated in the present study, the modified Hargreaves can be considered the best at replicating the measured daily ET values. The error statistics of the modified Hargreaves model were comparable to those of the modified Priestley-Taylor model and superior to those of the North American Regional Reanalysis product. Additionally, the data requirements of the

modified Hargreaves model (minimum and maximum daily air temperature) are more easily met than those of the modified Priestley-Taylor model, which requires both mean daily air temperature and the more difficult to obtain net radiation. The data requirements of the modified Hargreaves equation are ideal for retrospective investigations of ET because they are met by standard National Weather Service measurements that extend back over a century in parts of the Nation, including at Moorestown and Indian Mills, New Jersey. Likewise, in the absence of continuing eddy-covariance measurements, historical or real-time estimates of ET in the study area can be obtained through use of air-temperature data (available from the National Climatic Data Center [<http://www.ncdc.noaa.gov/oa/ncdc.html>] or the NJ Weather and Climate Network [<http://climate.rutgers.edu/njwxnet>], for example) and the modified Hargreaves equation. Sumner and Nicholson [59] presented historical and future probabilistic estimates of ET at the wetland site using a Hargreaves-based approach.

The ET models described in this report are best applied to estimate ET at locations or during time periods for which the environmental conditions are similar to those prevailing during the period of record for which these models were calibrated. Use of the models outside of these environmental conditions introduces additional uncertainty in the ET estimates. For example, under more extreme dry periods than those that occurred during the study period, ET may be overestimated by models that do not explicitly account for plant moisture stress.

**Based on the results of this research, it can be concluded:** Evapotranspiration (ET) was monitored above a wetland forest canopy in the New Jersey Pinelands during November 10, 2004–February 20, 2007. Meteorological, radiation, and eddy-covariance flux measurements were made near the top of a 24.5-meter tower; soil moisture and water-table depth at the site also were monitored. An analysis of the eddy-covariance sensors' source area and predominant wind directions indicated that the source of measured ET was primarily pitch pine/cedar wetlands. Three methods were evaluated for their utility in estimating ET. The standard eddy-covariance method was used to measure the two turbulent-flux components of the plant-canopy energy budget: latent and sensible heat fluxes. Regression analysis of measured 30-minute turbulent flux and net radiation data was used to estimate missing values of 30-minute turbulent fluxes, which occurred mostly at night and accounted for only 5 percent of the total estimated ET. Two variants of the eddy-covariance method were used to adjust turbulent flux measurements for daily energy-budget closure; one variant preserves the Bowen ratio (Bowen ratio energy-budget variant), and the other preserves the measured sensible heat flux (residual energy-budget variant). Relations between ET and several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) were explored.

Suspected hygrometer failure during the early part of the measurement period resulted in unreliable ET measurements determined by using the standard eddy-covariance and Bowen ratio energy-budget variant methods. The residual energy-budget variant was selected for use in estimating a time series of daily ET rates for the measurement period. The range of the 12-month ET totals, based on the residual energy-budget variant, is relatively narrow (786 to 821 millimeters (mm)) for the period of record compared to the range of the 12-month rainfall totals (1,124 to 1,452 mm). Minimum and maximum ET values were measured during December–February and July, respectively. Net radiation ( $r^2 = 0.72$ ) and air temperature ( $r^2 = 0.73$ ) were the dominant explanatory variables for daily ET. Air temperature was the dominant control on evaporative fraction with relatively more radiant energy used for ET at higher temperatures. During extended dry periods, soil moisture was shown to limit available energy partitioning into ET. As volumetric soil moisture fell below a threshold of 0.15, the evaporative fraction decreased until rain broke the dry period and the evaporative fraction sharply recovered. This observation indicates that lower water availability can result in lower rates of ET at this wetland site.

Annual ET totals measured at the wetland site were compared with those measured at three nearby upland sites dominated by oak, pine, or mixed oak and pine. A previous investigation by the U.S. Forest Service determined that, when averaged across all upland sites for all years of measurement (2005–09), annual upland ET was 606 mm/yr. The average annual ET measured at the wetland site during 2005–06 (801 mm/yr) is about 32 percent higher than the average of that at the upland sites. The average annual ET at the wetland site is about 17 percent higher than ET at the upland sites when averaged over years without disturbance at a particular stand. Factors contributing to differences in ET rates among different sites and among different years include water availability, dominant plant species, and leaf area. Inter-annual variability of wetlands ET may be less than that of uplands ET because the upland sites are more susceptible to periodic drought conditions, disturbance by fire, and insect defoliation.

Three ET models (Priestley-Taylor, modified Hargreaves, and North American Regional Reanalysis) were evaluated to determine their utility in predicting ET at the wetland site using data that may be more readily available in other areas and for other time periods. Of the three models, the modified Hargreaves may be of the most practical use, as it replicated the measured daily ET values reasonably well, and data requirements were relatively easily met. The ET models described in this report are best applied to estimate ET at locations or during time periods for which the environmental conditions are similar to those prevailing during the period of record for which these models were calibrated. Precipitation during the study period at the nearby National Weather Service Indian Mills weather station was slightly higher than the long-term (1902–2011) annual mean of 1,173 mm, with 1,325 and 1,396 mm of precipitation in 2005 and 2006, respectively.

## SUMMARY

Evapotranspiration (ET) was monitored above a wetland forest canopy dominated by pitch-pine in the New Jersey Pinelands during November 10, 2004–February 20, 2007, using an eddy-covariance method. Twelve-month ET totals ranged from 786 to 821 millimeters (mm). Minimum and maximum ET rates occurred during December–February and in July, respectively. Relations between ET and several environmental variables (incoming solar radiation, air temperature, relative humidity, soil moisture, and net radiation) were explored. Net radiation ( $r^2 = 0.72$ ) and air temperature ( $r^2 = 0.73$ ) were the dominant

explanatory variables for daily ET. Air temperature was the dominant control on evaporative fraction with relatively more radiant energy used for ET at higher temperatures. Soil moisture was shown to limit ET during extended dry periods. With volumetric soil moisture below a threshold of about 0.15, the evaporative fraction decreased until rain ended the dry period, and the evaporative fraction sharply recovered. A modified Hargreaves ET model, requiring only easily obtainable daily temperature data, was shown to be effective at simulating measured ET values and has the potential for estimating historical or real-time ET at the wetland site. The average annual ET measured at the wetland site during 2005–06 (801 mm/yr) is about 32 percent higher than previously reported ET for three nearby upland sites during 2005–09. Periodic disturbance by fire and insect defoliation at the upland sites reduced ET. When only undisturbed periods were considered, the wetland ET was 17 percent higher than the undisturbed upland ET. Inter-annual variability in wetlands ET may be lower than that of uplands ET because the upland stands are more susceptible to periodic drought conditions, disturbance by fire, and insect defoliation. Precipitation during the study period at the nearby Indian Mills weather station was slightly higher than the long-term (1902–2011) annual mean of 1,173 millimeters (mm), with 1,325 and 1,396 mm of precipitation in 2005 and 2006, respectively. The methods presented in this chapter can be used for other locations in the world.

## KEYWORDS

Aerodynamic resistance  
Anemometer  
Aquifer  
Atmospheric pressure  
Big leaf assumption  
Bowen ratio  
Bowen ratio energy-budget variant (of eddy covariance method)  
Cypress  
Eddy covariance  
Eddy covariance method  
Energy-budget closure  
Energy-budget variant  
Evaporation  
Evaporative fraction  
Evapotranspiration  
evapotranspiration, Potential  
evapotranspiration, Reference  
Fire  
New Jersey Pinelands  
Hargreaves equation  
Hygrometer  
Inertial sublayer  
Insect defoliation  
Latent heat flux  
National Centers for Environmental Prediction (NCEP)  
Net radiation  
New Jersey  
North American Regional Reanalysis (NARR)  
PAR  
Penman equation  
Penman-Monteith equation  
Photosynthetically active radiation (PAR)  
Pinelands  
Precipitation  
Priestley-Taylor equation  
Residual energy-budget variant  
Residual energy-budget variant (of eddy covariance method)  
Roughness sublayer  
Runoff  
Sensible heat flux  
Soil moisture  
Source area  
Source area (eddy covariance)  
Time-domain reflectometry (TDR)  
Turbulent fluxes  
United States Geological Survey

Uplands  
USGS  
Vapor flux  
Water balance  
Wetlands

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## BIBLIOGRAPHY

Refer to the bibliography for the literature cited.

## LIST OF SYMBOLS IN CHAPTERS 8 and 9

|                    |                                                                                                                                                    |
|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| $a$                | An empirical coefficient equal to a value of 0.0135                                                                                                |
| $b$                | An empirical coefficient equal to a value of 17.8                                                                                                  |
| $B$                | Bowen ratio = the ratio of sensible and latent heat fluxes                                                                                         |
| $C_p$              | Specific heat capacity of air, in J/(g·°C)                                                                                                         |
| $d$                | Momentum displacement height of vegetation, in m                                                                                                   |
| $e$                | Vapor pressure, in kPa                                                                                                                             |
| $E_s$              | Saturation vapor pressure, in kPa                                                                                                                  |
| $E$                | Evapotranspiration rate, in g/(m <sup>2</sup> ·s)                                                                                                  |
| $ET$               | Evapotranspiration rate, in mm/year                                                                                                                |
| $ET_a$             | Reference $ET$ , in the same water evaporation units as $R_a$                                                                                      |
| $F$                | Factor used in krypton hygrometer correction that accounts for molecular weights of air and atmospheric abundance of oxygen, equal to 0.229 g·°C/J |
| $G$                | Soil heat flux at land surface, in W/m <sup>2</sup>                                                                                                |
| $h$                | Canopy height, in m                                                                                                                                |
| $H$                | Sensible heat flux, in W/m <sup>2</sup>                                                                                                            |
| $H_{BREB}$         | Sensible heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method, in W/m <sup>2</sup>                        |
| $K_o$              | Extinction coefficient of hygrometer for oxygen, in m <sup>3</sup> /(g·cm)                                                                         |
| $K_{RS}$           | An empirical coefficient usually estimated as 0.16 and 0.19 for inland and coastal areas, respectively                                             |
| $K_w$              | Extinction coefficient of hygrometer for water, in m/(g·cm)                                                                                        |
| $P_a$              | Atmospheric pressure, in Pa                                                                                                                        |
| $q$                | Specific humidity = g water/g moist air                                                                                                            |
| $r_h$              | Aerodynamic resistance, in seconds per meter                                                                                                       |
| $R_a$              | Extraterrestrial radiation, in the same water evaporation units as $ET_a$                                                                          |
| $R_d$              | Gas constant for dry air, equal to 0.28704 J/°C/g                                                                                                  |
| $R_n$              | Net radiation, in W/m <sup>2</sup>                                                                                                                 |
| $R_s$              | Incoming solar radiation on land surface, in the same water evaporation units as $ET_a$                                                            |
| $S$                | Change in storage of energy in the biomass, air, and any standing water, in W/m <sup>2</sup>                                                       |
| $T_a$              | Air temperature, in °C                                                                                                                             |
| $TC$               | Daily air temperature, in °C                                                                                                                       |
| $TR$               | Daily temperature range, in °C                                                                                                                     |
| $T_s$              | Sonic temperature, in °C                                                                                                                           |
| $u$                | Lateral wind speed along coordinate x-direction, in m/s                                                                                            |
| $v$                | Lateral wind speed along coordinate y-direction, in m/s                                                                                            |
| $w$                | Wind speed along coordinate z-direction, in m/s                                                                                                    |
| $x$                | One of two orthogonal coordinate directions within a plane parallel to canopy surface                                                              |
| $y$                | One of two orthogonal coordinate directions within a plane parallel to canopy surface                                                              |
| $z$                | Coordinate direction perpendicular to canopy surface                                                                                               |
| $z_s$              | Height of sensors above land surface, in m                                                                                                         |
| $z_m$              | Roughness length of canopy for momentum, in m                                                                                                      |
| $\alpha$           | Priestley-Taylor coefficient, dimensionless                                                                                                        |
| $\Delta$           | Slope of the saturation vapor pressure curve, in kPa/°C                                                                                            |
| $\eta$             | Angle of rotation about the z-axis to align u into the x-direction on the x-y plane, in radians                                                    |
| $\gamma$           | Psychrometric constant, in kPa/°C                                                                                                                  |
| $\lambda$          | Latent heat of vaporization, in J/g                                                                                                                |
| $\lambda E$        | Latent heat flux, in W/m <sup>2</sup>                                                                                                              |
| $\lambda E_{BREB}$ | Latent heat flux as estimated by the Bowen ratio energy-budget variant of the eddy covariance method, in W/m <sup>2</sup>                          |
| $\lambda E_{REB}$  | Latent heat flux as estimated by the residual energy-budget variant of the eddy-covariance method, in W/m <sup>2</sup>                             |

|          |                                                                                   |
|----------|-----------------------------------------------------------------------------------|
| $\theta$ | Angle of rotation in the y-direction to align w along the z-direction, in radians |
| $\rho$   | Air density, in $\text{g/m}^3$                                                    |
| $\mu$    | Ratio of molecular weight of air to molecular weight of water                     |
| $\sigma$ | Ratio of vapor density ( $\rho_v$ ) to air density ( $\rho$ )                     |

## Chapter 10

### Water Management in Citrus<sup>1,2</sup>

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#### INTRODUCTION

Water is an important natural resource, a basic human need and of vital requirement for all developmental activities. The demand of water is increasing with increase in population and economic activities. Irrigation has been practiced in India since long ago. It is considered as a very important input for agriculture and hence continuous development has been taking in this field through the centuries. It is a means to mitigate the impact of irregular, uneven and inadequate or wide fluctuations in rainfall from year to year. India's annual rainfall is 117 cm and most of it occurs during monsoon. The irrigation potential in India has risen from 19.5 m-ha in 1950 to 67.89 m-ha in 1985.

The best estimates available indicate that the maximum amount of exploitable irrigation potential by all types of irrigation is 113.5 m-ha. This could be sufficient for 50% of the total cultivable area of the country and 50% of the area, would be left completely dependent on rainfed farming. Conjunctive use of rain and irrigation water offer scope for optimizing water use in areas having problems of surface drainage during, rainy season and water scarcity during the rest of the year.

Citrus is the third largest fruit crop grown in an area of 234570 ha. Nagpur mandarin and acid lime occupies 40% and 25% of the total area under citrus cultivation in the country. The large scale drying of the citrus orchards is mainly due to scarce water resources, frequent drought and lowered water table in mandarin growing areas of Vidarbha (Maharashtra) and Central India (Dass, 11).

The average yield of these orchards is 7 to 8 t/ha which is 3 to 4 times less than other citrus producing countries of the world. Citrus plant are more extracting in their demand for irrigation. Direct contact of water with the trunk adversely affect the trees growth. Citrus being a evergreen fruit crop utilize moisture constantly throughout the year of course at a much slower rate during winter and faster in summer. There is a good amount of research available on irrigation water management of citrus from abroad but a little work has been done under Indian conditions.

There is a need for carrying out the research on estimating the water requirements of the Nagpur mandarin and acid lime under sub-tropical conditions of the Central India. The use of micro-irrigation systems is gaining popularity amongst the citrus growers and it is necessary to standardise the best system for the citrus orchards. The moisture conservation techniques like mulching and fertigation are also equally important for water and fertilizer conservation point. So, the research in this regard is also required to be carried out for optimizing the productivity and efficient use of inputs including water.

#### 1. Irrigation scheduling and water requirement in Citrus

The literature on irrigation methods, irrigation systems, scheduling, water requirements and fertigation in citrus in International and under Indian conditions is reviewed. The literature cited related to water requirement and irrigation scheduling in Citrus is reviewed. The growth of 'Valencia' oranges slowed down at 32 cb and 55 cb soil suctions at 30 cm depth in light and medium textured soil respectively (Hilgeman, and Hewland, 22). The preliminary studies on the effect of soil management system on soil moisture in Sweet orange orchard was initiated by Randhawa *et al.*, (47). Stolzy *et al.*, (76) found that the treatments irrigated at 20 Kpa tensiometer readings were best as compared to calendar schedule. Hashemi and Gerber (19) attempted correlation between actual evapotranspiration (AET) and potential evapotranspiration computed with Penman's model. Koo (25) advised Florida citrus growers to maintain soil moisture at 55 to 65% of field capacity from bloom the young fruit exceeds 1 inch in diameter. Retiz (51) estimated the water requirement of citrus at 40-45 inch/year. Richards and Warnke (53) studied the irrigation systems to lemon and irrigation at 60 cb and extrapolations to 150 cb resulted in no measured differential response in tree growth and fruit yield under coastal conditions. Leyden (28) found that 610 mm irrigation water applied via a drip system at 0, 200, 300 and 400 liters/tree gave the significant difference in total yield and fruit size distribution.

Toledo *et al.*, (79) found that irrigation at 65% field capacity caused drought injury symptoms, excessive defoliation and less water consumption. Best results were obtained with irrigation at 85% field capacity. Evapotranspiration ranged from 3.78 to 4.42 and 1.46 to 1.3 mm/day for 85% and 65% field capacity irrigations respectively. Kelin (24) compared drip irrigation scheduling according to soil water potential to class A pan evaporation in different horticultural crops using a crop factor and concluded that 12 to 23% water could be conserved by using the irrigation scheduling based on soil water potentials. Moreshet *et al.*, (34) compared the 100% and 40% of soil volume irrigation in 'Shamouti' orange and found that partially irrigated plot was 66% of that of the fully irrigated plot one.

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<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

Transpiration from the trees of partially irrigated plots was 72% of that of the fully irrigated plot and the evaporation from the soil surface was 58%. Fruit TSS and acid contents were higher in partially irrigated plots. Smajstrla *et al.*, (71) found that greatest yields were obtained using spray-jet trickle irrigation. Yield increases were not linear with volume of rootzone irrigated but ranged from 39% for the drip irrigation treatments which irrigated 5-10% of the area beneath the tree canopies to 64% for 2-spray jet per tree, which irrigated 50.7% of the areas beneath the tree canopies.

Plessis (38) obtained the highest yields (190 kg/tree) and the largest average fruit size with irrigation at a crop factor of 0.9 on a 3 day cycle, with thin consumption micro-irrigation gave better results than drip irrigation. Makhija *et al.*, (31) obtained water need for 6 year old Kinnow mandarin varying from 539 to 1276 mm depending upon the level of irrigation with average consumptive use of water in 2 years as 61.5 cm. Smajstrla *et al.*, (73) concluded that the tree growth of young 'Valencia' orange was greatest when irrigations were scheduled at 20 centibar for no-grass and 40 centibar for the grass treatments. Randhawa and Srivastava (48) emphasized on irrigation aspects in Citriculture in India. Autkar *et al.*, (1) studied the distribution of active roots of Nagpur mandarin as it can be useful in planning irrigation nutrition, planting density and drainage management. The root depth and radial extent for trees aged 1-4 years was 7.5-8.0 cm deep and 5-12.5 cm respectively and for 10 years old age tree it was 2-3 m and 80-90 cm. Barbera and Carimin (4) studied the different levels of water stress on yield and quality of lemon tree and found that yield was lower in most stressed plot. The number of flower/m<sup>3</sup> of canopy was higher in most stressed treatment indicating a relationship between severity of stress and flowering response. Mageed *et al.*, (30) carried the research on influence of irrigation and nitrogen on water use and growth of Kinnow mandarin receiving 4 levels of irrigation and three levels of Nitrogen (0, 115 or 230 Kg N/tree). The consumptive use varied from 66.7 cm to 132.5 cm. Moreshet *et al.*, (35) studied on water use and yield of a mature 'Shamouti' orange orchard submitted to the root volume restriction and intensive canopy pruning.

Du Plessis (40) with a mature 'Valencia' orange trees and field experiment shown that the water use pattern over the entire season reaching a maximum of 87 lit/day in January. Highest net income was obtained with tensiometer scheduling. He (1989) also demonstrated that 690 liters irrigation when tensiometer reaching fell to -50kpa gave the highest net income. Use of tensiometer rather than evaporation pan scheduling could save 2000 m<sup>3</sup> water/ha annually. The water requirement of citrus plants varies with species, season and age governed with different climatic conditions. Plant growth retards below certain critical level of available moisture depending upon soil type, climatic factor and plant genetic make up (Rajput, 46). Autkar *et al.*, (2) also studied the effect of Pan evaporation, canopy size and tree age on daily irrigation water requirement of 1-5, 5-8 and above 8 years old Nagpur mandarin trees over 9 months (October-June) and concluded that the requirement rose with age. Ghadekar *et al.*, (17) estimated that the consumptive use of Nagpur mandarin by modified Penman equation using 40 years air temperature, relative humidity, wind velocity and Solar relation data. Under clean cultivation the water requirement of young, middle age and mature trees was 651.9, 849.0 and 997.3 mm/year respectively. An equation for daily water use was proposed and it can be used for drip irrigation. Sanehez *et al.*, (57) compared five flood irrigation treatments with daily drip irrigation at 0.475 Epan and concluded that the drip irrigation gave higher yields as compared to flood irrigated plants. Castel and Buj (8) carried out trials on mature 'Satsuma' average trees grafted on Sour orange rootstocks. Plants were irrigated with 60% of the estimated ET losses from a class A pan and 80% of the control throughout the year. Irrigation treatments affected both yield and fruit quality.

Ray *et al.*, (49) studied the response of young 'Kinnow' mandarin to irrigation. Irrigations were scheduled at -0.05, -0.1, -0.2, -0.4 and -0.8 MPa soil water potential 0.8 IW/CPE ratio and irrigation to replenish estimated crop ET. The water use increased as the frequency of irrigation increased as the frequency of irrigation increased. The highest bio-mass per plant was obtained when irrigation was scheduled at -0.05 MPa soil water potential (SWP) and 18-19 irrigations were required. The best tree growth in terms of trunk diameter, plant height, canopy volume, leaf number and shoot growth was also obtained at -0.05 MPa SWP using 182.4 cm water/tree/annum. He also studied (50) the effect of irrigation on plant water status and stomatal resistance in young Kinnow mandarin and found that the leaf water potential (LWP) and Relative water content (RWC) declined considerably with reduction in soil moisture in rootzone due to differential irrigation schedules. Reduction in RWC was more conspicuous where soil moisture dropped below 11% LWP measurements in early morning hours showed a significant curvilinear relationship with soil water status. Leaf stomatal values were lowest in September and highest in January. Shirgure *et al.*, (60) initiated the irrigation scheduling based on depletion of available water content and fraction of open pan evaporation in acid lime in pre-bearing stage. He studied (68) the effect of different soil moisture regimes with irrigation scheduling based on available soil moisture depletion and open pan evaporation on soil moisture distribution and evapotranspiration in acid lime and it was concluded that the evapotranspiration varied from 213.6 mm to 875.6 mm in various irrigation schedules. It was also found that the change in soil-moisture distribution in the rootzone of acid lime plants varied from 195.9 mm to 321.3 mm with different irrigation schedules.

## 2. Irrigation methods and drip irrigation systems in Citrus

The common methods of applying water to the orchards are basin, border strip, furrow, sprinkler and drip irrigation. Ring basin is generally followed in early establishment phase of fruit trees. Micro-irrigation to citrus is common in developed countries. Drip and microjet irrigation has the advantage over surface irrigation methods, for more uniform and complete wetting of the soil surface and adoption on sloppy terrain.

Faton (12) observed better tree growth and yield, less weed growth, evaporation and leaching with 16 gallon water applied through drip to each 4 years old lime trees at two weeks interval compared to 320 gallon water in flood irrigation. Fritz(15) observed that all applied water is transferred directly to rootzone of plants and 20-50 % water saving is reported depending on soil and climate. Raciti and Sckderi (44) compared drip irrigation with the basin and found that the fruits under drip system were more acid and lower maturity ratio. Ronday *et al.*, (55) observed better tree growth and less water consumption in Valencia orange under drip irrigation in sandy soil Suckderi and Raciti (58) compared basin irrigation with

different combination of drip irrigation and measured number, weight, quality of fruits in Valencia orange. He also studied micro-nutrient levels in leaves, annual trunk increments. Drip irrigation gave the higher yields. Simpson (69) found that there is a shift from furrow irrigation and over head sprinkler irrigation systems to under tree systems like microjets. Slack *et al.*, (70) demonstrated that trickle irrigation on young orange trees used 5400 liters of water compared to 23400 liters of water per tree for dragline.

Raciti and Barbargallo (45) found that the yields of lemon was more with localized irrigation amounting to 227.23 q/h and 213.2 q/h for basin irrigation. Ozsan *et al.*, (37) compared furrow, under tree, over tree and drip irrigation in lemons. amounts of water applied were greatest (1286 mm) with under tree method and least (207 mm) with drip irrigation system. Yield was more with over tree sprinkling and least with furrow. Water use efficiency was high in drip irrigation. Cevik and Yazar (9) demonstrated that a new irrigation system i.e. Bubbler irrigation for the orchards. He observed that under tree sprinkling and drip irrigation had the best pomological effects. Amounts of water applied per tree for over sprinkling, under sprinkling and drip irrigation were 22.01, 17.04 and 10.33 m<sup>3</sup>/season. Pyle (43) appraised the use of micro-irrigation in Citrus especially drip irrigation. Except the higher cost the advantages includes saving in labour, water and power, better orchard uniformity and immediate response to crop need, better soil-water relationships, rooting environment and better yield and quality.

Tash be kov *et al.*, (78) studied different irrigation methods. Drip irrigation and under tree sprinkling produced the highest yield with the least water requirements. The application rate for drip irrigation of 4 years old lemon trees was 7400 m<sup>3</sup>/ha annually. Capra and Nicosia (7) studied flooding, sprinkler, and sub-irrigation with sprays and concluded that the rates of water application affects the rate of growth of fruit diameter. Robinson and Alberts (54) compared under canopy sprinkler and drip irrigation systems in crop like Banana and found that the drip irrigation is superior to under canopy sprinklers. Increased tree growth and yield were recorded in young Valencia orange under drip irrigation method with emitter placed at distance of 1 meter from the trunk (Azzena *et al.*, 3). Greive (18) concluded that under tree micro-sprinklers increased yield by 12% and reduced water application by 9.3% compared to conventional full ground cover. Interligolo and Raciti (23) demonstrated that water saving with sub-surface irrigation was 32% over the traditional basin irrigation. The yield was higher but fruit quality was not much different. Marler and Davies (32) studied the effect of micro-sprinkler irrigation scheduling on growth of young Hamlin orange trees and found that growth was not affected by pattern of irrigation, suggesting that 90% emitters are enough for root system. Zekri and Parsons (80) studied drip, micro-sprinkler and overhead sprinkler irrigation at two water application rate and found that fruit size and tree canopy area were 9 to 20% greater in the overhead sprinkler treatments. Marler and Davies (33) studied the growth response of micro-irrigation on growth of young Hamlin orange and found that more than 90% of root dry weight was within 80 cm of the trunk at the end of first growing season.

Rumayor *et al.*, (56) studied three irrigation systems (drip, micro-sprinkler and flooding) and found that yields were higher for sprinkler irrigated trees and the fruits were smaller in flood irrigation. Smajstrala (74) researched on micro-irrigation for citrus production in Florida. Gangwar *et al.*, (16) studied the economics of investment on adoption of drip irrigation system in Nagpur mandarin orchards in Central India and concluded that the drip irrigation system is technically feasible and economically viable with Benefit to Cost ratio as 2.07. Shirgure *et al.*, (64) initiated the research work on evaluation of micro-irrigation systems in acid lime and a comparison was done with that of basin (ring) method of irrigation. Shirgure *et al.*, (66) studied the effect of dripper 8 liters per hour microjet 300<sup>0</sup>, microjet 180<sup>0</sup> and basin irrigation method on water use and growth of acid lime and found that microjet 300<sup>0</sup> recorded higher growth than rest of the systems. He also studied (67) the efficacy of these micro-irrigation systems and basin irrigation on fruit quality and soil fertility changes in acid lime.

### 3. Fertilization in citrus

Fertilization in application of liquid or water soluble solid fertilizer along with irrigation through the drip irrigation to the plants. It has many advantages like increasing fertilizer-use efficiency, ensured supply of water and nutrients, labour saving and improvement in yield and quality. It is a very new under Indian conditions but getting popular along with adoption of drip irrigation system.

The research related to injection of fertilizers through the drip irrigation systems was started during 1979 by Smith *et al.*, Koo (26) appraised the potential advantage of micro-irrigation systems and its usefulness to fertigation. Bielora *et al.*, (6) advocated use of fertigation technology in citrus as it resulted in higher production of good quality Shamouti oranges. He compared N fertigation at 100, 170 and 310 Kg/ha with broadcast application at 170 kg/ha through irrigation system. Phosphatic and potash fertilizers were given at same rate by conventional method in all the treatments. Average yields for 4 years were 62, 73 and 82 mg/ha with 100, 170 and 310 kg N/ha, through fertigation.

Koo and Smjstrala (27) supplied 15% and 30% of crop N and K requirements through fertigation and rest through conventional method to Valencia orange. Partial fertigation of N and K resulted in lower N contents of leaves. TSS and acid concentration in juice was also reduced but yield was not affected. Haynes (20) discussed the principles of fertilizer use for trickle irrigated crops. He (1988) also studied the comparison of fertigation with broadcast applications of urea on levels of available soil nutrients and on growth and yield of trickle irrigated peppers. He found that growth and yields were greatest at the low rate of N applied as fertigation or as a combination of broadcast plus fertigation.

Fouche and Bester (14) tried various fertilizer combinations through fertigation on 13 year old Navel oranges. Fertigation was given with a soluble fertilizer 'Triosol' (3:1:5) + 350 gm Urea by broadcast, fertigation of N and K with broadcast of single super phosphate and NPK through broadcast. Highest yields was obtained with fertigation of NPK through Triosol or by complete broadcasting of NPK fertilizers. No significant differences were observed as fruit size, acidity, percent juice content and TSS among treatments. Beridze (5) conducted trial on 5 year old lemon tree and fertilized 150 kg N + 120 kg P<sub>2</sub>O<sub>5</sub> + 90 kg K<sub>2</sub>O per hectare as basal dressing. The highest yield of 6.6 ton per hectare was obtained from trees fertilized with



basal dressing + 250 kg peat/tree as a mulch + FYM at 25 t/ha. Ferguson (13) studied the fertigation as growth of 'Sunburst' tangerine trees. Two years old citrus *reticulata* x *C. paradisi* cv. Sunburst was fertilized with 0.66 or 1.32 lb N/tree during 1988-89 and it was 0.52 or 1.05 lb N/tree during 1990. Leaf analysis showed that low to deficient concentrations of N, K, Mn and Zn with both N treatments. Zekri and Parsons (80) tried micro-nutrients through fertigation with different sources of various rates. Inorganic forms ( $\text{NO}_3$  and  $\text{SO}_4$ ) were ineffective in evaluating micro element levels in oranges. But chelated sources of Fe, Mn, Zn and Cu were very effective and their rates of application were comparable with rates through foliar applications. Neilsen *et al.*, (36) studied that fertigation with calcium ammonium nitrate showed increased vigour and leaf Ca concentration but decreased leaf Mg and Mn compared to trees fertigated with Urea or ammonium nitrate ( $\text{NH}_4\text{NO}_3$ ) in apple trees. Fertigation with P increased early tree vigour, leaf and fruit P concentration and decreased leaf Mn.

Syvevtsen and Smith (77) studied the nitrogen uptake efficiency and leaching losses from lysimeter grown trees fertilized at three nitrogen rates. He concluded that Average N uptake efficiency decreased with increased N application rates, overall canopy volume and leaf N concentration increased with N rate, but there was no effect of N rate on fibrous root dry weight. In the first 5 years of the experimentation fertigation did not provide a significant enough yield advantage over banded application to warrant the added cost of the fertigation equipment and higher labour requirement. A very little work was done on fertigation in India. The fertigation research in citrus was initiated during 1995 at NRC for Citrus on acid lime. Shirgure *et al.*, (61 and 62) studied the effect of differential doses of Nitrogen fertigation in comparison with band placement of fertilizer application on leaf nutrients, plant growth and fruit quality of acid lime during pre-bearing stage. The percentage increase in plant height, stock girth and canopy volume was more with 100 % N fertigation followed by 80 % N of recommended dose in acid lime. He also (63 and 64) studied that effect of N fertigation on soil and leaf nutrient build-up and fruit quality of acid lime.

## FUTURE WATER MANAGEMENT STRATEGIES IN CITRUS

- a. Citrus is a very sensitive crop. Any excess or deficit of water even for a short duration adversely affect its growth and productivity. Irrigation scheduling based on scientific principles like available water content, soil water potential and potential crop evapotranspiration is in practice in developed countries. The efficiency of different methods of irrigation scheduling varies with climate, irrigation method and citrus species. Since micro-irrigation systems are gaining popularity among the farmers due to scarcity of water resources and Govt. subsidy for these systems. A modern system of irrigation will effectively used if it is backed by scientific principles of irrigation application. The water management research pertaining to the citrus is still in a preliminary stage. There is urgent need to evolve efficient irrigation scheduling for citrus crops in different regions of India.
- b. Irrigation scheduling definitely help in maximising the utilisation of water resources and boosting the productivity. Scheduling using tensiometers of various depths, neutron moisture probe, climatological approach like modified Penman equation and water balance approach should be studied. Irrigation scheduling based on canopy temperature and leaf water potential may also be studied for better yield and quality.
- c. Method of irrigation scheduling varies with the irrigation system adopted. It needs to be standardised for both system adopted. It needs to be standardised for both conventional and modern methods like drip, sprinkler, microjet etc. Infiltration rates, water distribution and retention parameters vary greatly with soil composition and structure. Thus study on these aspects will help in formulating the scientific water management.
- d. Another aspect which requires immediate attention is that water requirement and root distribution of fruit crops increases with age. Therefore suitable design needs to be evolved which should enable to irrigate the entire root zone with required quantity of water. A farmer should use the installed system for longer period without much modifications which incur high cost otherwise.
- e. Citrus growers in Central India give water stress to induce flowering. In absence of any scientific information, farmers apply water stress according to the past experience. Plants are subjected to stress to the extent where complete restoration of vigour may be possible in all the plants. Relationship needs to be established between water stress and flowering on one hand and water stress and plant growth on the other hand. These in turn should be related to soil characteristics. Farmers should have idea about the duration of stress required for different kind of soils.
- f. The modern micro-irrigation systems have one potential advantage of giving soluble fertilizer through irrigation water known on 'fertigation'. It not only saves labours, fertilizer but gives higher yield and better quality. The fertilizers through water is applied to the rootzone which increases fertilizer use also. A comprehensive research related to different NPK soluble fertilizers, their rates and frequency of application at different growth stages of plants are required to be researched.
- g. Since the water available for irrigation is becoming scarce day by day. The applied water to the tree root zone needs to be conserved for longer period and that is possible with mulching. The material available to the farmers from the farm itself like grass, leaf litter, straw and trashes can be used for mulching. It not only helps in moisture conservation but also in thermal regulation, disease control and weed control. The research is required on use of organic (grass, straws, leaf litter and trashes) and synthetic (polythene sheets) mulches. The basin area of the citrus trees will be covered with above mulch material and effect may be studied on water saving, growth and yield of the trees. The synthetic mulches are commercially available. But in case of organic mulches around 5cm thickness of the mulch is required to be maintained uniformly in all the basins. All these strategies mentioned above are definitely make efficient use of water and enhances productivity in citrus.

## SUMMARY

Irrigation management is one of the prime concerns of modern citriculture irrespective of water resource availability. A variety of recommendations have emerged world over on irrigation scheduling based on analysis of meteorological pedigree, evapotranspiration, depletion of available water content, soil and leaf water potential. The review of literature has revealed best promising results on irrigation scheduling based on depletion pattern of soil available water content. Various micro-irrigation systems have established their superiority over traditionally used flood irrigation with microjets having little edge over rest of the others. Similarly, fertigation has shown good responses on growth, yield, quality and uniform distribution pattern of applied nutrients with the rootzone compared to band placement on other methods involving localized fertilization. Automated fertigation in citrus orchards is a new concept, which would be the only solitary choice of amongst many irrigation monitoring methods in near future.

