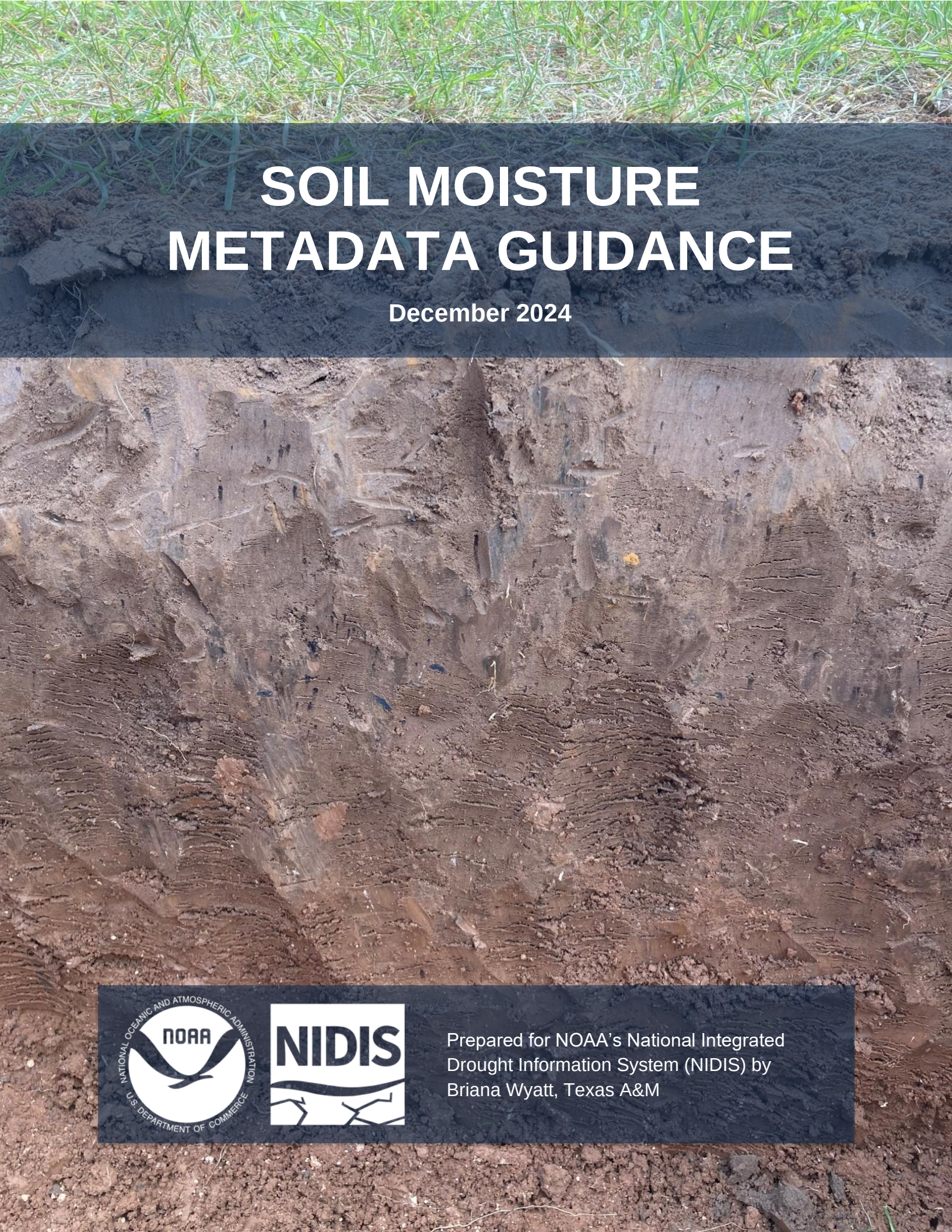

SOIL MOISTURE METADATA GUIDANCE

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Prepared for NOAA's National Integrated Drought Information System (NIDIS) by Briana Wyatt, Texas A&M

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Cover page photo: Soil profile prior to soil moisture sensor installation near College Station, Texas. Photo Credit: Briana Wyatt.

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ABOUT THE NATIONAL COORDINATED SOIL MOISTURE MONITORING NETWORK

NOAA's National Integrated Drought Information System (NIDIS), working in collaboration with the U.S. Department of Agriculture (USDA) and other partners, is leading the effort to implement the National Coordinated Soil Moisture Monitoring Network (NCSMMN): a multi-institutional initiative to integrate soil moisture data from across the country and to capitalize on its transformative potential across sectors of the economy. The mission of the NCSMMN is to "advance coordinated, high quality, nationwide soil moisture information for the public good" by:

- Establishing a "network of networks"
- Building a community of practice and expertise
- Supporting research and development on innovative techniques to merge in situ soil moisture data with remotely-sensed and modeled hydrologic data.

The 2021 *Strategy for the National Coordinated Soil Moisture Monitoring Network* describes a set of recommendations to solidify the NCSMMN's organizational structure and advance soil moisture monitoring and data application nationally. Included is a recommendation to "**Develop a Set of Criteria for High Quality Data Sources.**" This charge was created in recognition of the need for and value of a concerted, easily communicable approach to describing the quality of a data set for network operators, decision makers, resource managers, and others.

A working group was established to help fulfill this recommendation. The "Soil Moisture Metadata Guidance" document is one of two resources generated in direct response to this recommendation. The working group spearheaded the creation of both this document and its companion, "Soil Moisture Data Quality Guidance," through an intensive multi-year process of information gathering, peer review, and feedback from both the network operator and the data user communities.

CHAPTER 1
INTRODUCTION AND BACKGROUND

This document was developed in response to the identification of metadata and data quality guidelines for in situ soil moisture monitoring as a top priority for the National Coordinated Soil Moisture Monitoring Network (NCSMMN) at the National Soil Moisture Workshop in 2022. This document focuses on metadata guidelines, while an accompanying Soil Moisture Data Quality Guidance document outlines soil moisture data quality standards. Due to the rapid expansion of soil moisture monitoring networks in the past decades, a number of disparate practices and standards exist regarding the definition and reporting of appropriate and necessary metadata for soil moisture monitoring networks. This document is intended to address and harmonize these various practices into an overarching synthesis of best practice.

