USCRN soil moisture station installation, Fort Peck Tribes Reservation, Montana. Credit: Tilden Meyers

CHAPTER 5

INSTALLATION AND MAINTENANCE OF SOIL MOISTURE STATIONS

This chapter is meant to provide an overview of site installation and maintenance concerns for soil moisture stations. More detailed information and guidance on installation is currently in development by the NCSMMN, including a "Planning Guide for Installing and Maintaining Soil Moisture Monitoring Stations" and "Field Guide for Sensor Installation in a Pit or in Deep Auger Holes" (planned release Fall 2020). This chapter is intended to provide broad guidance on installations for a national soil moisture network, and as such, it covers requirements for sensing soil moisture near the surface, within the root zone, and below the root zone.

5.1 PRE-INSTALLATION GUIDANCE

Much must be considered and planned prior to installing soil moisture sensors (see Chapter 4). A geographic location must first be chosen at which the sensor will be installed. In making this decision there will be large-scale considerations that network purpose should help inform as discussed in Chapter 4, and small-scale considerations that the landscape will help inform. Whether thinking large or small scale, locations should be chosen that will be beneficial in representing the larger area of interest as much as possible, taking into consideration that soil moisture sensors take measurements within a relatively small volume. In this context, "representative" means making an inference about a larger area from measurements at a particular location.

In the case of soil moisture sensors being added to existing stations, the siting is already determined and only small-scale factors need to be considered. However, if soil moisture sensors are being added to an existing network at only a subset of stations these large-scale conditions might be considered in choosing the most appropriate subset. As soil moisture monitoring becomes more common, adding this technology to existing stations will become a likely occurrence. Another question is whether the primary concern is monitoring modified soils or monitoring otherwise natural soils. If the goal is to use the data to represent a larger area, then the prevailing soil type should be chosen for monitoring, and local disturbances should be avoided. However, if the goal is to understand the hydrology of a modified soil, then sensors should be placed in that type of soil.

As well as technical and scientific considerations, both permission from landowners and site access must also be considered when installing sensors on both private and public land if these are not already determined through a contract.

5.2 SENSOR INSTALLATION

There is not a singular method for installing a soil moisture sensor, just as there is not a single sensor which meets the variety of requirements of all soil moisture networks. Sensor technology will also affect the method of installation. Sensor installation may depend on requirement for sensor replacement plans, or network requirement, such as need certain monitoring depths. Figure 5.1 (*below*) provides a general schema of sensor installation, showing the common types of sensor layouts for different soil levels. The most common method is a soil pit or hole being dug with sensor installations in the side of the hole. The hole is then backfilled to the same density as prior to the digging. Other borehole sensors are inserted into a pre-augured hole requiring a close fit along the borehole wall. The sensor placements depicted here may raise questions if viewed through the lens of a one-dimensional soil water flux model. In reality, soils and soil water fluxes are heterogeneous in three dimensions and placing all sensors in one vertical line is unlikely to provide results that are more “true” than the placements illustrated here, particularly since soil water dynamics typically are slower at greater depths and redistribution tends to smear lateral differences. Near-surface phenomena change more with depth and time and placing sensors horizontally in a vertical line (one above the other) may help with some analyses.

The most important aspect of installation, regardless of methodology, is that the sensor is in firm contact with the soil providing a precise time series. During installation, a common mistake for inserted probes is to introduce air gaps within the sensing volume. For borehole probes, air gaps are also a challenge as are rocky soil installations that can act as voids in a sensing volume.

In general terms, there are a few common goals for a successful installation. The installation is best done in undisturbed soil, where possible. Avoiding air gaps is a necessity. A robust installation will be free of local hazards, which would dislodge the sensor, such as agricultural action, wildlife burrowing or interference, and safety/security of the station itself.

5.3 AFTER-SENSOR INSTALLATION

Sensor data should be routinely run through quality control procedures (section 5.6) so that sensor failure or abnormal operation can be detected and corrected.

Depending on the sensor and method of installation, there may be a necessary ‘settling time’ for the

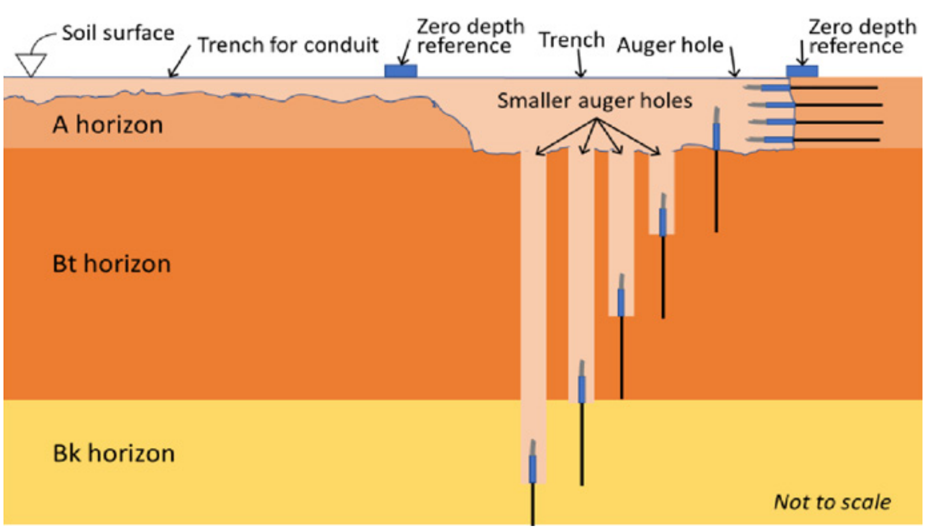

Figure 5.1: Installation of sensors horizontally into the side and vertically into the bottom of a trench pit and vertically into auger holes made in the bottom of the trench. The zero depth references span the trench and rest on the soil surface on either side.

