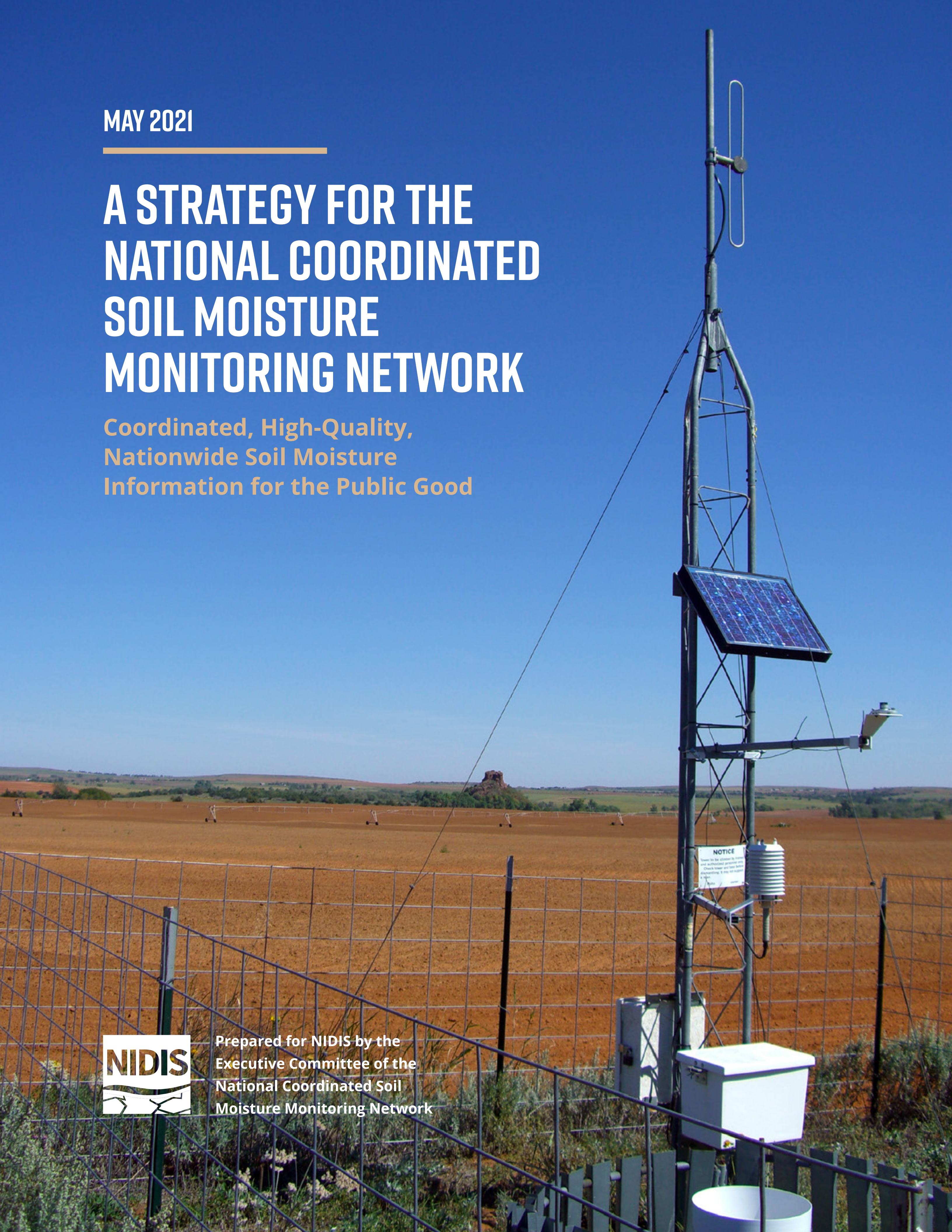

MAY 2021

A STRATEGY FOR THE NATIONAL COORDINATED SOIL MOISTURE MONITORING NETWORK

Coordinated, High-Quality, Nationwide Soil Moisture Information for the Public Good

Prepared for NIDIS by the
Executive Committee of the
National Coordinated Soil
Moisture Monitoring Network

On the cover: USDA soil moisture and weather station, Ft Cobb, Oklahoma. Credit: Mike Cosh