The purpose of this document is to describe the metadata that will allow robust in situ soil moisture data interpretation and to support an assessment of data quality. Metadata here refers to the data and information that provide context and details relevant to soil moisture measurements. The overall aim is to provide best management practices for researchers, state and regional monitoring network managers, and federal agencies regarding the type and quality of metadata that should be made available in conjunction with measured soil moisture data.

Below we summarize existing metadata guidelines, provide our recommendations for comprehensive metadata types and reporting, present a tiering system developed to guide data users and provide aspirational goals for soil moisture monitoring networks based on metadata availability, and relate the recommendations in this document to the accompanying Soil Moisture Data Quality Guidance document.

This document was developed alongside the Soil Moisture Data Quality Guidance working document, and both documents should be considered when developing new networks or reporting information for existing networks. The tiering system developed in this document is aligned with that of the Data Quality Guidance document. Considered together, these tiering systems outline community-defined standards for various levels of metadata and data quality reporting.

It is acknowledged that the metadata standards and tiers provided here are quite comprehensive. The listed metadata may not be necessary to meet the specific objectives of a particular monitoring network; however, such information is likely to be needed for a wide range of potential applications and thus should be considered to help maximize the use and utility of the soil moisture monitoring data to serve the public good.

CHAPTER 2
EXISTING METADATA GUIDELINES

Consistency within metadata collection and reporting is critical, especially in instances where monitoring data are utilized for purposes beyond their original intent, and correct interpretation of data depends upon the accuracy of metadata fields (Sprague et al., 2017). A handful of metadata collection and reporting standards have been developed in recent years, though few guidelines exist explicitly for soil moisture monitoring sites. Many existing networks provide various types of metadata for soil moisture monitoring sites, but since no widely-accepted guidelines are available, the reported information and methods used to determine that information vary from network to network.

American Association of State Climatologists (AASC)

In 2019, the AASC approved a document developed by its Mesonet Committee that outlined best practices for mesonets, including metadata guidelines for station and sensor siting, sensors and calibration procedures, station maintenance, and network quality assurance/quality control. To date, this is the most comprehensive document regarding suggested metadata reporting practices. However, this document addresses the full range of environmental monitoring, of which soil moisture monitoring is only one component. The AASC guidelines specify little soil-related information that should be reported: the only recommendations are that soil texture and underground infrastructure information be shared.

Upper Missouri River Basin (UMRB)

Recently, work has been done to install new and retrofit existing monitoring stations within the Upper Missouri River Basin (UMRB) with soil moisture and snowpack sensors. During this process, recommendations have been made for the collection of metadata relevant to soil moisture monitoring within this network. Recommended soil metadata include soil type, soil textural class, soil structure, erodibility and erosion characteristics, vegetation description, bulk density, water retention, particle size fractions, geomorphic characteristics, permeability and porosity, saturated water content, hydrologic soil group, and saturated hydraulic conductivity. However, these recommendations are currently still under development and are not yet generally available.

New York State Mesonet (NYSM)

Muller et al. (2013) documented metadata protocols for urban meteorological networks, drawing on current recommendations for urban climate stations and identified best practice in existing networks, to improve the quality and applicability of the increasing amount of data gathered by high-resolution urban networks. The New York State Mesonet adopted these practices across their network, which include monitoring soil moisture and temperature at three depths. Soil texture and classification, along with site photos and other information are publicly available on the New York Mesonet webpage on station information.

Kentucky Mesonet

The Kentucky Mesonet is a research-grade weather and climate observation network that monitors the near-surface atmosphere at over 70 locations. The network maintains a detailed database of station metadata that includes instrument and site maintenance history (Mahmood et al., 2019). Metadata also include a collection of directional site photographs. One half of Kentucky Mesonet sites currently monitor soil moisture and temperature at 5, 10, 20, 50, and 100 cm depths.

Other Guidelines

Several other networks have internally consistent metadata available through their websites. For example, the USDA Soil Climate Analysis Network (SCAN) provides detailed descriptions of soil conditions, including links to laboratory data, photos, sensor inventories, and maintenance history for every site visit (Schaefer et al., 2007). For the Oklahoma Mesonet, Fiebrich et al. (2006) note the importance of documenting each visit and recommend technicians perform three seasonal maintenance visits. Previous documents from the NCSMMN (Caldwell et al., 2022; Cosh et al., 2021; NIDIS, 2021) provide general guidance on metadata requirements for network details, site information, soil moisture sensors, and soil characterization.

This document builds on these resources to present a more detailed, systematic outline of soil moisture metadata.

CHAPTER 3
CONSIDERATIONS FOR METADATA GATHERING

One factor that network managers will need to consider when reporting metadata is the amount of information that is made publicly available. Some networks make nearly all metadata openly available (e.g., National Ecological Observatory Network [NEON] monitoring sites), whereas other networks make only basic metadata information available. The restriction of metadata sharing may be done for many reasons, including the cost of maintaining data availability, privacy for the landowners, the prevention of vandalism by limiting site location information, etc.

When deciding which information to make public, networks should consider the purpose of their network and the need for certain metadata to be easily accessible, either to the public or for research purposes. For example, a network whose purpose is to improve agricultural water management by employing soil moisture sensors may have photos or soil property data from the soil profile in which the sensors are installed. These photos and data likely contain information that would aid producers in the correct interpretation of data from that site and should be made publicly available. On the other hand, perhaps information regarding the exact location of a monitoring site is not pertinent to the interpretation of the data from that site or should not be shared publicly. For example, if the site is installed on private property, less-precise geographic coordinates (i.e., latitude and longitude to only 1 or 2 decimal places) are likely acceptable for providing general location information about a site while minimizing the risk of trespassing and vandalism.