## KEYWORDS

Acid lime  
Acidity  
Band fertilizer application  
Basin irrigation  
Black polythene mulch  
Canopy volume  
Citrus  
Drainage  
Drip irrigation  
Drippers  
Fertigation  
Fertilizer use efficiency  
Field drains  
Flowering  
Fruit quality  
Fruits  
Grass mulch  
Harvesting  
High density planting  
Input use efficiency  
Iron  
Irrigation  
Irrigation scheduling  
Juice percent  
Leaf nutrient composition  
Lemons  
Maturity period  
Micro-jet irrigation  
Micro-jets  
Mulches  
Mulching  
Nagpur mandarin (*C. reticulata* Blanco)  
Net returns  
Nitrogen  
Nutrient management  
Nutrient uptake  
Orchard efficiency  
Orchards  
Organic farming  
Organic mulches  
Phosphorous  
Plant growth  
Potash  
Production  
*Rangapur* lime  
Rootstock  
Rough lemon  
Scion girth

Stock girth  
Surface irrigation method  
Thermal balance  
Total soluble solids  
Trickle irrigation  
Water requirement  
Water stress period  
Water use  
Water use efficiency  
Weed population  
Weight  
Yield  
Zinc

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Refer to the bibliography for the literature cited.

## Chapter 11

### Vegetation Water Demand and Basin Water Availability in Mexico<sup>1,2</sup>

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#### INTRODUCTION

During the last decade, the riparian zones have received considerable attention in order to restore and manage them since they have an important role to plan water resources and land, among other functions in the ecosystem. The riparian zones are mainly located in the flood plain where the soil is characterised to be alluvial. However, arid zones channels and their floodplain are transitory and subject to frequent and rapid changes [12,13], thus there is not a clear distinction from where the channel finish and the floodplain starts. This condition could be disadvantageous to the vegetation settled in the floodplain which is subject to the floods' force, the wood debris and eroded sediments carried by. Conversely, this vegetation has the advantage to receive organic matter from the debris and minerals from the eroded soil resulting in a straightforward species capable to survive at adverse conditions [6]. The adaptation of this vegetation generates species drought and flood resistant. In the first case, plants develop long roots in order to access groundwater and be wet. In the second case, plants can afford inundation since the modification of the hydraulic roughness reduces the flood velocity and spread seeds increasing the moisture and nutrients availability in the area [6].

However, the access of the riparian vegetation to ground water produces high rates of transpiration and a high evaporative demand of the atmosphere. This is because water requirements are bigger in arid and semiarid regions, where rainfall is less and the vapour pressure deficit on the air is large. This implies great water consumption by this vegetation becoming as one of the components to be considered in the groundwater balance. Particularly, in semiarid sites where groundwater is the main water demand source, since water surface resources are highly compromised, temporal and spatially. Scott et al. [27] observed that as groundwater is used to provide water among the different users, there is a depletion of the water levels that affects directly the riparian zones and, in consequence, modify ecology and hydrology of the watershed.

Scott et al. [27] pointed out that in order to compute riparian water requirements it is common to use hydrological models that compute it as the residual discharge resulted after calibrated against known inputs, groundwater levels and discharges. This procedure could over or underestimate the groundwater balance in the basin, thus a better understanding of this component is needed to improve water demand among the users. In order to guarantee a better management of the river basins, Mexico has made different water reforms through the last three decades. Some of these reforms deal with the increasing water over-exploitation and, particularly, there were established aquifers management councils supported by a national water law [30]. In order to compute precise riparian water requirements, it is necessary to consider both internal (vegetation growth characteristics) and external conditions (atmosphere, plant and soil characteristics) of the vegetation [8]. The external conditions can be achieved computing the evapotranspiration (ET), which depends of the solar radiation, vapour pressure, wind speed and direction, stage of the plant development, and soils features as soil moisture, among others. Conventional methods can be used to compute ET, but there are also remote sensing methods that have the advantage to consider its spatial and temporal variability. Currently, there are not many studies focused on native riparian zones, researches have mainly carried out analysis for cropped income areas.

This chapter presents the study to establish the water requirement of native vegetation (mesquites and elms) along the main channel and in the floodplain of the Sonora River corresponding to the Pesqueira, Topahue, Ures, La Mesa-Seri and Horcasitas aquifers. To address the water requirements, the ET was estimated using remote sensing techniques based on the energy balance. The study was considered for two hydrological cycles (1996-1997 Spring-summer and 2002-2003 autumn-winter), in particular, for the dry season since the Sonora River tributaries are dry and the flow in the main channel reaches its minimum level. The chapter also presents the importance to consider a temporal and spatial analysis, for determining the water requirements of the riparian vegetation and its impact on the river basin water budget.

#### THEORETICAL METHODS FOR EVAPOTRANSPIRATION

Evapotranspiration (ET) is the total moisture lost to the atmosphere from the land surface when the vaporisation process starts as function of the input energy received and the vegetation present. Lakshmi and Susskind [18] described ET as a "useful tool", not only because it provides information that can be applied directly in the water budget, but also because ET has a high sensitivity which can be used to define some biophysical parameters. ET has been studied at different scales [21] providing a wide knowledge of how ET is affected or how it can affect the whole system [20]:

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<sup>1</sup> Judith Ramos Hernandez, PhD, Chemical Engineer, F.J. González, L. Marrufo and R. Dominguez, Institute of Engineering, National Autonomous University of Mexico, University Avenue 3000, 04510 Coyoacan – Mexico D.F. – Mexico. EMAIL: jramosh@ingen.unam.mx. This project was funded by the Sonora State Water Commission (CEA) in 2005 and by the Instituto de Ingeniería, UNAM, in 2008.

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<sup>2</sup> Numbers in parentheses indicate the bibliographical references in the bibliography.

1. Macro (e.g. impact of changes in available moisture on cloud formation, radiation budget and precipitation);
2. Meso (e.g. depletion of soil moisture, and therefore, crop water requirements of irrigated lands and partitioning of precipitation); and
3. Micro (e.g. crop water requirements).

In order to assess ET impacts on the water balance, and in consequence, on the land and water management, ET is defined for a specific crop and land condition. Thus, potential ET (ET<sub>p</sub>) considers a reference surface as grass with a crop height of 0.12 m, a fixed surface resistance of 70 s.m<sup>-1</sup> and an albedo of 0.23, whereas crop ET (ET<sub>c</sub>) is the rate of ET from disease-free, well fertilised crops, grown in large fields under optimum soil water conditions, and achieving full production under the given climatic conditions. The actual ET (ET<sub>a</sub>) refers to the ET from crops grown under management and environmental conditions that differ from the standard conditions [Allen et al. 1998, 2].

In general, the physics of the ET process is well understood, thus accurate ET values at local level are provided. However, as ET is highly sensitive to various land and atmospheric variables, particularly in their spatially distributed form, it makes regional ET estimations uncertain [7]. This uncertainty increases when the ET contribution from riparian vegetation needs to be considered to determine the water budget [11].

Although some authors have studied the direct and indirect influence of the riparian ET into the water availability in a basin [11], this vegetation is still poorly understood being a non-easy task to explain its hydro geomorphological influence since it interacts environmentally at different scales [6].

To compute actual riparian evapotranspiration (ET<sub>a</sub>) is complex since the vegetation communities are non-uniform linear varying in geometry, altitude and season. Also, the organisation and dynamics of the vegetation are strongly related to the channel river and its floodplain, thus the geomorphological process and forms define the pattern for the different aggregation communities maintained by the fluctuations of water discharge (Figure 1). Goodrich et al. [11] pointed out that this condition limits the application of traditional ET computations since the required fetch conditions are not achieved and in a strict term the definition of potential ET [2] did not apply due to differences in the canopy architecture, available energy, water availability and boundary layers differences between the atmosphere and leaf surfaces, among others. Additionally, only in few cases the crop coefficient has been defined for each riparian type [11].



**Figure 1.** Riparian vegetation along the Sonora River in Mexico.

## TRADITIONAL METHODS FOR EVAPOTRANSPIRATION

The relationship between the different ET definitions (potential, crop and actual) is not always determined easily, but an accurate value is required for different uses and users. Favourably, at regional scales whatever the type of ET, these are not independent of each other. For example, during the crop growing period, water needs to be diverted on to the field to meet the ET<sub>c</sub> demands and to compensate losses by seepage and percolation in order to maintain a saturated root zone. Thus, the estimation of ET<sub>p</sub> is crucial to obtain ET<sub>c</sub> rates and moreover to compute ET<sub>a</sub> values as the response to different reasons that generate non-standard conditions such as climate, pest, contamination, water shortage or water logging.

In the Sonora River Basin (SRB) and others semi-desert basins in Mexico, the Turc equation [28] have been used to estimate the hydrological water balance and to infer the groundwater balance since very few aquifer data is available. Other condition to apply the Turc equation is that the average ET<sub>a</sub> is used for longer periods in order to reduce to zero the water retention in the basin. The Turc equation is defined as:

$$\text{if } \left(\frac{P}{L}\right)^2 > 0.1; \quad \text{ET}_{\text{actual}} = \frac{P}{\sqrt{0.9 + \left(\frac{P^2}{L^2}\right)}} \quad /1/$$

$$\text{or } \left(\frac{P}{L}\right)^2 < 0.1; \quad \text{ET}_{\text{actual}} = P$$

$$L = 300 + 25 * \text{Ta}_{\text{prom}} + 0.05 * \text{Ta}_{\text{prom}}^3 \quad /2/$$

Where: P is the precipitation and T is air temperature. Sometimes equation /2/ is modified considering T at the power of 2 instead of 3 without any reason. The constant value of 300 in equation /2/ corresponds to the base runoff in the basin. Thus, L could increase above 300 as function of the T and ETa is related directly to rainfall. In 1964, the Truoc equation was modified by changing the 0.9 coefficient by 1.0 [Pike 1964, 29]. Despite to the simplicity of this method a high uncertainty is associated to it. Other methods based on meteorological data have been used such as Blaney-Criddle which is a temperature-based method that can be applied to different climates in a monthly base [11] or the Hargreaves-Samani equation that considers the air temperature and the extraterrestrial radiation [1]. However, these types of methods are recommended only when data is not available. However, when data is available it is recommendable to use the Penman-Montheith (PM) equation [2] but a crop coefficient accurate is necessary to compute ETc. Gazal et al. [10] applied the PM method to compute the transpiration of cotton/willow forest. The PM equation was inverted in order to asses the seasonal variation in stomatal resistance, results showed that the spatial and temporal heterogeneity of water availability modified the physiology of these riparian vegetation.

## ADVANCED METHODS FOR EVAPOTRANSPIRATION

Although riparian ETa values have been obtained with good accuracy using traditional methods and compared with available ET measurements for local areas, ETa values for large areas are still problematic. Also, it has been demonstrated by some authors such as Schultz and Engman [26] that studies based only on conventional field data collection are often limited because they cover a specific area. In addition, the lack of available and reliable data is a big constraint in the application of different methods to compute accurate ET values. As riparian vegetation interacts environmentally at different scales, remote sensing techniques have been shown to be a reliable alternative to estimate ET, since some of the main constraints about suitable and available data can be overcome providing a precise spatial representation. One important advantage is that it provides detailed and independent ET estimations on a pixel-by-pixel basis among other data as mapping soil properties based on the reflectance variations, land use and land cover using the spectral signatures of vegetation, water requirements, monitoring water availability, and detecting some properties like water stress effects. This wide range of alternative data offers new possibilities for managing soil, water and land resources efficiently.

Remote sensing techniques have provided accurate estimations of ETa at several scales as a function of the spectral resolution of the satellite sensors. ETa can be estimated using data that describes the conditions in the soil-plant-atmosphere system. Thus, remote sensing provides specific information of some of the parameters involved in the ET estimation such as surface temperature, surface soil moisture, water vapour gradients, surface albedo, vegetative cover and incoming solar radiation.

According to Kite and Droogers [17], methods and methodologies developed to estimate evapotranspiration (ET) using remote sensing data can be classified into four categories: i) satellite-derived feedback mechanisms, ii) biophysical processes based-model, iii) surface energy balance techniques, and iv) physically based analytical approaches. Qi et al. [24] noticed that the canopy temperature is lower than the air temperature as water evaporates result of the heat extracted from the canopy leaves and from the air near to the canopy surface. This implies a temperature difference and the “Surface Energy Balance Techniques (SEB)” can be applied because they are based on the spatial and temporal variability of the surface temperature (Ts) and air humidity as a reflection of the partitioning of net radiation available to the surface into soil, sensible and latent heat fluxes release to the atmosphere. Thus, the ET is obtained as the residual component of the energy balance equation:

$$\lambda E = [R_n - G - H] \quad /3/$$

Where:  $R_n$  is the net surface radiation ( $Wm^{-2}$ ),  $G$  is the soil heat flux ( $Wm^{-2}$ ),  $H$  is the sensible heat flux ( $Wm^{-2}$ ) and  $\lambda E$  is the latent heat flux ( $Wm^{-2}$ ). These methods estimate each parameter of the surface energy balance equation, which are characterised for a diurnal variation and are subject to significant changes from one day to another. To determine these critical variables, these methods first related the flux parameters of the energy balance in terms of variables such as the soil moisture profile, the surface, ground and near-surface air temperatures, and near-surface humidity. The algorithm employed was MEBES (Surface Energy Balance to Measure Evapotranspiration) that was based on the process theory of the original algorithm SEBAL (Surface Energy Balance Algorithm for Land) developed by Bastiaanssen et al. [3, 4] applying some modifications to the data and condition of the region. The algorithm was chosen since it presents major advantages to compute ETa values among other SEB techniques [25] using both remote sensing and meteorological-ground data for local and regional areas.

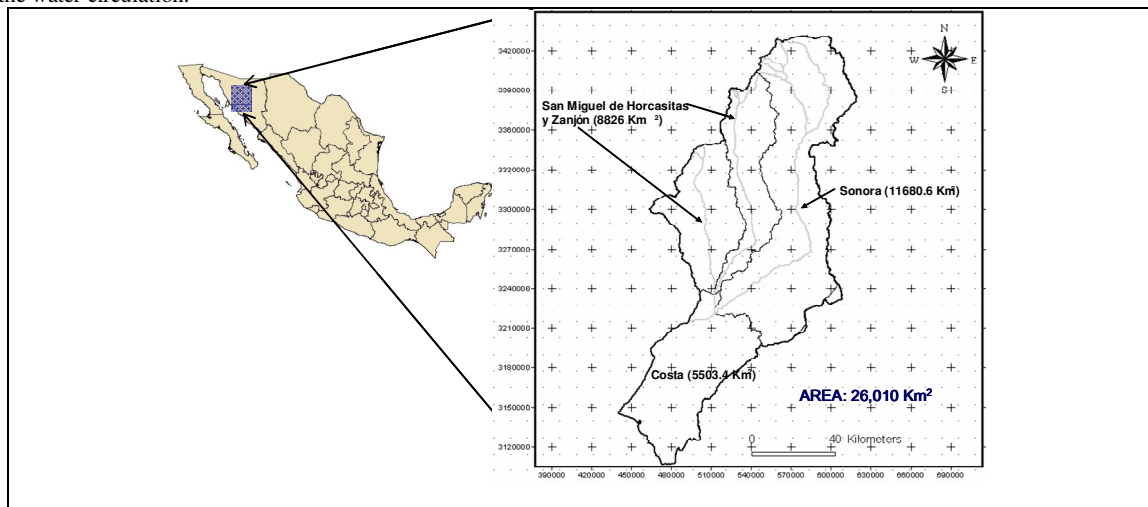
## SONORA RIVER WATERSHED

This research was conducted in the Sonora River Basin (SRB), that is located in the north-centre of the Sonora State in Mexico at the extreme latitude: 28°27' to 30°54' N and longitude: 110°06' to 111°03' W coordinates. The Sonora River Basin (SRB) is part of the Hydrological Region No. 9 and it has a total surface of 26,010 Km<sup>2</sup> almost 14.8% of the Sonora state. The SRB limits at the north with the USA and at the south with the Cortes Sea. The main river is the Sonora with 277 Km of longitude, starting at the north in the Cananea City with the union of several streams which down from the Magallanes, Los Ajos and Bacanuchi Mountain ranges. Then the river flows to the south crossing the Bacoachi, Chinipa, Arizpe, Banámichi, Baviácora, Ures and Hermosillo cities. In the last one the San Miguel de Horcasitas and el Zanjon affluents join the main river; both of them from the same basin. Finally, the Sonora River goes to the Coast but due to the sandy soil it disappears before reach the sea [INEGI 2000, 14]. The Figure 2 indicates the divisions of the SRB: the Zanjóna and San Miguel de Horcasitas (8826 Km<sup>2</sup>), Sonora (11680.6 Km<sup>2</sup>) and the Coast watersheds (5503.4 Km<sup>2</sup>).

The Sonora River has an erratic behaviour and, frequently, the runoff is concentrated into few days during the year. The river flow is controlled by a dam system that includes the Abelardo Rodríguez and Rodolfo Félix Valdés (El Molinito) dams with a total storage capacity of 525 Hm<sup>3</sup> [14]. Physiographically, the SRB is divided into two subprovinces [14]:

- Mountain ranges and North Valleys Subprovincia belonging to the Western Mother Mountain Range Province formed in the mountains by volcanic acid rocks with intrusive igneous outcrops and in the valleys by continental sediments. The mountain system is steep from 1000 to 2620 meters above sea level (masl). The weather is dry and semidry and varies as function of the altitude from warm and semi-warm to temperate and semi-cold.
- Sonorenses' Mountain range and plain subprovincia belongs to the Sonorenses' Desert covering 2/3 of the SRB. This subprovincia is characterised in lower mountain ranges separate by plains being the mountains narrower than the plains; the plains have 80% of the total area. In the central basin intrusive and lavic igneous rocks predominated as well as metamorphic, ancient limestone and Tertiary conglomerates. In the plains alluvial fans are present with smooth slopes from the near mountains. The weather is very dry semi warm and warm.

There is a high climatological variation observed at the SRB as result of the accidental topography with more than 1000 masl in the mountains and less than 100 masl in the coastline. The climate variation produced two severe droughts (1982-1983 and 1997-1998) which have been related with El Niño event [IPCC 2007, 15]. In fact, during 90s there were three events related to El Niño: 1991-1992, 1993-1994, 1997-1998, and in 2000s two events more in 2002-2003 and 2004-2005 [NOAA 2008, 22]. The mean annual precipitation is 376 mm with a runoff coefficient of 2.8% being the main use the agriculture, followed by domestic, industrial, livestock and recreational. During the drought season it is necessary the groundwater extraction which is used in agriculture (93%), domestic and commercial (4.8%), industry (1.5%) and the rest 0.7% in livestock, recreational and others. The intensive use of groundwater in agriculture has generated an overexploitation of the aquifers present in the SRB. The aquifers are characterized according to the subprovinces in the SRB, thus for the Mountain ranges and North Valleys the non-consolidates material gave a lower infiltration capacity as result of the metamorphic, sedimentary (limestone and conglomerates) and acid extrusive (tuff and riolites) rocks which have a low breaking and porosity reducing the water circulation. Opposite to the Sonorenses' Mountain range and plain subprovincia where non-consolidates materials present a high infiltration capacity since the presence of gravel and sand with different sizes and porosity favouring the intercommunication to the water circulation.



**Figure 2.** The Sonora River Basin and its watersheds: Sonora, Zanjón, San Miguel de Horcasitas and the Coast.

The climatic and topographic variation in the SRB provides a diversity of vegetation: pine woods in the north and mesquites (drought tolerant) in the rest of the basin, except irrigated areas aside the rivers and in the coast. The SRB vegetative coverage is quite similar to the state condition due to the extension of the basin, thus almost 50% of vegetal communities correspond to temperate climates under aridity conditions where drought-deciduous low woodlands of thorny and non-thorny trees and bushes are predominant. The thorny shrubs such as Gobernadora (*Larrea tridentata*), Mesquite (*Prosopis laevigata*), Palo Verde (*Parkinsonia aculeata*) and Sangregado (*Jatropha cuneata*) are mainly allocated in hills around the San Miguel de Horcasitas and its affluents, as well as in Bacanuchi, Arizpe and Ures towns (Figure 3).

The 20% of the vegetation coverage are other type of mesquites as sarcocaulous scrubland that is a subtype of the xerophyllous scrubland and elms (*Ulmus americana*) [León de la Cruz et al. 2008, 19]. These communities are in flat and deep soils, runoff areas, over yermosls, fluvisols or xerosols (Figure 4).

Grassland represents 13% of the total vegetation and two types can be found in the area: native and introduced. The first one is represented by bluegrass plants and some herbaceous and shrubs used to livestock. The second one is related to the agriculture practise with only 3% of the total (Figure 5a). Pine-oak forest and pines with herbaceous secondary vegetation represents 11% of the total vegetation and they can be found in subhumid temperate climates (mountain ranges) (Figure 5b).

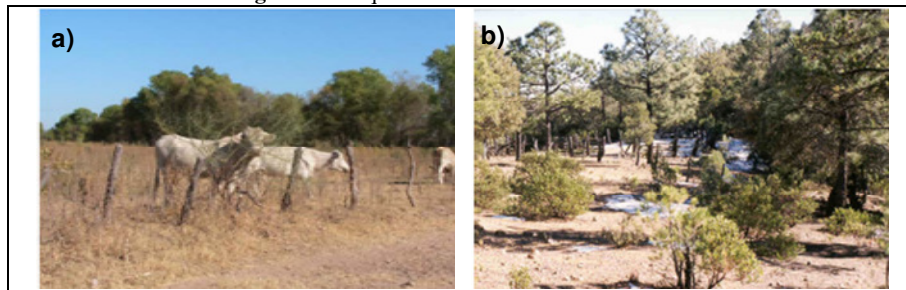




**Figure 3.** Mesquite scrubland along the Sonora River and floodplain.



**Figure 4.** Mesquites as sarcocaulous scrubland.



**Figure 5.** (a) Grassland for livestock and (b) pine-oak forest at the SRB.

Finally, introduced vegetation is 6.61% from which more or less 4% are agriculture lands where more than 95% of irrigation and the rest is rainfed. Crops are perennial as Lucerne, walnut and sugarcane and seasonal as ryegrass, barley, fodder oats, wheat, garlic and onion for autumn-winter period and fodder sorghum, beans, maize, and vegetables. The winter crops (i.e. wheat) showed a high vulnerability for prolonged drought seasons, thus farmers seemed to change into drought resistance crops or more economically productive crops, especially once the government stopped subsidizing grains.

## METHODS AND MATERIAL

The methodology was divided into three steps: firstly an evaluation of the climate variation, after that a land cover classification was performed in order to identify those areas where the riparian vegetation is present. In this case drought-deciduous low woodlands of thorny and non-thorny trees and bushes were analysed, in particular, thorny shrubs such as mesquite (*Prosopis laevigata*) and eml (*Ulmus americana*). Finally, MEBES was applied to estimated ETa and analysed to determine its influence to compute the water availability in the SRB.

### Climatic Data Analysis

The climatological data available include traditional weather stations (CLICOM database) recording precipitation (P) and air temperature (T) (maximum and minimum), and Observatorios weather stations recording P, T, relative humidity, wind speed and isolation hours. Three Observatorios were analysed: Hermosillo within the SRB, and Nacozari and Empalme at the North and South, respectively, of the neighbour basin at the East.

The CLICOM dataset was updated to 2004 for the Sonora state and it has registered 273 stations. Two filters were applied in order to obtain complete and continuous data for a 20 year period. The results obtained were from 21 stations distributed throughout the entire basin. In order to analyze how the variables related to climate vary in time and space; essential for any study over large areas, data mining techniques were employed. Grouping techniques such as K-means (non-hierarchical) and Ward (hierarchical) methods were evaluated and the result was the basin division into three regions: north, central and south. This definition of homogeneous zones represents the climatic variation in the area accurately.



### Remote Sensing Data Analysis

Two hydrological cycles were studied: spring-summer, 1996-1997, and autumn-winter, 2002-2003. LandSat images were acquired (Table 1) as well as aerial photographs orthorectified.

The images were used for both classification of the riparian vegetation and estimation of the riparian ETa. For classification, it was considered the spectral response of vegetation to the Visible (VIS) and Infrared (IR) electromagnetic spectrum. A high reflectivity is presented in the near IR as consequence of the leaves structure and in the medium IR where the spectral response is affected by the water content in the surface and a low reflectivity observed in the VIS because the chlorophyll absorption. Also, it was observed the dynamics of the stream interact close with the riparian community characterized by the grow form, size, density, and aerial coverage of the plants [Fischenich and Copeland 2001, 9].

The images were submitted to a pre-processing analysis to extract useful information from the images, and also to enhance them, to aid in the visual interpretation, and to correct or restore the images if these were subjected to geometric distortion, blurring or degradation. The pre-processing methods used include enhancement of the image, radiometric, atmospheric and geometric corrections, and the georeference of the scene for a chosen map scale and coordinate system.

In order to estimate the ETa, the first part involves the determination of the land surface physical parameters from spectral reflectance and radiance. This stage estimates surface albedo ( $\alpha_0$ ), emissivity ( $\epsilon_0$ ), surface temperature ( $T_s$ ), vegetation indices (NDVI and SAVI), fractional vegetation coverage ( $P_v$ ) and leaf area index (LAI), and the roughness height (or height of the vegetation,  $z_0$ ). Here ground data are required, however, if the data are not available, it can be replaced using the vegetation indices and considering a standard crop height of 1.0 m. The second stage includes the introduction of meteorological data such as air temperature, humidity, and wind speed at a reference height. The reference height is the measurement height at the weather station (2 m). The last stage includes the estimation of the energy flux parameters and obtains ET as the residual form of the energy balance equation [Bastiaanssen and Bandara 2001, 5].

## RESULTS AND DISCUSSION

### Classification

To achieve the classification, vegetation indices were used since they represent a direct relation to the vegetation health linking the biomass and the leaf area index (LAI) in a spatial basis. In particular, the normalised difference vegetation index (NDVI) was used as well as the soil and wetness indices in the temporal analysis. Additionally, bands 5 and 7 of Landsat were applied to separate areas with high soil moisture, in order to differentiate between irrigated lands and riparian vegetation. The reason to use bands corresponding to the medium IR is to cover a major reflective spectrum allowing the observation of watered overages. Finally, LAI was also monitored, this parameter offers advantages since the geometrical, size and other conditions for the riparian vegetation is very characteristic.

**Table 1.** Date and path/row of the Landsat satellite images acquired to the USGS.

| Sensor | Date of acquisition | Path/row       | Day of the year (DOY) |
|--------|---------------------|----------------|-----------------------|
| TM     | 1997/03/04          | 35/39<br>35/40 | 63                    |
|        | 1997/05/23          | 35/39<br>35/40 | 143                   |
|        | 1997/06/24          | 35/39<br>35/40 | 175                   |
| ETM+   | 2003/03/29          | 35/39<br>35/40 | 88                    |
|        | 2003/04/30          | 35/39<br>35/40 | 120                   |
|        | 2003/01/31          | 35/39<br>35/40 | 31                    |

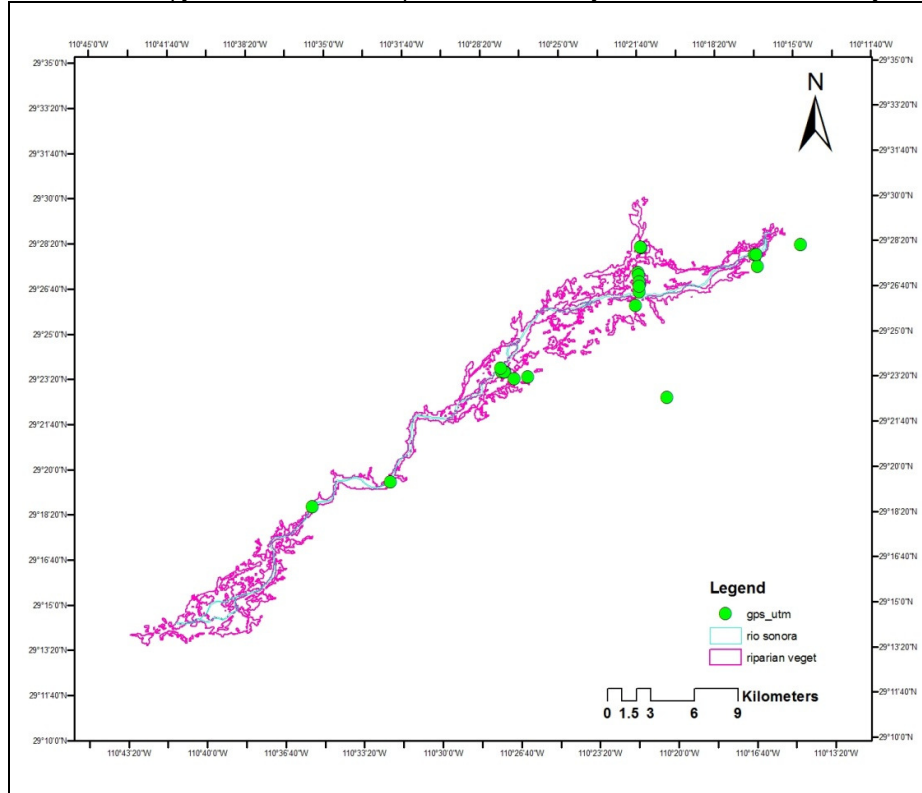
A supervised classification was performed using the NDVI values for each image available, then other classification was done to a multi-temporal image generated with the NDVI values. This classification allowed the identification of temporal homogenous areas. Finally, a multi-temporal image was produced using a combination of the vegetation, soil and wetness indices, and the ratio between bands 5 and 7. The number of classes was established into 6, as the main interest was the aggregation of riparian vegetation thus mesquites, elms, palo verde, grass, water and bare soil were selected and the agriculture zones were removed from the images. The error matrix showed a confident level of 12% associated to a mix between palo verde and mesquite, and to a very small surface. Figure 6 illustrates the aggregation of elms, mesquites and some herbaceous vegetation in the Ures and Topahue aquifer.

The number of hectares obtained for elms was 68% bigger than the mesquites one within the 2000 ha in the Topahue and Ures region. The mesquite tree is a drought resistance obligate phreatophyte and indicator of the water table, and soil and nitrogen fixed, thus it controls the erosion and the soil fertility. The mesquite tree can be 10 m tall and its roots can go up to 50 m deep reaching the water table, also it has lateral roots that can be extended to 15 m. However, as riparian areas are characterised by the growth form, size, density, and aerial coverage of the plants aboveground, it made elms the predominant species since they are a taller facultative phreatophyte usually with 12 to 15 m in height, although they can reach 20 to 30 m or more (Figure 7).

As well as mesquites, the roots of elms have the ability to go deep to get water, thus the elms can survive during the drought period. The elms have lateral surface roots that go deep as they need to gather nutrients for the photosynthesis process, approximately from 5 to 20 cm. As elms growth well in moisture and drainage soils, the first precipitation or runoff is enough to obtain the water they need. Elms seeds can be disseminated by wind and water.

The grass area or other secondary herbaceous vegetation was also important for the number of hectares covered (1090 ha). It was observed in the floodplain as a groundcover of the riparian vegetation and their presence is related to the amount of flooding and the radiation allowed by the trees.

Elms LAI [Leaf area index] values for DOY143 were from 0.7 until 2.0 being the lowest ones during the drought season, whereas for mesquites were from 1.2 to 2.0, these values agreed with Kiniry [1998(16)]. LAI for grass or herbaceous vegetation growing around the riparian corridor was between 0.2 and 0.4, and in well irrigated orchards was between 3 and 4. Gazal et al. [10] found that LAI is more sensitive in intermittent streams sites than in perennial ones due to the depth water table, thus plants modified their canopy structure in order to cope with water scarcity as it was observed in the study site.



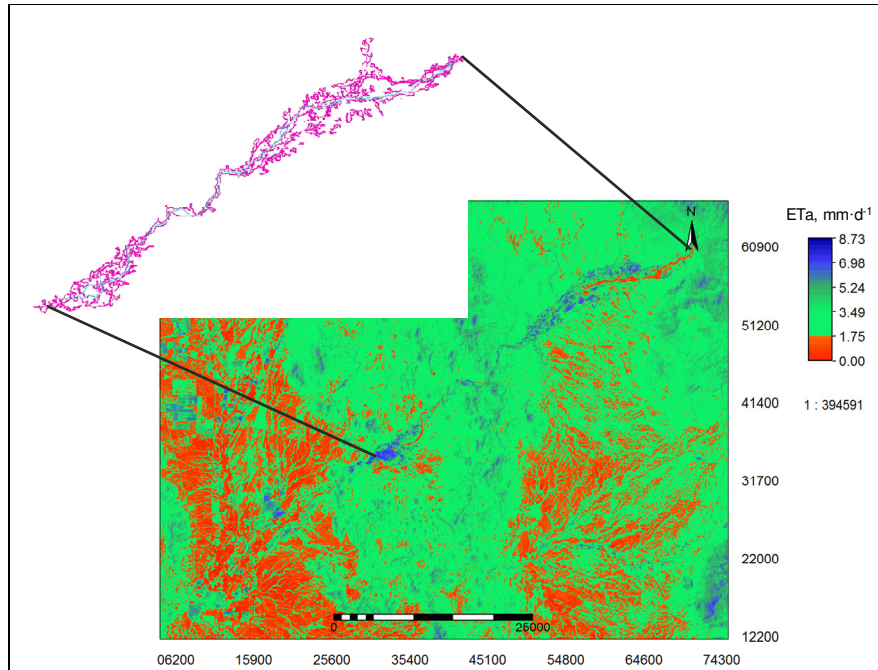
**Figure 6.** Elms and mesquites distribution following the river channel and the floodplain and the gps points used in the supervised classification.

#### ACTUAL EVAPOTRANSPIRATION [ $ET_a$ ] ESTIMATIONS

Average  $ET_a$  values in DOY63 (after winter) showed for elms and mesquites  $2.1 \text{ mm}\cdot\text{d}^{-1}$  and  $1.5 \text{ mm}\cdot\text{d}^{-1}$  for ground cover grass of the riparian vegetation, respectively. It was observed a similar  $ET_a$  rate for elms and mesquites and irrigated orchard. At this time the orchard is less irrigated since the fruit development is not impacted thus important water saving is made. For DOY143 and DOY120 during spring-summer where dry conditions are presented having more sunshine hours during the day, the average  $ET_a$  values were from 5 to  $8 \text{ mm}\cdot\text{d}^{-1}$  for riparian, and less than  $1 \text{ mm}\cdot\text{d}^{-1}$  for their groundcover grass. Also,  $ET_a$  values observed in mature orchard (more than 5 years old) and very well irrigated crops such as Lucerne were quite similar to riparian. The water evaporation was about  $28 \text{ mm}\cdot\text{d}^{-1}$  in these DOYs (Figure 8).



**Figure 7.** Elms predominance over mesquites and other thorny and non-thorny shrubs.



**Figure 8.** Actual evapotranspiration [ET<sub>a</sub>] values for DOY143.

A 20 year climatological analysis at the centre of the SRB showed that temperature starts to rise from March until June where it reaches its maximum peak (28°C) as well as the wind speed with values of  $5.2 \pm 0.2 \text{ km}\cdot\text{h}^{-1}$ , contrary to the precipitation that reach its minimum value in May (11 mm). The monsoon season starts late July and August increasing the relative humidity to  $50 \pm 5\%$ . As the monsoon rains did not wet the saturated zone for DOY143, the climatic conditions imply a high vapour exchange between the surface and the atmosphere, thus the water necessities of the plants need to be covered to prevent wilting and the only source of water is from the aquifer. Due to the elms are located along the main channel their facultative conditions help them to obtain water at bit deep, thus drought conditions impact less although they are more exposed to radiation. This condition is not the same for mesquites where the main disadvantage is the size competence with elms receiving less energy and being protected from the strong winds. Mesquites as obligate phreatophytes needs to go deep to reach the water table establishing a high soil water dependence and, in consequence, reducing their hydraulic capacity to carried water from the roots to the stomata cavities as Gazal et al. [10] noticed for cottonwood.

