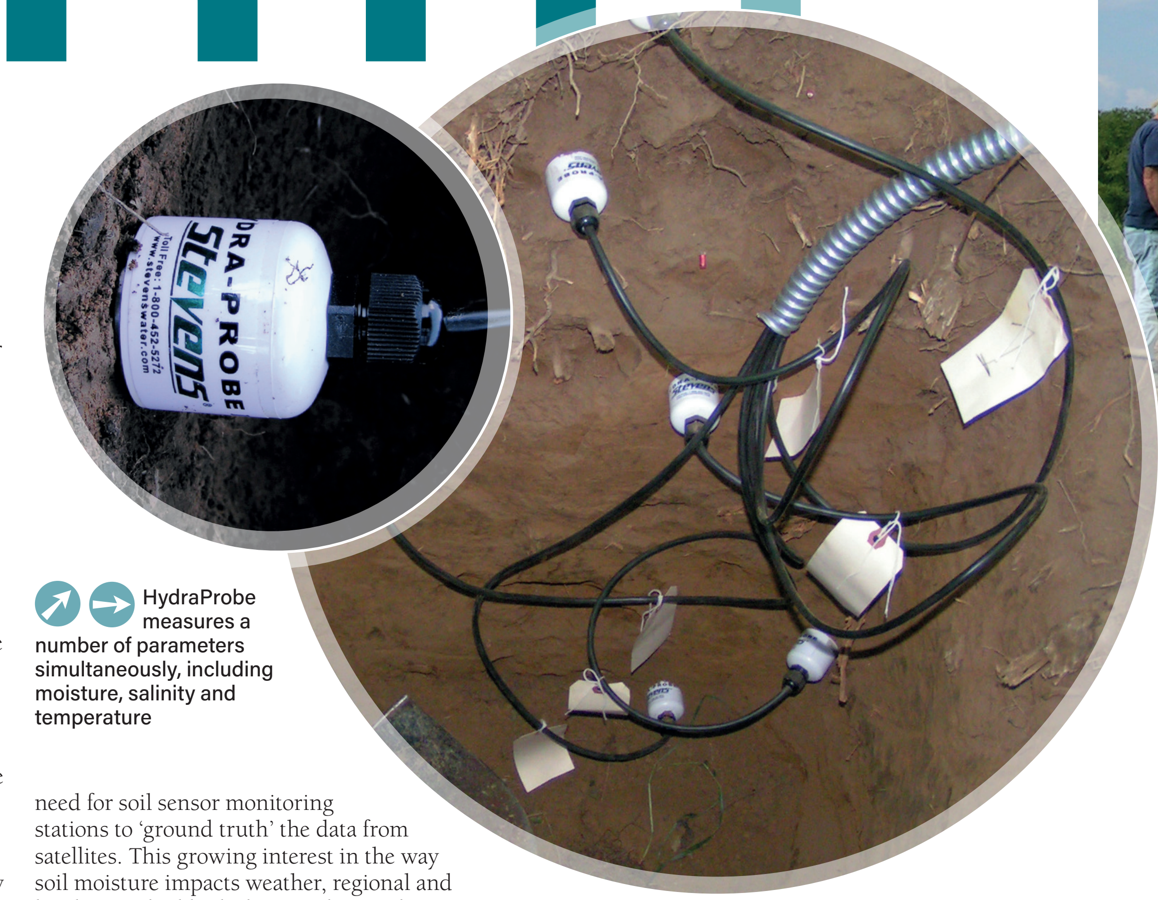
Keith Bellingham, soil scientist, Stevens Water Monitoring Systems

DOWN TO EARTH

Soil moisture data is helping enhance meteorological and hydrological models

The relationship between soil water content and the health and yield of crops has long been known. But only in recent decades has science quantified the specifics of these relationships. This research has expanded to develop a relationship between soil moisture levels and the impact on meteorological and hydrological models and forecasts.



HydraProbe measures a number of parameters simultaneously, including moisture, salinity and temperature

THE RELATIONSHIP EVOLVES

In the late 1970s, the met community became interested in soil moisture after studies were published addressing thermal fluxes between the atmosphere and the ground. The studies suggested that the water content in the soil played a major role in the water/energy balance between Earth's surface and the atmosphere, which has an influence on regional weather.

Water supply forecasts in streams for hydropower generation traditionally used snow water equivalent (SWE) and rainfall for their predictions. In the 1960s, soil moisture under the snow pack was recognized as a potential input parameter for watershed hydrology models, which could improve the water supply forecasts for hydropower management and all the other demands on water resources.

Agriculture management, food security, and the need to better understand drought drove a need for regional soil moisture and vegetation index maps, which led to the development of the remote sensing of soil moisture from satellites in the 1980s. Remote sensing of soil moisture then increased the need for soil sensor monitoring stations to 'ground truth' the data from satellites. This growing interest in the way soil moisture impacts weather, regional and local watershed hydrology, and agriculture, led to development of new analytics, formulas and equations to better quantify these relationships.

