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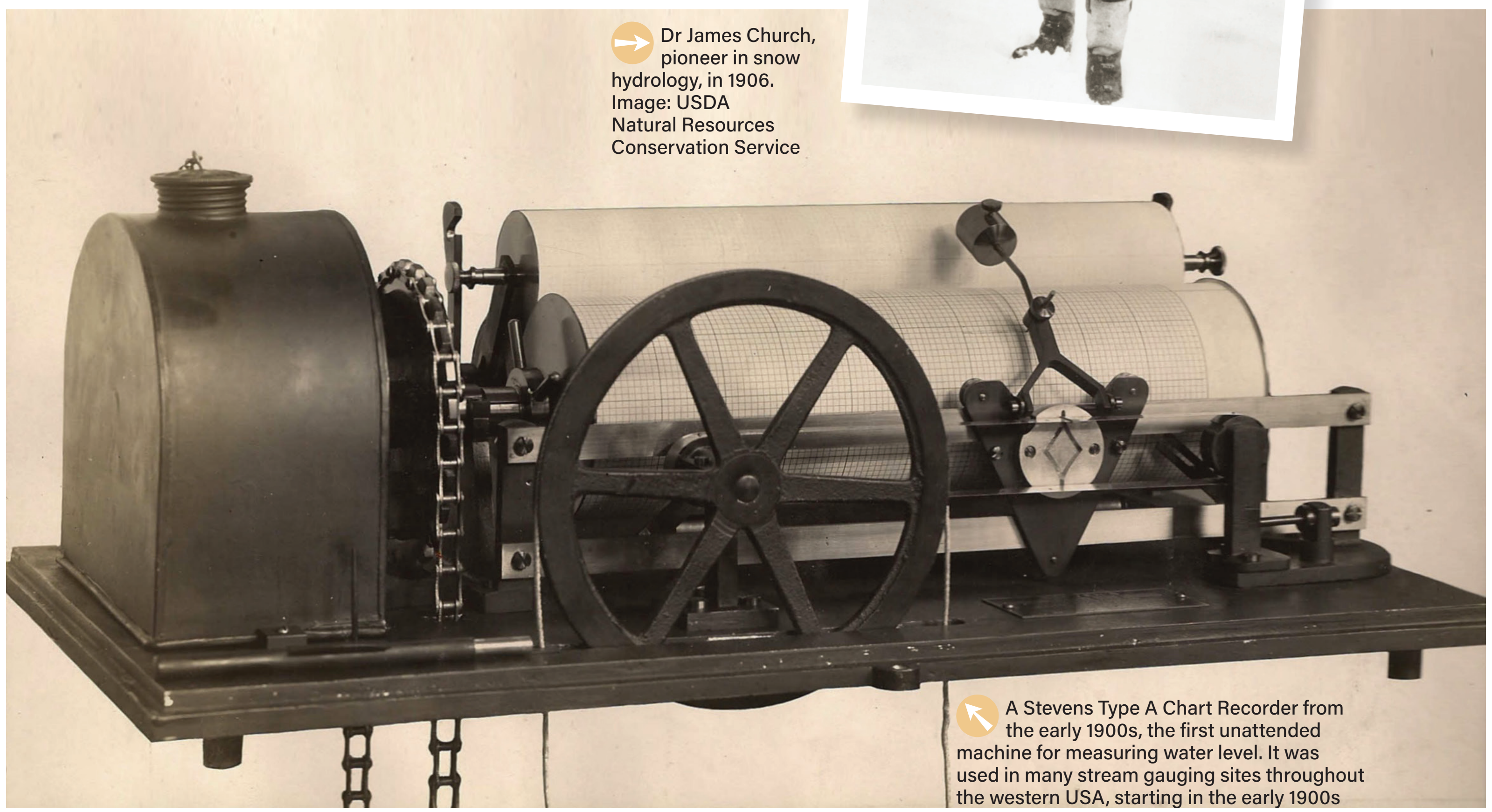
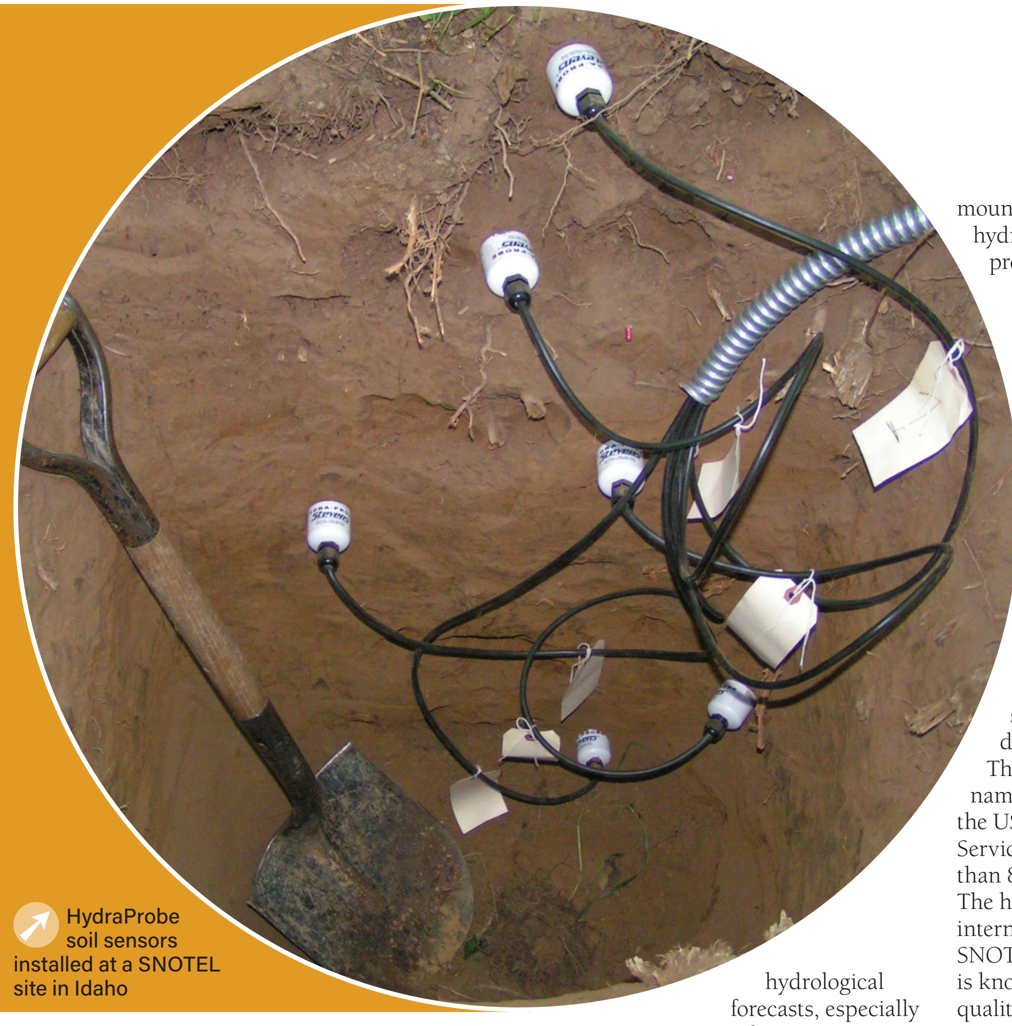
FLOW ANALYSIS