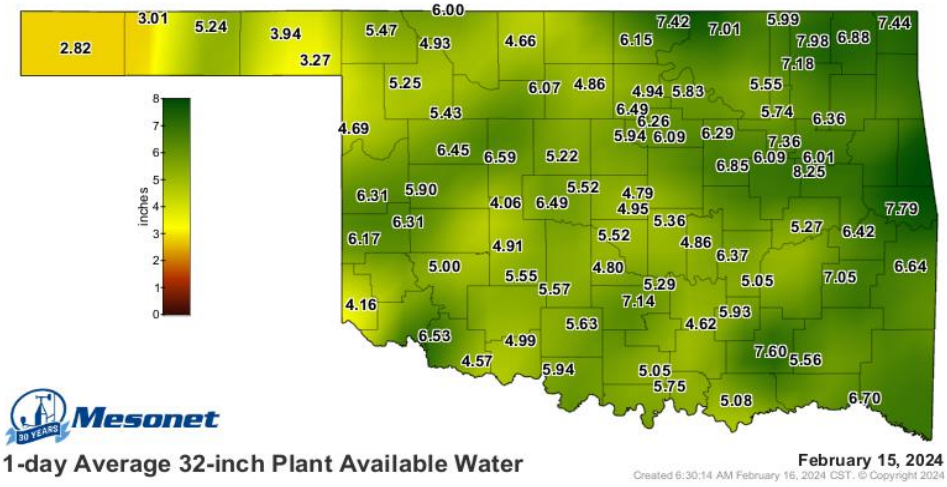

Figure 1. Map of plant available water (PAW) created using soil moisture data from the Oklahoma Mesonet. Image Credit: Oklahoma Mesonet.

The types of metadata described in this document have a wide variety of potential applications. For example:

- Site location information can be used to extract point data to support the evaluation of numerical models and remotely sensed products.
- Soil profile photos and measured soil properties can be used to interpret data and develop derived products such as the plant available water (PAW), which provides an estimate of the depth of water currently in the soil and available for plants to take up (Figure 1). The PAW variable has been used by many mesonets as a way of increasing the understanding and utility of soil moisture information by the public, but these derived values may only be estimated if site-specific soil property data are available.
- Photos of the monitoring site at the time of installation and in different seasons can provide context for interpreting both above-ground and below-ground variables.

Generally speaking, the more metadata a network is able to provide publicly, the more utility the data will have for both public and research uses, although it should be acknowledged that in some instances there are reasons to limit the amount of information shared publicly.

CHAPTER 4
METADATA TYPES

Proposed metadata requirements for soil moisture data collection by the NCSMMN can be grouped into the categories of network, site, sensor, and soils information, as originally proposed by Cosh et al. (2021). Descriptions of categories of metadata types are provided below. A complete list of all metadata variables, along with recommended units, data types, and file type is given in Appendix A.

Network

A description of the network, purpose, and data usage policies will help users understand how to interpret data for different applications.

- **Affiliation**: A statement or list of organizations managing the network.
    - University, department; federal, state, or local government agency; private or non-profit organization
- **Mission and intended data application**: A statement of the motivation, purpose, and intended use of data provided by the network. Examples of purposes are: for weather monitoring, emergency management, climate forecasting, or hydrologic prediction.
- **Quality Assurance/Quality Control (QA/QC) protocols**: A statement and explanation of any quality control procedures used to flag or remove data after collection but before distribution. (See the NCSMMN Soil Moisture Data Quality Guidance document for further information.)
    - Thresholds: Upper and lower limits of data values beyond which data are considered erroneous or inaccurate.
    - Removal of erroneous data: Description of how erroneous data are treated (i.e., removed, flagged but not removed, etc.)
    - Explanation of QC flags: If QC flags are used, each flag should have an accompanying explanation and justification.
- **Installation protocol**: A description of the installation procedure for soil moisture sensors, indicating the method used (i.e., pit, auger hole, other method), depths of installation, cable management strategy, and orientation of sensors at each depth (i.e., vertical or horizontal).
- **Operations and maintenance information**: A statement of the types and frequency of regular maintenance at monitoring sites.
    - Maintenance frequency: Statement of how often a person physically visits each site.
    - Types of checks done during visits: Description of instrumentation and site checks completed, ideally in the form of a checklist used by maintenance personnel.

- **Metadata update schedule**: Statement of frequency of updates to the metadata that may change over time (e.g., seasonal photos).
- **Contact information**: Who is the Principal Investigator or Primary Contact, and who is the Technical Point of Contact for questions about the data? If a user finds a problem with the data, how should it be reported?
- **Telemetry and latency**: Statement of how data are transferred from the station (i.e., cellular data, radio, wifi, satellite), how often they are transmitted, and the latency between data transmission and posting to an accessible archive.
- **Frequency of all measurement types**: Statement of how often data are measured and whether or not measurements are averaged or manipulated prior to reporting (i.e., 15-minute data aggregated to daily mean values).

Site

A description of site conditions including classifications, textual descriptions, and photographs or images will provide users helpful context about the conditions under which data are being gathered.

- **Photos**: Photographs provide users with context for understanding site characteristics including vegetation, soil profiles, and landscape position. All photos are helpful, but photos of soil profiles and the surrounding vegetation and landscape are especially useful. Photographs are listed in the order in which they should be taken during installation. All photographs should be properly named to include dates, site name, sensor depth, and other relevant information.
    - Before installation (for sites yet to be installed)
        - Sensor(s): Once soil moisture sensors are installed, they will no longer be visible.
        - Installation site: A photo of the soil moisture sensor installation location prior to disturbance, either from the air or from the ground, to provide context and for comparison to post-disturbance vegetation characteristics.
    - During installation (for sites yet to be installed)
        - The hole, pit, or trench in which the sensor will be installed: Prior to sensor installation, a photo should include a measuring tape or meter stick for scale and should clearly show the full depth of the soil profile into which sensors will be installed.

Figure 2. Photo of soil profile and soil moisture sensors installed to a depth of 1.0 m. Photo Credit: Briana Wyatt.