sensor to give reliable estimates. This time period can vary by soil texture and sensor type and there is no conclusive minimum time for settling as of yet. There is a broad consensus that at least one precipitation event is necessary to observe a response.

It is unfortunately the case that sensors sometimes need to be removed from the ground for maintenance or replacement. It is the recommendation of the NCSMMN that removal/replacement only occur when it is determined that the sensor is malfunctioning. Removal for ongoing regular maintenance is often unnecessarily disruptive to the data time series. If removal is necessary, this task should be done with great care so as to not cut or nick wires.

5.4 STATION DATA MANAGEMENT

5.4.1 Station Metadata

As data integration becomes more and more prevalent, it will be necessary to properly document the metadata associated with each station so that analysis may be harmonized efficiently and effectively. The Open Geospatial Consortium has a recommended standard for such data, via the WaterML.[15] Basing an input system on this framework would be relatively simple but requires a commitment to format and maintain data in a consistent format over time. Here is a list of the critical elements of the metadata, which would need to be cataloged.

- Sensor metadata: Model name, manufacturer, install date, calibration source, and method
- Reporting interval: Is the data instantaneous or averaged over an interval?
- Station Location: WGS84 Lat/Lon, elevation
- Soil pedon information: specifically, soil horizonation description, soil texture, vegetation type and condition, hydraulic conductivity, organic matter, and soil bulk density, among other parameters
- Photo records: soil trench and landscape, follow-up site photos
- Maintenance log for site visits and sensor replacement

Regarding soil pedon information, it should be noted that the National Soil Survey Laboratory (NSSL) in Lincoln, NE is an important resource for detailed soil information. In the Fall of 2019, NSSL began a process of coordinating soil analysis with NOAA's USCRN for the stations in that network. Ideally a similar effort could occur with other networks within the NCSMMN.

5.4.2 Sensor Sampling and Data Aggregation Methodology

The sampling and reporting rates need to be noted in metadata. Many soil moisture sensors cannot be sampled at high frequencies (i.e., less than 5 minutes) due to data acquisition requirements and the power management of station, which is often limited by available solar power. Many networks (e.g., USCRN and SCAN) sample soil moisture sensors every 15 minutes (with 5-cm sensors sampled at 5-minute intervals) and average these data into hourly reported values. Ideally, soil moisture data needs to be sampled sufficiently (i.e., more than 3 times/period) to provide a mean value although some technologies are limited.

5.5 MAINTENANCE

After the station is installed, it is likely that there will be operation and maintenance issues that occur, and therefore it is necessary to remain vigilant in the monitoring and maintenance of a station and its data.

5.5.1 Site Calibration

A field calibration of the sensor should be conducted along with the soil characterization of the soil pedon when possible. There are sensor calibrations per soil type, but there is also a thorough scaling validation as well, which requires a regular sequence of field samplings to determine how a permanent station is correlated to soil moisture in the surrounding region. This can lead to the computation of a scaling function that will provide a conversion of the time series record to a validated representative soil moisture estimate at some determined scale. The current goal of modeling efforts is a 1 km scale, though this may not be possible at all sites. In the future, higher resolution models may be implemented.

[15] *https://www.opengeospatial.org/standards/waterml*

Site calibration can be accomplished via a variety of methods depending on the soil sensor. Evett et al. (2008) provide a detailed examination of field calibration methods and factors affecting accuracy and precision of a variety of sensing systems, ranging from those deployed in access tubes to sensors that are inserted into soil.

The simplest means of scaling is to perform frequent site surveys over the domain of interest (~1 km) (Cosh et al., 2016), but this is time and cost intensive. Alternatively, a temporary network of sensors can be deployed across the broader region to provide a higher statistical sample of time series to understand the spatial dynamics of the area and allow a scaling of the permanent station to be scaled with a high degree of confidence (Cosh et al., 2013; Coopersmith et al., 2016b) using temporal stability analysis.

5.5.2 Preventive Maintenance

The most critical aspect of preventative maintenance and quality control is to have steady monitoring of the reporting conditions of the station to allow for a quick response to any observed anomalies. Local station hosts (such as universities, schools, fire departments, extension offices, etc.) can also provide quick response to events or activities that may harm a station. It is also important during scheduled maintenance to inspect sensor installations and hardware to the extent possible (Fiebrich et al., 2005). Regular maintenance can be conducted as frequently as feasible for a station, but an expected minimum is three visits per year (Fiebrich et al., 2005).