One of the world's largest meteorological networks, SNOTEL, is employing soil moisture sensors to monitor the impact of soil water content on stream flow forecasts

Dr James Church, pioneer in snow hydrology, in 1906. Image: USDA Natural Resources Conservation Service



A Stevens Type A Chart Recorder from the early 1900s, the first unattended machine for measuring water level. It was used in many stream gauging sites throughout the western USA, starting in the early 1900s



HydraProbe soil sensors installed at a SNOTEL site in Idaho

Many complex political, social, environmental and scientific challenges impact water resources. Snow telemetry (SNOTEL), one of the world's largest meteorological networks, working under the US Department of Agriculture (USDA), provides critical stream flow predictions for the understanding of hydrology in western USA.

For more than 100 years, predicting stream flow has been important for hydro-power generation, irrigation, water supply networks, and aquatic habitat protection. With more than 800 SNOTEL stations, along with hundreds of US Geological Survey (USGS) stream gauging stations, seasonal stream flow forecasts are published for most major watersheds in 12 US western states.

Policy decisions related to water management in the western US states depend on SNOTEL's stream flow forecasts. While the stream flow forecast models have traditionally relied on precipitation, snow pack and river flow data, new emerging models are starting to address the role soil moisture is having on streamflow.

Soil moisture is being recognized as an important measurement variable of a watershed's hydrological budget as research increasingly points to soil water content as strongly influencing the accuracy of hydrological forecasts, especially in areas of winter snow packs or heavy seasonal rains.

The analytical method for determining soil moisture in SNOTEL and many other networks is a unique impedance-based research-grade soil sensor technology with no sensor-to-sensor variations for a universal comparison on soil moisture across all locations, seasons, soil types or moisture ranges. SNOTEL has an innovative history and is a meteorology network leading the future of using soil moisture data in stream flow forecasting.

THE EVOLUTION OF SNOTEL

Much of the water in the western USA comes from the winter snowpack in the mountainous regions. The snowpack in the mountains of the western USA can range from nothing, or very little, up to 10m (33ft) or even 15m (49ft) deep of snow in the Cascade mountain range.

In 1906, a hydrologist at the University of Nevada, Dr James Church, began to document the relationship between winter snowpack in the mountains and stream flow throughout the year for certain watersheds. Church enhanced existing Russian technology for measuring snow water equivalent (SWE). Shortly after he developed these snow measurement techniques, the US Department of Agriculture began to construct 'snow courses' in the mountainous areas of the west so that hydrologists could make stream flow predictions from snow data.