## SUMMARY

The riparian vegetation has a very important role in the ecosystems not only because they are a habitat to flora and fauna species but also because they provide some hydrological control, particularly when flood and drought are present. The vegetation structure is highly related to the geomorphological process of the region being determinant in the valleys where the fluvial soils supply adequate conditions to the development of these plants. Also, the environmental and climatological conditions provide important characteristics since in arid and semi-arid zones the main river channel and the flood plain are undistinguished as result of the erosion and sediments deposition allowing the growth of obligate and facultative phreatophytes as well as herbaceous groundcover vegetation. This resulted in a hydro geomorphological influence on the vegetation being severely affected but at the same time benefit by flooding and developing the capacity to survive under drought conditions.

In early stages the hydrological regime and the available energy are the main factors to control ET from riparian corridors, although these conditions change as the vegetation growth. Also, as the dry conditions are a limitation, the plant's capacity to extract water from the aquifer is determinant during their mature lives.

The similitude between the irrigated land and the riparian corridor implies a good water resource, in the first case irrigation is the explanation but in the second the only one possibility is the adaptation of plants to obtain water from the aquifers reaching their roots the water table after the depletion of the soil moisture in the saturated zones.

In the SRB, 95% of irrigation is provided by groundwater extraction with an average volume of  $5 \text{ m}^3\cdot\text{s}^{-1}$  for a total cropped area of 12,300 ha in 2003. In the Ures and Topahue region the cropped lands were almost 2000 ha in 2003 with a total volume of  $1.5 \text{ m}^3\cdot\text{s}^{-1}$ , as ET<sub>a</sub> values were similar to very well irrigated lands, this would imply a volume of  $6.6 \text{ m}^3\cdot\text{s}^{-1}$  for riparian corridors considering elms, mesquites and grass. This raw estimation pointed out the amount required from the aquifer to cope with irrigation and riparian corridors without consider other uses. This amount needs to be carefully used since there is not still enough data to provide confident recharge values to these aquifers (Ures and Topahue), however, it is clear the high influence of the ET<sub>a</sub> to compute water requirements in arid zones. Further work is required in order to compute accurately each component of the water balance paying also attention to the precipitation and interception effect on the riparian corridor since its rapid recovering after the first precipitation during the monsoon months.

## **KEYWORDS**

Aquifer  
Arid zone  
Drainage  
Evaporative demand  
Evapotranspiration  
Flood plain  
Irrigation  
Leaf area index  
MEBES  
Mexico  
Photosynthesis  
Phreatophytes  
Remote sensed data  
Riparian vegetation  
SEBAL  
Semi-arid zone  
Sonora – Mexico  
Sonora river  
Sonora river watershed  
Transpiration  
Water availability  
Water demand  
Watershed

## **BIBLIOGRAPHY**

Refer to the bibliography for the literature cited.

## Chapter 12

### Water Conservation for Turfgrass<sup>1,2</sup>

#### INTRODUCTION

Turfgrass irrigation practices have come under intense scrutiny in recent years due to concerns over increasing population growth and diminishing water availability. Municipal water restrictions have become commonplace and more recently, the U.S. Environmental Protection Agency has developed guidelines that would restrict irrigation and/or amount of turf within the landscape [15]. Thus, turfgrass managers are increasingly faced with the challenge of maintaining acceptable turfgrass quality using less water. Understanding the minimal irrigation requirements and extent of water stress that a particular turfgrass species can tolerate while exhibiting acceptable quality is therefore highly valuable information for turfgrass managers and homeowners.

Deficit irrigation is the practice of intentionally under-irrigating of a plant to below its maximum water demand. This practice has been long used in crop production, where it often culminates in overall reductions in growth, development, and yield. Turfgrass systems are perhaps uniquely adapted for deficit irrigation because reductions in shoot growth are perceived to be beneficial, as long as visual and functional quality are not significantly sacrificed. Deficit irrigation has been practiced across a number of species, although the particular level of irrigation needed to maintain acceptable quality appears to vary among species. Using minilysimeters in the field, DaCosta & Huang [2] determined that bentgrass species required  $\geq 60\%$   $ET_a$  for maintaining acceptable summer quality, but that irrigating at only  $40\%$   $ET_a$  was sufficient for maintaining acceptable quality during fall months. Qian and Engelke [9] found that minimal irrigation requirements for grasses grown along a linear gradient of irrigation ranged from  $26\%$  to  $68\%$  of Class A pan evaporation ( $E_p$ ) in a study of five turfgrass species along a linear gradient of irrigation. Feldhake et al. [3] studied deficit irrigation of three turfgrass species grown in lysimeters and determined that irrigation deficits up to  $\sim 27\%$  only decreased growth, but greater deficits resulted in significant loss of quality for Kentucky bluegrass and tall fescue.

Zoysiagrass is a warm-season ( $C_4$ ) turfgrass native to Southeast Asia, but has become an increasingly popular turfgrass for use on lawns and golf courses throughout the southern half of the United States and many other tropical, subtropical, and temperate regions of the world [14]. Whereas some turfgrass species are capable of avoiding drought through production of a deep root system, physiological studies indicate that zoysiagrass tolerates drought largely through osmotic adjustment [10]. Very little information is available regarding the minimal irrigation requirements or response of this species to deficit irrigation practices. Therefore, this chapter presents the research on how to determine the response of 'Empire' zoysiagrass to four levels of deficit irrigation and to identify the maximally acceptable irrigation deficit at which acceptable turf quality could be maintained in this species.

#### MATERIALS AND METHODS

This study was carried out from August 27 through October 15, 2008 in a greenhouse at the University of Florida campus in Gainesville, FL. 'Empire' zoysiagrass (*Zoysia japonica* Steud.) was grown in pots constructed from 10 cm diameter, 20 cm tall PVC pipes fitted with a flat end cap. A small hole was drilled into the center of each end cap for drainage. The top, open end of the pipes was fitted with a toilet flange for attaching a photosynthesis chambers. Four weeks prior to deficit irrigation studies, zoysiagrass sod pieces (2.5 cm depth) were removed from established, sand-based research plots at the University of Florida G.C. Horn Memorial Turfgrass Research Field Laboratory, Citra, FL, using a 10-cm diameter golf cup cutter. The sod was washed free of soil and established atop medium-coarse textured sand in PVC pots. A complete slow-release fertilizer (24-5-11, Turfpro Professional, Sanford, FL) was applied and grasses were grown in the greenhouse for four weeks to fully root in the soil prior to deficit irrigation experiments. Greenhouse temperatures during the study period were controlled at  $32/22^\circ\text{C}$  (day/night). During this time, grasses were clipped weekly at a height of 6.4 cm. Visual observations confirmed that grass roots had reached container bottoms at the start of the experiment. A full cover of turf was also present on all pots at the start of the experiment, so that water loss was primarily a function of transpiration.

The study was initiated by fully saturating all pots. Following 24-hour period, when drainage had ceased, holes in pot bottoms were plugged to prevent drainage for the duration of the six-week study. At this time, four pots were randomly selected to be fully watered controls; and the initial, well-watered weights of these pots were measured. These pots were kept fully watered throughout the study by adding water daily in an amount equivalent to  $100\%$  of  $ET_a$ , measured gravimetrically. In order to more rapidly attain the desired water stress levels within the irrigation deficit treatments, drought-stress treatments were allowed to dry down the soil as a result of transpirational water loss, as described by Sinclair and Ludlow, 1986 [12]. Four plants were assigned to each of four deficit irrigation treatments ( $80\%$ ,  $60\%$ ,  $40\%$ , and  $20\%$  of  $ET_a$ ), which were initiated by allowing soil water content to decrease below that of fully watered controls prior to the beginning of the experiment. For example, in the  $80\%$   $ET_a$  treatment, plants were allowed to decrease soil water content until the daily transpiration was measured to be  $80\%$  of that for well-watered plants. Upon reaching  $80\%$  relative transpiration (RT) rate, this stress level was permanently maintained by replenishing the pots daily with  $80\%$  of  $ET_a$ .

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Printed with permission and modified from: "Benjamin Wherley, 2011. *Turfgrass growth, Quality and Reflective Heat Load in Response to Deficit Irrigation Practices*. Chapter 18, pages 419-431 In: *Evapotranspiration* by Leszek Labedzki (Editor), ISBN 978-953-307-251-7, InTech. Available from: <http://www.intechopen.com/books/evapotranspiration/turfgrass-growth-quality-and-reflective-heat-load-in-response-to-deficit-irrigation-practices>".

<sup>2</sup> Numbers in parentheses refer to references in the bibliography.

The number of days of soil dry down required to reach targeted stress levels varied from 2 days for 0.8 RT (80% ET<sub>a</sub>) to 6 days for the 0.2 RT (20% ET<sub>a</sub>) stress treatment. As each of the stress treatments were reached, irrigation was returned to pots daily at 100% (controls), 80%, 60%, 40%, or 20% of ET<sub>a</sub>. ET rates within the water stress treatments were also measured each afternoon to determine water loss, and corresponded highly to the prescribed irrigation amounts added to the respective treatments (data not shown). As such, ET of deficit treatments maintained a steady state proportional to fully irrigated controls.

Over the course of the six weeks, data were collected including daily ET rates, turfgrass visual quality, clipping dry weights, degree of leaf wilt and firing, photosynthetic rates, and reflective heat load in response to deficit irrigation. Turfgrass visual quality was visually estimated on a 1-9 scale, with 6 representing minimally acceptable turf (Morris & Shearman, 2006). For measuring clipping dry weights, grasses were clipped to 6.4 cm weekly, with clippings oven dried at 65 C for 72 hrs. Percent leaf wilt and firing were determined weekly by visually estimating the percentage of leaves within the 10 cm diameter plug that were either wilted or firing during the afternoon on a clear day. A portable chamber system modified from that described by Pickering et al., 1993, was used to measure canopy photosynthetic rates within the treatments at the conclusion of the study. This involved a portable photosynthesis system (LI-6200, LI-Cor Inc., Lincoln, NE) with an open leaf chamber mounted inside the translucent canopy chamber (figure 9). Chambers caused a 20% reduction in incoming photosynthetic active radiation (PAR). Three readings were recorded for each pot on a cloudless day during the afternoon hours, during which PAR levels within chambers always exceeded 1200  $\mu\text{mol m}^{-2} \text{s}^{-1}$ . Temperatures inside chambers during the measurement period averaged 37.7  $\pm$  0.2 C. Canopy net photosynthetic rate (Pn) was expressed as CO<sub>2</sub> uptake per unit turf canopy area ( $\text{m}^{-2}$ ). Reflective heat load from within the treatments was determined with a handheld Crop Trak Mini IR thermometer (Spectrum Technology, Plainfield IL) by measuring leaf canopy temperatures during the afternoon on a clear day.

## RESULTS AND DISCUSSIONS

The objective of this study was to determine the response of 'Empire' zoysiagrass to four levels of deficit irrigation, provided daily. Actual evapotranspiration (ET<sub>a</sub>) and (equivalent to irrigation requirements) for control plants over the 42-day study ranged from 2 to 9 mm d<sup>-1</sup>, with total irrigation volume applied of 246 mm (Figure 1). Deficit irrigated treatments received a total of 197 mm (80% ET<sub>a</sub>), 157 mm (60% ET<sub>a</sub>), 126 mm (40% ET<sub>a</sub>), and 101 mm (20% ET<sub>a</sub>).

### Visual Quality

Our results demonstrated that irrigating zoysiagrass at > 60% of ET<sub>a</sub> was sufficient to sustain acceptable turfgrass quality over the six-week study (Figures 2 and 8). Conversely, visual quality of 40% ET<sub>a</sub> treatments gradually declined over the study, but fell to unacceptable levels after five weeks. Within two weeks of initiating treatments, turf receiving 20% ET<sub>a</sub> declined rapidly to unacceptable levels characterized by rapid wilt and significant leaf firing throughout the entire turf canopy. Previous work has shown that irrigating to 80% ET<sub>a</sub> twice weekly was necessary to maintain acceptable zoysiagrass quality [4] and irrigating above 73% ET<sub>a</sub> three times weekly was necessary for maintaining adequate Kentucky bluegrass quality [3]. Our results indicate that acceptable zoysiagrass quality may be achievable at even greater irrigation deficits if irrigation is supplied with greater frequency.

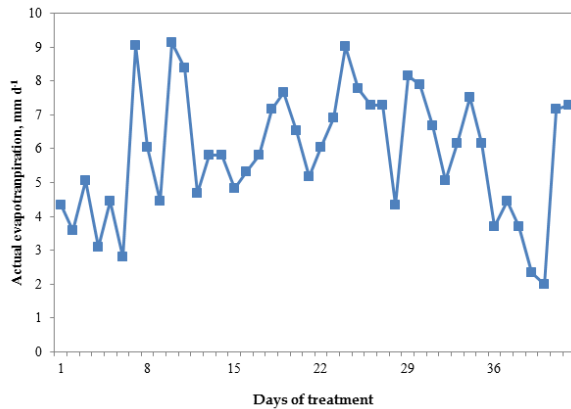
### Photosynthesis and Shoot Growth

Canopy photosynthetic rates of fully watered (100% ET<sub>a</sub>) plants exceeded that of all deficit irrigated treatments and decreasing irrigation amounts resulted in proportional reductions in photosynthetic rates (Figure 3). Rates of photosynthesis ranged from an average of 6.1  $\mu\text{mol m}^{-2} \text{s}^{-1}$  at 100% ET<sub>a</sub> to 0.8  $\mu\text{mol m}^{-2} \text{s}^{-1}$  at 20% ET<sub>a</sub>. This is not surprising, given that dry matter accumulation and transpiration have been shown to be intimately linked to leaf gas exchange through stomata [13].

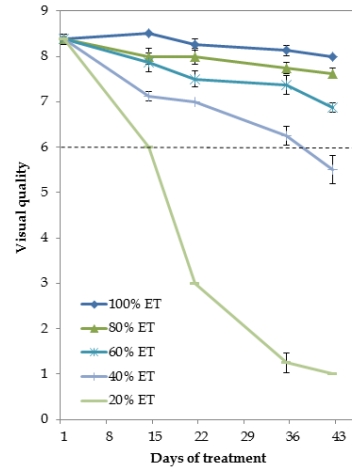
Shoot growth is a process that is dependent on increases in cell volume, and thus, is generally highly sensitive to water deficit. Turfgrass shoot growth in this study was measured by weekly clipping collections, and was found to be progressively reduced with decreasing irrigation (Figure 4). Our data show that reducing irrigation to levels of 60% of ET<sub>a</sub>, while causing little change in overall quality, led to as much as 25% reductions in shoot growth. Increased rates of turfgrass shoot growth have been correlated with higher turfgrass ET in a number of other warm and cool-season turfgrasses [1, 11, 6]. Interestingly, while there was generally a proportional decrease in transpiration and shoot growth as deficits increased; shoot dry weights did not change between the 60% and 80% ET<sub>a</sub> treatments. Thus, in terms of shoot growth, transpirational water use efficiency was greatest at 60% ET<sub>a</sub> with this species (data not shown). From a practical standpoint, whereas soil water deficits may negatively affect field crop yields, moderate growth reductions in turfgrass systems may actually be desirable, as they could result in less mowing requirements.

### Leaf Wilt and Firing

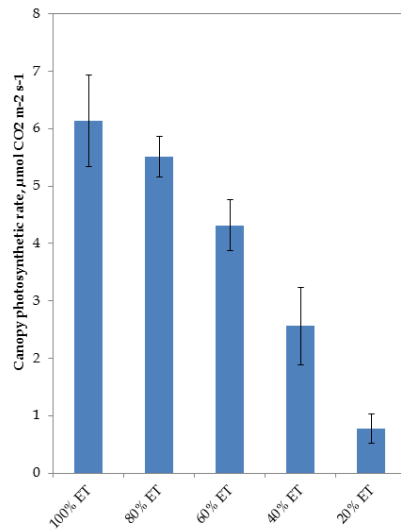
Leaf wilt and firing were the primary symptoms of plant water stress leading to quality loss in grasses receiving  $\leq$  60% of ET<sub>a</sub> in the study (Figures 5 and 6). Leaf canopies of 20% ET<sub>a</sub> plants declined most rapidly, with half of the canopy wilted within two weeks of initiating treatments, and becoming almost entirely fired by week six. 40% ET<sub>a</sub> plants were nearly 50% wilted, with 30% of the canopy firing by week six. Only 5-10% of the canopy in 60% ET<sub>a</sub> plants showed signs of wilt or firing; thus, quality was deemed acceptable throughout the study. Zoysiagrass irrigated at  $\geq$  80% ET<sub>a</sub> never showed signs of wilt during any measurement period, indicating that soil moisture was sufficient to meet transpirational demand.



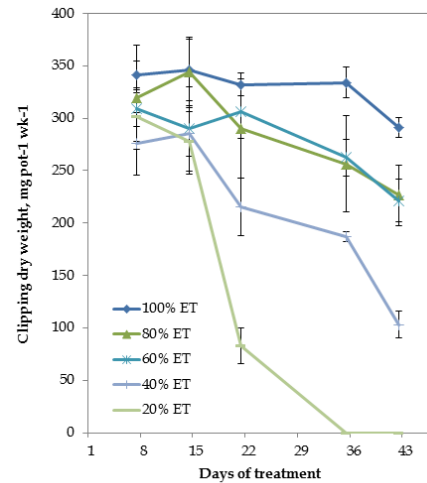
**Figure 1.** Mean evapotranspiration ( $ET_a$ ) rates for 100% ET control plants over the six week study. Amounts are equivalent to the daily irrigation supplied to 100% ET control plants, with deficit ET treatments receiving a fraction (80, 60, 40, or 20%) of this amount.



**Figure 2.** Visual quality of turfgrass plants over six-week experiment, based on a 0-9 scale, with 0 = brown, dead turf, 6 = minimally acceptable and 9 = optimal color, density, and uniformity. Error bars denote standard error of the mean ( $n=4$ ).



**Figure 3.** Canopy photosynthesis rates measured at the conclusion of the six-week study. Error bars denote standard error of the mean ( $n=4$ ).



**Figure 4.** Clipping dry weights collected weekly from 81  $cm^3$  pots. Error bars denote standard error of the mean ( $n=4$ ).

### Reflective Heat Load

A substantial amount of incident solar radiation is converted to latent heat during the transpiration process. Therefore, vegetated surfaces such as turfgrass systems possess significant cooling capacity and play a critical role in heat dissipation within urban areas. It has been reported that green turfs and landscapes can save energy by reducing the energy input required for interior mechanical cooling of adjacent homes and buildings [5]. Decreasing irrigation levels for water conservation conserves resources and maintenance requirements, but it also is likely to substantially impact reflective heat loads. Over the five sampling dates, we observed up to a 16 °C increase in canopy temperatures from fully irrigated to 20%  $ET_a$  irrigated turf (Figure 7). Interestingly, this heat load difference was reduced by half when irrigation was only slightly increased to 40%  $ET_a$ , due to the presence of significantly more green vegetation (Figure 8). Our data for zoysiagrass are similar to those of [3], who reported a 1.7 °C increase in Kentucky bluegrass canopy temperature for each 10% reduction in  $ET$ . While a non-irrigated control treatment was not used in this study, it seems likely that even greater heat loads would result from turf receiving no irrigation, as no living vegetation would likely be present. From a practical standpoint, these data suggest that large-scale landscape deficit irrigation practices, such as those mandated through municipal water restrictions, could contribute to significantly increased surface temperatures.



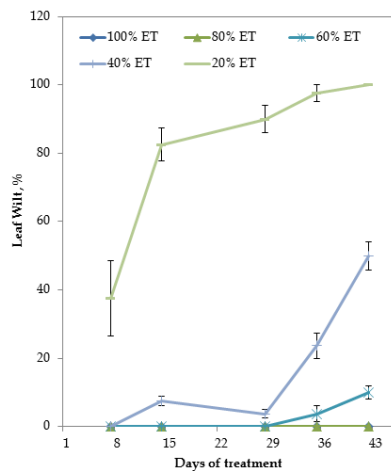


Figure 5. Percentage of leaf wilt visible within the 81 cm<sup>2</sup> turfgrass canopy. Measurements were obtained during mid-afternoon hours on cloudless days. Error bars denote standard error of the mean (n=4).

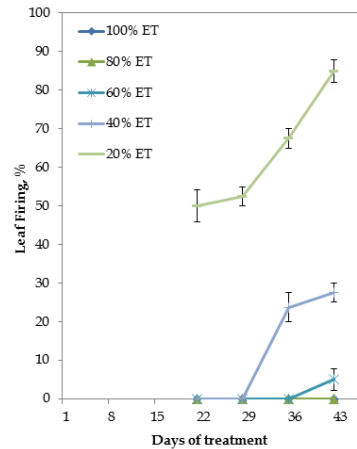


Figure 6. Percentage of leaf firing visible within the 81 cm<sup>2</sup> turfgrass canopy. Measurements were obtained during mid-afternoon hours on cloudless days. Error bars denote standard error of the mean (n=4).

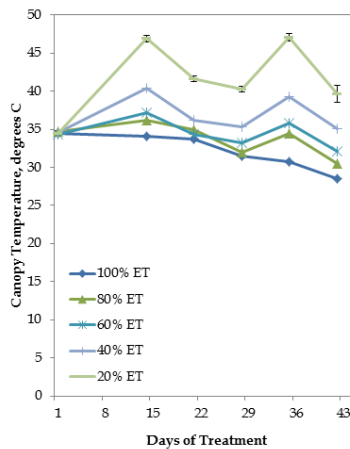


Figure 7. Canopy temperatures within the irrigation treatments. Measurements were obtained during mid-afternoon hours on cloudless days. Error bars denote standard error of the mean (n=4).

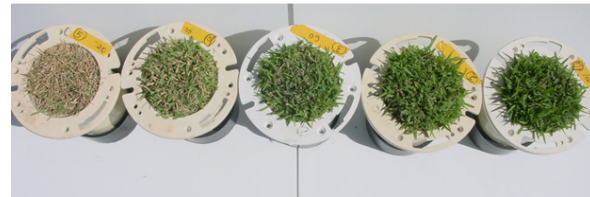


Figure 8. Visual appearance of 'Empire' zoysiagrass following six weeks of deficit irrigation, applied daily. (From left to right: 20% ET<sub>a</sub>, 40% ET<sub>a</sub>, 60% ET<sub>a</sub>, 80% ET<sub>a</sub>, and 100% ET<sub>a</sub>).



Figure 9. Portable chamber system for measuring canopy gas exchange.

On the basis of our results, deficit irrigation can be a useful means of conserving water in the management of turfgrass. Irrigating zoysiagrass at up to a 40% deficit (60% ET<sub>a</sub>) was sufficient to maintain acceptable turfgrass quality over a six-week period. Zoysiagrass response to the deficit irrigation included a reduction in evapotranspiration and photosynthetic rates, as well as shoot growth reductions. Such effects on shoot growth may be viewed as beneficial, as they would likely result in fewer mowing requirements. Our results suggest that irrigating this species at >40% irrigation deficits would not be advisable, as significant leaf wilt and firing occurred which negatively affected the appearance of the turf canopy and produced less-than-acceptable visual quality of the turf. While we were able to maintain acceptable quality at these levels with daily watering, it is likely that less frequent irrigation scheduling (2 or 3 days per week) might result in greater loss of quality at similar levels of ET replacement, due to longer periods of water stress encountered. An important consideration with deficit irrigation practices is the increasing reflective heat loads that are generated with diminishing amounts of irrigation. Canopy temperatures in this study progressively increased with greater deficits to a maximum increase of 16° C between 100% and 20% ET<sub>a</sub> plants. This is an important consideration that could have large-scale implications on the surface temperatures and human comfort levels within urban environments.



## SUMMARY

Water conservation in the landscape has become critically important in recent years due to diminishing water supplies and population growth. Deficit irrigation, or irrigating to a fraction of a plant's maximal transpiration rate is one way water may be conserved, but this practice may impact turfgrass quality, performance, and heat load within the landscape. The objective of this study was to determine the response of a commonly used warm-season ( $C_3$ ) turfgrass 'Empire' zoysiagrass (*Zoysia japonica* Steud.) to deficit irrigation practices. Pots of established zoysiagrass were irrigated at various levels of deficit irrigation including 80%, 60%, 40%, and 20% of actual evapotranspiration ( $ET_a$ ) of well-watered turf over a six-week period. Over the course of the study, changes in shoot growth, canopy temperatures, turfgrass quality, and rates of photosynthesis were recorded. Results of the study indicated very little change in quality, growth, and photosynthetic rates between plants irrigated at either 100% or 80% of daily  $ET_a$ . Supplying turf with only 60% of maximal irrigation produced lower, but still acceptable quality. Deficit irrigation levels of 40% and 20% were not sufficient to maintain acceptable quality and promoted significantly greater reflective heat loads. The results of this study indicate that deficit irrigation can be an important tool for conserving water in managed turfgrass, however, the effect of the practice on reflective heat loads is an important, but often overlooked consideration that could impact the energy balance within the urban environment.

## KEY WORDS

Canopy temperatures  
Deficit irrigation  
Evapotranspiration  
Photosynthesis  
Shoot growth  
Transpiration  
Turfgrass  
Turfgrass evapotranspiration  
Turfgrass irrigation  
Turfgrass water conservation  
Turfgrass water requirements  
Water conservation  
Water use  
Zoysiagrass (*Zoysia japonica*)

## BIBLIOGRAPHY

Refer to the bibliography for the literature cited.

## Chapter 13

### Evapotranspiration for Saudi Arabia: Modified Hargreaves Model<sup>1,2</sup>

#### INTRODUCTION

Estimation of reference evapotranspiration ( $ET_o$ ) is important for several hydrological and agricultural sciences, like water resources management, crop-water requirements, irrigation scheduling, and land use planning [21, 26]. Though, a good amount of research is done by the scientists to estimate the  $ET_o$  accurately, especially for the sensitive fields like irrigation scheduling [9, 25]. Due to its comprehensive theoretical base, the Penman–Monteith method [PM] method is recommended by the United Nations Food and Agricultural Organization (FAO) as the sole method to calculate ( $ET_o$ ) and for evaluating other  $ET_o$  calculation methods as well [3, 19]. The FAO approach to calculate  $ET_o$  using the PM method was published in the FAO irrigation and drainage paper number 56 [FAO-56]. The objectives of this chapter were: 1. To investigate whether the  $ET_o$  values calculated by PM method are affected significantly by Allen [2] temperature adjustments or not, and 2. To adjust the Hargreaves equation's parameters to use it in prediction of the actual  $ET_o$  values from non-standard weather stations, for all zones of the Kingdom of Saudi Arabia. The “FAO-56 PM” method is shown in equation /1/ and requires measurements of air temperature, relative humidity, solar radiation, and wind speed.

$$ET_o = \frac{0.408\Delta(R_n - G) + \frac{900}{T_a + 273} \gamma U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad /1/$$

Where  $ET_o$ : reference evapotranspiration [mm day<sup>-1</sup>];  $R_n$ : net radiation at the crop surface [MJ m<sup>-2</sup> day<sup>-1</sup>];  $G$ : soil heat flux density [MJ m<sup>-2</sup> day<sup>-1</sup>];  $T_a$ : mean daily air temperature [°C];  $U_2$ : wind speed at 2 m height [m s<sup>-1</sup>]; ( $e_s - e_a$ ): vapor pressure deficit [kPa];  $e_s$ : saturation vapor pressure [kPa];  $e_a$ : actual vapor pressure [kPa];  $e_s$ : slope vapor pressure curve [kPa °C<sup>-1</sup>];  $\gamma$ : psychrometric constant [kPa °C<sup>-1</sup>].

The formulas of the equation's parameters are detailed by Allen *et al.*, [3] in chapters 2 and 3. Nonetheless, the FAO-56 method requires climatic data from standard weather stations. Standard FAO56 weather stations are stations having “a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation” [6]. Allen [2] reported that data gathered from non-standard weather station should be adjusted before using it in  $ET_o$  calculation. He suggested a method for this data-adjustment especially for temperature. On the other hand, Jia *et al.*, [18] concluded that non-standard weather stations yield to non-significant bias from the correct  $ET_o$  value, except under high wind speed conditions where the bias is significant.

In fact, the number of weather stations where there are reliable data for these parameters are limited [25] especially for Middle-Eastern and developing countries [10]. Hargreaves [13] developed a temperature-based formula to find the  $ET_o$  and it was further modified by Hargreaves and Samani [16]. The modified version is called Hargreaves-85 equation in this chapter and is shown in equation /2/:

$$ET_o = 0.0135 \cdot R_s \cdot (T_a + 17.8) \quad /2/$$

Where:  $R_s$  = Global solar radiation, same units as  $ET_o$ ;  $T_a$  = Average temperature, °C.

The equation /2/ was evaluated at several locations [14]. Hargreaves and Samani [15] formula estimates global solar radiation,  $R_s$ , when the temperature range ( $TR$ ) and the extraterrestrial radiation ( $R_a$ ) are known.

$$R_s = k_r \cdot R_a \cdot TR^{0.5} \quad /3/$$

Where:  $k_r$  is an empirical coefficient depending on the station location (Also called coastality value).

The extraterrestrial radiation ( $R_a$ ) is calculated using procedure described by Allen *et al.* [3] as shown in equations /4/ to /8/. Since the Hargreaves' formula requires very few climatic data than the PM-FAO56 method; it urges many investigators to test its reliability compared to PM method. Allen *et al.*, [3]; and Sau *et al.*, [24] concluded the importance of local calibration of the HRG to ensure reliable data. Lee [20] found that the HRG formula provides excellent results for the Korea Peninsula after local calibration. So did Jamshidi *et al.*, [17] for different climates in Iran. Amatya *et al.*, [5] and Trajkovic [27] reported that in humid regions; HRG provides an overestimate to the PM values. Martínez-Cob and Tejero-Juste [22] found that the Hargreaves method overestimated  $ET_o$  at stations with wind speeds less than 2 m/s in Spain.

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<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

Gavilán *et al.*, [12] reported similar results for inland locations with low wind speeds and large daily temperature ranges, and for coastal locations with high wind speeds and small daily temperature ranges. On the other hand, for semiarid environments, the HRG method was found to underestimate the PM values in most stations of Iran [19], Turkey [8], Australia [7], and Jordan [29]. For hyper-arid regions, the HRG equation also underestimates the  $ET_o$  values for Saudi Arabia as reported by several investigators [1, 4, 23].

The Extraterrestrial radiation,  $R_o$ , with latitude in radians =  $\Phi$  : /4/

$$R_o = 37.6 d_r (\omega_s \sin \varphi \sin \delta + \sin \omega_s \cos \varphi \cos \delta)$$

In equation /4/, the parameters are defined by equations /5/ to /8/ below. The relative distance Earth to Sun,  $d_r$  : /5/

$$d_r = 1 + 0.033 \cos(0.0172 J)$$

Sunset hour angle in radians: /6/

$$\{\omega_s = \arccos(-\tan \varphi \tan \delta)\}$$

Solar declination in radians: /7/

$$\delta = 0.409 \sin(0.0172 J - 1.39)$$

Julian day (Ranges from 1 to 366) = J with M = Month of the year and D = Day in the month: /8/

$$J = \text{int}\left(\frac{275}{9} M + D - 30\right) \mapsto \text{if } (M > 2) \begin{cases} \text{And LeapYear} \rightarrow \text{Subtract 1} \\ \text{AndNot LeapYear} \rightarrow \text{Subtract 2} \end{cases}$$

Dew point temperature: /9/

$$T_d = \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)}$$

Actual vapor pressure: /10/

$$e_a = 0.005(RH_x e_o[T_n] + RH_n e_o[T_x])$$

Saturation vapor pressure: /11/

$$e_o[T] = 0.611 \cdot \exp(17.27 T / (T + 237.3))$$

Temperature difference between minimum and dew point temperatures: /12/

$$\Delta T = T_n - T_d$$

Corrected value of maximum temperature, for  $\Delta T = \text{Temperature difference} > 2$ : /13/

$$T_x^{\{corr\}} = T_x - 0.5(\Delta T - 2)$$

## METHODS AND MATERIAL

### Weather Data

The most reliable weather dataset in the Saudi Arabia is the database of the Presidency of Meteorology and Environment (PME) in KSA, the official climate agency in the country. Weather stations are equipped with up-to-date monitoring devices and are subjected to regular inspection and replacement for defected devices (personal communication with the PME). This Database represents daily values of 29 meteorological stations distributed spatially over the 13 districts and temporally over a time span since 1980 to the end of 2010 for most of the stations. Details about the weather stations and associated parameters are presented in Table 1. All the PME stations are located inside airports for aviation information services; hence these stations are not standard FAO-56 weather stations, and accordingly Allen [2] corrections of temperature were applied. The recorded climatic factors for all stations are dry bulb and wet bulb temperatures (max., min., and avg.), relative humidity (max., min., and avg.), rainfall, wind speed (average), wind direction, atmospheric pressure (sea and station levels), the cloud cover, and the actual vapor pressure. Most of the listed factors were used to find the FAO-56  $ET_o$  values.

### Estimation of Reference Evapotranspiration with FAO-56 PM Method

The procedure is described below to calculate the reference evapotranspiration [ $ET_o$ ] using FAO-56 PM method.

**Step 1:** Calculate the global solar radiation using equation /3/ and coastality value ( $k_r$ ) for each weather station from Table 1.

**Step 2:** Calculate the Extraterrestrial radiation,  $R_o$ , with equations /4/ to /8/.

**Step 3:** The parameters in equation /1/ were calculated using the procedure described by Allen *et al.*, [3] and summarized by ElNesr and Alazba [10]. The equations /9/ to /12/ were used.

- Calculate the dew point temperature [ $T_d$ ] with equation /9/.
- Gather data for  $T_n$ , minimum air temperature [ $^{\circ}\text{C}$ ];  $T_x$ , maximum air temperature [ $^{\circ}\text{C}$ ];  $RH_x$ , maximum relative humidity [%];  $RH_n$ , minimum relative humidity [%];  $e_o[T]$
- Calculate the actual vapor pressure [ $e_a$ ] with equation /10/.
- Calculate the saturation vapor pressure [ $e_o[T]$ ] with equation /11/.
- Calculate the temperature difference between minimum and dew point temperatures with equation /12/.

- Calculate the  $ET_o$  values by substituting values of parameters [with equations /9/ to /12/] in equation /1/.