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ACRONYMS

3D/4D	3-Dimensional / 4-Dimensional
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
ANN	Artificial Neural Network
API	Application Program Interface
ARM	DOE Atmospheric Radiation Measurement Program
ARS	USDA Agricultural Research Service
ASCAT	Advanced Scatterometer
ASM	Average Soil Moisture
ATBD	Algorithm Theoretical Basis Documents
CART	Cloud and Radiation Testbed
CLM	Community Land Model
CLSM	Catchment Land Surface Model
CMI	Crop Moisture Index
CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
COOP	NOAA Cooperative Observer Program
CORS	Continuously Operating Reference Stations
COSMOS	Cosmic-ray Soil Moisture Observing System
CRNP	Cosmic-Ray Neutron Probe
CSV	Comma Separated Variables
CyGNSS	Cyclone Global Navigation Satellite System
DA	Data Assimilation
DEOS	Delaware Environmental Observing System
DEWS	Drought Early Warning System
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EC	Executive Committee
EM	Electromagnetic
EnkF	Ensemble Kalman Filter
EPA	U.S. Environmental Protection Agency
ESA	European Space Agency
ExpF	Exponential Filter
ftp/LDM	File Transfer Protocol / Local Data Manager
GCOM-W	Global Change Observation Mission for Water
GeoTiff	Geo-reference Tagged Image File Format
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPSR	GPS Reflectometry
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	GRACE-Follow On

HUC	Hydrologic Unit Codes
ISMN	International Soil Moisture Network
ISRO	Indian Space Research Organization
JPL AIRSAR	Jet Propulsion Laboratory's Airborne Synthetic Aperture Radar
LIS	Land Information System
LR	Linear Regression
LSM	Land Surface Model
LULC	Land Use and Land Cover
MAWN	Michigan Automated Weather Network
MODIS	Moderate Resolution Imaging Spectroradiometer
MOISST	Marena, Oklahoma In Situ Sensor Testbed
MOU	Memorandum of Understanding
NASA	National Aeronautics and Space Administration
NASMD	North American Soil Moisture Database
NASS	USDA National Agricultural Statistics Service
NCSMMN	National Coordinated Soil Moisture Monitoring Network
NDMC	National Drought Mitigation Center
NDVI	Normalized Difference Vegetation Index
NEON	National Ecological Observatory Network
NEPA	National Environmental Policy Act
netCDF	Network Common Data Form
NGS	National Geodetic Survey
NGWMN	National Ground Water Monitoring Network
NIDIS	National Integrated Drought Information System
NISAR	NASA ISRO Synthetic Aperture Radar
NLCD	National Land Cover Dataset
NLDAS	North American Land Data Assimilation System
NLDAS-2	North American Land Data Assimilation System, Phase 2
NMP	National Mesonet Program
NOAA	National Oceanic and Atmospheric Administration
NOAA HMT	NOAA Hydrometeorology Testbed Observing Network
Noah-MP	Noah-Multi Physics Model
NOHRSC	NWS-National Operational Hydrologic Remote Sensing Center
NRCS	USDA Natural Resources Conservation Service
NWS	National Weather Service
PAW	Plant Available Water
PHS	Pulse Height Spectrum
QA/QC	Quality Assurance / Quality Control
RDM	Robust Decision Making Under Uncertainty
RFC	NOAA River Forecast Center
RFI	Radio Frequency Interference
RMA	USDA Risk Management Agency
RMSD	Root Mean Squared Difference
RMSE	Root Mean Squared Error
SAR	Synthetic Aperture Radar
SCAN	Soil Climate Analysis Network
SFIR	South Fork Iowa River
SFIR WASM	SFIR Weighted-Average Soil Moisture

SHRU	Soil Hydrological Response Unit
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture Ocean Salinity
SMOS L2SM	SMOS Level 2 Soil Moisture
SNOTEL	Snow Telemetry Network
SOGW	Subcommittee on Ground Water
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardized Precipitation Index
SSURGO	Soil Survey Geographic Database
SWAT	Soil and Water Assessment Tool
TDR	Time Domain Reflectometry
TEUI	Terrestrial Ecological Unit Inventory
Txt	Text Format
UMB	Upper Missouri River Basin
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USCRN	U.S. Climate Reference Network
USDA	U.S. Department of Agriculture
USDM	U.S. Drought Monitor
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VIC	Variable Infiltration Capacity
WTM	West Texas Mesonet
Z-index	Palmer’s Z-index

EXECUTIVE SUMMARY

Soil moisture is a critical land surface variable, impacting a wide variety of climatological, agricultural, and hydrological processes. As a result, soil moisture measurements are needed for applications ranging from agricultural monitoring, to weather prediction, to drought and flood forecasting. At the same time, the means and methods of monitoring soil moisture are undergoing rapid growth and innovation with the advent of new in situ and proximal sensors, new remote sensing technologies, and enhanced modeling capabilities. Despite these opportunities, there is currently no coordinated national strategy for the deployment and maintenance of soil moisture networks, or for the development of nationally-integrated soil moisture data products.