- Installed sensor(s) and placement of cables or leads: After sensor installation, a photo should be taken showing the positions of sensors relative to the top and bottom of the pit, trench, etc., as well as relative to the other sensors, if any (Figure 2).

- After installation
  - Vegetation cover and soil above the sensor's location: A photo showing the disturbance resulting from sensor installation.
  - Images in each cardinal direction showing site surroundings: Four photos taken from the sensor installation location showing vegetation, landscape, obstructions, etc., in each cardinal direction.
  - Aerial imagery: Image showing location of site, as well as surroundings within a given radius (Figure 3).

- Seasonally
  - Vegetation cover above the sensor's location: Photos of vegetation above the sensors may be useful to determine whether the installation disturbance caused changes in vegetative cover.
  - Changes in soil conditions: If applicable, photos of dynamic soil properties such as cracks from dry soils, erosion, deposition, or accumulating organic matter (Figure 4).
- Decommissioning (if applicable)
  - Vegetation cover: Photo of the sensor installation site prior to removing sensors as documentation of last known condition of the site.
  - Sensor/sensor damage: If any sensor prongs, heads, or cables are damaged, document with a photo.
- Daily/Live: Daily photos of a site using equipment such as a PhenoCam (Figure 5).
  - Image information: Cardinal direction and tilt angle of the camera.

Figure 3. Panoramic image of a soil moisture monitoring site showing the vegetation conditions surrounding the site. Photo Credit: Ali Azizi.

- **Station name/ID**: The unique identifier used by network to distinguish between sites
    - Full station name
    - Unique station ID: May include numbers, letters, or a combination of the two, but should be unique to a single site and contain no spaces.
- **State/County**
    - The state name
    - County name
    - Federal Information Processing Standards (FIPS) code
- **Latitude and Longitude**
    - Latitude and longitude in decimal degrees, to five decimal places (~1 m in accuracy) using the World Geodetic System 1984 (WGS84) datum. Any additional geolocation information should be consistent with this reference point and all information should be provided. For instance, any UTM coordinates should include zones and units.

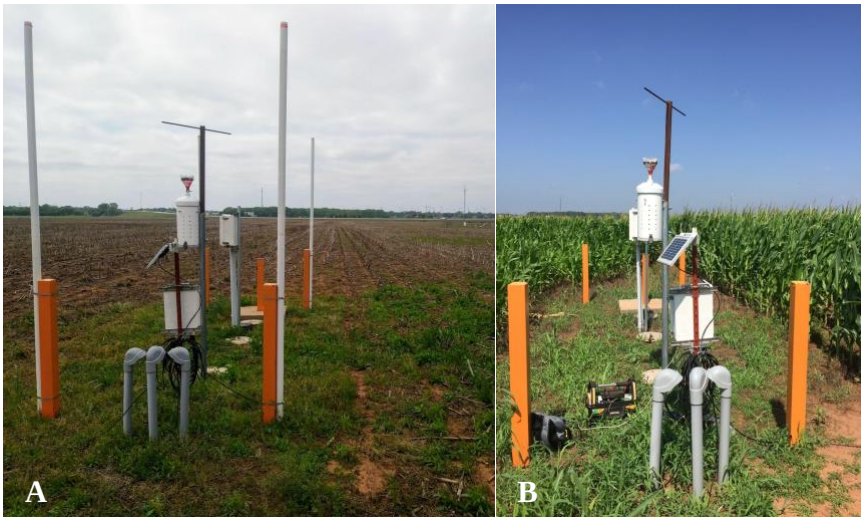

Figure 4. Photos showing differences in dormant (A) and growing season (B) vegetation in an agricultural field adjacent to a soil moisture monitoring site. Photo Credit: Briana Wyatt.

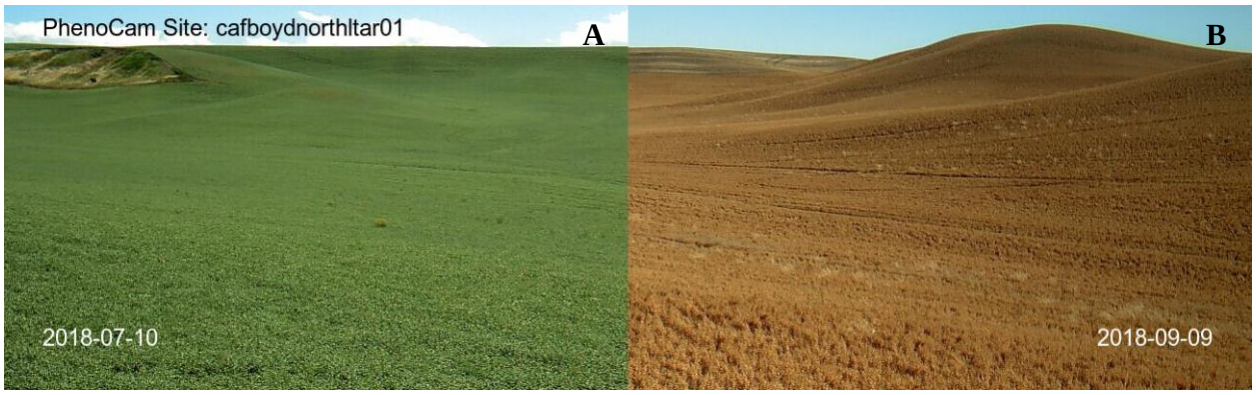

Figure 5. PhenoCam imagery from July (A) and September (B) 2018 at the CAF-LTAR Boyd North National Ecological Observatory Network (NEON) site. Image Credit: PhenoCam.