**Step 4:** The  $ET_o$  values were calculated for daily basis and then were averaged for monthly basis.

**Table 1.** The Characteristics of weather stations in Kingdom of Saudi Arabia.

| Station |                 | Station Location    |                        |               |                       | Logged<br>Years | Average<br>Temperature°C | Coastalityvalue<br>(kr)* |
|---------|-----------------|---------------------|------------------------|---------------|-----------------------|-----------------|--------------------------|--------------------------|
| ID      | Name            | Latitude<br>deg. N. | Longitude<br>deg. East | Altitude<br>m | Coastal /<br>Interior |                 |                          |                          |
| St:01   | A'Dhahran       | 26.16               | 50.1                   | 17            | Coastal               | 30              | 26.48 ± 7.49             | 0.184                    |
| St:02   | Abha            | 18.14               | 42.39                  | 2093          | Interior              | 30              | 18.60 ± 3.72             | 0.171                    |
| St:03   | Ad Dammam       | 26.42               | 50.12                  | 1             | Coastal               | 10              | 26.72 ± 7.86             | 0.179                    |
| St:04   | Al Ahsa         | 25.3                | 49.48                  | 179           | Interior              | 25              | 27.26 ± 8.27             | 0.173                    |
| St:05   | Al Baha         | 20.3                | 41.63                  | 1652          | Interior              | 25              | 22.83 ± 4.92             | 0.178                    |
| St:06   | AlJouf          | 29.47               | 40.06                  | 671           | Interior              | 30              | 22.03 ± 8.61             | 0.177                    |
| St:07   | AlMadina        | 24.33               | 39.42                  | 636           | Interior              | 30              | 28.45 ± 7.00             | 0.178                    |
| St:08   | AlQaisumah      | 28.32               | 46.13                  | 358           | Interior              | 30              | 25.23 ± 9.28             | 0.173                    |
| St:09   | AlQassim        | 26.18               | 43.46                  | 650           | Interior              | 30              | 24.94 ± 8.26             | 0.166                    |
| St:10   | AlQuraiait      | 31.5                | 37.5                   | 560           | Interior              | 5               | 20.04 ± 7.91             | 0.167                    |
| St:11   | AlWajh          | 26.12               | 36.28                  | 21            | Coastal               | 30              | 25.00 ± 3.98             | 0.216                    |
| St:12   | Arar            | 31                  | 41                     | 600           | Interior              | 30              | 22.01 ± 9.17             | 0.173                    |
| St:13   | ArRiyadh Middle | 24.63               | 46.77                  | 624           | Interior              | 30              | 26.66 ± 8.10             | 0.181                    |
| St:14   | ArRiyadh North  | 24.42               | 46.44                  | 611           | Interior              | 25              | 25.80 ± 8.12             | 0.167                    |
| St:15   | AtTa'if         | 21.29               | 40.33                  | 1454          | Interior              | 30              | 22.92 ± 5.12             | 0.172                    |
| St:16   | Bisha           | 19.59               | 42.37                  | 1163          | Interior              | 30              | 25.69 ± 5.40             | 0.158                    |
| St:17   | Gizan           | 16.54               | 42.35                  | 3             | Coastal               | 30              | 30.22 ± 2.80             | 0.209                    |
| St:18   | Hafr El-Batin   | 28.2                | 46.07                  | 360           | Interior              | 20              | 25.26 ± 9.21             | 0.172                    |
| St:19   | Hail            | 27.26               | 41.41                  | 1013          | Interior              | 30              | 22.47 ± 8.20             | 0.172                    |
| St:20   | Jeddah          | 21.3                | 39.12                  | 17            | Coastal               | 30              | 28.23 ± 3.50             | 0.197                    |
| St:21   | Khamis Mushait  | 18.18               | 42.48                  | 2057          | Interior              | 30              | 19.49 ± 3.75             | 0.168                    |
| St:22   | Makkah          | 21.4                | 39.85                  | 213           | Interior              | 25              | 30.78 ± 4.57             | 0.179                    |
| St:23   | Najran          | 17.37               | 44.26                  | 1210          | Interior              | 30              | 25.51 ± 5.54             | 0.166                    |
| St:24   | Rafha           | 29.38               | 43.29                  | 447           | Interior              | 30              | 23.33 ± 9.05             | 0.169                    |
| St:25   | Sharurah        | 17.47               | 47.11                  | 725           | Interior              | 25              | 28.57 ± 5.81             | 0.168                    |
| St:26   | Tabuk           | 28.22               | 36.38                  | 776           | Interior              | 30              | 21.99 ± 7.53             | 0.170                    |
| St:27   | Turaif          | 31.41               | 38.4                   | 818           | Interior              | 30              | 19.06 ± 8.27             | 0.173                    |
| St:28   | Wadi Al Dawasir | 20.5                | 45.16                  | 652           | Interior              | 25              | 28.15 ± 7.01             | 0.168                    |
| St:29   | Yenbo           | 24.09               | 38.04                  | 6             | Coastal               | 30              | 27.56 ± 4.72             | 0.184                    |

\* The coastality value data were gathered from El-Nesr *et al.*, (2011)

#### Reestimation of Reference Evapotranspiration with FAO-56 PM Method and Temperature Corrections

**Step 5:** The  $ET_o$  values with FAO-56 PM method were recalculated after applying Allen [2] temperature corrections and equations /9/ to /13/. The following procedure was followed for this step:

- Calculate the dew point temperature [ $T_d$ ] with equation /9/.
- Gather data for  $T_n$ , minimum air temperature [°C];  $T_x$ , maximum air temperature [°C];  $RH_x$ , maximum relative humidity [%];  $RH_n$ , minimum relative humidity [%];  $e_o[T]$
- Calculate the actual vapor pressure [ $e_a$ ] with equation /10/.
- Calculate the saturation vapor pressure [ $e_o[T]$ ] with equation /11/.
- Calculate the temperature difference between minimum and dew point temperatures with equation /12/.
- For arid and semi-arid regions, calculate corrected value of maximum temperature adjustment using equation /13/ for  $\Delta T =$  Temperature difference  $> 2$ .  $T^{(Corr)}$  stands for a corrected value in equation /13/. Repeat the same procedure for minimum temperature [ $T_n$ ]. Note that no correction is needed for  $\Delta T \leq 2$ .
- Applying the temperature corrections, the  $ET_o$  is recalculated and is renamed as  $ET_o^{(Corr)}$ .

#### Estimation of Reference Evapotranspiration with Hargreaves - Samani Method

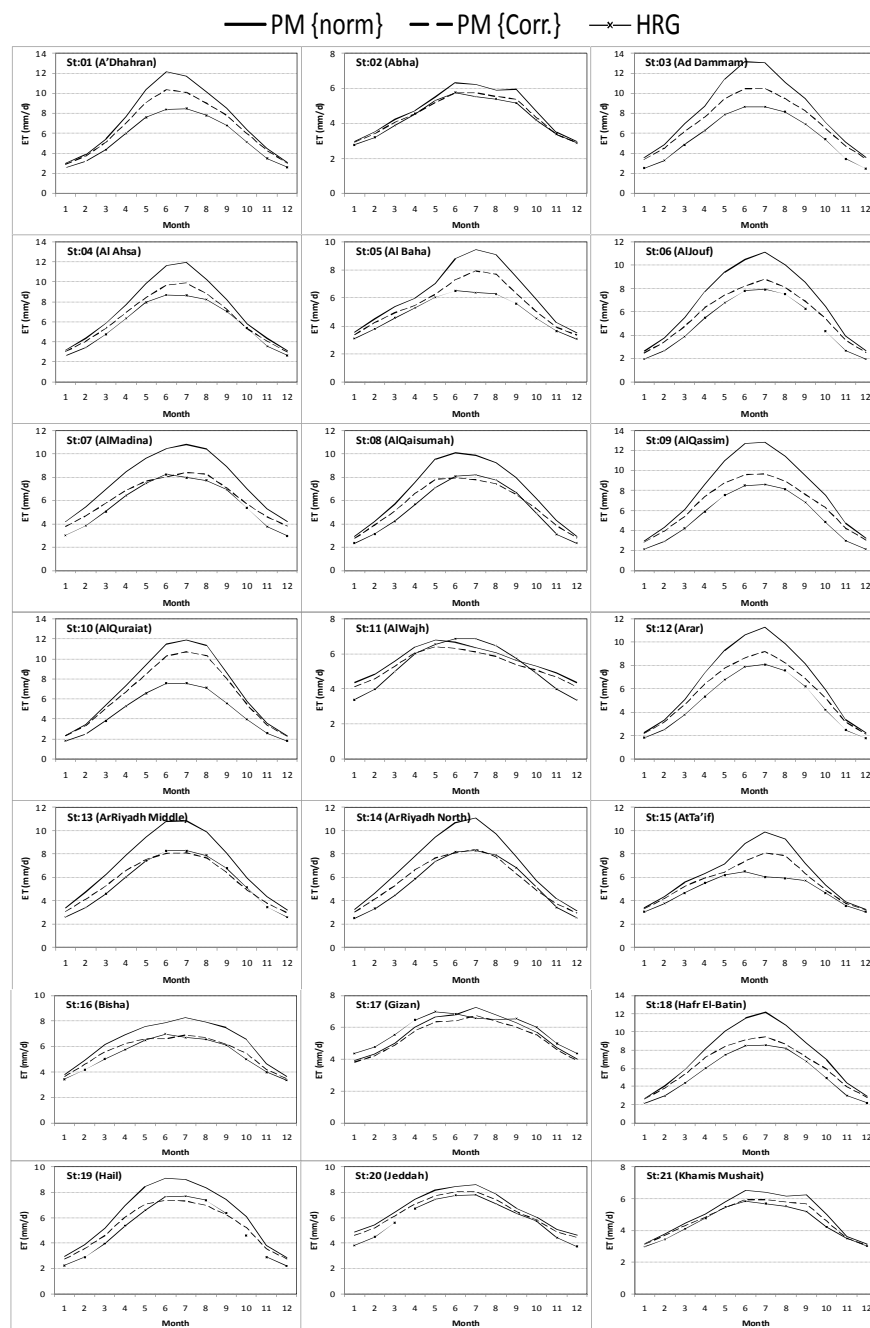
Reference evapotranspiration [ $ET_o$ ] values were estimated using Hargreaves - Samani method [HRG method] and the equation /2/. In equation /2/,  $R_s$  value was calculated using equation /3/. The monthly  $ET_o$  values were calculated as the average of the daily calculated values.

To find a best fit for each station, the linear regression analysis [ $y = a + b * x$ , where a and b are regression coefficients] was used between “the  $ET_o$  values calculated by HRG method” and “both uncorrected and corrected PM values”. The resultant Hargreaves equation was compared to the original corrected and uncorrected PM values. The prediction precision was tested with statistical indices: The root mean squared deviation [RMSD: coefficient of variation (RMSD<sub>CV</sub>)]; and the mean percent error (MPE). The procedure is described in equations /14/ and /15/, where  $F$  is a forecasted (estimated) value;  $A$  is an actual (measured) value;  $n$  is a number of observations; and  $i$  is a counter.

$$RMSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (F_i - A_i)^2}$$

/14/

$$MPE = \frac{100}{n} \sum_{i=1}^n \frac{(F_i - A_i)}{A_i}$$



**Figure 1a.** Monthly  $ET_o$  values of the studied stations calculated by  $PM^{(norm)}$ ,  $PM^{(Corr)}$ , and HRG.

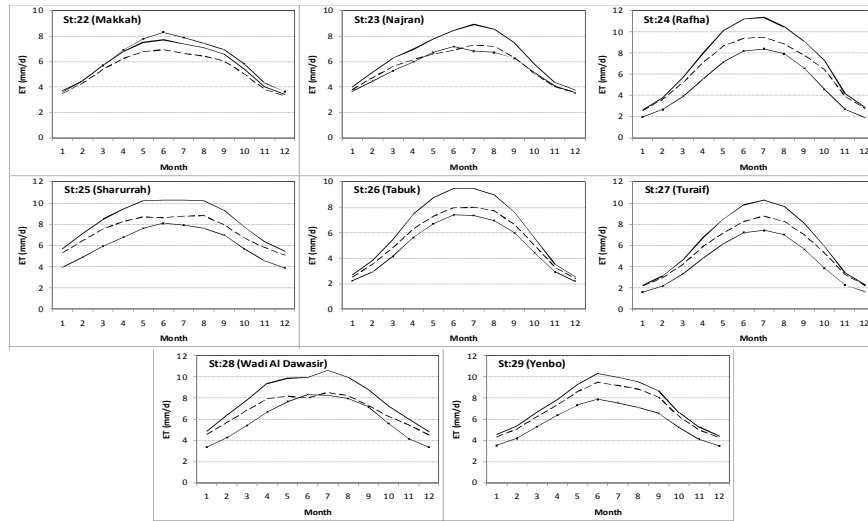


Figure 1b. Monthly  $ET_o$  values of the studied stations calculated by  $PM^{(norm)}$ ,  $PM^{(Corr)}$ , and HRG.

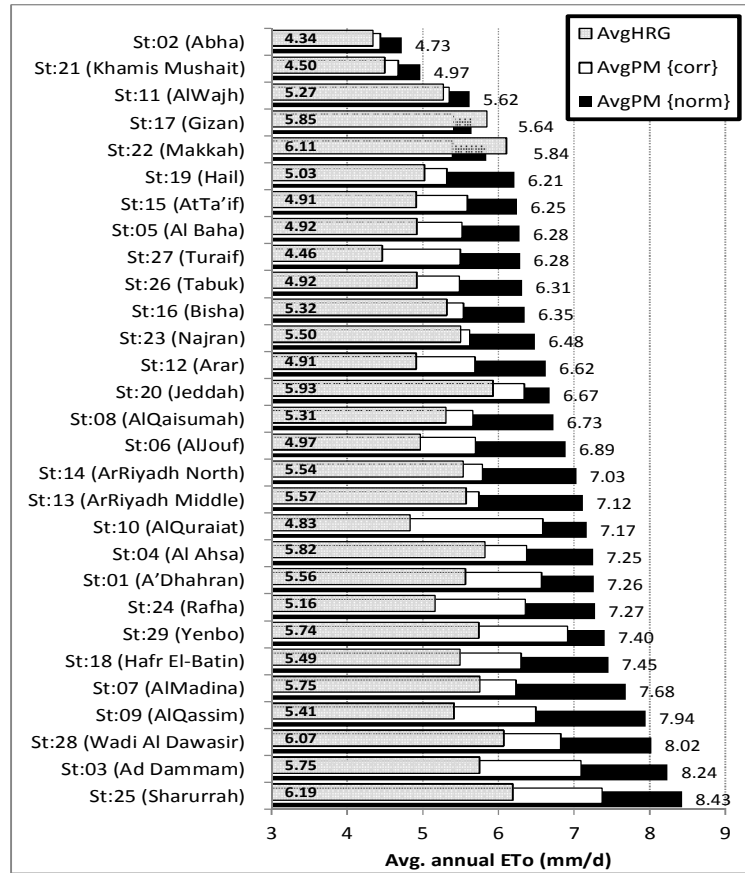


Figure 2. Average annual  $ET_o$  (mm/day) for the studied stations sorted ascending from top to bottom. Numbers outside series indicate  $PM^{(norm)}$  values, while numbers inside series indicate HRG values.

## RESULTS AND DISCUSSION

The average monthly values of PM for each station were calculated by three methods; the normal PM method without corrections ( $PM^{(norm)}$ ), the corrected PM method ( $PM^{(Corr)}$ ) and HRG method. As illustrated in Fig. 1 a, b, the HRG method seemed to underestimate the  $PM^{(norm)}$  method for almost all the 29 studied stations except 2 stations namely Makkah, and Gizan, in addition to AlWajh station in some months. In Makkah, HRG method overestimated the  $PM^{(norm)}$  and  $PM^{(Corr)}$  in all months. Makkah city has special climate (steady hot all the year), and special topography (very rugged mountains and valleys), and even special demographic nature (due to its religious characteristics, it is always occupied by

pilgrims and visitors). These special circumstances made this arid city (Makkah) to act like a non-arid city [11]. In humid locations, HRG method always overestimates PM as discussed earlier. For similar reason, Gizan, the semi-island, behaved like humid location and the overestimation occurred. In AlWajh station, HRG method overestimated the  $PM^{(norm)}$  in summer months (June, July, August, and September) while its underestimation occurred for the rest of the year. This could be due to the weather effects for its coastal location at the top-north of the kingdom's shore on the Red Sea and exposure to the Mediterranean Sea's weather effects as well.

**Table 2.** Percent of error between the corrected  $ET_o$  value and the normal  $ET_o$  value.

| Station                 | Error % |
|-------------------------|---------|
| St:17 (Gizan)           | 4.36    |
| St:11 (AlWajh)          | 5.01    |
| St:20 (Jeddah)          | 5.24    |
| St:21 (Khamis Mushait)  | 6.19    |
| St:02 (Abha)            | 6.37    |
| St:29 (Yenbo)           | 7.01    |
| St:22 (Makkah)          | 8.23    |
| St:10 (AlQuraiat)       | 8.86    |
| St:01 (A'Dhahran)       | 10.53   |
| St:15 (AtTa'if)         | 11.75   |
| St:04 (Al Ahsa)         | 13.78   |
| St:05 (Al Baha)         | 13.83   |
| St:27 (Turaif)          | 14.28   |
| St:25 (Sharurrah)       | 14.34   |
| St:24 (Rafha)           | 14.41   |
| St:16 (Bisha)           | 14.62   |
| St:26 (Tabuk)           | 15.09   |
| St:23 (Najran)          | 15.38   |
| St:03 (Ad Dammam)       | 16.12   |
| St:12 (Arar)            | 16.37   |
| St:19 (Hail)            | 16.77   |
| St:28 (Wadi Al Dawasir) | 17.50   |
| St:18 (Hafr El-Batin)   | 18.35   |
| St:08 (AlQaisumah)      | 18.77   |
| St:06 (AlJouf)          | 20.95   |
| St:14 (ArRiyadh North)  | 21.46   |
| St:09 (AlQassim)        | 22.27   |
| St:07 (AlMadina)        | 23.27   |
| St:13 (ArRiyadh Middle) | 23.96   |

**Table 3.** Calculation formulas of  $PM^{(Corr)}$  when the  $PM^{(norm)}$  is known.

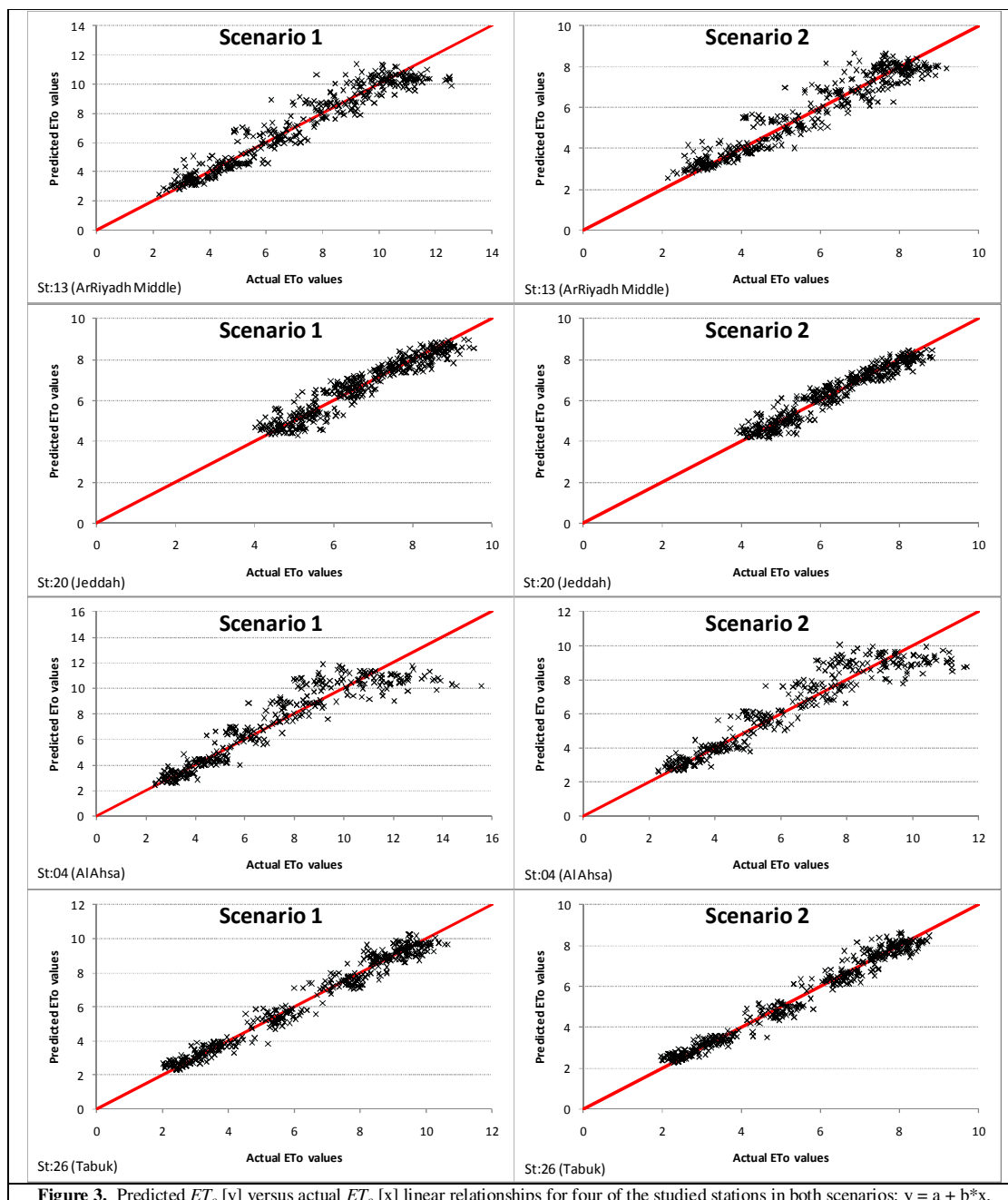
| Station                 | Formula                                         | r <sup>2</sup> |
|-------------------------|-------------------------------------------------|----------------|
| St:01 (A'Dhahran)       | $PM \{cor\} = 0.821 \times PM \{norm\} + 0.610$ | 0.995          |
| St:02 (Abha)            | $PM \{cor\} = 0.851 \times PM \{norm\} + 0.420$ | 0.989          |
| St:03 (Ad Dammam)       | $PM \{cor\} = 0.744 \times PM \{norm\} + 0.964$ | 0.990          |
| St:04 (Al Ahsa)         | $PM \{cor\} = 0.781 \times PM \{norm\} + 0.713$ | 0.993          |
| St:05 (Al Baha)         | $PM \{cor\} = 0.758 \times PM \{norm\} + 0.758$ | 0.987          |
| St:06 (AlJouf)          | $PM \{cor\} = 0.734 \times PM \{norm\} + 0.639$ | 0.994          |
| St:07 (AlMadina)        | $PM \{cor\} = 0.701 \times PM \{norm\} + 0.849$ | 0.988          |
| St:08 (AlQaisumah)      | $PM \{cor\} = 0.731 \times PM \{norm\} + 0.748$ | 0.977          |
| St:09 (AlQassim)        | $PM \{cor\} = 0.689 \times PM \{norm\} + 1.023$ | 0.983          |
| St:10 (AlQuraiat)       | $PM \{cor\} = 0.874 \times PM \{norm\} + 0.319$ | 0.995          |
| St:11 (AlWajh)          | $PM \{cor\} = 0.925 \times PM \{norm\} + 0.155$ | 0.993          |
| St:12 (Arar)            | $PM \{cor\} = 0.774 \times PM \{norm\} + 0.566$ | 0.990          |
| St:13 (ArRiyadh Middle) | $PM \{cor\} = 0.683 \times PM \{norm\} + 0.879$ | 0.985          |
| St:14 (ArRiyadh North)  | $PM \{cor\} = 0.697 \times PM \{norm\} + 0.886$ | 0.983          |
| St:15 (AtTa'if)         | $PM \{cor\} = 0.735 \times PM \{norm\} + 0.997$ | 0.978          |
| St:16 (Bisha)           | $PM \{cor\} = 0.744 \times PM \{norm\} + 0.815$ | 0.977          |
| St:17 (Gizan)           | $PM \{cor\} = 0.895 \times PM \{norm\} + 0.357$ | 0.996          |
| St:18 (Hafr El-Batin)   | $PM \{cor\} = 0.736 \times PM \{norm\} + 0.811$ | 0.983          |
| St:19 (Hail)            | $PM \{cor\} = 0.750 \times PM \{norm\} + 0.663$ | 0.988          |
| St:20 (Jeddah)          | $PM \{cor\} = 0.919 \times PM \{norm\} + 0.207$ | 0.997          |
| St:21 (Khamis Mushait)  | $PM \{cor\} = 0.858 \times PM \{norm\} + 0.415$ | 0.987          |
| St:22 (Makkah)          | $PM \{cor\} = 0.850 \times PM \{norm\} + 0.429$ | 0.996          |
| St:23 (Najran)          | $PM \{cor\} = 0.720 \times PM \{norm\} + 0.954$ | 0.955          |
| St:24 (Rafha)           | $PM \{cor\} = 0.787 \times PM \{norm\} + 0.633$ | 0.993          |
| St:25 (Sharurrah)       | $PM \{cor\} = 0.741 \times PM \{norm\} + 1.125$ | 0.956          |
| St:26 (Tabuk)           | $PM \{cor\} = 0.797 \times PM \{norm\} + 0.451$ | 0.993          |
| St:27 (Turaif)          | $PM \{cor\} = 0.798 \times PM \{norm\} + 0.483$ | 0.994          |
| St:28 (Wadi Al Dawasir) | $PM \{cor\} = 0.698 \times PM \{norm\} + 1.227$ | 0.962          |
| St:29 (Yenbo)           | $PM \{cor\} = 0.889 \times PM \{norm\} + 0.336$ | 0.995          |

For somewhat simpler explanation, Figure 2 illustrates the annual averages of  $ET_o$  calculated by the three methods for the 29 stations. The overestimation in Gizan and Makkah is clear in Fig. 2, while the partial overestimation appeared for AlWajh station. It appears that Abha station has the least  $ET_o$  in all over the kingdom with an average annual value of 4.73 mm/d. This low value of  $ET_o$ , however, was due to the cold weather of the region due to its high altitude (2093 m above sea level, Table 1). The maximum average annual  $ET_o$ , 8.43 mm/d, was found for Sharurrah station which is the nearest urban zone to the Empty Quarter region (Rub' al Khali). The Empty Quarter region is one of the largest hyper-arid sanddeserts in the world with very high temperatures of about 47°C in normal days and up to 60°C during July and August ([25], [28]).

For all of the stations except Gizan and Makkah, HRG method resulted in the least value of the  $ET_o$  followed by the  $PM^{(Corr)}$  and the  $PM^{(norm)}$  methods. This could mean that  $ET_o$  values from non-standard weather stations were always overestimated if calculated from standard AWSs. This could be attributed to the temperature drop in the standard weather stations due to the surrounding vegetation cover. In some stations, however, the overestimating ratio (error) was small, like in Gizan, AlWajh, and Jeddah; where the error was around 5% (Table 2). Table 2 summarizes the error values with eight stations below 10%, between 10 and 15% for similar number of stations, between 15% and 20% for eight stations, and five stations having more than 20% error. The importance of knowing these values was to think twice when dealing with uncorrected values of  $PM ET_o$  in the stations with huge errors, especially for the top five stations of AlJouf, ArRiyadh North, AlQassim, AlMadina, and ArRiyadh Middle having error values of 20.95%, 21.46%, 22.27%, 23.27%, and 23.96%, respectively.

In fact, these zones are occupied by massive agricultural projects in addition to "Wadi Al Dawasir" and lately some of these agricultural projects probably use the non-standard weather data to calculate  $ET_o$  resulting up to 25% increase in water usage. This situation clearly demonstrates the importance of using standard weather stations' data in  $ET_o$  calculation especially in these areas, or to use the suggested correction formulas when the  $PM^{(norm)}$  is calculated from non-standard weather stations (Table 3).

For most of the small to medium size projects' landowners and agronomists in the KSA, it is not easy to compute the  $ET_o$  by PM equation, however, HRG equation requires less parameters, and minimum efforts to calculate the  $ET_o$ . The HRG equation, however, underestimates the PM value in most regions in the kingdom and hence the correction formulas suggested by Allen *et al.*, [3] were derived for all of the studied stations (Table 4).



**Figure 3.** Predicted  $ET_0$  [y] versus actual  $ET_0$  [x] linear relationships for four of the studied stations in both scenarios:  $y = a + b \cdot x$ .

Because of the different scenarios in the agricultural projects, two formulas were derived for each station, one for each scenario. The first scenario's formula is applied when the climatic data (which is used to calculate HRG value) was obtained from the standard AWS. In this case, both PM and HRG were calculated without temperature correction, so HRG value can easily be calculated, and the corresponding PM value was computed through the related formula in Table 4. On the other hand, the second scenario's formula is applied when the climatic data was obtained from non-standard AWS, so the HRG value was calculated by un-corrected data but the resulting PM value is corrected to the standard conditions.

The coefficient of determination,  $r^2$ , for all stations in both scenarios was extremely high and encouraging i.e. an average value of about 0.92 with values ranging from 0.72 to 0.98. Only two stations, AlWajh and Sharurrah, had  $r^2 < 0.80$ , nine stations had  $0.80 < r^2 < 0.90$ , and eighteen stations with  $r^2 > 0.90$ . However, the calculated error values (Table 5) indicate an acceptable precision of the derived formulas. The RMSD for 'scenario 1' ranged between 0.36 to 1.19, with an average value of 0.73, while it got better results for 'scenario 2' and ranged from 0.28 to 0.86 with an average value of 0.56. These deviations are reasonable and acceptable, especially when taking into account the excellent MPE values that range from 0.11% to 3.02% with average value of 1.22% for 'scenario 1', and 0.03% to 2.75% with average value of 1.12% for 'scenario 2'.



To validate the formulas reliability, four stations were selected, one from each geographic zone; 'Tabuk' from the North, 'Arriadh-Middle' from the Middle, 'AlAhsa' from the east, and 'Jeddah' from the South-West. For each station, the measured vs. predicted values of PM  $ET_o$  were plotted, Fig. 3, for both of the studied scenarios. The graphs show the closeness of the points to the 45° line, with some bias for AlAhsa for  $ET_o$  values >12mm/d while the rest of the stations show very good representation of the efficiency for the predicted formulae. These good values of the validation indices (in Table 5) confirm the reliability of the presented formulae.

**Table 4.** Conversion formulas between HRG and PM values for the studied stations.

| Stations                | Scenario 1*                   |                | Scenario 2**                 |                |
|-------------------------|-------------------------------|----------------|------------------------------|----------------|
|                         | Formula                       | r <sup>2</sup> | Formula                      | r <sup>2</sup> |
| St:01 (A'Dhahran)       | PM {norm} = 1.450×HRG - 0.806 | 0.9482         | PM {cor} = 1.203×HRG - 0.124 | 0.9643         |
| St:02 (Abha)            | PM {norm} = 1.144×HRG - 0.241 | 0.9192         | PM {cor} = 0.988×HRG + 0.155 | 0.9349         |
| St:03 (Ad Dammam)       | PM {norm} = 1.449×HRG - 0.097 | 0.9496         | PM {cor} = 1.097×HRG + 0.784 | 0.9730         |
| St:04 (Al Ahsa)         | PM {norm} = 1.313×HRG - 0.395 | 0.8603         | PM {cor} = 1.041×HRG + 0.309 | 0.8815         |
| St:05 (Al Baha)         | PM {norm} = 1.559×HRG - 1.396 | 0.8538         | PM {cor} = 1.200×HRG - 0.393 | 0.8696         |
| St:06 (AlJouf)          | PM {norm} = 1.335×HRG + 0.258 | 0.9552         | PM {cor} = 0.979×HRG + 0.833 | 0.9473         |
| St:07 (AlMadina)        | PM {norm} = 1.226×HRG + 0.630 | 0.9253         | PM {cor} = 0.853×HRG + 1.325 | 0.9013         |
| St:08 (AlQaisumah)      | PM {norm} = 1.183×HRG + 0.447 | 0.9172         | PM {cor} = 0.857×HRG + 1.115 | 0.8799         |
| St:09 (AlQassim)        | PM {norm} = 1.419×HRG + 0.258 | 0.9163         | PM {cor} = 0.994×HRG + 1.112 | 0.9318         |
| St:10 (AlQuraiat)       | PM {norm} = 1.631×HRG - 0.712 | 0.9748         | PM {cor} = 1.431×HRG - 0.332 | 0.9778         |
| St:11 (AlWajh)          | PM {norm} = 0.637×HRG + 2.259 | 0.7167         | PM {cor} = 0.616×HRG + 2.099 | 0.7790         |
| St:12 (Arar)            | PM {norm} = 1.376×HRG - 0.137 | 0.9553         | PM {cor} = 1.065×HRG + 0.459 | 0.9460         |
| St:13 (ArRiyadh Middle) | PM {norm} = 1.260×HRG + 0.099 | 0.9192         | PM {cor} = 0.860×HRG + 0.948 | 0.9054         |
| St:14 (ArRiyadh North)  | PM {norm} = 1.256×HRG + 0.082 | 0.9218         | PM {cor} = 0.878×HRG + 0.927 | 0.9126         |
| St:15 (AtTa'if)         | PM {norm} = 1.661×HRG - 1.916 | 0.8247         | PM {cor} = 1.269×HRG - 0.645 | 0.8704         |
| St:16 (Bisha)           | PM {norm} = 1.241×HRG - 0.252 | 0.8754         | PM {cor} = 0.927×HRG + 0.608 | 0.8615         |
| St:17 (Gizan)           | PM {norm} = 1.110×HRG - 0.848 | 0.8618         | PM {cor} = 1.011×HRG - 0.505 | 0.8885         |
| St:18 (Hafir El-Batin)  | PM {norm} = 1.346×HRG + 0.062 | 0.9324         | PM {cor} = 0.992×HRG + 0.852 | 0.9178         |
| St:19 (Hail)            | PM {norm} = 1.109×HRG + 0.643 | 0.9111         | PM {cor} = 0.832×HRG + 1.140 | 0.9026         |
| St:20 (Jeddah)          | PM {norm} = 0.945×HRG + 1.074 | 0.9089         | PM {cor} = 0.877×HRG + 1.141 | 0.9245         |
| St:21 (Khamis Mushait)  | PM {norm} = 1.152×HRG - 0.221 | 0.8811         | PM {cor} = 1.011×HRG + 0.129 | 0.9081         |
| St:22 (Makkah)          | PM {norm} = 0.906×HRG + 0.310 | 0.8822         | PM {cor} = 0.765×HRG + 0.723 | 0.8676         |
| St:23 (Najran)          | PM {norm} = 1.314×HRG - 0.744 | 0.8290         | PM {cor} = 0.949×HRG + 0.396 | 0.7988         |
| St:24 (Rafha)           | PM {norm} = 1.314×HRG + 0.492 | 0.9164         | PM {cor} = 1.037×HRG + 1.005 | 0.9150         |
| St:25 (Sharurrah)       | PM {norm} = 1.175×HRG + 1.150 | 0.7623         | PM {cor} = 0.885×HRG + 1.893 | 0.7516         |
| St:26 (Tabuk)           | PM {norm} = 1.321×HRG - 0.190 | 0.9703         | PM {cor} = 1.057×HRG + 0.283 | 0.9695         |
| St:27 (Turaiif)         | PM {norm} = 1.358×HRG + 0.220 | 0.9584         | PM {cor} = 1.091×HRG + 0.628 | 0.9649         |
| St:28 (Wadi Al Dawasir) | PM {norm} = 1.040×HRG + 1.708 | 0.8617         | PM {cor} = 0.717×HRG + 2.471 | 0.8098         |
| St:29 (Yenbo)           | PM {norm} = 1.345×HRG - 0.316 | 0.9263         | PM {cor} = 1.207×HRG - 0.012 | 0.9402         |

\* Scenario 1: If HRG was calculated from Standard Agro-climatic Weather Stations (SAWS).

\*\* Scenario 2: If HRG was calculated from Non-standard agro-climatic weather station.

## SUMMARY

In case of absence of non-standard AWS, it is recommended to use the temperature correction procedure suggested by Allen [2] for calculating  $ET_o$ . A severe increase of  $ET_o$  values may result (up to +24% ), however, when considering the non-standard AWS. It is also recommended to use the suggested modified Hargreaves formulas instead of using the FAO56 PM method for small to middle size farms in the cases where the landowners are incapable to deal with FAO56 PM Method. It is also recommended to use the modified Hargreaves formulas when some of the important weather factors are missing like wind-speed and relative humidity. To make it easy, three types of formulas were introduced in this chapter, 1- formulas to convert non- standard to standard PM value. 2- formulas to convert HRG value to PM value when the HRG values were calculated from non-standard AWS. 3- same as 2, but when HRG values were calculated from standard AWS.