The Topp Equation in 1980 quantified an analytical relationship between soil moisture and a measurable parameter characterizing the storage and distribution of the energy in soil using radio frequencies called the dielectric permittivity, in which soil is the dielectric. Soil moisture sensor technologies were then developed using the fundamentals of the Topp Equation and an electromagnet wave propagation through the soil.

THE TECHNOLOGY

Such sensor technology includes time domain reflectometry (TDR), which sends an electromagnetic wave down two parallel guides and measures the time the energy reflects back from the end of the wave guide. Time domain transmission (TDT) sensors measure the time the electrometric wave travels around a wave guide. Frequency domain reflectometry (FDR) sensors derive soil moisture from changes in an electromagnet wave's frequency after a reflection of the signal through soil. However, these sensors make certain assumptions in determining the dielectric permittivity that could wrongly influence the measurements.

Raising a meteorological tower for a remote soil monitoring station

Dielectric permittivity is a complex number containing both energy storage and energy loss terms. Because technologies such as TDR and FDR soil moisture sensors make assumptions on radio frequency (RF) energy loss, factors such as the variability of soil morphologies, and changes in temperature and salinity, introduce instability in the determination of soil water content. Since soil conditions and soil types vary from region to region, the expanding interest of soil moisture monitoring on a large scale had researchers concerned over the quality, consistency and stability of the soil moisture estimations determined by a dielectric measurement. Large regional and continental scale soil moisture networks require a suite of sensors including soil moisture sensors that have a high level of consistency, accuracy and long-term stability. The quality of the sensors is important in providing the high level of confidence in the data sets required by the end users.

Responding to the need for a consistent, accurate and uniformly comparable soil sensor, physicists at Dartmouth College, New Hampshire, developed technology to fully characterize the dielectric spectrum from a single frequency based on a series of reflected RF signals. This research brought major improvements in the stability of soil moisture measurements by eliminating many of the measurement errors associated with soil morphology and salinity. The HydraProbe soil sensor (a complex coaxial impedance soil sensor) evolved out of this research.

THE RISE OF NETWORKS

Over the past 10 years, new soil moisture networks have emerged and soil moisture sensors have been added to existing weather station networks. According to the International Soil Moisture Network, an international cooperation established to maintain a global *in situ* soil moisture database, there are 50 to 100 meteorological networks with more than five soil moisture monitoring stations. About 60% of the soil sensors in these networks are HydraProbe soil sensors at various depths down to 1m (3.3ft).

Among the largest networks is the US Department of Agriculture's Soil Climate Analysis Network (SCAN), and SNOTEL (snow telemetry) networks, with a combined 620 stations that account for 3,000 soil sensors installed throughout the country.

Another large network in the USA is NOAA's Climate Reference Network (CRN), which maintains 125 sites with 600+ soil sensors.

Mesonets and other expanding international soil monitoring networks have deployed around 6,400 soil sensors in more than 1,800 stations globally. The majority of these stations include the HydraProbe because of its research-quality features, which include a more complete characterization of the dielectric permittivity that helps eliminate uncertainties associated with soil types, soil morphology and salinity.

The interest in soil moisture and its impact on weather, hydrology and agriculture continues to grow, and is driving growth in the soil sensor market. According to MarketsAndMarkets' independent research, the combined global market size for soil sensors in 2016 was US$99.3m, and this is expected to rise to US$288.3m by the end of 2025. While agriculture is the main application for soil sensors, particularly economy qualitative sensors that track relative changes in soil moisture conditions, there is a demand for more quantitative soil moisture data enabling water mass balance calculations for satellite active passive remote sensing outputs.

THE USE OF SATELLITES

While there are about a dozen satellites in space collecting soil data, the Soil Moisture Active Passive (SMAP) satellite is one of the most important. SMAP is a low Earth orbiting satellite launched by NASA in 2013 that has a revisit time of 1-2 days and uses a microwave L-band providing soil moisture data with a resolution of 10-40km (6-25 miles). Typically measurement depths are 2-6cm (0.8-2.4in). The SMAP Mission offers considerable data critical for many studies and international scientific collaborations benefitting society. SMAP observation of soil moisture from outer space allows for improved estimates of water energy and carbon transfer between the land and the atmosphere. The better accuracy of these models from SMAP improves weather predictions, as well as flood, draught and climate assessments.

Soil moisture data collected by large satellite and ground-based networks such as SMAP, SCAN and CRN is critical to the development and functionality of enhanced meteorological and hydrological models and forecasts. Research-grade quality sensors that are accurate, consistent and durable with long-term stability continue to advance in performance, providing experts with a high level of confidence in data sets. In addition to hundreds of smaller studies conducted by universities and research institutions worldwide, the HydraProbe soil sensor has largely been chosen for most climate reference networks in North America. ∎