- **Elevation**
    - Distance in meters above Mean Tide Level (MTL), formerly Mean Sea Level (MSL), as an integer value.
- **Slope, aspect, and landform (for sites with relief)**
    - Aspect (degrees): Cardinal direction that a landscape primarily faces.
    - Slope Gradient (percent): The steepness of the landscape slope calculated as length of rise over length of run as a ratio.
    - Slope Shape: The description of the curvature of the landscape both vertically and horizontally (e.g., linear slope, convex slope, concave slope, Figure 6).
    - Landscape Position: Position of site within a hillslope, if applicable (Figure 7).
- **Land use or land cover**
    - Land use/land cover category from the USGS National Landcover Database
        - At site
        - Nearby (within 100 m), if different than site
    - Dominant vegetation cover (if available and different than USGS classification)
    - Changes in land use or land cover and approximate date of change: A description of the history of the site or recent land use is helpful to understand long-term data series. If possible, include information about prior soil disturbances, such as the presence of roadways, trails, and other soil movement.

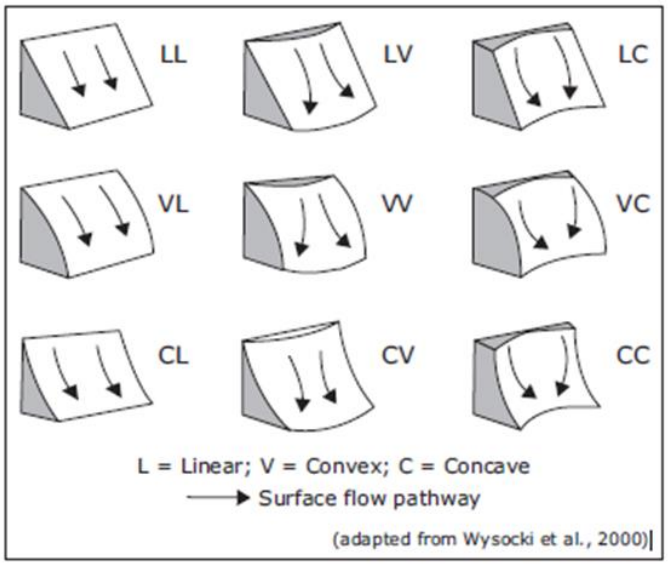

Figure 6. Diagram showing nine types of landscape shapes. Figure Credit: Wysocki et al (2000).

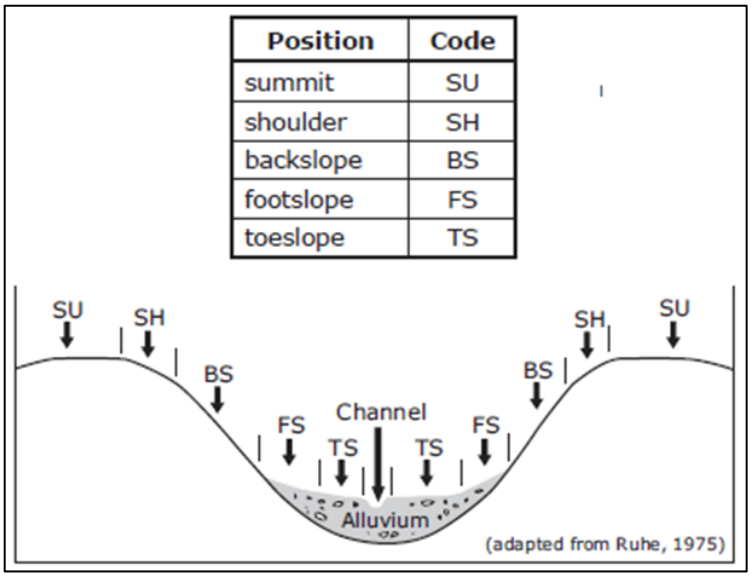

Figure 7. Diagram of landscape positions. Figure Credit: Ruhe (1975).

- **Dates**
  - Installation date
  - Data connectivity date: Date site was connected to cellular, satellite, or radio communications network.
  - Data availability date: Date that data from the site became available for use. If a soil "healing time" is used, include that information here.
  - Decommission Date

  - Relocation date (if applicable): If a site is moved to a location more than 10 m from the original site, the date of the relocation should be recorded, along with new metadata information regarding site location and description. If a site is moved to a location more than 10 m away from the original site, or to a location with significantly different soil types, this should be considered as a new site and given its own unique ID.

- **Nearby obstructions and water features**
  - Type of obstruction or water feature- Description of all obstructions or water features within 100 m radius of the site (i.e., tree, building, stream, dam, etc.).
  - Height of obstructions- For each obstruction, provide an estimated height.
  - Distance from site- For each obstruction, provide an estimated distance from the monitoring location.
  - Aerial photo of site.
- **Site maintenance record**: Documentation of all maintenance performed at a given site. Records may be digital or hand-written but should be stored in perpetuity and available for reference internally, even if not publicly available.
  - Date and time of visit.
  - Name of person doing maintenance.
  - Type of maintenance done or any observations while on-site.
- **Record of sediment deposition or erosion**: If deposition or erosion is known to occur at a site, measurements should be made using an erosion pin or other method near the sensor location, taking care not to disturb or injure soil moisture sensors.
- **Ancillary soil measurements**- Additional data reported by soil moisture sensors or necessary for proper data interpretation
  - Bare soil versus vegetated: Description of soil surface and vegetation characteristics, including whether vegetation is trimmed or cut and when.
  - Soil temperature: Expressed in °C, these data may be especially important in regions where soils freeze during the winter.
  - Matric potential: Expressed in kPa.
  - Electrical conductivity: Expressed in dS m^{-1}.
- **Ancillary weather measurements**
  - List of any above-ground variables measured (i.e., precipitation, wind speed/direction, incoming solar radiation, etc.), instrument type used to collect them, and heights of measurements for each variable.

Soil Moisture Sensors

- **Depths**: Depth of installation below soil surface [cm] and estimated measurement volume being captured.
- **Location** (direction and azimuth) relative to the instrument tower.
- **Sensor model and manufacturer**
- **Sensor calibration type**: Manufacturer vs. site-specific, etc.
    - If site-specific, describe method of calibration
- **Date of sensor installation** (if different than site deployment date)
- **Raw data types and associated units**

Soils and Soil Samples

Samples should be collected at each sensor depth at the time of installation, even if there is no budget or plan for future analyses.