5.5.3 Unscheduled Maintenance

When conditions merit, unscheduled maintenance may be necessary when a warning or quality control flag is triggered. One of the best sources of notification is a local site host who visits the station regularly in the course of their travels, but not all networks will have this luxury. Other triggers include unusual activity from the time series itself, perhaps when a soil moisture or soil temperature deviates from an expected confidence interval or exceeds a physical threshold such as the soil porosity. Causes of station malfunction are numerous, but there are some common anomalies:

- Soil erosion, soil cracking, and improper installation often lead to errors far larger than sensor accuracy.
- Animal interaction can cause soil sensor to be dislodged or wires to be shorted from chewing.
- Wind storms can introduce debris into the area, or can interfere with station power or communications. Lack of station communications is one of the most common causes of station maintenance.
- Lightning can damage sensors, data loggers, and telemetry.
- Vandalism and theft are other possibilities for time series interruption, which is another reason to be careful with site selection and also to have local host support to discourage this activity.

5.5.4 Maintenance of Site Land Cover

Soil moisture data is intrinsically linked not only to the soil, but also to the vegetation on the surface, as it measures water demand and flux source for the soil column. The ideal situation would be to have the station be maintained with a land cover that is congruent with the surrounding area, usually via regular intervention by a local team. For instance, a rangeland site should have a similar vegetation cover (i.e., short grass, shrubs) as the surrounding region. However, this is often a challenge, especially in heavily agricultural regions or forests which have soil tillage or no clear sky view. Even forage sites need to be protected from cattle with fencing, so the grass at a site will grow taller than the grazed field adjacent to it. There is no perfect answer for what is the best cover, but consensus is to maintain a low water demand so as not to significantly bias the measurements. Scaling of such unrepresentative stations should be addressed in the metadata with a scaling function, as described previously.

5.6 QUALITY CONTROL

5.6.1 Seasonal Range Tests

Local extremes of soil moisture and temperature are a constantly evolving metric, but these are a valuable first quality control step for determining the performance of a station. Other local stations or regional model estimates can help inform what the expected extreme values are, and when these are exceeded, further investigation is warranted.

5.6.2 Sensor Intercomparisons

With proper resources, it is recommended that sensors be deployed in triplicate (three separate soil sensor profiles in close proximity) to provide local references to detect anomalies. The USCRN is one of the few networks that has been able to deploy in triplicate, and it has been found to be very helpful in troubleshooting time series. This also helps to identify when sensors do not respond to events like rainfall, that other sensors can detect (Bell et al., 2013). Similarly, complementary sensor response can also be used for quality control and for gap filling. The advantage of triplicate sensor profile for quality control is so beneficial that it is recommended to install triplicate sensor profiles for stations within the NCSMMN when possible. Rain gauge data will help to identify reasonable time frames for soil moisture increase, when a minimum threshold for precipitation is reached. Depending on locality, air temperature, humidity, and soil temperature are also useful data for detecting changes in soil moisture sensor performance. For example, because EM sensors are sensitive to soil freezing (especially at the 5 cm level), soil and air temperature measurements can confirm this event and correct errors in the data.

5.6.3 Temporal Consistency

More conventional trends in soil moisture over time may also provide evidence of quality loss if a sensor increases dramatically, beyond an average sensor response. The training of this metric improves as the sensor is installed for longer time periods and would require reanalysis upon sensor replacement as there is some mild variability between installations. Step changes with no corresponding change in indicators (e.g., precipitation), or alternately no change when there are changes in indicators, can indicate a fundamental shift in the temporal performance of the station that requires inspection. Step changes associated with adverse events such as lightning, wind storms, and flooding indicated problems to be investigated on site.

5.6.4 Spatial Coherency

As networks increase in density, it will be possible to provide an assessment of spatial coherence to a network. If all surrounding stations have a soil moisture increase with associated precipitation records, the one station that did not experience an increase merits inspection. This “buddy check system” is invaluable not only as sanity check, but also to provide a record of similar dynamic behavior in time (Rayner et al., 2006).

5.7 RECOMMENDATIONS FOR NCSMMN

A soil moisture network quality control plan should employ at a minimum five categories in an automated flagging structure to indicate varying levels of confidence in each observation, either with a scale of 1–5 (or categories such as Excellent, Very Good, Moderate, Poor, Very Poor). There should also be a set of rules against which data are tested (Hubbard et al., 2005). Quality control should strive to be in real time along with the data, necessitating automated systems, which forward flagged issues to a human quality control. Instead of changing the suspicious observations, quality assurance flags can be linked to each datum, identifying the quality of the observation, and the original observations can be examined further (Fiebrich et al., 2010). The ultimate flagging structure should be well documented, and data that are deemed not of sufficient quality should be redacted from the official record through human intervention, though maintained in the raw files. This is to prevent accidental data use. There is a common assumption that more data is better data, regardless of quality, but that has not proven to be true in this case.

It should be noted that there are other QA/QC tests that could be performed both automatically and through observation and monitoring, yet currently there is a lack of guidance for this type of testing. This is a priority area for the NCSMMN to address, in conjunction with the larger data provider community.