Due to the lack of standard Agro-climatic Weather Stations (AWS) in Saudi Arabia, simple conversion formulas were derived to find the average daily  $ET_o$  value per month for 29 weather stations. The Hargreaves (HRG) formula was used instead of the Penman-Monteith formula due to the ease of calculation of HRG formula, as it almost require only temperature. For each station, two formulas were derived considering both standard and non-standard AWS. Results show very good statistical representation of the formulas, with average root mean squared deviations of 0.73 and 0.57 and the mean percent errors of 1.22%, and 1.12% while considering the standard and non-standard AWS, respectively. Results also confirm the importance of temperature correction when using data from non-standard AWS, especially for the stations in the Middle to Midwest region (e.g. Arriadh, AlQassim, and Almadina); where the errors of using non-standard AWS data may be up to +24% of the correct  $ET_o$  value, which results in a massive waste of water.

**Table 5.** Models evaluation parameters of the defined scenarios.

| <b>Table 5:</b> Models evaluation parameters of the defined scenarios. |                         |             |        |             |        |
|------------------------------------------------------------------------|-------------------------|-------------|--------|-------------|--------|
| Station                                                                | Tested on<br>... Months | Scenario 1* |        | Scenario 2* |        |
|                                                                        |                         | RMSD        | MPE    | RMSD        | MPE    |
| St:01 (A'Dhahran)                                                      | 368                     | 0.743       | -0.55% | 0.508       | -0.64% |
| St:02 (Abha)                                                           | 369                     | 0.368       | -0.60% | 0.283       | -0.45% |
| St:03 (Ad Dammam)                                                      | 131                     | 0.759       | -0.32% | 0.416       | -0.39% |
| St:04 (Al Ahsa)                                                        | 307                     | 1.193       | -1.62% | 0.861       | -1.43% |
| St:05 (Al Baha)                                                        | 306                     | 0.817       | -1.45% | 0.589       | -1.04% |
| St:06 (AlJouf)                                                         | 368                     | 0.644       | -1.46% | 0.514       | -1.36% |
| St:07 (AlMadina)                                                       | 368                     | 0.666       | -0.74% | 0.539       | -0.74% |
| St:08 (AlQaisumah)                                                     | 369                     | 0.775       | -1.90% | 0.690       | -2.06% |
| St:09 (AlQassim)                                                       | 368                     | 1.039       | -2.02% | 0.652       | -1.83% |
| St:10 (AlQuraia)                                                       | 67                      | 0.554       | -0.11% | 0.456       | -0.30% |
| St:11 (AlWajh)                                                         | 367                     | 0.518       | -0.83% | 0.424       | -0.62% |
| St:12 (Arar)                                                           | 367                     | 0.692       | -1.29% | 0.592       | -1.67% |
| St:13 (ArRiyadh Middle)                                                | 369                     | 0.790       | -1.31% | 0.588       | -1.37% |
| St:14 (ArRiyadh North)                                                 | 308                     | 0.779       | -1.18% | 0.579       | -1.25% |
| St:15 (AtTa'if)                                                        | 365                     | 0.954       | -1.35% | 0.610       | -0.89% |
| St:16 (Bisha)                                                          | 368                     | 0.599       | -1.00% | 0.475       | -0.86% |
| St:17 (Gizan)                                                          | 368                     | 0.442       | -0.54% | 0.356       | -0.40% |
| St:18 (Hafr El-Batin)                                                  | 245                     | 0.870       | -1.73% | 0.712       | -1.87% |
| St:19 (Hail)                                                           | 367                     | 0.709       | -1.81% | 0.560       | -1.61% |
| St:20 (Jeddah)                                                         | 369                     | 0.439       | -0.44% | 0.368       | -0.35% |
| St:21 (Khamis Mushait)                                                 | 367                     | 0.450       | -0.81% | 0.342       | -0.54% |
| St:22 (Makkah)                                                         | 307                     | 0.546       | -1.00% | 0.493       | -0.97% |
| St:23 (Najran)                                                         | 368                     | 0.764       | -1.31% | 0.610       | -1.19% |
| St:24 (Rafha)                                                          | 365                     | 0.950       | -3.02% | 0.756       | -2.75% |
| St:25 (Sharurrah)                                                      | 306                     | 0.992       | -1.48% | 0.769       | -1.17% |
| St:26 (Tabuk)                                                          | 369                     | 0.448       | -0.95% | 0.363       | -0.86% |
| St:27 (Turaif)                                                         | 367                     | 0.609       | -1.56% | 0.448       | -1.43% |
| St:28 (Wadi Al Dawasir)                                                | 306                     | 0.770       | -1.09% | 0.643       | -1.04% |
| St:29 (Yenbo)                                                          | 369                     | 0.602       | -0.57% | 0.483       | -0.43% |
| Summary                                                                |                         | 0.730       | -1.22% | 0.557       | -1.12% |

\* refer to Table 4 footnote for definitions

## KEYWORDS

Alfalfa  
 Arid regions  
 Climatic data  
 Conversion formulae  
 Evapotranspiration  
 Extraterrestrial radiation  
 FAO56 correction  
 Food & Agriculture Organization, FAO  
 Grass  
 Hargreaves  
 Hargreaves modified model  
 Hargreaves Samani  
 Makkah  
 Penman Monteith  
 Radiation  
 Riyadh  
 Saudi Arabia  
 Temperature correction  
 Temperature, dew point  
 The extraterrestrial radiation  
 Vapor pressure  
 Weather correction  
 Weather station, agroclimatic

Weather station, non-reference

Weather station, reference

## **BIBLIOGRAPHY**

Refer to the bibliography for the literature cited.

## Chapter 14

### Evapotranspiration with distant Weather Stations: Saudi Arabia<sup>1, 2</sup>

#### INTRODUCTION

Determining the evapotranspiration (ET) is the base of many disciplines including the irrigation system design, irrigation scheduling and hydrologic and drainage studies [12]. Perfect determination of ET is a big challenge for investigators especially in arid and hyper-arid regions. Actual crop ET is computed by multiplying reference ET by the crop factor. Reference ET is the summation of evaporation and transpiration produced by a reference crop in specific growth conditions (height, coverage and health). ET value depends on two main factors: the selected reference crop and the climatic data [4]. This chapter discusses the possibility of using the weather data recorded at these stations instead of reference agro-climatic data. Hence, the objective of this chapter is to estimate the ET values for the RWS [Reference weather station] and the NRWS [non reference weather station] at Riyadh - Saudi Arabia; and to compare these ET values with the reference evapotranspiration based on lysimeter observations for reference conditions.

The Kingdom of Saudi Arabia (KSA) is one of the most arid countries in the world and suffers persistent water shortage problems and more than 88% of water consumption in KSA is due to agricultural related activities [10]. Hence, several researches have been performed to assess the ET in KSA. Researchers have estimated the reference ET [2, 9]; and assessed the ET for specified crops [1, 7]; and have determined crop coefficients.

For open field agriculture, the reference ET has traditionally been predicted by using either grass ( $ET_0$ ) or alfalfa ( $ET_f$ ). Each of these two crops use some conditions to be considered as a reference crop [14]. The selection of either crop as reference crop has been studied by several investigators [6, 11, 13, 14]. It was recommended by the American Society of Civil Engineers Task Committee (ASCE-TC) to use a single equation for both reference crops, each with different constants [5]. They recommended standardizing the equation with two surfaces, the short crop (about 0.12 m height e.g., the clipped cool season grass) and the tall crop (about 0.50 m height e.g., the full cover alfalfa). The heights of crop, however, may vary according to the crop variety and location's geography. When using crop with different height, one should clearly mention the used height beside the ET data.

Climate data are acquired from Weather Stations (WS) whose location is an important consideration for the quality of the data. RWS should be located inside a cropped area (normally with grass) in order to ensure the same environmental conditions for station's gauges as that of the cultivated crops. On the other hand, stations located in these reference conditions usually record less temperature than Non-Reference (NR) weather stations [3]. This was attributed to the cooling effect of the crop. Allen [3] suggested an adjustment for the recorded temperature in NRWS so that the resultant temperatures could be used to give the reference  $ET_0$ .

In many locations, RWS are not found especially for newly reclaimed desert areas. To perform preliminary studies for an area, one should use the data from nearest station. This situation is probably affected by the distance between the field and the weather station. There are 13 districts in KSA and some of these are larger in size than many countries. Arriyadh District's area, for instance, is 380,000 Km<sup>2</sup>, which is 17% of the geographical area of KSA. The main weather stations in Arriyadh and other places in the kingdom are situated at airports.

#### MATHEMATICAL MODELS FOR ESTIMATING EVAPOTRANSPIRATION [ET]

Table 1 indicates selected theoretical models to estimate ET that were used in this chapter. For a complete list of all models, the reader should consult chapter 4 in this book.

The original Penman-Monteith (PM) equation for determining the evapotranspiration [4] is given in equation /1/. The chapters 2 and 3 of the publication by Allen [4] describe in detail all the variables in equation /1/ [See Table 1]. The main component of ET calculation is the air Temperature (T). Although it does not appear explicitly in the equation /1/, yet it is included in most of the parameters:  $\Delta$ ,  $R_n$ ,  $c_p$ ,  $\rho_a$ ,  $e_s$ ,  $e_a$ ,  $\lambda$ ,  $\gamma$ ,  $r_s$ ,  $r_a$ , and G. Allen [3] concluded that correcting the temperature values of the non-reference weather stations [NRWS] to an adjusted value fixes the entire ET equation to give an acceptable value close to the reference weather station [RWS] value.

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<sup>2</sup> Modified and reprinted from: American Journal of Agricultural and Biological Sciences, 6 (3): 433-439, 2011.  
Numbers in parentheses refer to the references in the bibliography.

**Table 1.** List of equations used in this chapter.

The original Penman-Monteith equation (PM) for determining the evapotranspiration [4] is given in equation /1/:

$$ET = \frac{\Delta(R_n - G) + \rho_a \cdot c_p \cdot \frac{(e_s - e_a)}{r_a}}{\lambda \left( \Delta + \gamma \left( 1 + \frac{r_s}{r_a} \right) \right)} \quad /1/$$

Where :

- ET = Evapotranspiration [mm day<sup>-1</sup>]
- Δ = Slope of the vapor pressure curve [kPa°C<sup>-1</sup>]
- R<sub>n</sub> = Net radiation at the crop surface [MJ m<sup>-2</sup> day<sup>-1</sup>]
- G = Soil heat flux density [MJ m<sup>-2</sup> day<sup>-1</sup>]
- ρ<sub>a</sub> = Mean air density at constant pressure [kg m<sup>-3</sup>]
- C<sub>p</sub> = Specific heat at constant pressure [MJ kg<sup>-1</sup>°C<sup>-1</sup>]
- e<sub>s</sub>-e<sub>a</sub> = Vapor pressure deficit [kPa]
- e<sub>s</sub> = Saturation vapor pressure [kPa]
- e<sub>a</sub> = Actual vapor pressure [kPa]
- r<sub>a</sub> = Aerodynamic resistance [s m<sup>-1</sup>]
- r<sub>s</sub> = The bulk surface resistance [s m<sup>-1</sup>]
- λ = Latent heat of vaporization [MJ kg<sup>-1</sup>]
- γ = The psychrometric constant [kPa°C<sup>-1</sup>]

Actual vapor pressure is determined by equation /2/:

$$e_a = 0.005(RH_x e_o [T_n] + RH_n e_o [T_x]) \quad /2/$$

Where:

- T<sub>n</sub> = Minimum dry bulb air temperature [°C]
- T<sub>x</sub> = Maximum dry bulb air temperature [°C]
- RH<sub>x</sub> = Maximum relative humidity [%]
- RH<sub>n</sub> = Minimum relative humidity [%]

Instead of using RH<sub>x</sub> and RH<sub>n</sub> in equation /2/, one may use average relative humidity (RH<sub>a</sub>) as shown in equation /3/:

$$e_a = 0.005RH_a (e_o [T_n] + e_o [T_x]) \quad /3/$$

Allen's method is summarized in equations /1/ to /5/ [See Table 1]. The actual vapor pressure is calculated with equations /2/ and /3/ [Table 1]. The dew point temperature is determined with equation /4/, in the absence of measured values [See Table 1]. The temperature difference is determined with equation /5/, where T<sub>n</sub> is a minimum temperature. For arid and semi-arid environments, if ΔT > 2 then the maximum temperature [T<sub>x</sub>] is adjusted to: T<sub>x</sub><sup>(corr)</sup> = [T<sub>x</sub> - 0.5 (ΔT - 2)], where <sup>(corr)</sup> = Refer to the corrected value. Finally doing the same for T<sub>n</sub> : if ΔT ≤ 2, then no correction is needed.

For sites with limited weather data, Allen [4] suggested using a modified version of the Hargreaves equation (HG) as an alternative method for determining ET. He also suggested calibrating the HG equation [Equation /6/] using linear regression equation [Equation /7/ in Table 1] using the corresponding values from the PM equation /1/ in Table 1. The units are: MJ-m<sup>2</sup> for extraterrestrial radiation in equation /8/; MJ-m<sup>-1</sup>-h<sup>-2</sup> for ET<sub>HG</sub> in equation /6/; and mm-day<sup>-1</sup>. The parameters in equation /6/ were estimated with equations /8/ to /12/ in Table 1.

## WEATHER DATA SOURCES

Two types of data were used in this study: weather data to estimate the ET value; the field data to determine ET experimentally. For weather data, two weather stations (Campbell and Davis) at the educational farm of the King Saud University were selected as agro-climatic RWS [reference weather station]. Also two weather stations at Old Riyadh airport and King Khaled airport [See Figure 1] were used as domestic NRWS [non-reference weather stations]. Reference field data was obtained from Al-Amoud *et al.* [1] based on five years project of ET evaluation through lysimeter studies in 9 zones throughout the country.

The dew point temperature is determined with equation /4/, in the absence of measured values:

$$T_d = \frac{116.91 + 237.3 \ln(e_a)}{16.78 - \ln(e_a)} \quad /4/$$

The temperature difference is determined with equation /5/, where T<sub>n</sub> is a minimum temperature:

$$\Delta T = T_n - T_d \quad /5/$$

Modified version of Hargreaves method is shown in equation /6/.

The equation /6/ should be calibrated for local conditions using data of equation /1/ using equation /7/ with C<sub>1</sub> and C<sub>2</sub> as linear regression coefficients:

$$ET_{HG} = 0.0023R_a (T_a + 17.8) (T_x - T_n)^{0.5} \quad /6/$$

$$ET_{PM} = c_1 + c_2 ET_{HG} \quad /7/$$

In equation /6/, the extraterrestrial radiation, R<sub>a</sub>, is by equation /8/:

$$R_a = 37.6 d_r (\omega_s \sin \phi \sin \delta + \sin \omega_s \cos \phi \cos \delta) \quad /8/$$

Where:

d<sub>r</sub> is a relative distance from earth to sun (Equation /9/):

$$d_r = 1 + 0.033 \cos(0.0172 J) \quad /9/$$

Solar declination in radians is given by equation /10/:

$$\delta = 0.409 \sin(0.0172 J - 1.39) \quad /10/$$

Sunset hour angle in radians is determined by equation //11/, with φ = latitude in radians:

$$\omega_s = \arccos(-\tan \phi \tan \delta) \quad /11/$$

Julian day (J) is calculated with equation /12/, with M = Month of the year and D = Day of the month. J ranges from 1 to 366 (366 is for leap year).

$$J = \text{int} \left( \frac{275}{9} M + D - 30 \right) \quad \text{if } (M > 2) \begin{cases} \text{And LeapYear} \rightarrow \text{Subtract 1} \\ \text{And Not LeapYear} \rightarrow \text{Subtract 2} \end{cases} \quad /12/$$



**Figure 1.** Location and distances between the weather stations in this research.

All of the weather data were recorded on daily bases while the field data was recorded on monthly bases. Hence, daily ET values for all the studied weather stations were calculated and later, the data was summarized as average monthly ET values. The recorded dataset varies from station to station. For airport's weather stations, complete records from 1985 to 2009 were obtained. For Campbell and Davis weather stations, the records were from 1993-2006. This research was limited to the least-size data set i.e., Campbell's dataset for an appropriate comparison. The databases of the studied weather stations were not so coincident. For all stations, the commonly available data parameters included: the dry bulb temperature (max., min. and avg.), relative humidity (max., min. and avg.), rainfall and wind speed (average). In addition to the common variables for airports stations, the wet bulb temperature (max., min. and avg.), the atmospheric pressure at sea level and at station level and the actual vapor pressure were also recorded. While for Campbell station, the actual vapor pressure and solar radiation are recorded. Finally, for Davis station, the only addition to common parameters was the solar radiation. This information is summarized in Table 2. Solar Radiation ( $R_s$ ) and vapor pressure ( $e_a$ ) are essential parameters for computing ET. If not recorded at the weather station, these parameters were calculated using equations /2/ to /5/ and /8/ to /12/.

As mentioned above, the field data were obtained from Al-Amoud *et al.* [1]. The five years project used Alfalfa cultivated in weighing lysimeters located at Riyadh and at 8 more locations in the KSA. The daily and monthly values of irrigation, drainage, precipitation and water consumption were recorded for these stations. However, only the monthly results were available in the published research.

## METHODS AND MATERIAL

For each of the four stations mentioned in Table 2, weather data were observed as daily records. Using the raw data, the researchers calculated  $ET_{PMg}$ ,  $ET_{PMa}$  and  $ET_{HG}$ ; where the suffixes PMg and PMa stand for Penman Monteith formula for 0.12 m grass reference crop and 0.25 m alfalfa reference crop, respectively.

The entire calculations were repeated after applying Allen [3] corrections to the temperature data but only for non agro-climatic stations. To simplify data representation and discussion, the symbol and numerical value were assigned to each data source as the shown in Table 3. Since the published data by Al-Amoud *et al.* [1] were on monthly bases and Allen [4] suggested calibrating Hargreaves formula using monthly data, subsequently, the research team converted the daily calculated data to the data on monthly bases.

## RESULTS AND DISCUSSION

The ET data for the six datasets are presented graphically in Figure 2. The charts are denoted by letters 'a' to 'f' for Campbell reference WS, Davis reference WS, old Riyadh airport corrected dataset, old Riyadh airport raw dataset, King Khalid airport corrected dataset and King Khalid airport raw dataset, respectively. Four ET values were plotted for each dataset: measured ET,  $\{P_x(L)\}$ ; grass based PM evapotranspiration{g}; alfalfa based PM evapotranspiration{a}; and Hargreaves method ET.

All of the calculated data groups were compared with the measured dataset and the correlation coefficient for each data group pair was calculated. The correlation coefficients are illustrated in Figure 3. Then, the regression coefficients, mentioned in equation /7/, were calculated between HG and PM formulas [See Table 4]. Finally, the ET ratio between alfalfa and grass was calculated and compared to the value of 1.15 that has been reported by Doorenbos and Pruitt [8]. Table 5 shows the regression coefficients for the linear relationships between ET alfalfa and ET grass ET in this study.

| <b>Table 2.</b> The climatic parameters that were recorded at the weather stations. |                           |                        |                  |                |                    |               |                          |               |          |
|-------------------------------------------------------------------------------------|---------------------------|------------------------|------------------|----------------|--------------------|---------------|--------------------------|---------------|----------|
|                                                                                     | Temperature<br>(Dry bulb) | Relative<br>(Wet bulb) | Wind<br>Humidity | Solar<br>speed | Vapor<br>radiation | Atm. pressure | Commulative<br>sea level | Station level | Rainfall |
| Campbell station                                                                    | ✓                         | ✓                      | ✓                | ✓              | ✓                  | ✓             | ✓                        | ✓             | ✓        |
| Davis station                                                                       | ✓                         | ✓                      | ✓                | ✓              | ✓                  | ✓             | ✓                        | ✓             | ✓        |
| Riyadh old airport                                                                  | ✓                         | ✓                      | ✓                | ✓              | ✓                  | ✓             | ✓                        | ✓             | ✓        |
| King khaled intl. airport                                                           | ✓                         | ✓                      | ✓                | ✓              | ✓                  | ✓             | ✓                        | ✓             | ✓        |

| <b>Table 3.</b> The data source for the research and identification.                                                                                                                                |                                        |           |           |                    |           |                           |           |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------|-----------|-----------|--------------------|-----------|---------------------------|-----------|
| Data is                                                                                                                                                                                             | Measured                               |           |           | Calculated         |           |                           |           |
| Location                                                                                                                                                                                            | Educational Farm, King Saud University |           |           | Airport            |           |                           |           |
| Name                                                                                                                                                                                                | Project data                           | Campbell  | Davis     | Riyadh Old Airport |           | King Khaled Intl. Airport |           |
| #                                                                                                                                                                                                   | 0                                      | 1         | 2         | 3                  | 4         | 5                         | 6         |
| Reference data?                                                                                                                                                                                     | -                                      | yes       | yes       | no                 | no        | no                        | no        |
| Corrected data?                                                                                                                                                                                     | no need                                | no need   | no need   | yes                | no        | yes                       | no        |
| Symbols                                                                                                                                                                                             | Px(L)                                  | Cs(a,g,H) | Ds(a,g,H) | Oc(a,g,H)          | On(a,g,H) | Kc(a,g,H)                 | Kn(a,g,H) |
| Longitude: 24N,                                                                                                                                                                                     | 44°12.24"                              | 44°12.24" | 44°12.24" | 42°35.46"          | 42°35.46" | 57°27.00"                 | 57°27.00" |
| Latitude: 46E,                                                                                                                                                                                      | 37°14.90"                              | 37°14.90" | 37°14.90" | 43°30.54"          | 43°30.54" | 41°55.54"                 | 41°55.54" |
| Symbols: A: Alfalfa; C: Corrected; C: Campbell; D: Davis; g: Grass; H: Hargreaves; K: King Khalid airport; L: Lysimeters; n: Normal; O: Old airport; P: Project data; s: Reference; x: Experimental |                                        |           |           |                    |           |                           |           |

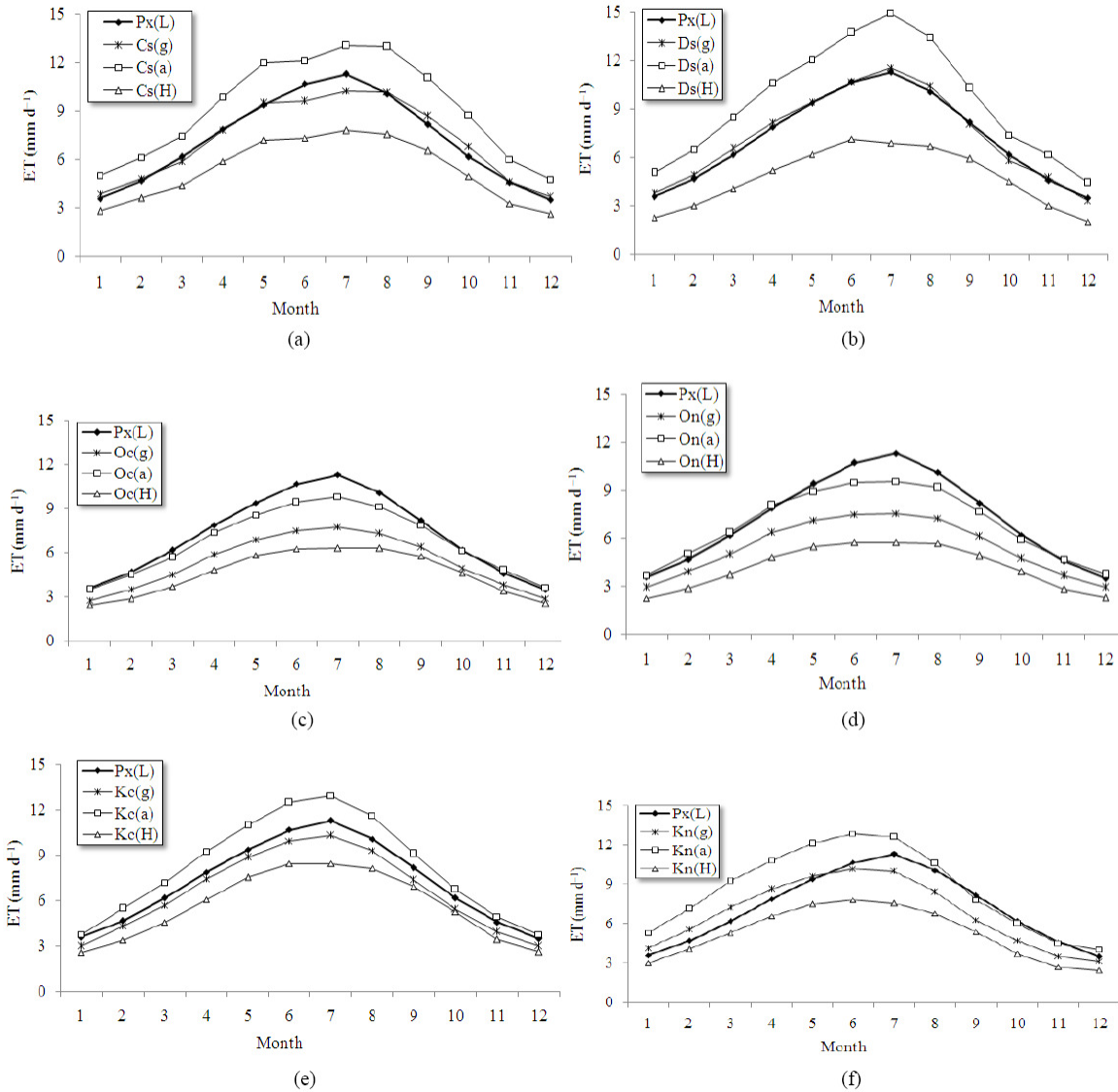
| <b>Table 4.</b> Linear regression analysis for ET values between Hargeaves [HG] and Penman-Monteith [See Table 1]. |                       |                |  |                       |        |                |  |
|--------------------------------------------------------------------------------------------------------------------|-----------------------|----------------|--|-----------------------|--------|----------------|--|
| Grass                                                                                                              |                       |                |  | Alfalfa               |        |                |  |
| Equation                                                                                                           |                       | r <sup>2</sup> |  | Equation              |        | r <sup>2</sup> |  |
| Cs                                                                                                                 | PMg= 1.280 HG + 0.324 | 0.9983         |  | PMA= 1.608 HG + 0.526 | 0.9985 |                |  |
| Ds                                                                                                                 | PMg= 1.563 HG - 0.122 | 0.9591         |  | PMA= 1.993 HG - 0.046 | 0.9746 |                |  |
| Kc                                                                                                                 | PMg= 1.189 HG - 0.140 | 0.9792         |  | PMA= 1.481 HG - 0.140 | 0.9874 |                |  |
| Kn                                                                                                                 | PMg= 1.296 HG + 0.013 | 0.9857         |  | PMA= 1.619 HG + 0.109 | 0.9912 |                |  |
| Oc                                                                                                                 | PMg= 1.214 HG - 0.211 | 0.9812         |  | PMA= 1.517 HG - 0.243 | 0.9879 |                |  |
| On                                                                                                                 | PMg= 1.298 HG - 0.021 | 0.9908         |  | PMA= 1.624 HG + 0.055 | 0.9940 |                |  |

| <b>Table 5.</b> The regression coefficients for the linear relationships between ET alfalfa and ET grass ET in this study. |        |        |        |        |        |        |
|----------------------------------------------------------------------------------------------------------------------------|--------|--------|--------|--------|--------|--------|
|                                                                                                                            | Cs     | Ds     | Kc     | Kn     | Oc     | On     |
| Slope                                                                                                                      | 1.2553 | 1.2691 | 1.2428 | 1.2470 | 1.2458 | 1.2493 |
| Intercept                                                                                                                  | 0.1250 | 0.1576 | 0.0533 | 0.1070 | 0.0399 | 0.0919 |
| r <sup>2</sup>                                                                                                             | 0.9998 | 0.9995 | 0.9997 | 0.9998 | 0.9996 | 0.9998 |

Campbell and Davis weather stations are located at the educational farm of the King Saud University; the lysimeters' experiment of Al-Amoud *et al.* [1] was held at the same location. Figures 2a and 2b show the results of measured and calculated ET by the three mentioned methods. Both stations show underestimation of Hargreaves formula and overestimation of PM alfalfa, 'a', calculations. It is strange that the grass ET, 'g', almost coincides with the measured alfalfa data. This may be attributed to some lack of precision either in the field measurements devices or to some calibration errors of the weather stations. The data at old airport (Figures 2c and 2d) behaves differently and the closer values to the measured alfalfa ET are the calculated alfalfa values, especially at months 1-3 and 9-12. The situation is different for King Khalid airport's station (Figures 2e and 2f) as the raw data appear to give fuzzy trend dissimilar to the measured data, Figure 2f. After applying the data correction, the shape of the curve improved dramatically, Figure 2e. This is confirmed in Figure 3, which shows the Correlation Coefficient (CC) between measured data versus each data group. Although all the values of CC are more than 0.9, which is a very good value, however, the 'Kn' dataset is the worst representation of actual state. On the other hand, it strangely appears that the corrected values of King Khalid's airport (K) are the top most accurate representatives of the measured data. This is probably due to the geographic condition of the 'K' airport, which is outside of the city and almost surrounded with desert lands, in addition to the long distance between the Educational Farm stations (EF) and the 'K' airport (about 25.7 km), as shown in Figure 1. The Old airport (O) is near (10.9km), in fact almost in the middle of the city and surrounded by buildings, roads and some green areas. The correction of the 'O' data improves the 'g' and 'a' data groups, while it worsens the 'H' data group, as shown in Figure 3.

From Figure 3, it can be concluded that the PM calculations improve dramatically after applying the Allen [3] correcting algorithm to the data, while for HG formula, applying the corrections improves the accuracy for 'K' station but worsens it for 'O' station.



**Figure 2.** Monthly evapotranspiration of the studied region, showing three datasets in each chart compared to measured evapotranspiration, where: a: Alfalfa; c: Corrected; C: Campbell; D: Davis; g: Grass; H: Hargreaves; K: King Khalid airport; L: Lysimeters; n: Normal; O: Old airport; P: Project data; s: Reference; x: Experimental.

In general, Hargreaves equation gives very satisfactory results of ET for Riyadh city and the equation can be used trustfully especially in the absence of some climatic factors like wind speed and radiation. However, we applied the linear correction equations and found some excellent fitted equations, as listed in Table 3. All the equations are excellently fitted with minimum value of coefficient of determination ( $r^2$ ) of 0.974. It can be approximated that  $PM_g = [1.30 \cdot HG - 0.05]$  for grass reference crop, while  $PM_a = [1.64 \cdot HG + 0.1]$  for alfalfa reference crop. For more accurate values each station should be calibrated, as shown in Table 4. The ratio between alfalfa ET and grass ET,  $[ET_{alfalfa}/ET_{grass}$ , or  $ET_r/ET_o$ ], is always taken as 1.15 for arid regions, as recommended by Doorenbos and Pruitt [8]. This value has been used by many researches [2] when studying the Saudi Arabia ET. We evaluated this value for each of the studied data groups and a linear relationship between  $ET_{alfalfa}$  and  $ET_{grass}$  was obtained, as shown in Table 5. The slope of  $ET_r/ET_o$  is almost 1.25 for all stations and using less value may result in some bias in data.

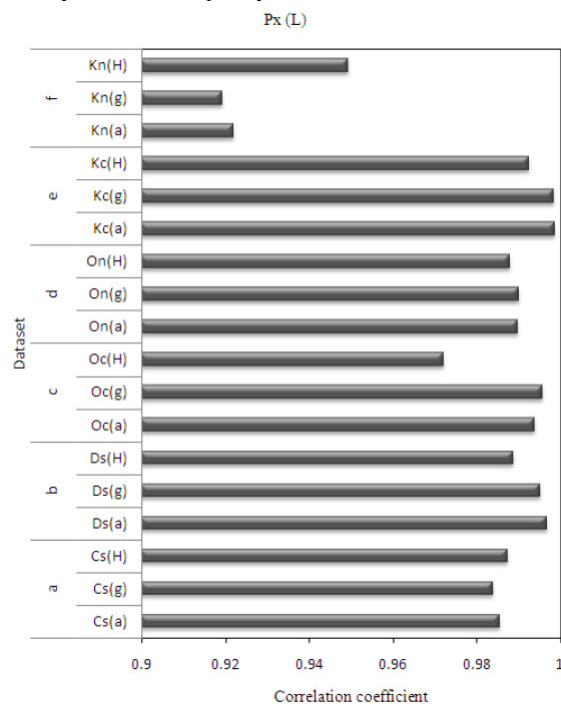
## SUMMARY

Due to the easiness of finding non-reference agro-climatic WS than the agro-climatic ones in the newly reclaimed areas, their weather data had to be corrected through simple procedure. Two reference and two non-reference WS were taken in Riyadh city and corrections were applied to non-reference WS only. We calculated the evapotranspiration using Penman



Monteith and Hargreaves formulas. PM was calculated for two reference crops i.e., alfalfa and grass. Calculated data were compared with measured data. Results show an admirable enhancement in data accuracy after applying the data correction to the non-reference stations. The simple ET formula of Hargreaves underestimates the actual ET. The situation changes after applying the simple linear fitting equation to the resulted values. The ratio between alfalfa and grass ET was found to be 1.25 for Riyadh area. It is concluded to use the temperature correction method when using non-reference stations. Hargreaves formula is recommended to be used after applying the suggested fit in this study, especially when the wind speed and radiation data are missing.

Reference agro-climatic Weather Stations (WS) are rarely found in newly reclaimed areas. The usage of weather data from non-reference WS may lead to inaccurate estimations of Evapotranspiration (ET), especially if the non-reference stations are distant from the reclaimed location. Weather data from four WS located at Riyadh were used to calculate ET by using Penman Monteith (PM) and Hargreaves equations. PM equation was applied with both alfalfa and grass reference crops. Calculations were done with and without temperature correction for non-reference weather stations. All calculations were compared with measured lysimeter data and corrections in Hargreaves formula were suggested. **Results:** (1): Weather data from non-reference WS can be used safely to calculate ET only when temperature corrections are applied. (2) Hargreaves formula underestimates ET at all locations in the study area. By applying the simple linear correction to the data, highly acceptable results are obtained. (3) The ET ratio between alfalfa and grass in Riyadh is 1.25. The study concludes that temperature correction for non-reference WS is essential to ensure acceptable ET calculations. Usage of Hargreaves formula is recommended with the corrections suggested in the study due to its simplicity.



**Figure 3.** The correlation coefficients between the measured data and the calculated data for all data groups in the six datasets.

## KEYWORDS

Alfalfa  
Arid Regions  
Climatic data  
Climatic stations integrity  
Data correction  
Dew point temperature  
ET  
Evapotranspiration  
Extraterrestrial radiation  
Grass  
Hargreaves method  
Hargreaves modified method  
Kingdom of Saudi Arabia

Lysimeter  
Non reference weather station  
Penman-Monteith method  
Reference crop  
Regression analyses  
Riyadh, Saudi Arabia  
Saudi Arabia  
Vapor pressure  
Weather station  
Weather station, non-reference  
Weather station, reference

## **BIBLIOGRAPHY**

Refer to the bibliography for the literature cited.