- **NRCS Soil Survey Geographic Database (SSURGO) map unit key**
    - Note if consistent or not with observed soil type/texture.
- **Profile or pedon description**
    - Based on USDA-NRCS classification system/nomenclature.
    - Photo of profile or soil core with depth reference (meter stick or tape).
- **Texture**: Sand, silt, clay
    - Sand, silt, clay percentages at each sensor depth
    - Method used to determine percentages (hydrometer, pipette, other)
    - Fraction of course fragments (i.e., rocks) by volume
    - Textural class (USDA-NRCS system)
- **Bulk density**: Mass of dry soil per unit volume
    - Measured bulk density at each sensor depth.
    - Method used for estimating bulk density (core method, clod, other).
- **Mineralogy**
    - Major and minor components of the minerals in the soil and/or parent material derived at each sensor depth.
- **Soil water retention**
    - Water retention at -10 kPa (optional), -33 kPa, and -1500 kPa at each depth.

  - Intact or disturbed samples.
  - Additional water retention points, if available.
  - Method used to measure water retention (Tempe cells, pressure chambers, Hyprop, dewpoint potentiometer, other).
  - Water content at saturation (θ_s) - calculated using saturated and dried mass of soil sample, or estimated using the measured bulk density and assuming saturation water content is equal to porosity.

- **Saturated hydraulic conductivity (K_s)**
  - Method used to estimate K_s.
- **Aggregate stability**
  - Method of determining aggregate stability (wet, dry, other).
- **Organic matter layer**
  - Depth to mineral soil
  - Percent (%) area covered surrounding site
  - Type of vegetation litter: evergreen vs. deciduous.
  - Relative amount of decomposition: fresh, intact material verse unrecognizable litter (e.g., peat).
  - Hydrophobicity: description of whether soil is hydrophobic and method used to determine hydrophobicity.
  - Changes over time: Description of losses or accumulations of organic matter during monitoring period.

CHAPTER 5
TIERING SYSTEM

Network development and operations benefit from setting goals and criteria for the data and products they produce. It is necessary to provide a set of guidelines or goals for soil moisture metadata which can be self-assessed for a time series or station. Thus, a tiering system for metadata availability has been developed in conjunction with the Soil Moisture Data Quality Guidance document (*Soil Moisture Data Quality Guidance*, Chapter 8). The metadata tiering system here was designed to be used in conjunction with the data quality tiering system given in that document. Any tiering system must be comprehensive in the critical and common characteristics for networks, while also being flexible and applicable to the variety of conditions found among the many networks deployed in the past, present, and future. These criteria have been selected after discussions with data users and data providers that identified factors that they use to select data products for application and analysis. Broadly, the tiering system is built on network evaluation of having 'None', 'Some', or 'All of the Ideal Criteria'. These tier classifications are intended to provide quick guidance for researchers considering application of a dataset, but it is recognized that some datasets may be of research value regardless of the quality of their associated metadata. Tier classifications can also be used to provide network operators with goals for network upgrades and justification for associated funding.

These elements associated with different tiers can be self-evaluated by the networks themselves but may also be subject to peer review as usually occurs in scientific reviews and publications. Generally, a station would be classified only as high as their lowest tier class among the three tiers, however, there may be some situations where temporal caveats are reasonable.

The metadata standards for each of the three tiers are listed below, in order of least comprehensive (Tier 3) to most comprehensive (Tier 1). Tier 3 is based on what should be considered a bare minimum of metadata necessary to interpret soil moisture sensors measurements and should be relatively easy to achieve for all networks; Tier 2 represents a moderate level of metadata, reflecting an added value for data applications but also requiring more effort in collection; Tier 3 is the most comprehensive level of metadata, requiring more significant effort but representing the most value to the broader user community.

It is noted that networks may not want to make all the information in each tier publicly available for security purposes. For this reason, the only information that we recommend be made fully available to the public are those items listed within Tier 3 (see below), and in certain cases even that information may be generalized to provide additional security. For example, site coordinates may be rounded to fewer decimal places to obscure the exact location of a site.

Tier III: Basic Metadata

(Provides the bare minimum of metadata, all listed items are publicly available, tier may include citizen science-like networks.)

- **Network**
    - Network name and aliases
    - Host institution/affiliation
    - Mission and intended data application
    - Contact information
    - List of all measurement types
    - Frequency of all measurement types
- **Site**
    - Station name/ID
    - State/County
    - Latitude/Longitude
    - Elevation
- **Soil Moisture Sensors**
    - Depths of installation
- **Soils**
    - NRCS Soil Survey Geographic Database (SSURGO) map unit key

Tier II: Moderate Metadata

(All metadata components for Tier II are publicly available; additionally, the following information is on record, although metadata types listed below may not necessarily be publicly available based on the discretion of the network managers. Network should denote that these metadata exist and level of availability [e.g., public, on-request, not for dissemination].)

- **Network**
    - QA/QC protocols
    - Telemetry and statement of latency
- **Site**
    - Ancillary soil measurements (e.g., soil matric potential or temperature)
    - Ancillary weather measurements (e.g., air temperature, precipitation, etc.)

- **Soil Moisture Sensors**
    - Sensor model, manufacturer
    - Date installed, if different than site deployment date
    - Raw data types and associated units
- **Soils**
    - Profile/pedon description
        - Based on USDA-NRCS classification system/nomenclature
        - Photo of profile or soil core with depth reference (meter stick)
    - Texture (sand, silt, clay)
        - Sand, silt, clay percentages at each sensor depth (minimum)
        - Method used to determine percentages (hydrometer, pipette, other)
        - Fraction of course fragments by volume
        - Textural class (USDA-NRCS system)
    - Organic matter layer
        - Depth
        - % area covered surrounding site
        - Type of vegetation litter: evergreen vs. deciduous
        - Hydrophobicity
        - Changes over time

Tier I: Best Metadata

(Provides high level of detail and high-quality information; metadata supports multiple research applications. All metadata recommendations of Tier II and Tier III are met in addition to following requirements ,and these metadata are kept on record internally. Metadata may or may not be made publicly available, based on the discretion of the network manager.)