These snow courses were areas free of trees, where the snow survey staff could take manual measurements of the snowpack. Around that same time, the USGS began installing stream gauging stations so that stream data could be compared with the snow data. In 1911, these USGS gauging 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 Stevens Water Monitoring Systems.

Starting in the 1980s, the USDA's snow courses added weather sensors, dataloggers, and telemetry systems.

These snow course telemetry sites were named SNOTEL or snow telemetry. Today, the USDA's Natural Resources Conservation Service (NRCS), manages and operates more than 800 (and growing) SNOTEL stations. The hourly data is now displayed on the internet for every station. The data from SNOTEL is of high quality, and SNOTEL is known worldwide for having the best quality-control protocols of any meteorological environmental network. Parameters measured at a SNOTEL site include solar radiation, total precipitation, snow depth, wind speed and direction, relative humidity, SWE and temperature. SNOTEL began adding soil moisture sensors in the late 1990s.

SIGNIFICANCE OF THE SWE PARAMETER

Traditional stream flow prediction models use SWE as a measurement variable. SWE is the amount of water contained within a core of snowpack that is manually measured by pushing a pre-weighed cylindrical tube into the snow. The tube is then weighed to get the weight of the snow, from which scientists are able to determine the amount of water in 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. The SWE measurement can provide universal comparisons for snow data across regions, locations and time for widely accepted stream flow forecasting models.

CALCULATING SNOTEL STREAM FLOW FORECASTS

The stream flow forecasts from the SNOTEL data are derived from the statistical relationship between the SWE on April 1 each year, precipitation, and the stream flow

Example of a typical SNOTEL site. Image: USDA Natural Resources Conservation Service

throughout the summer. Based on many years of historical data between the snow courses, SNOTEL and the USGS stream flow data, a mathematical algorithm can be generated from a matrix method to correlate the data so that a stream flow prediction can be generated. 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. While many stream flow forecasts provided by SNOTEL have a skill of 0.9 or greater, the need for more accuracy put an increased emphasis on a major part of the hydrological cycle that was previously ignored – the soil moisture.

SOIL MOISTURE INFLUENCE ON STREAM FLOW

Traditionally stream flow forecast models primarily used the antecedent SWE and precipitation values in their calculations. Soil represents a huge water reservoir and can introduce errors into the forecasts. Excluding run-off, water from snowmelt and precipitation will first percolate through the soil before entering the groundwater. Once the water is in the aquifer, it will travel down gradient and eventually discharge into a stream or lake. 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 only move in one dimension – up and down. 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 (ET). ET is the primary mechanism responsible for removing water from soil. During the winter months with a snowpack, ET 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 an aquifer. 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 ET.

Because ET is negligible under snowpack, the soil moisture value just before the winter snow arrives will be the same soil moisture value in the spring when the snow begins to melt. If there is a dry autumn, and if winter arrives quickly, the soil moisture under the snowpack will be low. When the snow melts in the spring, much of the water will be retained by the soil, and not as much water will reach the streams. Accordingly, dry falls can result in below-average stream flow the next spring and summer even with an above-average winter snowpack. 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 low snowpack.

Even though many SNOTEL sites have been equipped with HydraProbe soil sensors since the 1990s, not enough historical soil moisture data has been collected to be included as an input parameter in official stream flow forecasts. It takes at least 10 years of data to run a successful model forecast simulation. However, the new innovative SNOTEL models, which include soil moisture measurements, are showing more accurate stream flow forecasting results.

New SNOTEL forecasts are coming from sites where soil sensors have been installed for more than a decade, and they include evaluation of the soil moisture under snowpack. One possible input parameter to the forecast models based on soil moisture is called the 'soil moisture deficit index'. The soil moisture deficit is the difference between the current soil moisture and the soil's field capacity; it represents the amount of water that can enter into the soil before migrating downward to the water table. Thus, the soil moisture deficit index represents the amount of water the soil can hold based on the real-time water content and the soil properties. The deficit can then be used to adjust the chance of exceedance forecasts. This technique shows promise in improving forecasts by incorporating soil moisture data. As more SNOTEL sites are equipped with HydraProbe soil sensors, and as more historical data is accumulated, soil moisture will be incorporated into the forecast models.

CONCLUSION

SNOTEL, under the USDA, is leading the innovation in new stream flow and water supply forecasts that provide key insight for the management of hydropower generation, irrigation, and aquatic habitat protections. While once neglected and not well understood, soil moisture has been shown to improve the accuracy of the forecasts and USDA continues to instrument SNOTEL sites with HydraProbe soil sensors. As more historical data accumulates, soil moisture data will be incorporated into the stream flow models that will improve the accuracy of the water supply forecasts.

Companies such as Stevens Water Monitoring Systems, the manufacturer of the HydraProbe, continue to provide and develop advanced technology to help scientists and engineers solve the challenges facing water resources management. ∎