## Chapter 15

### Actual Evapotranspiration using Satellite Image in Thailand<sup>1, 2</sup>

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#### INTRODUCTION

In the water cycle, evapotranspiration is one of the most important components, but it is one of the most difficult to measure and monitor. Evapotranspiration relates to the exchange of energy in the atmosphere, ground surface, and root zone. Some elements of calculated evapotranspiration can be measured by weather stations, while others are estimated from empirical equations. Then, the calculated evapotranspiration has some inaccuracy. To improve upon this problem, the combination of meteorological data and remote sensing observations are an alternative evapotranspiration [14,18]. On the other hand, temperature is normally measured in a number of weather stations. Since temperature relates to many weather data, temperature can imply the characteristic of other weather data. For example, low temperature is included high humidity but low evaporation can be occurred in the condition of low temperature. Moreover, the variable spatial resolution is the characteristic of both actual evapotranspiration and temperature. At present, satellite images are used for studying the Earth's surface and it bolsters spatial resolution. This chapter discusses effects of temperature on actual evapotranspiration using satellite image.

Evapotranspiration occurs from evaporation and transpiration, and it can be obtained from weather data and satellite images. Evaporation is the primary process of water transfer in the hydrological cycle. The water is transformed into vapour and transported into the sky. Evaporation can be classified into potential evaporation and actual evaporation. The potential evaporation is defined as the amount of evaporation that would occur if a sufficient water source were available. On the other hand, the actual evaporation is the amount of water which is evaporated a normal day. The potential evaporation is the maximum value of the actual evaporation. Transpiration is included by the vaporization of liquid water contained in plant tissues and the vapor removal to the atmosphere [14,18]. Evapotranspiration is normally computed from the Penman-Monteith FAO 56 equation using weather data. This equation is affected by principal weather parameters such as radiation, air temperature, humidity and wind speed. These parameters can be measured by weather station and computed by the equation of FAO irrigation and Drainage Paper No. 56 [2]. In addition to the Penman-Monteith FAO 56 equation, evapotranspiration can be estimated from the concept of energy balance. The main components of the energy balance equation are sensible heat flux, latent heat flux, soil heat flux, and net radiation. These elements relate with incoming and outgoing radiation in the atmosphere, ground surface, and root zone. They are estimated from remote sensing data and weather data [4, 5, 26, 27].

Remotely sensed data are used for studying the Earth's surface. Current technology allows continuous acquisition of data, regular revisit capabilities [resulting in up-to-date information], broad regional coverage, good spectral resolution [including infra-red bands], good spatial resolution, ability to manipulate/enhance digital data, ability to combine satellite digital data with other digital data, cost-effective data, map-accurate data, possibility of stereo viewing, and large archives of historical data. Remote sensing helps to record data from remote locations. Satellite data provides timely and detailed information about the Earth's surface, especially in relation to the management of our renewable and non-renewable resources. The advantages of satellite data for many fields include for example; assessment and monitoring of vegetation types and their status, soil surveys, mineral exploration, map making and revision, production of thematic maps, water resources planning and monitoring, urban planning, agricultural property planning and management, crop yield assessment, and natural disaster assessment.

The Surface Energy Balance Algorithm for Land or SEBAL [7,8] is an image processing model to calculate evapotranspiration by using satellite imagery and weather data with the concept of energy balance at the land surface, so evapotranspiration for each pixel is calculated. Satellite images that can be used in SEBAL are LANDSAT, NOAA-AVHRR, MODIS, and ASTER. The advantages of SEBAL are easily applicable because of minimal collateral data needed, applicable to various climates because of physical concepts, no need for land use classification, no need to involve data demanding hydrology, and is a suitable method for all visible, near-infrared and thermal radiometers. However, the disadvantages of SEBAL include cloud-free conditions being required and that surface roughness is poorly described, so that SEBAL is only suitable for flat terrain [1, 3, 16, 17, 20, 25].

#### LANDSAT 5 TM

Landsat 5 TM has a unique and necessary role in the realm of earth observing satellite orbits, because no other satellite of the earth observing system matches with the synoptic coverage, high spatial resolution, spectral range and radiometric calibration of Landsat's system. Landsat 5 TM satellite imagery Path/Row:127/48 was mainly input data. The spatial resolution of Landsat 5 TM satellite imagery is 30 m and the swath width covered by the image is 185 km. The details of Landsat 5 TM characteristics are shown in Tables 1 and 2 [12]. At the ground stations, the Landsat ground system consists of a spacecraft control center, ground stations for uplinking commands and receiving data, a data handling facility and a data archive, which

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<sup>2</sup> Numbers in parentheses refer to references in the bibliography.

were developed by the Goddard Space Flight Center, Greenbelt, MD., in conjunction with the U.S. Geological Survey [USGS] EROS Data Center [EDC], Sioux Falls, SD. These facilities will receive, process, archive, and distribute ETM+ data to users. Raw ETM+ data can be transmitted to the EROS Data Center by the ground system within 24 hours of its reception [12, 22,].

This Landsat 5 TM image covers Sri Songkhram sub-river basin which is located in the lower part of Mekhong river basin, in the northeast of Thailand. The time period of this study is from November 2006 to January 2007, belonging to the dry season. Also, These are conditions of clear sky. Moreover, there is the cultivation during this time so there are both evaporation and transpiration that is evapotranspiration.

## RADIATION

Extraterrestrial radiation [ $R_a$ ] is the solar radiation received at the top of the earth's atmosphere on a horizontal surface. The values of extraterrestrial radiation depend on seasons change, the position of the sun, and the length of the day. Therefore, the extraterrestrial radiation is a function of latitude, the date and time of day. The solar constant is the radiation striking a surface perpendicular to the sun's rays at the top of the earth's atmosphere and it is some  $0.082 \text{ MJ m}^{-2} \text{ min}^{-1}$ . If the position of the sun is directly overhead, the incidence angle of extraterrestrial radiation is zero. In this case, extraterrestrial radiation is some  $0.082 \text{ MJ m}^{-2} \text{ min}^{-1}$ .

**Table 1.** Landsat 5 TM mission specifications.

| Characteristics          | Specifications                       |
|--------------------------|--------------------------------------|
| Swath width              | 185 km                               |
| Repeat coverage interval | 16 days [233 orbits]                 |
| Altitude                 | 705 km                               |
| Quantization             | Best 8 of 9 bits                     |
| On-board data storage    | ~ 375 Gb [solid state]               |
| Inclination              | Sun-synchronous, 98.2 degrees        |
| Equatorial crossing      | Descending node; 10:00 am +/- 15 min |
| Launch vehicle           | Delta II                             |
| Launch date              | April 1999                           |

**Table 2.** Landsat 5 TM characteristics.

| Channel                                    | Spectral range [microns] | Ground resolution [m] |
|--------------------------------------------|--------------------------|-----------------------|
| 1 [Visible and near infrared: VNIR]        | 0.450 - 0.515            | 30                    |
| 2 [Visible and near infrared: VNIR]        | 0.525 - 0.605            | 30                    |
| 3 [Visible and near infrared: VNIR]        | 0.630 - 0.690            | 30                    |
| 4 [Visible and near infrared: VNIR]        | 0.750 - 0.900            | 30                    |
| 5 [Short wavelength infrared: SWIR]        | 1.550 - 1.750            | 30                    |
| 6 [Thermal long wavelength infrared: LWIR] | 10.40 - 12.50            | 60                    |
| 7 [Short wavelength infrared: SWIR]        | 2.090 - 2.350            | 30                    |
| Pan [Visible and near infrared: VNIR]      | 0.520 - 0.900            | 15                    |

Solar or shortwave radiation [ $R_s$ ] is the amount of radiation penetrating from the atmosphere to a horizontal plane. The sun emits energy by electromagnetic waves that include short wavelengths so solar radiation is referred to as shortwave radiation. In the atmosphere, radiation is absorbed, scattered, or reflected by gases, clouds, and dust. For a cloudless day, the solar radiation is about 75% of the extraterrestrial radiation, while it is about 25% of the extraterrestrial radiation on a cloudy day. The solar radiation, which is known as global radiation, is a summation of direct shortwave radiation from the sun and a diffuse sky radiation from all upward angles.

Relative shortwave radiation [ $R_s/R_{s0}$ ] is a relationship between shortwave radiation [ $R_s$ ] and clear-sky solar radiation [ $R_{s0}$ ]. The shortwave radiation is solar radiation that actually reaches to the earth's surface in a given time, while clear-sky solar radiation is solar radiation that reaches to the same area with a clear-sky condition. The relative shortwave radiation is affected by the cloudiness of the atmosphere. On a cloudy day, the ratio is smaller than on a cloudless day. The range of this ratio is between 0.33 [cloudy condition] to 1.00 [cloudless condition].

Relative sunshine duration [ $n/N$ ] shows the cloudiness in the atmosphere. It is a ratio of the actual duration of sunshine [ $n$ ] to the maximum possible duration of sunshine, or daylight hours [ $N$ ]. For the cloudless condition,  $n$  is equal to  $N$ , while  $n$  and  $n/N$  are nearly zero for the cloudy condition. The maximum possible duration of sunshine, or daylight hours [ $N$ ], depends on the position of the sun, so it is a function of latitude and date. The daily values of  $N$  throughout the year differ with latitude.

Albedo [ $\alpha$ ] is a relationship between reflected radiation and total incoming radiation. It varies with both the characteristics of surface and the angle of incidence, or the slope of ground surface. Albedo can be more than 0.95 for freshly fallen snow, and it is smaller than 0.05 for wet bare soil. The range of albedo for green vegetation is about 0.20 – 0.25 and albedo for the green grass reference crop is 0.23.

Net solar radiation [ $R_{ns}$ ] is the fraction of the solar radiation that is reflected from the ground surface. It can be calculated by Equation 1/:

$$R_{ns} = (1 - \alpha)R_s \quad /1/$$

Net long wave radiation [ $R_{nl}$ ] is the difference in value between outgoing and incoming long wave radiation. The longwave radiation is solar radiation absorbed by the earth and turned to heat energy. Since the temperature of the earth is less than the sun, so the earth emits longer wavelengths. Terrestrial radiation is referred to as longwave radiation. The emitted long wave radiation [ $R_{l,up}$ ] is absorbed by the atmosphere or lost into space. The long wave radiation received by the atmosphere [ $R_{l,down}$ ] increases its temperature. Therefore, the earth's surface both emits and receives longwave radiation. The value of outgoing longwave radiation is normally more than incoming longwave radiation, so the net longwave radiation is used to present the energy loss.

Net radiation [ $R_n$ ] is the difference in value between incoming and outgoing radiation of both short and long wavelengths. It is the balance among energy absorbed, reflected, and emitted by the earth's surface. The net radiation is also the difference in value between the incoming net shortwave [ $R_{ns}$ ] and the net outgoing long wave [ $R_{nl}$ ] radiation. It is a positive value during daytime, while it is a negative value during nighttime. For the total daily value, it is a positive value except for the condition of high latitude.

Soil heat flux [ $G$ ] is energy that is used in heating the soil. It is a positive value under the condition of warming soil and negative value under the condition of cooling soil. The soil heat flux is very small when compares with net radiation but it cannot be ignored.

## TEMPERATURE ESTIMATIONS

Normally, Landsat 5 TM satellite image data is in the form of Digital Number [DN] so it is necessary to convert from Digital Number to Radiance for all bands in Landsat 5 TM imagery. The conversion equation is shown below:

$$L_{\lambda} = \frac{(LMAX_{\lambda} - LMIN_{\lambda})}{(QCALMAX - QCALMIN)} \times (QCAL - QCALMIN) + LMIN_{\lambda} \quad /2/$$

Where:  $L_{\lambda}$  is spectral radiance at the sensor aperture in watts/[meter squared \*ster\*  $\mu$  m], QCAL is the quantized calibrated pixel value in DN,  $LMIN_{\lambda}$  is the spectral radiance that is scaled to QCALMIN in watts/[meter squared \*ster\*  $\mu$  m],  $LMAX_{\lambda}$  is the spectral radiance that is scaled to QCALMAX in watts/[meter squared \*ster\*  $\mu$  m], QCALMIN is the minimum quantized calibrated pixel value [corresponding to  $LMIN_{\lambda}$ ] in DN and QCALMAX is the maximum quantized calibrated pixel value [corresponding to  $LMAX_{\lambda}$ ] in DN.

$LMAX_{\lambda}$  and  $LMIN_{\lambda}$  are the spectral radiances for each band at digital number 1 and 255 [i.e QCALMIN, QCALMAX], respectively. QCAL or DN,  $LMAX_{\lambda}$  and  $LMIN_{\lambda}$  are input data. These elements are values in header file information. Thereafter a thermal band or band 6 imagery is converted to the effective at satellite temperature [ $T_{bb}$ ] calculated by equation /3/:

$$T_{bb} = \frac{K_2}{\ln\left(\frac{K_1}{L_6} + 1\right)} \quad /3/$$

For thermal band, calibration constants,  $K_1$  and  $K_2$ , are 666.09 watts/[meter squared \*ster\*  $\mu$  m] and 1282.71 Kelvin, respectively.  $L_6$  is the spectral radiance for band 6 in watts/[meter squared \*ster\*  $\mu$  m]. Then, surface temperature [ $T_s$ ] is computed by equation/4/.

$$T_s = \frac{T_{bb}}{\epsilon_o^{0.25}} \quad /4/$$

Where:  $\epsilon_o$  is surface emissivity.

## ESTIMATIONS OF ACTUAL EVAPOTRANSPIRATION

SEBAL is a tool to estimate actual evapotranspiration for flat areas with the most accuracy and confidence. Satellite image and weather data are used in the SEBAL model to calculate actual evapotranspiration by using a surface energy balance at the land surface. SEBAL evaluates an instantaneous actual evapotranspiration flux for the image time, because the satellite image provides information for the overpass time only. The actual evapotranspiration flux can be calculated for each pixel of the image as a residual of the surface energy budget equation. SEBAL needs both shortwave and thermal bands. The required ground-based data is wind speed. The SEBAL energy balance calculates actual evapotranspiration for each pixel for the time of the satellite image, so the results are instantaneous actual evapotranspiration. To obtain actual evapotranspiration using the conception of SEBAL, equations /6/ to /10/ are used.

Firstly, data in the format of radiance is converted to reflectance for all bands. For this converting, thermal band [band 6] is not considered. In practice, band 6 is converted, but it is a dummy in this file. The equation /5/ is used to convert radiance to reflectanc.

$$\rho_{\lambda} = \frac{\pi \times L_{\lambda}}{ESUN_{\lambda} \times \cos \theta \times d_r} \quad /5/$$

Where:  $\rho_{\lambda}$  is unitless planetary reflectance,  $L_{\lambda}$  is calculated from equation /1/,  $ESUN_{\lambda}$  is mean solar exoatmospheric irradiances from Table 3,  $\theta$  is solar zenith angle in degrees, and  $d_r$  is the Earth-Sun distance in astronomical that can be obtained from equation /6/:

$$d_r = 1 + 0.033 \cos \left( DOY \frac{2\pi}{365} \right) \quad /6/$$

Where: DOY [or J] is number of day in one year for example DOY for January 1 is 1 while DOY for December 31 is 365.  
 $\cos \theta = \cos(90 - \beta)$  /7/

Where:  $\beta$  is sun elevation angle in degree and  $\cos \theta$  is in degree. Albedo for the top of atmosphere [ $\alpha_{toa}$ ] can be considered from equation /9/. The weighting coefficient is calculated from equation /10/.

$$[\text{Radians}] = \frac{\pi}{180} \times [\text{decimal degrees}] \quad /8/$$

$$\alpha_{toa} = \sum (\omega_{\lambda} \times \rho_{\lambda}) \quad /9/$$

$$\omega_{\lambda} = \frac{ESUN_{\lambda}}{\sum ESUN_{\lambda}} \quad /10/$$

Where:  $\omega_{\lambda}$  is weighting coefficient, which is constant value. Solar spectral irradiances values are shown in Table 3.

**Table 3.** Solar Spectral Irradiances.

| Band | Solar Spectral Irradiances<br>watts/[meter squared *ster* $\mu\text{m}$ ] |
|------|---------------------------------------------------------------------------|
| 1    | 1969.00                                                                   |
| 2    | 1840.00                                                                   |
| 3    | 1551.00                                                                   |
| 4    | 1044.00                                                                   |
| 5    | 225.70                                                                    |
| 7    | 82.07                                                                     |
| Pan  | 1368.00                                                                   |

Surface albedo [ $\alpha$ ] can be estimated using equation /11/:

$$\alpha = \frac{\alpha_{toa} - \alpha_{path\_radiance}}{\tau_{sw}^2} \quad /11/$$

$$\tau_{sw} = 0.75 + 2 \times 10^{-5} \times z \quad /12/$$

In equations /11/ to /16/:  $\alpha_{toa}$  is calculated from equation /9/ and  $\alpha_{path\_radiance} \approx 0.03$ ;  $z$  is an elevation of area which is defined from Digital Elevation Map [DEM];  $G_{sc}$  is solar constant value of  $1367 \text{ W/m}^2$ ;  $\rho_3$  and  $\rho_4$  are reflectance value in red and near-infrared bans [band 3 and 4], respectively;  $L$  is constant for SAVI [ $L=0.5$ , when an area have no information for  $L$ ].  $L=0.5$  is suitable for this practice. Incoming solar radiation [ $R_{s\downarrow}$ ] is estimated in spreadsheet using equation /13/. The vegetation indices can be considered from equations /14/ to /16/.

$$R_{s\downarrow} = G_{sc} \times \cos \theta \times d_r \times \tau_{sw} \quad /13/$$

$$NDVI = \frac{\rho_4 - \rho_3}{\rho_4 + \rho_3} \quad /14/$$

$$SAVI = \frac{(1+L)(\rho_4 - \rho_3)}{L + \rho_4 + \rho_3} \quad /15/$$

$$LAI = -\frac{\ln \left( \frac{0.69 - SAVI}{0.59} \right)}{0.91} \quad /16/$$

Surface emissivity [ $\epsilon_o$ ] can be estimated using equation /17/:

$$\epsilon_o = 1.009 + 0.047 \times \ln(NDVI) \quad /17/$$

Outgoing longwave radiation [ $R_{L\uparrow}$ ] can be calculated by equation /18/:

$$R_{L\uparrow} = \varepsilon_o \sigma T_s^4 \quad /18/$$

$$R_{L\downarrow} = \varepsilon_a \times \sigma \times T_{cold}^4 \quad /19/$$

$$\varepsilon_a = 0.85 \times (-\ln \tau_{sw})^{0.09} \quad /20/$$

Where:  $\sigma = 5.67 \times 10^{-8} \text{ W/[m}^2\text{-K}^4]$ . For the selection of “anchor pixel”, SEBAL process utilizes two “anchor” pixels to fix boundary condition for the energy balance.

- “Cold” pixel: a wet, well-irrigated crop surface with full cover [ $T_s \equiv T_{air}$ ]. In cold pixel, sensible heat flux [H] is usually zero so cold pixel should be selected from water area.
- “Hot” pixel should be located in a dry and bare agricultural field where one can assume there is no evapotranspiration taking place, and should have a surface albedo similar to other dry and bare field in the area of interest. It should have a LAI in the range of 0 to 0.4. After the temperatures of both cold and hot pixel are defined, these values are used for calculation in the next step. Incoming longwave radiation [ $R_{L\downarrow}$ ] is computed in spreadsheet using equations /19/ and /20/:

In equation /19/ and /20/:  $\varepsilon_a$  is an atmospheric emissivity. Net surface radiation flux [ $R_n$ ] can be computed by equation /21/. The soil heat flux [G] is given by equation /22/.

$$R_n = R_{s\downarrow} - \alpha R_{s\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_o) R_{L\downarrow} \quad /21/$$

$$\frac{G}{R_n} = \frac{T_s}{\alpha} (0.0038\alpha + 0.0074\alpha^2) (1 - 0.98NDVI^4) \quad /22/$$

$$H = \frac{\rho \times c_p \times dT}{r_{ah}} \quad /23/$$

After the parameters in equations /1/ to /22/ computed, now we can estimate sensible heat flux, latent heat flux, evaporative fraction, and 24-hour actual evapotranspiration as shown below. Sensible heat flux [H] is the flux of heat from the earth's surface to the atmosphere [equation /23/]. It is not associated with phase changes of water. In equation /23/:  $\rho$  is air density [ $\text{kg/m}^3$ ],  $c_p$  is air specific heat [ $1004 \text{ J/kg/K}$ ],  $dT$  [K] is the temperature difference [ $T_1 - T_2$ ] between two heights [ $z_1$  and  $z_2$ ], and  $r_{ah}$  is the aerodynamic resistance to heat transport [s/m]. The estimation of sensible heat flux is most tedious job, because the temperature difference and aerodynamic resistance to heat transport are unknown for the sensible heat flux calculations. To find these unknowns, SEBAL first calculates the sensible heat flux at extreme dry and wet locations. They are manually identified by the user on the image. The aerodynamic resistance to heat transport is computed from the lower integration constant for  $r_{ah}$  [ $z_1 = 0.1 \text{ m}$ ] and the upper integration constant for  $r_{ah}$  [ $z_2 = 2 \text{ m}$ ].

For a dry pixel or hot pixel, it should be located in a dry and bare agricultural field where one can assume that there is no evapotranspiration taking place. The wet pixel or cold pixel will include a surface temperature equal to air temperature. The sensible heat flux for the cold pixel is usually zero. The linear relationship is developed between the temperature difference [ $dT = a + bT_s$ ] and the surface temperature [ $T_s$ ], and the regression coefficients [a and b] are defined from the two [ $dT$ ,  $T_s$ ] pairs applicable to the hot and cold pixels. Then sensible heat flux can be computed for every pixel that has the condition of free convection. Next, the values of friction velocity [ $u^*$ ] are estimated from the wind speed at the blending height, a value of 200 m will be used. Thereafter, the condition of mixed convection is applied, and the pixel-dependent aerodynamic resistance to heat transfer,  $r_{ah}$ , is calculated by using the Monin-Obukhov hypothesis. The new temperature difference is calculated. Finally the processes from the calculation of sensible heat flux to the temperature difference are repeated until the aerodynamic resistance to heat transfer and temperature difference are stable values. To compute sensible heat flux, following procedure is considered:

**STEP 1:** Friction velocity [ $u^*$ ] can be computed using equation /24/.

$$u^* = \frac{k u_x}{\ln \left( \frac{z_x}{z_{om}} \right)} \quad /24/$$

The calculation of the friction velocity requires a wind speed measurement [ $u_x$ ] at a known height [ $z_x$ ] in the time of the satellite image.  $k$  is a constant [0.41]. Then,  $u_x$  and  $z_x$  are known, but  $z_{om}$  is unknown.  $z_{om}$  can be calculated in many ways: from  $z_{om} = 0.12 \times \text{height of vegetation [h]}$  for agricultural area, from a land-use map, or from a function of NDVI and surface albedo. At weather station,  $u_x$ ,  $z_x$ ,  $z_{om}$ , and  $u^*$  can be determined.

**STEP 2:** Wind speed at a height 200 m above the weather station can be computed using equation /25/.

$$u_{200} = \frac{u * \ln\left(\frac{200}{z_{om}}\right)}{k} \quad /25/$$

**STEP 3:** The friction velocity for each pixel is calculated using the wind speed at a height 200 m [  $u_{200}$  ] that is assumed to be constant for all pixels of the image because it is defined as occurring at a “blending height” unaffected by surface features. From equation /26/,  $z_{om}$  is unknown to calculate the friction velocity, so  $z_{om}$  need to be estimated.

$$u^* = \frac{ku_{200}}{\ln\left(\frac{200}{z_{om}}\right)} \quad /26/$$

Where:  $z_{om}$  is the particular momentum roughness length of each pixel. The  $z_{om}$  for each pixel can be computed by two methods: using a land-use map or using NDVI and surface albedo data [  $z_{om}$  is calculated in spreadsheet]. For this pattern, a land-use map is not available, and then NDVI and surface albedo data are used. In the method using NDVI and surface albedo,  $z_{om}$  is computed from the following equation:

$$z_{om} = \exp\left[\left(a \times \frac{NDVI}{\alpha}\right) + b\right] \quad /27/$$

Where: a and b are correlation constants derived from a plot of  $\ln[z_{om}]$  vs  $\frac{NDVI}{\alpha}$  for two or more sample pixels representing specific vegetation types. To determine the constants a and b in equation /27/, a series of sample pixels representing vegetation types and conditions of interest are selected and the associated values for NDVI and surface albedo are obtained. Typical surface albedo values are 0.17 to 0.22 for rice field and 0.15 to 0.20 deciduous forest, respectively.

**STEP 4:** Aerodynamic resistance to heat transport [  $r_{ah}$  ] is computed as following equation:

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right)}{u * k} \quad /28/$$

Where:  $z_1$  and  $z_2$  are 0.1 m and 2 m, respectively.

**STEP 5:** Near surface temperature difference [dT] for each pixel is calculated using equation /29/. A linear relationship is assumed between  $T_s$  and dT [equation /30/].

$$dT = T_s - T_a \quad /29/$$

$$dT = b + aT_s \quad /30/$$

In equations /29/ and /30/:  $T_a$  is unknown; a and b are the correlation coefficients. To define coefficients a and b, SEBAL uses the “anchor” pixel when a value for sensible heat flux [H] can be reliably estimated.

a. At the “Cold” pixel:

$$H_{cold} = R_n - G - LE_{cold} \quad /31/$$

$$dT_{cold} = \frac{H_{cold} \times r_{ah}}{\rho \times c_p} \quad /32/$$

If “Cold” pixel is chosen from a body of water, then  $H_{cold} = 0$  and equation /31/ reduces to:

$$LE_{cold} = R_n - G \quad \text{and} \quad /33/$$

$$dT_{cold} = 0 \quad /34/$$

b. At the “Hot” pixel:

$$H_{hot} = R_n - G - LE_{hot} \quad \text{and} \quad LE_{hot} = 0 \quad /35/$$

Therefore:

$$H_{hot} = R_n - G \quad /36/$$

$$dT_{hot} = \frac{H_{hot} \times r_{ah}}{\rho \times c_p} \quad /37/$$

Therefore:  $dT_{cold} = 0$  from step 5a and  $dT_{hot} = \frac{H_{hot} \times r_{ah}}{\rho \times c_p}$  from step 5b.



**STEP 6:** The sensible heat flux is calculated in this step, called initial sensible heat flux.

**STEP 7:** Monin-Obukhov theory in an iterative process is applied in SEBAL to account for the buoyancy effects, which are generated by surface heating. The Monin-Obukhov length [L] is used to define the stability conditions of the atmosphere in the iterative process [this is not the same “L” as used in the SAVI computation]. It is a function of the heat and momentum fluxes and is computed as follows:

$$L = -\frac{\rho c_p u_*^3 T_s}{kgH} \quad \text{or} \quad /38/$$

$$L = -\frac{1 \times 1004 \times u_*^3 T_s}{0.41 \times 9.81H} \quad /39/$$

**STEP 8:** The values of the stability corrections for momentum [ $\psi_m$ ] and and heat transport [ $\psi_h$ ] are computed as follows. These values depend on the conditions of atmosphere.

a. If  $L < 0$  [unstable atmospheric condition]:

$$\psi_{h(200m)} = 2 \ln \left( \frac{1 + x_{(200m)}}{2} \right) + \ln \left( \frac{1 + x_{(200m)}^2}{2} \right) - 2 \text{ARCTAN}(x_{(200m)}) + 0.5\pi \quad /40/$$

$$\psi_{h(2m)} = 2 \ln \left( \frac{1 + x_{(2m)}^2}{2} \right) \quad /41/$$

$$\psi_{h(0.1m)} = 2 \ln \left( \frac{1 + x_{(0.1m)}^2}{2} \right) \quad /42/$$

In equations /40/ to /42/:

$$x_{(200m)} = \left( 1 - 16 \frac{200}{L} \right)^{0.25} \quad /43/$$

$$x_{(2m)} = \left( 1 - 16 \frac{2}{L} \right)^{0.25} \quad /44/$$

$$x_{(0.1m)} = \left( 1 - 16 \frac{0.1}{L} \right)^{0.25} \quad /45/$$

b. If  $L > 0$  [stable atmospheric condition]:

$$\psi_{h(200)} = -5 \left( \frac{2}{L} \right) \quad /46/$$

$$\psi_{h(2m)} = -5 \left( \frac{2}{L} \right) \quad /47/$$

$$\psi_{h(0.1m)} = -5 \left( \frac{0.1}{L} \right) \quad /48/$$

c. If  $L = 0$  [neutral condition]:  $\psi_m$  and  $\psi_h = 0$

**STEP 9:** The friction velocity [ $u_*$ ], which is a corrected value, is now computed for each successive iteration as follows:

$$u_* = \frac{u_{200}k}{\ln \left( \frac{200}{z_{om}} \right) - \psi_{m(200m)}} \quad \text{Where: } u_{200} \text{ is in m/s and } k \text{ is } 0.41. \quad /49/$$

**STEP 10:** The aerodynamic resistance to heat transport [ $r_{ah}$ ], which is a corrected value, is now computed during each iteration as follows:

$$r_{ah} = \frac{\ln \left( \frac{z_2}{z_1} \right) - \psi_{h(z_2)} + \psi_{h(z_1)}}{u_* k} \quad /50/$$

**STEP 11:** Repeat the steps 5 to 10 until the successive values for  $dT_{hot}$  and  $r_{ah}$  at the hot pixel have stabilized.

**STEP 12:** The latent energy of evaporation [LE] was computed using following equation:

$$LE = R_n - G - H \quad /51/$$

After the latent energy of evaporation has been computed, then the evaporative fraction [  $\Lambda$  ] is obtained using equation /52/. The evaporative fraction at each pixel of a satellite image can be estimated using the 24-hour evaporatranspiration for the day of the image. The evaporative fraction is assumed to be a constant value over the full 24-hour period.

$$\Lambda = \frac{LE}{R_n - G} = \frac{LE}{LE + H} \quad /52/$$

The 24-hour actual evaporatranspiration is estimated using equation /53/:

$$ET_{24} = \frac{86400\Lambda(R_{n24} - G_{24})}{\lambda} \quad /53/$$

Where:  $R_{n24}$  is daily net radiation,  $G_{24}$  is daily soil heat flux, 86,400 is the number of seconds in a 24-hour period, and  $\lambda$  is the latent heat of vaporization [J/kg]. The 24-hour actual evaporatranspiration,  $ET_{24}$ , can be expressed in mm/day. Since energy, on average, is stored in the soil during the daytime and released into the air at night,  $G_{24}$  is very small for the combined vegetative and soil surface, so it can be assumed as zero at the soil surface [24]. Therefore, equation /53/ can be rewritten as:

$$ET_{24} = \frac{86400\Lambda R_{n24}}{\lambda} \quad /54/$$

**Steps 1 to 11** are summarized in Figure 1. Thereafter, to determine the relationship between the temperature and actual evapotranspiration, the maximum and minimum values of actual evapotranspiration in each temperature were ignored. The selected actual evapotranspiration in each temperature was averaged. Finally, the relationship between temperature and actual evapotranspiration was determined using a polynomial equation.

### Validation of Temperature

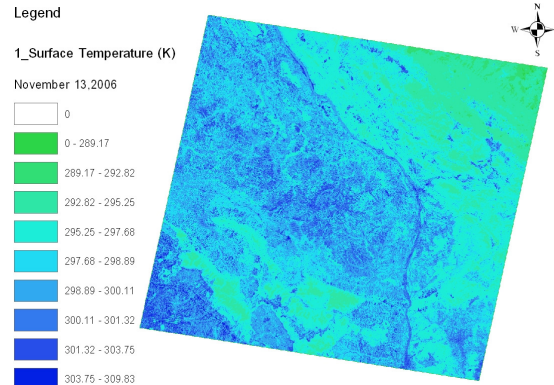
For the validation of temperature computed by using Landsat satellite image, it was compared with recorded temperature. On the other hand, to validate actual evapotranspiration calculated by SEBAL, recorded pan evaporation was used. Pan evaporation is the amount of water evaporated during a period [mm/day] with an unlimited supply of water [potential evaporation]. It is a function of surface and air temperatures, insolation, and wind, all of which affect water-vapor concentrations immediately above the evaporating surface [11]. On the other hand, actual evapotranspiration is a function of temperature, wind, humidity and net radiation. It can be concluded that there is a relationship between the pan evaporation and actual evapotranspiration. [11, 13, 15] indicate that the decreasing trend detected in the pan evaporation and actual evapotranspiration can be attributed to the significant decreasing trends in the net radiation and in the wind speed. Also, it can be attributed to the significant increasing trend in the air temperature.



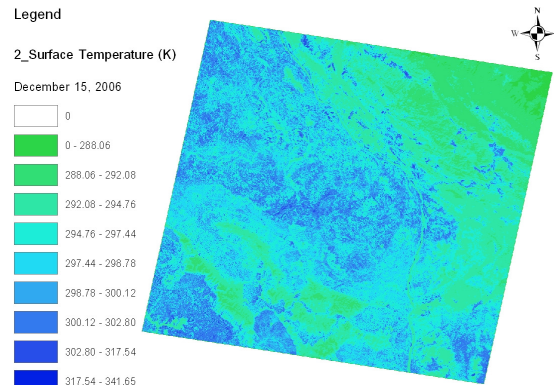
3], respectively. On the one hand, the minimum temperatures from these three figures are 283.21, 278.93 and 284.02°K, respectively while the maximum temperatures from these three figures are 308.62, 313.63 and 310.65°K, respectively.

### Spatial Actual Evapotranspiration

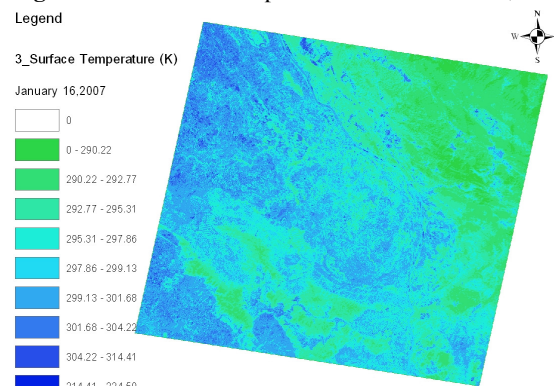
The spatial distributions of actual evapotranspiration were calculated by using Landsat 5 TM satellite images and SEBAL, these values are presented in Figure 5 to 7 [Kosa, 2009]. The mean actual evapotranspiration from these three figures are 3.67, 4.50 and 4.26 mm per day, respectively.



**Figure 2.** The surface temperature on November 13, 2006.



**Figure 3.** The surface temperature on December 15, 2006.



**Figure 4.** The surface temperature on January 16, 2007.

### Relation between Temperature and Actual Evapotranspiration

The spatial temperature and spatial actual evapotranspiration estimations are shown in Figures 2 to 7. The relationships between the temperature and actual evapotranspiration are shown in Figures 8 to 9 [19]. In the regression equations /55/ for Figure 8 and /56/ for Figure 9, y is the actual evapotranspiration [mm/day] and x is the temperature in the unit of °K and °C, respectively.