- **Network**
    - Operations and maintenance information
    - Installation protocol, including soil moisture sensor orientation(s)
    - Metadata update schedule (for items that change with time, such as seasonal photos)
- **Site**
    - Photos

  - Installation date (and date[s] of relocation, if applicable)
  - Slope/aspect/landform (for mountainous sites)
  - Land use/land cover (LU/LC)
  - Nearby obstructions
  - Site maintenance record
- **Soil Moisture Sensors**
  - Sensor calibration type: manufacturer, manufacture year/model, site-specific, etc.
  - Location relative to tower
- **Soils (at each sensor depth)**
  - Bulk density
  - Mineralogy
  - Soil water retention
  - Saturated hydraulic conductivity (K_{sat})
  - Aggregate stability

An itemized list of variables for each tier is given in Appendix A.

CHAPTER 6
CONCLUSION

This document outlines recommended soil moisture monitoring metadata guidelines, including information about the monitoring network, sites, soil moisture sensors, and soil types. The purpose of this document is to provide network managers a reference for reporting the metadata information necessary for maximizing the utility of soil moisture monitoring data and to provide data users a quick reference for metadata availability relative to data applications and use. The tiering system given here allows monitoring networks to self-identify the general quality of available metadata and provides a clear outline for network managers regarding the improvement of metadata availability.

This document has been designed to provide a path forward to harmonize the metadata available from existing and upcoming in situ soil moisture datasets. However, it is clear that this effort will continue to evolve as the community of soil moisture monitoring networks grows, changes, and gains news techniques and knowledge over time. As a result, it is expected this document will continue to be reviewed and updated by the NCSMMN community over time.

REFERENCES

American Association of State Climatologists. (2019). *Recommendations and Best Practices for Mesonets, Version 1*. American Association of State Climatologists. https://stateclimate.org/best-practices/

Brotzge, J. A., J. Wang, C. D. Thorncroft, et al. (2020). A Technical Overview of the New York State Mesonet Standard Network. *Journal of Atmospheric and Oceanic Technology, 37*: 1827-1845. https://doi.org/10.1175/JTECH-D-19-0220.1

Caldwell, T. G., M. H. Cosh, S. R. Evett, et al. (2022). In situ Soil Moisture Sensors in Undisturbed Soils. *Journal of Visualized Experiments*. https://doi.org/10.3791/64498

Cosh, M. H., T. G. Caldwell, C. B. Baker, et al. (2021). Developing a Strategy for the National Coordinated Soil Moisture Monitoring Network. *Vadose Zone Journal, e20139*:1-13. https://doi.org/10.1002/vzj2.20139

Fiebrich, C. A., D. L. Grinisley, R. A. Mcpherson, and K. A. Kesler. (2006). The Value of Routine Site Visits in Managing and Maintaining Quality Data from the Oklahoma Mesonet. *Journal of Atmospheric and Oceanic Technology*, *23*: 406-416. https://doi.org/10.1175/JTECH1852.1

Mahmood, R., M. Schargorodski, S. Foster, and A. Quilligan. (2019). A Technical Overview of the Kentucky Mesonet. *Journal of Atmospheric and Oceanic Technology*, *36*: 1753-1771. https://doi.org/10.1175/JTECH-D-18-0198.1

Muller, C. L., L. Chapman, C. S. B. Grimmond, D. T. Young, and X.M. Cai. (2013). Toward a Standardized Metadata Protocol for Urban Meteorological Networks. *Bulletin of the American Meteorological Society*, *94*: 1161-1185. https://doi.org/10.1175/BAMS-D-12-00096.1

NIDIS. (2021). *A Strategy for the National Coordinated Soil Moisture Monitoring Network Coordinated, High-Quality, Nationwide Soil Moisture Information for the Public Good*. National Integrated Drought Information System. https://www.drought.gov/documents/strategy-national-coordinated-soil-moisture-monitoring-network

Schaefer, G. L., M. H. Cosh, and T. J. Jackson. (2007). The USDA Natural Resources Conservation Service Soil Climate Analysis Network (SCAN). *Journal of Atmospheric and Oceanic Technology*, *24*: 2073-2077. https://doi.org/10.1175/2007JTECHA930.1

Sprague, L. A., Oelsner, G. P., & Argue, D. M. (2017). Challenges with Secondary Use of Multi-Source Water-Quality Data in the United States. *Water Research, 110*: 252-261. https://doi.org/10.1016/j.watres.2016.12.024

APPENDIX A
METADATA TIERS AND VARIABLES INCLUDED IN EACH TIER

Tier III is considered the minimum needed, Tier II is moderate level of effort, and Tier I is best and most complete.

Tier	Network	Site	Sensors	Soil
Tier III (bold)	• **Affiliation** • **Mission and intended data application** • **Contact info** • **Frequency of all measurement types**	• **Station name/ID** • **State/County** • **Latitude/Longitude** • **Elevation**	• **Depths**	• **SSURGO map unit key**

Tier II (bold)	• **QA/QC protocols**
	• **Telemetry and statement of latency**
	• Affiliation
	• Mission and intended data application
	• Contact info
	• Frequency of all measurement types
		• **Ancillary soil measurements**
		• **Ancillary weather measurements**
		• Station name/ID
		• State/County
		• Latitude/Longitude
		• Elevation
			• **Sensor model, manufacturer**
			• **Date installed, if different than site deployment date**
			• **Raw data types and associated units**
			• Depths
				• **Profile/pedon description**
				  ○ **Based on USDA-NRCS classification**
				  ○ **Photo of profile or soil core with depth reference (meter stick)**
				• **Texture (sand, silt, clay)**
				  ○ **Sand, silt, clay percentages at each sensor depth (minimum)**
				  ○ **Method used to determine percentages**
				  ○ **Fraction of coarse fragments by volume**
				  ○ **Textural class (USDA-NRCS system)**
				• **Organic matter layer**
				  ○ **Depth**