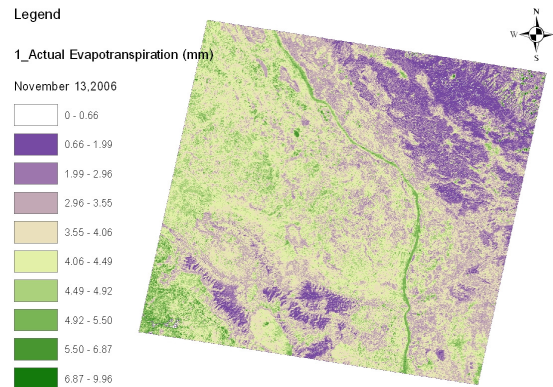
$$y = -0.028x^2 + 17.069x - 2593.2, \text{ where } x \text{ is in } ^\circ\text{K} [R^2 = 0.987] \text{ and } /55/$$

$$y = -0.028x^2 + 1.7608x - 22.932, \text{ where } x \text{ is in } ^\circ\text{C} [R^2 = 0.987] /56/$$

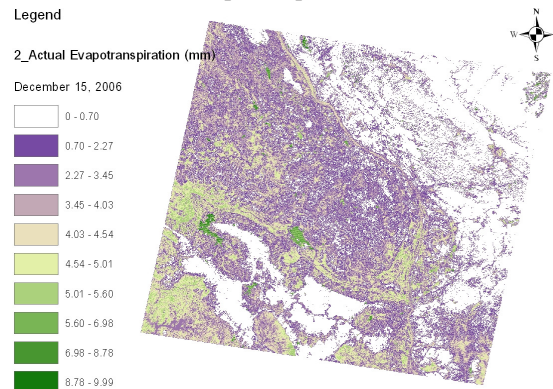
## SUMMARY

The results in this chapter indicate that the mean temperature was 296.44 °K [23.44 °C] and the mean actual evapotranspiration was 4.14 mm per day, respectively. The relationship between the temperature [°K and °C] and actual evapotranspiration [mm/day] is a polynomial equation. For the temperature in Kelvin, an equation /55/ is  $y = [-0.028x^2 + 17.069x - 2593.2]$  and for the temperature in Celsius, an equation /56/ is  $y = [-0.028x^2 + 1.7608x - 22.932]$ .

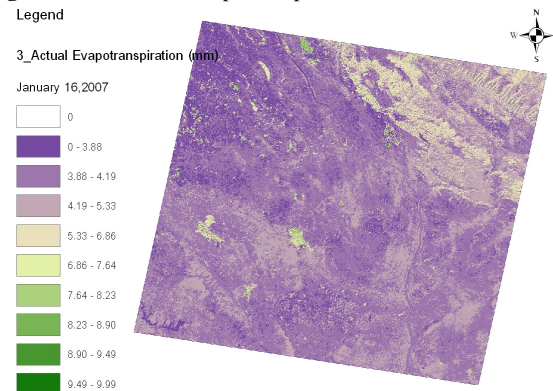
The spatial temperature and spatial actual evapotranspiration during November 2006 to January 2007 that are the result are in the condition of both dry season and clear sky. Also, the relationship between temperature and actual evapotranspiration is a result. These results are useful for irrigation project and water management. For spatial temperature, it presents temperature for each area. Since temperature relates to many weather data, temperature can imply the characteristic of other weather data. For example, high temperature is included low humidity but high evaporation can be occurred in the condition of high temperature. For spatial actual evapotranspiration, it can be used to present daily actual evapotranspiration. This daily actual evapotranspiration leads to the planning of water management in each area. Then, it is easy to manage water for irrigation. For the relationship between temperature and actual evapotranspiration, it can be used to estimate actual evapotranspiration when temperature is not unknown.



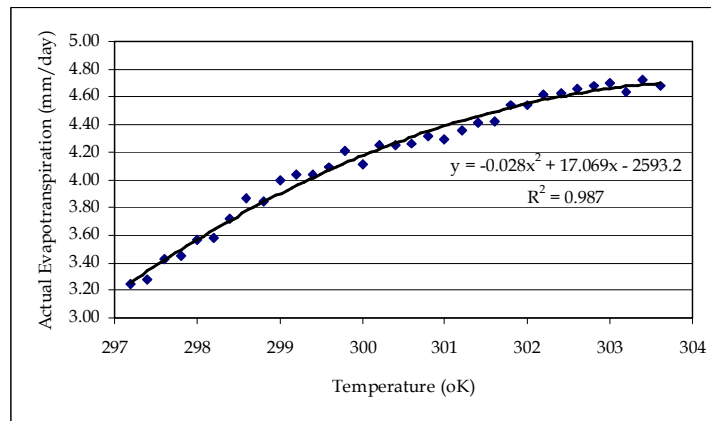
**Figure 5.** The actual evapotranspiration on November 13 2006.



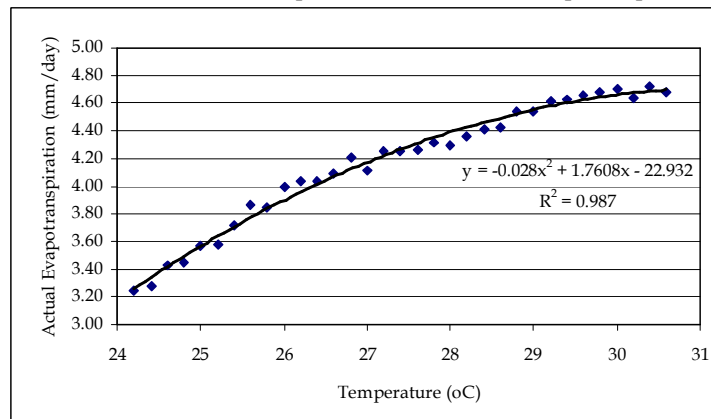
**Figure 6.** The actual evapotranspiration on December 15, 2006.



**Figure 7.** The actual evapotranspiration on January 16, 2007.



**Figure 8.** The relation between the temperature [°K] and actual evapotranspiration [mm/day].



**Figure 9.** The relation between the temperature [°C] and actual evapotranspiration [mm/day].

## KEYWORDS

Landsat 5 TM  
SEBAL  
Spatial Actual Evapotranspiration  
Spatial Temperature  
Thailand

## BIBLIOGRAPHY

Refer to the bibliography for the literature cited.

## Chapter 16

### Sensor Based Irrigation Scheduling<sup>1,2</sup>

#### INTRODUCTION

In the western United States, irrigation accounts for about 80% of the water consumed [Hutson, 8]. Concerns about changes in land use due to growing populations, climate change, and the protection of aquatic habitats are driving a need to conserve water. Optimization of irrigation will not only benefit the environment, but also benefit local economies. Over irrigation may lead to dangerous increases in the total maximum daily loads (TMDL) of temperature, nitrates, and salinity in natural waters [Chapman, 6]. Nitrate fertilizers leached out of the soils get transported to natural waters causing eutrophication and other aquatic impairments. Run off from over irrigation may affect water quality parameters such as pH, total suspended solids (TSS), and dissolved oxygen [Winter, 18]. Other negative impacts associated with over irrigation include wastes of water and energy, and reduced crop yields. The negative impacts associated with under irrigation are more intuitive. Under irrigation may reduce crop yields which will reduce profit margins. This chapter discusses a soil water balance model incorporated into a data acquisition system that is a power tool for scheduling and optimizing irrigation. A case study for blueberries is presented.

Advancements in computer microprocessors, memory and software development tools has improved data acquisition methods and made data acquisition system integration more reliable and more cost effective. The soil water balance model incorporates inputs of soil moisture, water application and evapotranspiration (ET). The soil moisture data acquisition system retrieves the input parameters via telemetry and populates software that accommodates the soil water balance model. The soil data acquisition software integrated with a soil water balance model is commercially available from Stevens Water Monitoring Systems, Inc.

#### SOIL MOISTURE BUDGET

To begin our discussion about soil moisture budgets, we first describe the components and the hydrological conditions of soil. In general, inorganic soil is composed of mixes of sands, silts and clays. Sands, silts and clays differ not only by particle size distribution, but also in the atomic arrangement and charge distribution at the molecular level [McBride, 9]. Soil geomorphology is the process by which sands and silts chemically and physically transform into clays as the soil ages [Birkeland, 2]. The soil textural class is determined by the gravimetric percentage of sand silt and clay. Figure 1 shows the soil texture classifications based on gravimetric percentage.

Sands, silts, clays and organics represent the solid particle composition of soil while air and water fill the pore spaces between the solid particles. When soil is completely saturated with water, the porosity will be equal to the volumetric soil moisture content [Warrick, 16]. The amount of organics in soil will affect the bulk density and the porosity. Some organic soils may have porosities of over 90%, but in general, most inorganic agricultural loams will have a porosity of near 50%. The pores can be nearly microscopic (micro-pores) or visible with the naked eye (macro-pores) [Brady, 3].

The hydrologic properties of soil play an important role in a crop's ability to transpire water with their root systems. Knowledge of volumetric soil moisture content ( $\theta$ ,  $\text{m}^3 \text{m}^{-3}$ ) is an important input into the soil water balance model. Permanent wilting point ( $\theta_{\text{pw}}$ ) is the soil moisture level at which plants can no longer adsorb water from the soil. Plant transpiration and direct evaporation will decrease the moisture level in soil to a point below  $\theta_{\text{pw}}$  and, in some cases, down to near dryness.

Field capacity ( $\theta_{\text{fc}}$ ) is defined as the threshold point at which the soil pore water will be influenced by gravity. Above field capacity, the gravitational force will overcome the capillary forces suspending the moisture in the pores of the soil allowing for down movement of water in the soil column. Below  $\theta_{\text{fc}}$ , there will be a net upward movement of water driven by ET. Field capacity and permanent wilting point are heavily influenced by soil textural classes, particularly clay content [Rowell, 10]. Clays interact with water in ways uniquely different from sand, silt and organics. Clays will have a physical and chemical affinity for water due to the negative charge distribution and the planner molecular lattice. The positive portion of the water molecule will be oriented toward the negatively charged clay lattice and the oxygen's lone electron pair will be pointed outwards [Grim, 7].

Positively charged cations will also be influenced by the negative charged distribution of clay [McBride, 9]. Figure 4 shows two cations of different valance states ( $\text{Ca}^{++}$  and  $\text{Na}^{+}$ ) chemically influenced by clay at the molecular level. Figure 4 also shows the charge distribution of the water molecule. The available water capacity ( $\theta_{\text{ac}}$ ) of soil is the water that is available to a plant. It represents the range of soil moisture values that lie above permanent wilting point and below the field capacity.

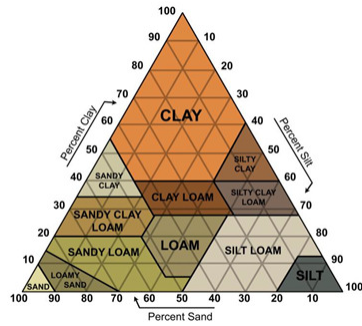
$$\theta_{\text{pw}} < \theta_{\text{ac}} < \theta_{\text{fc}} \quad /1/$$

Table 1 shows the typical values for permanent wilting point and field capacity for common soil textural classes [Rowell, 10]. Plants are able to uptake water from soil if the soil moisture is above permanent wilting point. As the soil moisture approaches permanent wilting point, the plant will become increasingly stressed as the soil pore water becomes depleted. The point below field capacity where plants become stressed is called the maximum allowable depletion (MAD).

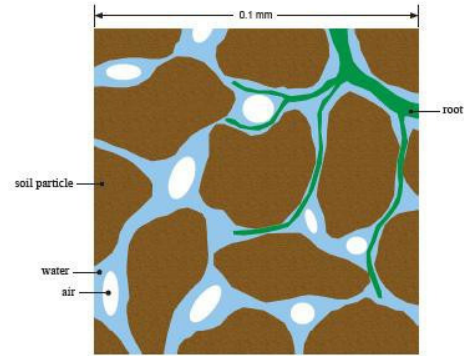
<sup>1</sup> B. Keith Bellingham, Certified Professional Hydrologist, Soil Scientist and Hydrologist, Stevens Water Monitoring Systems Inc., 12067 NE Glenn Widing Drive Suite 106, Portland, Oregon 97220, Phone: United States (800) 452-5272, EMAIL: <kbellingham@stevenswater.com>; <<http://www.stevenswater.com/contact.aspx>>. Author is thankful to Stevens Water Monitoring Systems, Inc. for the support. Printed with permission from: <<http://www.stevenswater.com/articles/irrigationscheduling.aspx>>

<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

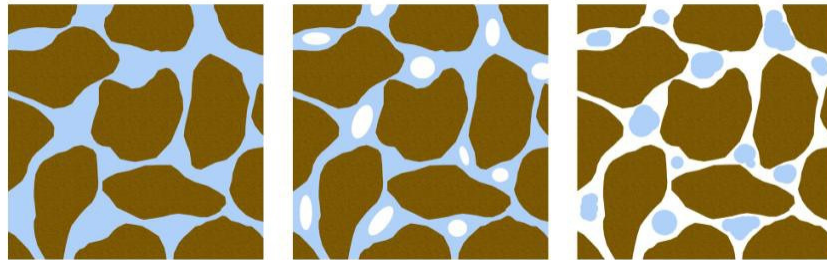




**Figure 1.** Soil textural classes based on the percentage of sand, silt, and clay.



**Figure 2.** Unsaturated soil is composed of solid particles, organic material and pores. The pore space will contain air and water.

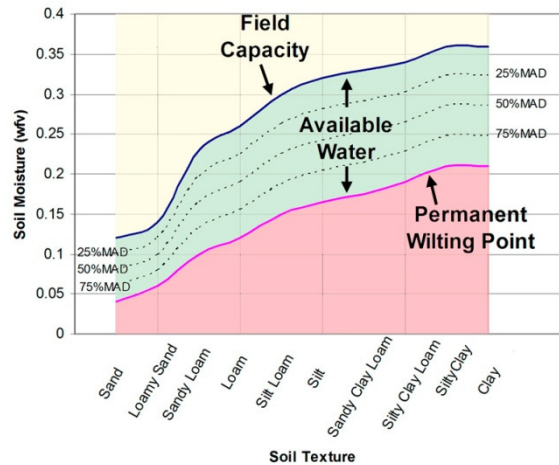


**Figure 3.** Soil moisture: Saturation, field capacity and permanent wilting point.



**Figure 4.** Planner clay lattice: a negative charge distribution [left]; cation influence [center]; and Dipole moment of a water molecule [extreme right].

### Soil Moisture Target



**Figure 5.** The relationship between soil textural classes and the hydrological thresholds  $\theta_{PW}$ ,  $\theta_{AC}$ , and  $\theta_{FC}$ . The 25%, 50% and 75% MAD levels are displayed in the available water capacity region.

The MAD value is expressed as a percent of the available water capacity. Table 2 shows typical MAD values for a few selected crops. Figure 5 shows the soil field capacities and the permanent wilting points for common soil textural classes. The green region in Figure 5 is the available water capacity showing 25%, 50% and 75% MADs. As shown in Figure 5, the field capacity and the permanent wilting point will increase with the percentage of clay. With specific knowledge of field capacity, soil



textural class and the maximum allowable depletion, a soil moisture target can be determined for irrigation optimization [Brouwer 4]. The soil moisture target is the range of soil moistures that lie above the MAD but below the field capacity. Below the MAD value the crop will still have the ability to receive water from the soil, however the crop will become stressed after a period of time. If the crop becomes stressed due to the lack of water, the plant will have a reduced yield and become more susceptible to pathogens. If the soil moisture gets above field capacity, water will be transported downward by gravity potentially wasting water and leaching nutrients. Upper soil moisture target for the soils in the root zone will be the field capacity. The lower soil moisture target is determined by the MAD,  $\theta_{FC}$ , and  $\theta_{PW}$ :

$$\text{Lower Soil Moisture Target} = \theta_{FC} - (\theta_{FC} - \theta_{PW}) \times \text{MAD} \quad /2/$$

For example, green beans with a MAD of 50% have a root zone depth of 18 inches. If the green beans are growing in a silt loam, the field capacity will be 0.3 water fraction by volume (wfv) and the permanent wilting point will be 0.15 wfv. Using equation /2/, the lower soil moisture target will be 0.23 wfv. In this example, the soil moisture target for the green beans will lie between 0.23 wfv and 0.3 wfv from 5 inches to 18 inches deep adjacent to the root ball. It is important to note that the values in Table 1 are typical values and could vary slightly with bulk density of soil, mineralogy and organic content. Similarly, the MAD values in Table 2 are typical values and may vary by species, age of crop, region and soil chemistry.

**Table 1.** Field capacity and permanent wilting point for common soil textural classes.

| Soil Texture    | Field capacity | Permanent wilting point |
|-----------------|----------------|-------------------------|
| Sand            | 0.12           | 0.04                    |
| Loamy Sand      | 0.14           | 0.06                    |
| Sandy Loam      | 0.23           | 0.1                     |
| Loam            | 0.26           | 0.12                    |
| Silt Loam       | 0.3            | 0.15                    |
| Silt            | 0.32           | 0.165                   |
| Sandy Clay      | 0.33           | 0.175                   |
| Silty Clay Loam | 0.34           | 0.19                    |
| Silty Clay      | 0.36           | 0.21                    |
| Clay            | 0.36           | 0.21                    |

**Table 2.** Maximum allowable depletion and effective root zone depth for selected crops [Smesrud 12].

| Crop           | Maximum allowable depletion | Effective root Depth, inches |
|----------------|-----------------------------|------------------------------|
| Grass          | 50%                         | 7                            |
| Table beet     | 50%                         | 18                           |
| Sweet Corn     | 50%                         | 24                           |
| Strawberry     | 50%                         | 12                           |
| Winter Squash  | 60%                         | 36                           |
| Peppermint     | 35%                         | 24                           |
| Potatoes       | 35%                         | 35                           |
| Orchard Apples | 75%                         | 36                           |
| Leafy Green    | 40%                         | 18                           |
| Cucumber       | 50%                         | 24                           |
| Green Beans    | 50%                         | 18                           |
| Cauliflower    | 40%                         | 18                           |
| Carrot         | 50%                         | 18                           |
| Blue Berries   | 50%                         | 18                           |

**Table 3.** Typical values for sprinkler efficiencies for various sprinkler systems [Smesrud, 12].

| Irrigation System        | Sprinkler efficiency ( $E_f$ ) | Sprinkler efficiency (sprinkler spacing over 40 x40 feet) |
|--------------------------|--------------------------------|-----------------------------------------------------------|
| Solid set                | 0.70                           | 0.63                                                      |
| Hand move or side roll   | 0.80                           | 0.74                                                      |
| Pivot or linear move     | 0.90                           | 0.81                                                      |
| Offset managed hand move | 0.90                           | 0.81                                                      |

## WATER APPLICATION

While soil moisture data provides information about the root zone, the measured application of water can be used concurrently with the soil moisture values to provide a more complete suite of tools for the irrigator. The measured application of water ( $D$ ) is the amount of water applied to the crops with sprinklers, plus the amount of natural precipitation measured in inches/day. It is the total depth of water received by the crop.

### Sprinkler Efficiency

In order to effectively use the application of water in a water budget model, a high sprinkler efficiency ( $E_f$ ) is required. Sprinkler efficiency ( $E_f$ ) is the measure of uniformity of water application. Ponding of irrigation water, and uneven application of water over the field is the result of poor sprinkler efficiency. Soil moisture data and rain gauge data are less meaningful if the monitoring site receives more or less water than the rest of the irrigation regime. Sprinkler efficiency is determined by placing catch cans or a set of containers of uniform size in the field. The catch cans can be placed in grid or uniformly distributed

amongst the crops. After running the sprinklers for a length of time, the amount of water in the catch cans is measured. The sprinkler efficiency is expressed as a fraction and an  $E_f$  value of 1 is perfect uniformity. There are a number of methods for calculating  $E_f$ . The most common method for determining  $E_f$  involves averaging the lower 25% of the measured catchment of catch cans divided by the mean. An  $E_f$  value greater than 0.8 is preferred. Table 3 shows typical  $E_f$  values for several different types of sprinkler systems.

### Evapotranspiration

An important factor for quantifying the water budget is the evapotranspiration rate ( $ET$ ). Evapotranspiration is the water that is transpired out of the soil by the plant plus the amount of water lost to evaporation [Allen 1].  $ET$  represents the rate of water consumed by the plant and lost by direct evaporation. The factors that affect the  $ET$  rate include wind, temperature, relative humidity, and solar radiation. The units for  $ET$  are inches/day. Based on the Penman Monteith model for  $ET$  estimations,  $ET$  is not measured directly for an individual crop, but rather it is determined from a standard reference grass and then adjusted for different crops and plants with a crop coefficient [Allen 1]. The evapotranspiration for a reference grass is referred to as the potential evapotranspiration ( $ET^o$ ). Potential evapotranspiration values will vary regionally and seasonally and are available in the literature. If literature values for  $ET^o$  are not available or if the irrigator wishes to have a real time  $ET$  measurements,  $ET$  data acquisition systems are commercially available.  $ET$  data acquisition systems consist of weather sensors, telemetry and software that can retrieve the weather sensor inputs and perform the Penman Monteith model calculations. While an  $ET$  data acquisition system could potentially provide accurate real time  $ET^o$  values, these systems are very expensive and do not necessarily represent microclimates. Because  $ET^o$  is the  $ET$  for a standard reference grass, a crop coefficient ( $K_C$ ) is necessary to determine the  $ET$  for the crop of interest. With information about sprinkler efficiency, crop coefficient and potential evapotranspiration, the water consumption ( $ET''$ ) for a specific crop (in inches per day) are calculated from the equation /3/. Typically,  $K_C$  values will range from 0.75 to 1.25 depending on species of the plant, the growth stage of the plant, and vary regionally. In practice,  $ET^o$  and  $K_C$  values can be obtained from a local government crop extension or a local crop advisor.

$$ET'' = ET^o \times K_C / E_f \quad /3/$$

### Applied water Scheduling

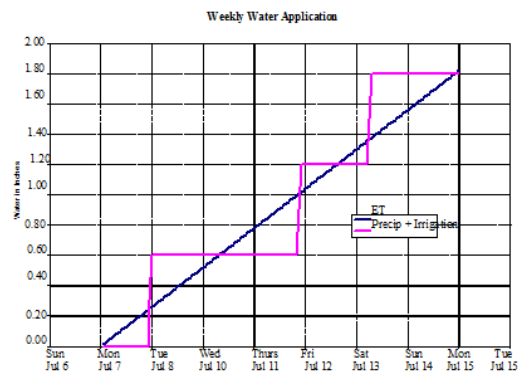
In general, the water application ( $D$ ) in inches/day should be roughly equal to the system water loss ( $ET''$ ) due to  $ET$  and sprinkler uniformity. The water loss calculated by equation /3/ can be compared to the applied water measured with a rain gauge to set an irrigation target.

$$D \approx ET'' \quad /4/$$

It is difficult to keep  $D \approx ET''$  on an hourly or daily basis due to factors such as pivot lap speed and soil infiltration rates. Equation /4/ should define a water application target on a weekly basis. In general, depending on the crop and the irrigation system, crops should be irrigated 3 to 7 times a week and net weekly sum of the daily  $D$  values should be roughly equal to the net weekly sum of the daily  $ET''$  values. Figure 5 demonstrates a weekly water application target. In Figure 5, there are three irrigation events and an  $ET''$  rate of 0.26 inches per day. Based on an  $ET''$  rate of 0.26 inches per day and the  $E_f$  by the end of the week, 1.80 inches of water was consumed and approximately 1.80 inches would need to be applied. The application rate in figure 5 is 0.3 inches per hour for 2 hours.

**Table 4.** Typical Infiltration rates based on soil texture.

| Soil Texture | Typical infiltration rate inches/hour |
|--------------|---------------------------------------|
| Sand         | 1.5 or more                           |
| Sandy Loam   | 1 to 1.5                              |
| Loam         | 0.5 to 1                              |
| Clay Loam    | 0.25 to 0.5                           |
| Clay         | 0.05 to 0.25                          |



**Figure 6.** There are three irrigation events, and an  $ET''$  rate of 0.26 inches per day.  $D \approx ET''$  after the 3 irrigation event at the end of the week during the July, 2008.

To minimize the water loss due to direct evaporation, the irrigation events take place between sunset and sunrise. It is important to irrigate at a rate that is less than the infiltration rate of the soil. Runoff and ponding may occur if the rate of application exceeds infiltration rate of the soil. Table 4 provides infiltration rates of soils based on soil textural class [Brouwer, 2]. The infiltration of water into soil will vary with texture, but it will also depend on soil moisture, vegetation, bulk density and soil geomorphology among other factors. Soil infiltration rates can be determined from tests and area soil surveys data.

## DATA ACQUISITION

Data acquisition systems are the most effective tool for identifying and reaching soil moisture and water application targets for irrigation optimization. A data acquisition system with the water budgeting method was constructed and is commercially available from Stevens Water Monitoring Systems, Inc.. The Stevens Agricultural Monitoring (SAM) Package integrates the input from sensors, displays the data from the remote field locations and integrates the water balance method described in the previous section. The SAM package includes rain gauges, the Stevens Hydra Probe Soil Sensor, a Stevens DL3000 data logger, telemetry and the software program. Described below is the engineering that collects field data (soil moisture and precipitation) and the software program that acquires the data from the data loggers through the telemetry. The data is either exported to the internet or is imported into the SAM software where it can be used to make informed decisions about irrigation scheduling.

### Soil Moisture Data Collection

The soil moisture is collected using the Stevens Hydra Probe. The Hydra Probe is the soil sensor used in the USDA's Soil Climate Analysis Network (SCAN) and NOAA's Climate Reference Network (CRN). The Hydra Probe uses electromagnetic waves to measure both the real and imaginary dielectric permittivity [Campbell 5]. The real component of the dielectric permittivity represents the energy storage based on the high rotational dipole moment of water compared to that of dry soil [Topp 14]. The measured real dielectric permittivity ( $\epsilon_r$ ) is used to accurately calculate the soil moisture in water fraction by volume in most soils (Seyfried 2005) with the calibration equation:

$$\theta = A\sqrt{\epsilon_r} + B \quad /5/$$

Where:  $A$  is 0.109 and  $B$  is equal to -0.179. The Hydra Probe is digital and equation /5/ is written into the firmware of the probe. The digital communication between the Hydra Probe and the data logger is the standard communication format Serial Data Interface at 1200 Baud (SDI-12). The advantages of SDI-12 include connecting many sensors on a single serial addressable bus and cable lengths up to 1000 feet from the sensor to the data logger. Multiple digital sensors are "daisy chained" together and the longer cable lengths provide flexibility in the architecture of the system in the field. Up to 4 or more SDI-12 soil moisture profiles can be installed up to 1000 feet away from the data logger reducing the cost by using common data loggers and telemetry.

### Rain Data Collection

The precipitation and the irrigation from sprinklers are measured together with a tipping bucket rain gauge. A tipping bucket is a 6 to 10 inch in diameter cylinder with a screen at the top facing end and a drain out the bottom. Inside of the bucket is a dual sided tray that is located under a funnel. The tray will tip over and drain after receiving 0.01 inches of rain. After tipping, the other half of the tray will fill with water, tip and drain after receiving another 0.01 inches of water. Every time the tipping bucket's tray tips (0.01 inch of rain), an electrical pulse is sent to the DL3000 data logger. The data logger counts the tips and calculates the depth of rain fall over time. It is important that the tipping bucket remain level and is placed in a location that will receive a representative application of water from the sprinklers.

If an irrigation method is used that does not include the use of sprinklers such as furrow or drip irrigation, the method described in Figure 5 and equation /4/ will not be as applicable. In this case, one or no rain gauge would be used in the data acquisition package.

### Data Logger and Field Station

The Stevens Data Logic 3000 (DL3000) data collection platform resides inside a weather proof fiber glass enclosure located in the field. The cable from each SDI-12 Hydra Probe enters the enclosure by running through bulkhead bushings located on the bottom of the enclosure. The Hydra Probe power, ground and SDI-12 communication wires are "daisy chained" together with a multiplex inside the enclosure. A single SDI-12 communication wire runs from the multiplexer to the DL3000's SDI-12 communication port. The DL3000 will log data on a set time interval typically every 30 minutes, and will hold up to 2 Gigabytes of data. The wire from the tipping bucket also runs into the enclosure through a bulkhead and is wired into the DL3000's pulse port. The data logger has a wireless RS232 communication radio attached. A coaxial cable runs from the radio out of the enclosure through the bulkhead to an Omni directional antenna. Also contained in the field enclosure is a 9 Amp/hour 12 volt DC battery, and charge regulator for the solar panel power supply. Figure 9 describes a field station with a subsurface soil moisture monitoring profile.

### Wireless Telemetry

After the data from the sensors is received by the data logger, the data is transmitted from the field to the base station computer via radio. The frequency and type of radio would depend on the distance from the field to the base station computer. The radio communication between the field and the base station is usually line of sight. Large obstacles such as buildings, mountains and trees will impede the radio signal and prevent the signal from reaching its destination. If there is a large obstacle in the way, a repeater station could be installed, however repeater stations will increase the overall cost of the system. Radio communication always takes place between two or more radios. The radio at the base station is called the server or master radio and the radios in the field are call client or slave radios. The master radio is connected to the base station computer and a directional Omni antenna. Each radio has a Media Access Control (MAC) address written into the radio's firmware, identifying it. When the master radio needs communication with a specific radio, the master radio will address the radio with the MAC address. Radios

will only respond their specific MAC address from the master radio. In a network of radios, the master radio will communicate with each slave radio one by one and retrieve the sensor data from each logger individually.

Distance from the field site to the base station is the main factor determining the most appropriate radio and frequency. In most agriculture applications, 900 MHz Spread Spectrum radio with a 5 miles line of sight range is the most common. While satellite communication is common in the water resources industry, it is less common at the farm level due to licensing and hardware costs. Table 5 lists the different kinds of telemetry solutions, the ranges and the frequencies.

**Table 5.** Summary of telemetry options and ranges.

| Radio              | Range            | Frequency                |
|--------------------|------------------|--------------------------|
| Blue Tooth         | 100 m            | 2,400 to 2,483.5 MHz     |
| Spread Spectrum    | 5 miles          | 902 to 928 MHz           |
| Wi-Fi              | 100 m            | 2.4 GHz                  |
| VHF                | 30 miles         | 30 to 300 MHz            |
| UHF                | 30 miles         | 300 to 1,000 MHz         |
| Wi-Max             | 30 miles         | 2.3 to 3.5 GHz           |
| Cellular Modem     | Cell Coverage    | 824.01 to 848.97 MHz     |
| Geosynchronous     | 1/3 the of Earth | 401.7010 to 402.0985 MHz |
| Low Earth Orbiting | Global Coverage  | 148 to 150.05 MHz        |

### Soil Profile

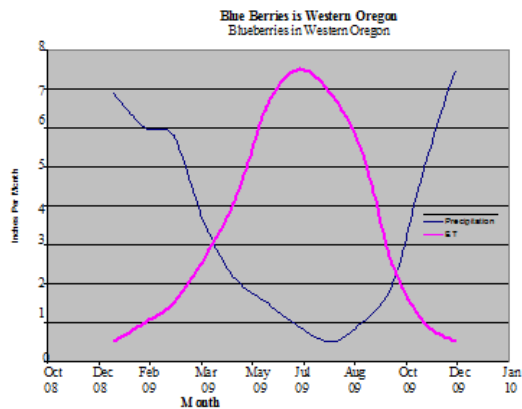
Soil moisture probes at different depths in the soil column are referred to as a soil profile. Depending on the root zone depth, the typical soil profile consists of four soil sensors. One probe in the top soil (2 to 4 inches) two probes in the root zone (6 to 30 inches) and one probe below the root zone (36 inches). The Hydra Probe in the top soil will experience the greatest moisture fluctuation because it will be the most influenced by ET and downward flow. The top soil may reach saturation or reach a soil moisture value over the field capacity thus conducting water downward into the root zone of the crop. The lower soil moisture target for the two Hydra Probes in the root zone however are calculated from the MAD,  $\theta_{FC}$  and  $\theta_{PW}$  in equation /2/ and the upper soil moisture target in the root zone will be the soil's field capacity. The soil sensor below the root zone should stay below field capacity. If the soil moisture below the root zone reaches values above field capacity, there will be downward conductance of water.

The soil profile should be placed in a location that will most represent the irrigated area. Soil moisture can be highly variable spatially [Western 17]. The factors that affect soil moisture variability are slope, vegetation type, bulk density, soil type, microclimate, and other variables. An irrigation regime represents an area that is homogenous enough that the soil moisture variability will be low and the soil moisture data will represent the entire irrigation regime. There should be at least one soil profile for every irrigation regime. Irrigation regimes are determined by crop type, crop age, soil type, slope, and irrigation method. If the irrigation regimes are less than 1000 feet apart, it may reduce cost to tie multiple soil profiles into one data logger. By tying multiple profiles into a single data logger, the irrigator can save on the number of solar panels, batteries, radios, data loggers and other necessary accessories.

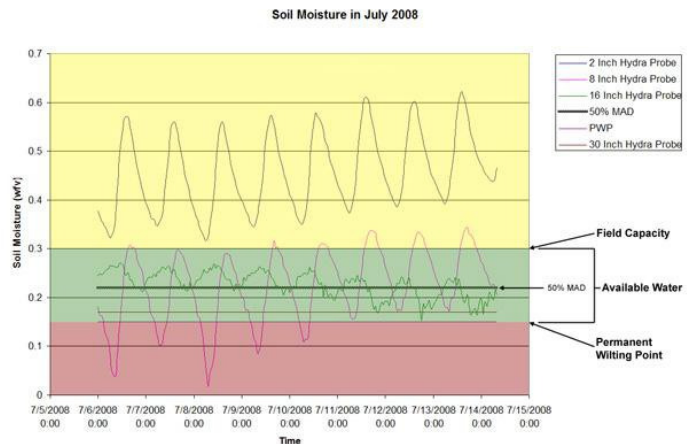
### Data Acquisition Software

The central user interface of the data acquisition package is the software. The Stevens Agricultural Monitoring (SAM) Software is commercial available and can be subsidized by some energy and water conservation grants. The SAM software runs on a computer that is connected to the master radio. A master radio is not necessary if the system has a field cellular modem or satellite transceiver. The SAM Software acquires the sensor data in the field from a polling sequence. The polling sequence runs at a user specified time interval, which is usually every 15 or 30 minutes. Communication begins with a serial command from the software to the data logger to take a current a current reading from all of the sensors. The SAM sends the command to the master with instructions to use a specific slave radio. The data logger becomes active after receiving the command and takes a current reading from all of the sensors that are connected to it. Next the data logger sends a comma delimited string of sensor data back to the SAM software through the slave and master radio. The SAM software parses the data and populates the tables and graphical displays in the software.

The irrigator can then view the real time data and make decisions about when to irrigate based on the soil moisture targets and the rate of water consumption by the crop from the ET. Other features in the software include battery voltages for power management. In the SAM Software, a display of MAD,  $\theta_{FC}$ ,  $\theta_{PW}$  and the lower soil moisture limit based on the calculations from equation /2/ are superimposed onto the real time soil moisture data. The superimposed real time soil moisture onto the soil moisture targets are displayed on a screen similar to Figure 8.



**Figure 7.** Typical values for monthly ET and precipitation for blue berries in western Oregon.



**Figure 8.** Soil moisture measurements in a profile 2, 8, 16 and 30 inches in depth. Daily irrigation events with subsequent decrease in soil moisture from a high ET rate.

At the beginning of the irrigation season, the irrigator can manually input the weekly ET values or the values from equation /3/ into the SAM setup page. A real time display similar to Figure 6 is displayed. With real time displays of the real time data superimposed onto the targets in a graphical representation will allow the irrigator to easily interpret the data.

#### SAM Data Acquisition Polling Sequence for Station 1

The flow chart below describes the process by which the SAM [Stevens Agriculture Monitoring] software communicates with the field stations. Figure 9 shows a diagram of a field station. The SAM Software will poll data from each station in consecutive order starting with the first field station. After retrieving the data from one field station the software will move on to the next field station.

1. The Polling Sequence initiates on a fixed time interval.
2. The Acquisition command "Take Current Readings Data Logger 1" along with a command to the master radio to communicate with radio 1 with its MAC address. These two commands are sent by the software out the serial port of the computer.
3. With an RS232 or USB connection to the computer, the Master Radio receives the "Take Current Readings Data Logger 1" message and transmits this message to slave radio 1 as commanded by the SAM software.
4. Slave radio 1 receives the "Take Current Readings Data Logger 1" and passes the message to the data logger via a RS232 cable.
5. Data Logger 1 receives the command "Take Current Readings Data Logger 1" from the slave radio and one by one collects the current data readings from each sensor that is connected to it.
6. Data Logger 1 sends a comma delimited data string back to the SAM software through the radios and serial ports.
7. The SAM software receives the data string, parses the data, and populates the graphical displays and tables in the software viewable by the user.
8. After the SAM software receives the data from data logger 1, it repeats steps 1 through 7 for data logger 2 and slave radio 2.