Tier	Network	Site	Sensors	Soil
				○ **% area covered surrounding site** ○ **Type of vegetation litter- evergreen vs deciduous** ○ **Hydrophobicity** ○ **Changes over time?** • SSURGO map unit key
Tier I (bold)	• **Operations and maintenance information** • **Installation protocol, including soil moisture sensor orientation(s)** • **Metadata update schedule (For those items changing over time, like vegetation)** • QA/QC protocols • Telemetry and statement of latency • Affiliation • Mission and intended data application • Contact info • Frequency of all measurement types	• **Photos** • **Installation date (and date[s] of relocation, if applicable)** • **Slope/aspect/landform (for mountainous sites)** • **Land use/land cover (LU/LC)** • Ancillary soil measurements • Ancillary weather measurements • Station name/ID • State/County • Latitude/Longitude • Elevation	• **Sensor calibration type- manufacturer, site-specific, etc.** • **Location relative to tower** • Sensor model, manufacturer • Date installed, if different than site deployment date • Raw data types and associated units • Depths	• **Bulk density** • **Mineralogy** • **Soil water retention** • **Saturated hydraulic conductivity (K_{sat})** • **Aggregate stability** • Profile/pedon description • Texture (sand, silt, clay) • Organic matter layer • SSURGO map unit key

APPENDIX B
COMPREHENSIVE LIST OF METADATA

List of metadata fields, recommended units for each field, data type, and recommended file type for storing metadata.

Metadata field	Recommended Units	Data Type	Recommended File Type
Network	-	Text	Word, PDF, or website
Affiliation	-	Text	Word, PDF, or website
Mission and intended data application	-	Text	Word, PDF, or website
QA/QC protocols	-	Text	Word, PDF, or website
Thresholds	Units associated with each measurement type	Text	Word, PDF, or website
Removal of erroneous data	-	Text	Word, PDF, or website
Explanation of QC flags	-	Text	Word, PDF, or website
Installation protocol	-	Text, Photos	Word, PDF, or website
Operations and maintenance information	-	Text	Word, PDF, or website
Maintenance frequency	months	Numerical	Word, PDF, or website
Types of checks done during visits	-	Text	Word, PDF, or website
Metadata update schedule	months	Numerical	Word, PDF, or website
Contact information	-	Text, Numerical	Word, PDF, or website

Metadata field	Recommended Units	Data Type	Recommended File Type
Telemetry and latency	Telemetry: none, Latency: minutes	Text, Numerical	Word, PDF, or website
Frequency of all measurement types	minutes	Numerical	Word, PDF, or website
Photos	-	Image	Word, PDF, or website
Station name/ID	-	Text, Numerical	Spreadsheet
Full station name	-	Text, Numerical	Spreadsheet
Unique station ID	-	Text, Numerical	Spreadsheet
State/County	-	Text	Spreadsheet
Latitude/Longitude	Decimal degrees	Numerical	Spreadsheet
Elevation	m	Numerical	Spreadsheet
Aspect	degrees	Numerical	Spreadsheet
Gradient	Percent slope	Numerical	Spreadsheet
Shape	-	Text	Spreadsheet
Position	-	Text	Spreadsheet
Land use/land cover	-	Text	Spreadsheet
Date: Initial installation	YYYY/MM/DD	Numerical	Spreadsheet
Date: Data connectivity	YYYY/MM/DD	Numerical	Spreadsheet
Date: Data availability	YYYY/MM/DD	Numerical	Spreadsheet

Metadata field	Recommended Units	Data Type	Recommended File Type
Date: Decommission	YYYY/MM/DD	Numerical	Spreadsheet
Date: Relocation	YYYY/MM/DD	Numerical	Spreadsheet
Nearby obstructions and water features	-	Text	Spreadsheet
Type of obstruction	-	Text	Spreadsheet
Height of obstruction	m	Numerical	Spreadsheet
Obstruction distance from site	m	Numerical	Spreadsheet
Date and time of maintenance visit	YYYY/MM/DD HH:MM	Numerical	Spreadsheet or hand-written
Name of person doing maintenance	-	Text	Spreadsheet or hand-written
Type of maintenance done	-	Text	Spreadsheet or hand-written
Record of sediment deposition/erosion	mm	Numerical	Spreadsheet
Bare soil versus vegetated	-	Text	PDF or website/Spreadsheet
Soil temperature	°C	Numerical	Spreadsheet
Matric potential	kPa	Numerical	Spreadsheet
Ancillary weather measurements: list	various	Text	Word, PDF, or website
Ancillary soil measurements: list	various	Text	Word, PDF, or website
Soil moisture sensor depths	cm	Numerical	Spreadsheet

Metadata field	Recommended Units	Data Type	Recommended File Type
Sensor model, manufacturer	-	Text	Word, PDF, or website
Sensor calibration	-	Text	Word, PDF, or website
Date installed	YYYY/MM/DD	Numerical	Spreadsheet
Location relative to tower	Cardinal direction, m	Text, numerical	Word, PDF, or website
Raw soil moisture data types and associated units	various	Numerical	Word, PDF, or website
SSURGO map unit key	-	Text	Word, PDF, or website
Profile/pedon description	-	Text	Word, PDF, or website
Soil texture	Percentage by volume	Numerical	Spreadsheet
Soil bulk density	g cm^{-3} or kg m^{-3}	Numerical	Spreadsheet
Soil mineralogy	-	Text	Word, PDF, or website
Soil volumetric water content at -33 and -1500 kPa	cm^3 cm^{-3} or m^3 m^{-3}	Numerical	Spreadsheet
Saturated hydraulic conductivity	cm d^{-1}	Numerical	Spreadsheet
Soil aggregate stability	-	Numerical	Spreadsheet
Organic matter layer thickness	mm	Numerical	Spreadsheet