#### Blueberry Farm in Washington County Oregon: Case Study

A SAM Soil Moisture data acquisition package complete with telemetry and software was installed on a 200 acre blueberry farm in Washington County, Oregon. The soil unit is Woodburn Silt Loam with less than 3% slope and the soil taxonomic description is Typic Plinthoxeralf. There are two irrigation regimes based on the age of the crop. Two stations, one in each irrigation regime, were installed with 4 Hydra Probe soil sensors, a tipping bucket rain gauge, and an air temperature sensor. Soils data for this location and most locations in the United States are provide for free by the US Department of Agriculture's Web Soil Survey Program, <<http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx>>.

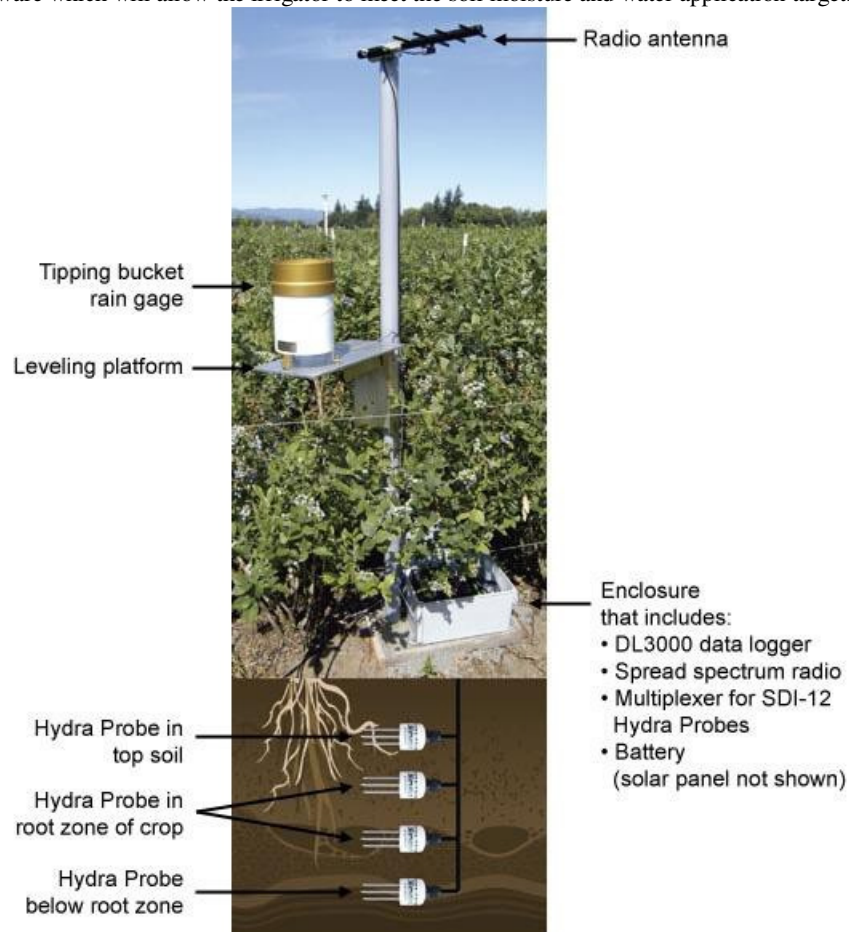
Figure 7 shows the annual precipitation and ET rate for blueberries in Washington County Oregon [Smesrud, 12]. The ET exceeds precipitation from April to October and this generally defines the irrigation season.

Each station is located 1 mile away from the computer with the master radio; therefore, this network uses spread spectrum radios. The stations each have one soil profile consisting of 4 Hydra Probes at various depths (2", 8" 16" and 30"). The SDI-12 Hydra Probe Soil Sensors are wired into a multiplexer which is connected to the Stevens Data Logger. Each station is power with a solar panel and the enclosure houses the battery, multiplexer, charge regulator and radio. The radio antennas are mounted to the same mast as the tipping bucket. Figure 9 illustrates one of the field stations with the soil profile.

Using Tables 1 and 2, the permanent wilting point is 0.15 the field capacity is 0.3 and the MAD is 50%. The lower soil moisture target as calculated from equation /2/ is 0.22.

Figure 8 shows the soil moisture for a warm week in July 2008. The yellow region of the chart represents soil moisture levels over field capacity, the green region shows the range of soil moistures available to the crop (available water capacity) and the red region is below permanent wilting point. The two inch deep soil moisture values fluctuate the most for downward conductivity and ET and stays above field capacity. This is typical because if the top 2 inches of the soil stayed below field capacity then the root zone would not receive the water. The 8 inch soil moisture values fluctuate widely due to ET and there is a 4 hour lag time between the 2 and 8 inch soil moisture probes from the downward movement time of the wetting front. During extremely hot days, it is not uncommon to have the soil moisture values briefly drop below permanent wilting point between irrigation cycles. The 16 inch soil moisture mirrors the 8 inch values with a 4 hour latency from the soil moisture values above it and the rise and fall of soil moisture values with the irrigation events. The 30 inch deep soil moisture probe below the root zone is remaining constant about 0.10 wfv indicating that water is not percolating downward to the water table.

The solid set sprinklers rotator (with an efficiency of 0.90) apply water daily. For the month of July ET ( $=ET^o \times Kc$ ) is 0.25 inches per day. Using equation /3/, the daily water consumption will be 0.28 inches. A weekly display similar to Figure 6 is displayed in the software which will allow the irrigator to meet the soil moisture and water application targets.



**Figure 9.** Typical soil moisture profile station which includes four Hydra Probe Soil Sensors, Stevens DL3000 data logger, radio, antenna and accessories.

It was concluded: As the demand for water increases, along with the need to protect aquatic habitats, water conservation practices for irrigation need to be effective and affordable. Precision irrigation will optimize irrigation by minimizing the waste of water, and energy, while maximizing crop yields. The most effective method for determining the water demands of crops is the based on the real time monitoring of soil moisture, and direct water application used in conjunction with the information about soil hydrological properties and evapotranspiration. The Stevens Agriculture Monitoring data acquisition system wirelessly acquires rain and soil data from the field and integrates the data into water management tools. The water management tools use information about evapotranspiration, soil and the crop to set specific irrigation targets. These irrigation targets will help the irrigator optimize the amount of water used on a weekly basis. Optimization of irrigation water will increase crop yields while conserving water resources.

## SUMMARY

The water requirements of crops are dependent on evapotranspiration (ET), soil chemistry, and the maximum allowable depletion (MAD). Direct measurements of root zone soil moisture, water application along with published ET values and soil textures, can be used in a soil water balance model that can significantly optimize irrigation efficiency. Over the past five years, advancements in computer microprocessors, memory, and software development tools has improved data acquisition methods and made data acquisition system integration more reliable and more cost effective. This chapter presents an irrigation scheduling method based on a volumetric soil moisture balance model and data acquisition.

## KEY WORDS

Antenna  
Available water capacity  
Baud rate  
Blue berry  
Bluetooth  
Capillary forces  
Catch can  
Cellular modem  
Clay  
Cloud based server  
Computer software  
Crop  
Crop coefficient  
Data acquisition  
Data collection platform  
Data logger  
Data polling  
Dielectric permittivity  
Dipole moment  
Enclosure  
Eutrophication  
Evapotranspiration (ET)  
Field capacity (FC)  
Geosynchronous satellite communication  
Grants  
Green beans  
Hydra probe soil sensor  
Imaginary dielectric permittivity  
Internet  
Irrigation  
Irrigation optimization  
Irrigation regime  
Irrigation scheduling  
Irrigation system  
Loam  
MAC address  
Master radio  
Maximum allowable depletion (MAD)  
Microclimate  
Mineralogy  
Natural waters  
Omni directional antenna  
Pathogens  
Penman-Monteith ET Method  
Permanent wilting point (PWP)  
Ponding  
Porosity  
Radio frequency  
Rain gage  
Real dielectric permittivity  
Root zone  
RS232 communication

Salinity  
Sand  
SDI-12 communication  
Silt  
Slave radio  
Soil bulk density  
Soil chemistry  
Soil climate analyses network  
Soil geomorphology  
Soil infiltration  
Soil macro pores  
Soil micro pores  
Soil moisture  
Soil moisture budget  
Soil moisture sensor  
Soil particle size  
Soil saturation  
Soil sensor  
Soil survey  
Soil textural class  
Solar panels  
Spatial variability  
Spread spectrum radio  
Sprinkler  
Sprinkler efficiency  
Stevens Water Monitoring Systems  
Telemetry  
Tipping bucket  
Total maximum daily load  
Total suspended solids  
Unsaturated soil  
Volumetric soil moisture content  
Water molecule  
Web soil survey  
Wetting front  
Wireless telemetry

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Refer to the bibliography for the literature cited.



## Chapter 17

### Snow Data and Water Resources<sup>1,2</sup>

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#### INTRODUCTION

There are many complex political, social, environmental, and scientific challenges surrounding water resources in the western United States [Gottfried 9]. Water is scarce and does not occur when and where people need it the most. According to the US Geological Survey (USGS), about 80 percent of fresh water used in the western United States is appropriated for irrigation [Hutson 10]. Over the past 150 years, society has diverted streams, built wells and created reservoirs to better distribute water to where it is needed the most. Over the past 30 years, the impact to the environment of water withdrawals from natural sources has become more evident with increasing demand. Some of the environmental challenges associated with water withdrawals from streams include maintaining enough flow to support the habitats, increase temperature, and nutrient loading [Chapman 3]. For more than 100 years, knowing and predicting stream flow has been very important for water managers, not only to provide enough water for human consumption, but to protect the aquatic habitats in our natural water ways as well. United States Irrigation Companies such as Stevens Water provide instrumentation that is critical to the prediction of water resource availability in the western United States and throughout the world. This chapter presents critical role of the USDA SNOTEL NETWORK in Protecting Water Resources in the Western United States of America [USDA 13].

#### HISTORY OF USDA SNOTEL NETWORK

Much of the water in the western United States comes from the winter snowpack in the mountainous regions. The snowpack in the mountains of western USA can range from nothing or very little up to 30 or 40 feet of snow in the high Cascades [Gottfried 9]. In 1906, Dr. James Church, Hydrologist at the University of Nevada [Snow Survey 13], began to document the relationship between winter snowpack in the mountains and stream flow throughout the year for certain watersheds [Figure 1]. Dr. Church enhanced the existing Russian technology for measuring snow water equivalent (SWE). Shortly after Dr. Church developed these snow measurement techniques, the United States Department of Agriculture (USDA) began to construct "Snow Courses" in the mountainous areas of the west so that hydrologists could make stream flow predictions from snow data [USDA 5].

These snow courses were areas free of trees where the snow survey staff could take manual measurements of the snowpack. About that same time, the United States Geological Survey [USGS] began installing stream gauge stations so that stream data could be compared to the snow data. In 1911, these USGS stream gauge stations began using mechanical chart recorders an innovative new technology for automatically measuring water level developed by J. C. Stevens, one of the founders of Leupold & Stevens, which later became Stevens Water Monitoring Systems [Stevens, 12].

Beginning in the 1980s, the USDA's snow courses became more sophisticated, adding an array of weather sensors, data loggers and telemetry systems. These snow course telemetry sites were named SNOTEL. Today, the US Department of Agriculture - National Resources Conservation Service [USDA-NRCS], manages and operates over 600 (and growing) SNOTEL stations [USDA 13]. Using <http://www.wcc.nrcs.usda.gov/snow/>, the hourly data is now displayed on the internet for every station. The data from SNOTEL is of high quality, and SNOTEL is known the world over for having the one of best quality control protocols of any environmental network.

#### SNOW COURSE AND SNOW WATER EQUIVALENT

For the traditional stream flow prediction models, the parameter Snow Water Equivalent (SWE) was needed. SWE is the amount of water contained within a core of snowpack. This is a manual measurement where a technician would push a preweighed cylindrical tube into the snow. The tube is then weighed to get the weight of the snow. From this weight, they are able to determine the amount of water equivalent of the snow. The density of snow can change with temperature and precipitation throughout the year. The same depth of snowpack can yield different water amounts depending on the density. With the SWE measurement, apples to apples comparisons can be made with snow data across regions and time [USDA 5]. Some locations have ground truthing markers for determining snow depth visually. Sometimes ground truthing is performed from an air craft.

#### SNOTEL COMPONENTS

While this manual SWE measurement method is still used on most snow courses several times a year, SNOTEL has automated ways for collecting information about snowpack. Each SNOTEL site is equipped with a radar sensor that can provide snow depth, and a precipitation gauge that measures the total amount of precipitation (both solid and liquid) using a pressure transducer inside of a collector. These total precipitation gauges are made of metal and stand 10 to 15 feet tall and are often called "rockets"

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<sup>2</sup> Numbers in parentheses refer to the references in the bibliography.

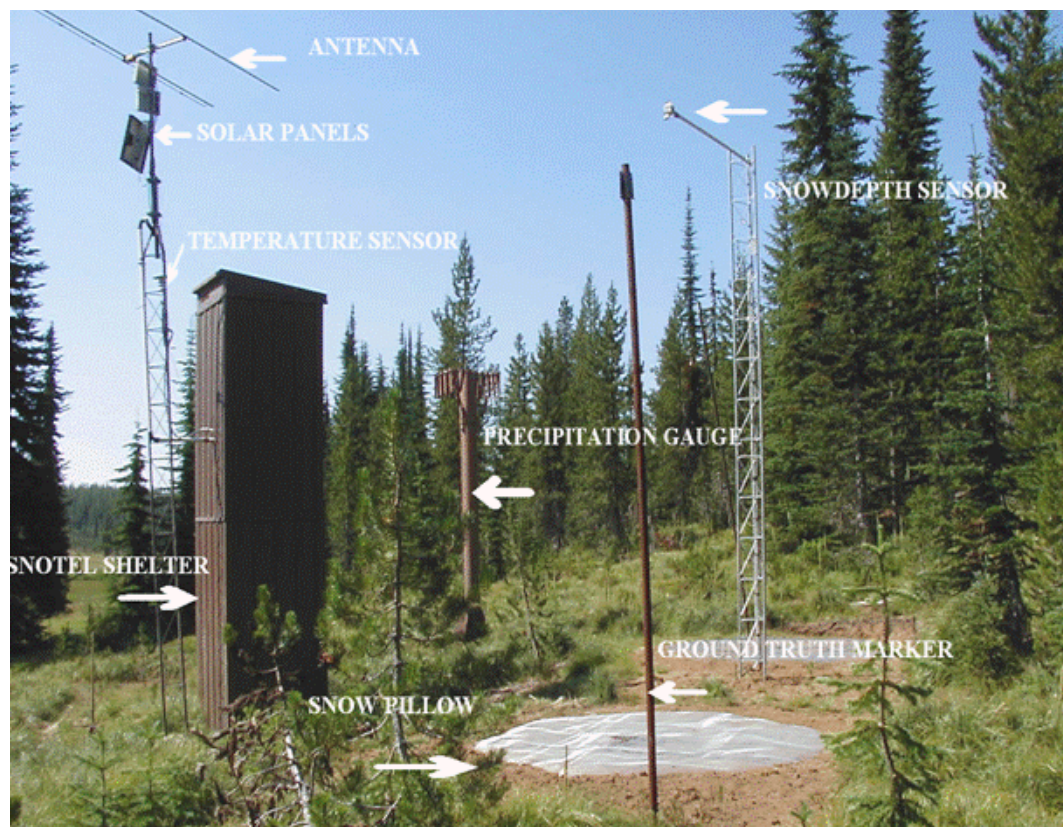
because they look like rockets. Another device at a SNOTEL is that measure SWE is a snow pillow. A snow pillow is a big bladder filled with a non-toxic liquid antifreeze solution. As the snowpack builds on a snow pillow throughout the winter, the antifreeze is displaced up a stand pipe. From the pressure of antifreeze in the stand pipe, a SWE is calculated. SNOTEL sites also collect air temperature, wind speed and direction, relative humidity, barometric pressure, and solar radiation data [USDA 13].



**Figure 1.** Dr. James Church in 1906: Picture compliments of the USDA Natural Resources Conservation Service [USDA 13]



**Figure 2.** Left: A Stevens Type F Chart Recorder from the 1960's, which was used in many USGS Stream Gaging sites. Right: The current production model of the Stevens Type F Chart Recorder [Stevens 12].

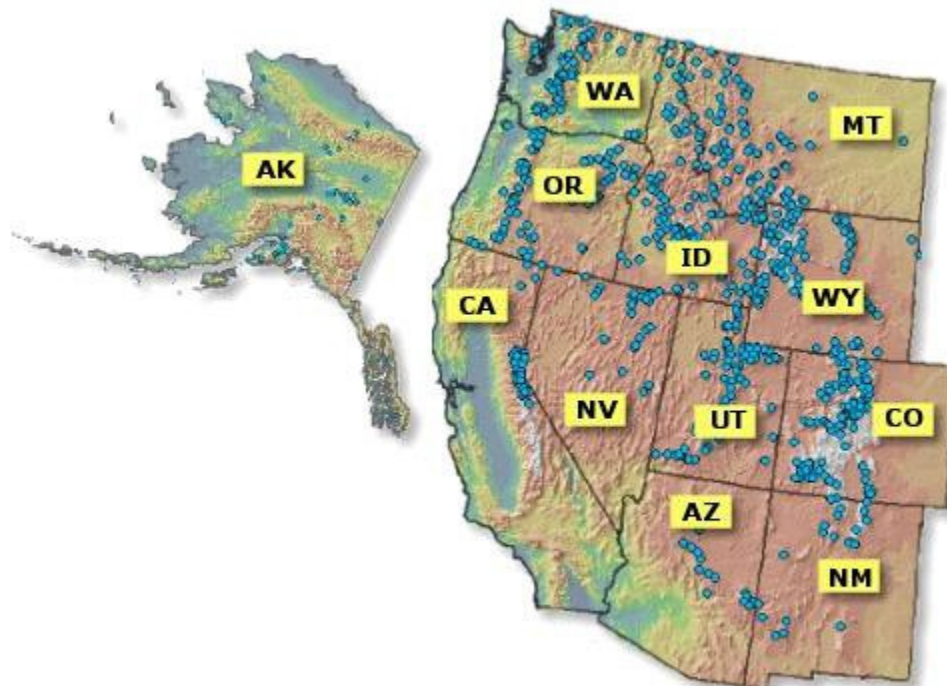


**Figure 3.** Typical SNOTEL site: Picture compliments of the USDA Nation Resources Conservation Service [USDA 13].

## ESTIMATIONS OF STREAM FLOW FORECASTS

The stream flow predictions from the USDA's SNOTEL data are derived from the statistical relationship between the SWE on April 1st and the stream flow throughout the summer [Figures 2, 3, 4]. The snow courses are standardized plots of ground where a transect of SWE measurements can be taken. These SWE measurements need to be collected consistently year after year so that the hydrologic trends can be statistically quantified.

Based on many years of historical (antecedent) data between the snow courses, SNOTEL and the USGS stream flow data, a mathematical algorithm can be generated from a matrix regression method to correlate the data so that a stream flow prediction can be generated [Garen 7]. The comparison between the stream flow prediction and the actual flow is called “skill”. The closer the skill is to 1.0, the closer the prediction was to the actual stream flow. The skill is the same as a Pearson correlation coefficient or  $r^2$  value used in statistics. Many stream flow forecasts provided by SNOTEL have a skill ( $r^2$ ) of 0.9 or greater [Garen 7].



**Figure 4.** USDA’s SNOTEL Network within the western United States [USDA 13].

#### How Does Stream Forecasting Work?

The stream flow forecasts or Surface Water Supply Index (SWSI) is calculated for specific points along streams and is SNOTEL’s main publically available product. Stream flow forecasts are available for over 750 locations in the western US. The SWSI is given as a distribution of probabilities that accommodates a wide number of applications depending on the user’s interest.

**Table 1. Example of a Stream Flow Forecast Table [USDA 13].**

| Forecast Pt                                              | Chance of Exceeding |          |          |          |          |             |     |
|----------------------------------------------------------|---------------------|----------|----------|----------|----------|-------------|-----|
| Forecast                                                 | 90%                 | 70%      | 50%      | 30%      | 10%      | 30 Yr. Avg. |     |
| Period                                                   | (1000AF)            | (1000AF) | (1000AF) | (% Avg.) | (1000AF) | (1000AF)    |     |
| Emma at Lake Outlet: 1000 AF = 1000 acre – feet of water |                     |          |          |          |          |             |     |
| APR-JUL                                                  | 285                 | 345      | 385      | 65       | 425      | 485         | 590 |

The Table 1 is an example of a typical stream flow forecast from April to July in units of 1000 acre feet of water. The 50% exceedance forecast provides the percent of average. In this example, the out flow of Emma Lake is 65% of average for April to July of this particular year. An irrigation district that withdraws water directly downstream of Emma Lake outlet would plan for the 70% exceedance. There is a 70% chance that there will be at least 345,000 acre feet of water flowing out of the lake from April through July and a 30% chance that there would be less than 345,000 acre feet of water. Because in this example, the 50% exceedance forecast only shows 65% of average, the irrigation district would use caution and use the 90% exceedance forecast to be on the safe side. There will be a 10% chance that there will only be 285,000 acre feet of water flowing out of the lake from April to July.

A hydrologist at the US Highway Department Planning for Flood Conditions, for example, would use this forecast differently. There is only a 10% chance that there will be more than 485,000 acre feet draining out of the lake for this time period. Like the irrigation district, the highway department can look at the USGS stream gauge station to get actual daily rates. In this example, the forecast is 65% of average, so the highway department should not be concerned about flooding, while the irrigation district needs to use more caution with water allocations.



## Stream Flow and Soil Moisture

Traditionally, stream flow forecast models primarily use the antecedent SWE values in their calculations and ignore soil moisture. Soil represents a huge water reservoir and can introduce errors into the forecasts. Excluding runoff, water from snow melt and precipitation will first percolate through the soil before entering the water table or saturated ground water zone. Once the water is in the saturated zone, it will travel down gradient and eventually discharge into a stream or lake [Figure 5]. The vadose zone is the soil above the water table and represents a hydrological regime that can hold large amounts of water.

Once water enters the vadose zone, it will generally only move in one dimension, up and down [Warrick 16]. In unsaturated soils, water will migrate upward because of evaporation and the uptake of water by plants and trees. This upward movement of water is called evapotranspiration [Allen 1]. Evapotranspiration is the primary mechanism responsible for removing water from soil. During the winter months with a snowpack, evapotranspiration is almost zero, and the soil moisture values stay relatively constant.

The downward movement of water in soil obeys an entirely different set of rules than it would in saturated conditions. Water will suspend itself and adhere to soil particles. This attraction between water and soil particles is called capillary force. As the soil moisture increases, gravity will pull the water downward. The point at which the gravitational influence exceeds the capillary influence is called field capacity. Above field capacity, water will be conducted downward through the soil and will discharge into the water table. If the soil moisture stays below field capacity, water can only travel upward due to evapotranspiration [Warrick 16].

Field capacity is an important parameter in determining the fate and direction of water transport in soil [Figure 6]. The field capacity of a particular soil is largely a function of the soil texture. In general, the more clay-rich the soil is the more water it will hold on to.

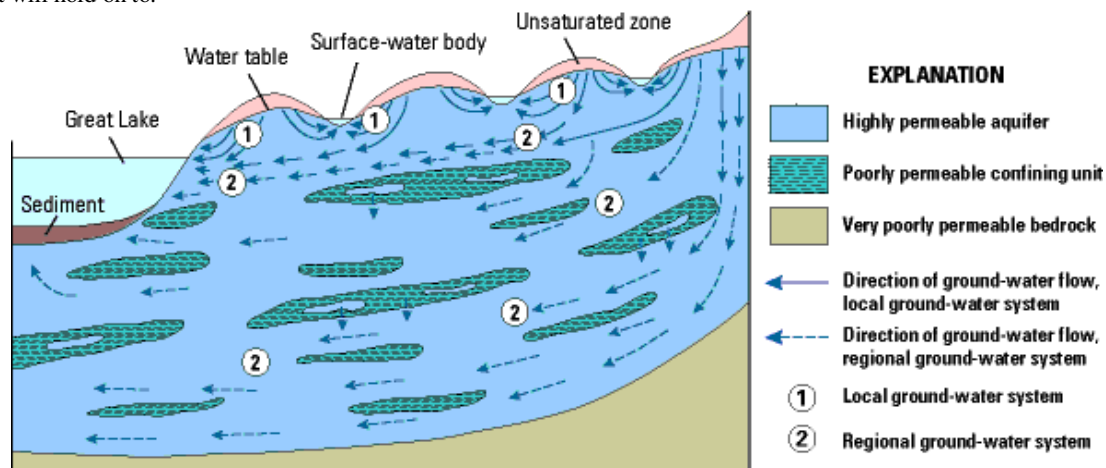


Figure 5. Groundwater flow diagram taken from the USGS Report 00-4008 [Grannemann, 8].

## Soil Moisture Target

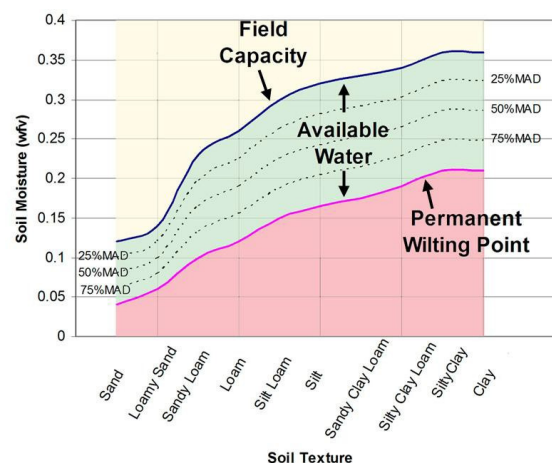


Figure 6. The availability of water at different soil moisture levels for various types of soil [Bellingham 2].

Soil moisture targets are used also in irrigation scheduling for optimization of water. Assuming the soil stays frozen, the soil moisture value before the winter snow arrives will generally be the same soil moisture value in the spring when the snow begins to melt because evapotranspiration will be negligible in the winter [Flint 6]. If there is a dry fall, and if winter arrives quickly, the soil moisture under the snowpack will be low. When the snow melts in the spring in western USA, much of the water will be retained by the soil, and not as much water will reach the streams. There can be a below-average stream flow

even if there is an above- average snowpack because the soils dried out the previous fall. Conversely, if there is a rainy autumn, the soil will already be at field capacity when the snow melts in the spring, and all of the water from the snowpack will enter the water table pushing an equal amount of water out into the streams. A wet fall can cause flooding in the spring even if there is a below average snowpack.

The transport of water from snow pack is very complex and can be driven by not only air temperature, but by thermal fluxes in the soil and surrounding vegetation as well as sublimation (solid to vapor phase). Because soil moisture was recognized as a major factor of the hydrology of a watershed starting in the late 1990s, SNOTEL began installing high quality soil sensors at SNOTEL sites. The soil sensor selected to go into SNOTEL sites was the [Stevens Hydra Probe](#). Now there are almost 300 sites nationwide that are equipped with Stevens Hydra Probes.

Even though many SNOTEL sites are equipped with [Hydra Probe Soil Sensors](#) [Figure 7], the official stream flow forecasts do not yet include soil moisture data in their models. Recently, the SNOTEL office in Utah began evaluating soil moisture under snowpack. They suggest a correction to the forecasts based on a parameter called soil moisture deficit [Vaughan 14]. The soil moisture deficit is the difference between the current soil moisture and the soil's field capacity and represents the amount of water that can enter into the soil before migrating downward to the water table. The soil moisture deficit can then be used to adjust the chance of exceedance forecasts. While this technique shows promise in improving forecasts by incorporating soil moisture data, it is not yet used system wide. More new SNOTEL sites equipped with [Hydra Probes](#) are scheduled to be installed.

## SNOTEL AND ENVIRONMENTAL ISSUES

"The Clean Water Act's 303d stream listing" is a list of streams that do not meet the water quality standards required by law. Streams on the 303d list are said to be "impaired". While streams in the US no longer catch on fire from excessive pollution, they can still become impaired from storm water runoff and from agricultural/irrigation land uses.

As water is withdrawn from streams for irrigation purposes, the temperature may increase, as well as the salinity and nutrient level. This loading of temperature, nutrients and salinity causes algal blooms and threatens the aquatic ecosystems [Chapman 3]. The demand for water from urban areas and for irrigated crops is increasing every year. The stream forecasts provided by the NRCS offer part of a potential solution for water conservation in western US.

Climate change is also a concern for many water managers and stake holders. Climate change can of course affect the quantity of the snowpack, but, it also impacts the timing of the melt. Timing of the availability of the water dictates the management and the operation of reservoirs, which in turn affects power generation.

The SNOTEL Network also provides high quality data for scientists modeling climate change. SNOTEL offers uniform, hourly data in real time for hundreds of watersheds in mountainous regions, and it is all available to the public for free.

The quality control policies for SNOTEL are mimicked by other network and mesonets in the US and in Europe such as the NRCS's Soil Climate Analysis Network (SCAN), NOAA's Climate Reference Network and the Kentucky Mesonet. Some of the policies include strategic placement of sensors to capture the particular characteristic of the site. For example, air temperature sensors and precipitation gauges are placed high enough off the ground so that they do not become buried in snow. The precipitation gauges use elaborate wind shields that help diminish the effects of wind on precipitation measurements. Each station is also ground truthed several times a year by highly trained staff that can collect measurements as well as perform maintenance on the stations, ensuring accurate readings year-round.

The data is also evaluated with special modeling software called "Parameter-Elevation Regression on Independent Slopes Model (PRISM)" developed at Oregon State University [Daly 4]. PRISM statistically examines the data from SNOTEL sites and can calculate the variability of the data. PRISM can make regional prediction of the parameters. For example, if an air temperature gauge is suspected of malfunctioning, PRISM software can take temperature data from other nearby SNOTEL sites and other sources and calculate what the expected temperature would be at the suspect site. If necessary, the data archives can be edited to provide the highest quality data possible.

## Water Rights in the Western United States

Water rights in the western United States are exceedingly complex and vary from region to region. In general, water rights are based on Prior Appropriation which means whoever got there first has the senior water rights.

The availability of water determined where people settled in the west in the 1800s. Reservations were created for the Indian tribes which often time included large amounts of land high in the mountains that hold a snowpack much of the year. In 1908 the US Supreme Court ruled that the Indian tribes own the water rights on their reservations. Because snow occurs up gradient from the irrigated lands, as the snow melts, it travels though several if not many jurisdictions before returning to the natural water body. Figure 8 shows a water withdraw head works diverting water from a river by an irrigation district that will sell water for irrigation purposes. Figure 9 shows a gaging station on an irrigation lateral that is logging water level and flow [Stevens Water 12].

Often times, the first water jurisdiction is snowpack on Indian Reservations, however many tribes have chosen not to exercise their water rights. Structures that divert state or tribe owned natural waters are built and paid for by the US Bureau of Reclamation. The US Bureau of Reclamation will then sell the water to irrigation districts, municipalities, and other water users that hold or service holders of water rights. Under the US Department of the Interior, the US Bureau of Reclamation is the nation's largest wholesale supplier of water and the nation's second largest producer of hydroelectric power. Its facilities also provide substantial flood control, recreation, and fish and wildlife benefits.



When water passes through jurisdictions, the stakeholders and the holders of the water rights do not always come to full agreement on the pricing, usages, Total Maximum Daily Loads, and ownership of the water. These disagreements can erupt into a “water war” where SNOTEL and USGS data are often times used in litigation. In 1969, the National Environmental Policy Act (NEPA) was established to help settle disputes while using sound environmental assessments of the particular issues.



**Figure 7.** Installation of a Stevens Hydra Probe into native soil at a SNOTEL site [Bellingham 2].



**Figure 8.** An example of irrigation district river diversion in Oregon [Stevens Water 12].



**Figure 9.** Measurement of water flow in an irrigation ditch, using the Stevens AxSys Flowmeter [Stevens Water 12].

## THE SNOW SCIENCE COMMUNITY

The Western Snow Conference started in the early 20<sup>th</sup> century as the American Geophysical Union’s committee on snow hydrology under the chairman Dr. Church. In the 1930’s, a special conference was held highlighting the advances in stream forecasting from snow surveys [Figure 10]. Since the 1930’s, the Western Snow Conference has been held every year [15].

To this day, the yearly Western Snow Conference continues to promote snow science and stream forecast modeling. At the yearly conference there are technical exhibits, a forum of talks and a peer reviewed journal. The organization is

divided into four sub-organizations based on region. Some of the topics at this year's Western Snow Conference included effects of dust on the melt rate of snow, water management, the challenges of hydrological modeling, the bark beetle and other invasive species, and prediction of landslide hazards based on SNOTEL data.

For almost 100 years, snow surveys in the western US have helped resolve some fundamental issues regarding the availability of water. With increasing water demand, climate change, and changes in land use, we will need to rely more and more on monitoring and modeling technology to help protect valuable water resources. SNOTEL, in cooperation with the USGS, Bureau of Reclamation, NOAA and other agencies, is providing products such as real time data and forecasts free of charge to help water resource managers meet the new challenges facing water in the west.

To learn more about SNOTEL, the reader is advised to visit the US Department of Agriculture NRCS SNOTEL site at: [<http://www.wcc.nrcs.usda.gov/snow/>](http://www.wcc.nrcs.usda.gov/snow/).



**Figure 10.** Western Snow Conference visit to the Columbia Ice Sheet in 2009 [15].

## SUMMARY

The US Department of Agriculture, Natural Resources Conservation Service operates about 600 remote snow monitor stations (SNOTEL) in the mountains of the western United States. About 30% currently have soil moisture sensors and the number of sites that have soil moisture sensor increases every year. In the western United States, the majority of the water used for irrigation originates as snow pack. Data from SNOTEL sites along with hydrological models are used to provide water availability forecasts to whole sales water users, local governments, and the general public. Adding addition sensors such as soil moisture sensors and can improve forecast accuracies. The snow science community gathers once a year at the Western Snow Conference to promote the advances in measurement technology, hydrological model and snow science.

## KEY WORDS

303d listing  
Acre foot  
American Geophysical Union  
Available water capacity  
Clean water act  
Climate change  
Data acquisition  
Data logger  
Evapotranspiration (ET)  
Exceedance forecast  
Field capacity

Field capacity (FC)  
Flood  
Head works  
Hydra probe soil sensor  
Hydroelectric power  
Hydrological model  
Impaired stream,  
Irrigation District  
Irrigation scheduling  
Maximum allowable depletion (MAD)  
National Environmental Policy Act (NEPA)  
Natural waters,  
Permanent wilting point (PWP)  
Prior appropriation  
Radar sensor  
Rain gage  
Rocket gauge  
SNOTEL  
Snow course  
Snow depth  
Snow pack  
Snow pillow  
Snow pillow  
Snow survey  
Snow water equivalent (SWE)  
Soil climate analyses network  
Soil moisture  
Soil moisture sensor  
Soil moisture sensor  
Soil saturation  
Stevens Water Monitoring Systems  
Stream gaging  
Surface water supply index (SWSI)  
Telemetry  
Tipping bucket  
Total maximum daily loads  
Type F recorder  
US Bureau of Reclamation  
US Department of Agriculture (USDA)  
US Geological Survey (USGS)  
Vadose zone  
Water allocation  
Water forecast  
Water Resources  
Water rights  
Water war,  
Water withdraws  
Western snow conference  
Wetting front

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