Sponsored by the National Oceanic and Atmospheric Administration's (NOAA) National Integrated Drought Information System (NIDIS), the National Coordinated Soil Moisture Monitoring Network (NCSMMN) is a collaborative effort among soil moisture scientists, mesonet[1] operators, and other interested individuals to plan for and support nationally coordinated soil moisture monitoring and data assimilation. As a key milestone of this effort, and in direct response to the NIDIS Reauthorization Act of 2018 (Public Law (P.L.) 115-423)[2] call for a national soil moisture strategy, the NCSMMN community has prepared this document,[3] with the goal of identifying a roadmap forward and the resources needed for implementing a coordinated national network; specifically, a network that will provide coordinated, high-quality, nationwide soil moisture information for the public good.

This strategy document includes: a summary of current in situ networks as well as remote sensing and model resources, a discussion of network design considerations, guidance for in situ network installation and quality assurance/control, and the implementation strategy for the proposed NCSMMN. The following recommendations are detailed as a part of the implementation strategy:

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[1] A mesonet is a regional network of observing stations (usually surface stations) designed to diagnose mesoscale weather features and their associated processes (*https://forecast.weather.gov/glossary.php?letter=m*).

[2] *https://www.congress.gov/115/plaws/publ423/PLAW-115publ423.pdf*

[3] See list of Report Contributors on *page 5*.

1. **Determine Home Agency and Management Structure for the NCSMMN.** It is recommended that NIDIS continue as the near-term "home" for the NCSMMN, and that a review be undertaken of models and best practices across the Federal Government to inform the choice of a formalized management structure for the NCSMMN going forward.
2. **Establish a Web Presence and Formalize Communication & Outreach Planning for the NCSMMN.** A visible, user-friendly website for the NCSMMN is important for both communication and product delivery. In addition, the NCSMMN will need to do broader communications and outreach planning. As a cornerstone engagement activity, the NCSMMN will continue to host an annual meeting of soil moisture monitoring experts from across the United States.
3. **Formalize Partnerships with the National Mesonet Program and Existing Monitoring Networks.** To obtain in situ soil moisture data from existing monitoring networks across the country, the NCSMMN should formalize a partnership with NOAA's National Mesonet Program (NMP) and establish Memoranda of Understanding (MOUs) with networks outside of the scope of NMP.
4. **Develop a Set of Criteria for High-Quality Data Sources.** It is proposed that a set of criteria be established to qualify an in situ soil moisture network as producing high-quality versus moderate- or provisional-quality data. These criteria will be developed in coordination with the research, data provider, and user communities.
5. **Support Research Necessary to Develop or Improve NCSMMN Methodologies.** Although preliminary research and demonstration projects have shown the feasibility of the envisioned NCSMMN products, further research is required to enable the creation of these products at the national scale and to rigorously quantify the uncertainty in those products.
6. **Increase In Situ Soil Moisture Monitoring Nationwide.** There is a clear need to increase the number of long-term, high-quality, in situ soil moisture monitoring stations across the United States, especially for underrepresented regions, such as in forests, grazing lands, and croplands. The NCSMMN will work with partners from across the country to optimize locations of new monitoring stations to meet Federal and state goals.
7. **Explore Increasing Partnerships with the Private Sector.** A concerted effort must be made to engage with private sector weather and soil monitoring network operators not only to expand the impact of monitoring efforts from all sources, but also to share methodologies and validation protocols developed by the NCSMMN community.
8. **Engage with the Citizen Science Community.** One potential way to increase in situ soil moisture monitoring – as well as public support for such monitoring – is to invite the participation of citizen scientists, particularly through collaboration with groups such as NOAA's Cooperative Observer Program (COOP) and the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS).
9. **Develop, Release, and Promote NCSMMN Products.** The aim of the NCSMMN effort is to provide coordinated, high-quality, nationwide soil moisture information for the public good. This will require developing, releasing, and promoting new, nationwide point-based and gridded soil moisture data products that meet the needs of diverse end-user groups, and that support crucial applications such as drought and flood monitoring, fire danger ratings, and streamflow forecasting.

Implementing these recommendations will provide a unifying structure for the national soil moisture community, not only enhancing in situ monitoring activities, but complementing remote sensing and modeling activities as well. Through efforts to: 1) develop a strong organizational home; 2) engage in communication and outreach; 3) establish partnerships and build out the network; 4) conduct needed research; and 5) develop and refine data collection, integration, and quality standards, the NCSMMN will be positioned to deliver transformative soil moisture products to the Nation.

CHAPTER I

INTRODUCTION

1.1 BACKGROUND

Soil moisture[4] is a critical land surface parameter affecting a wide variety of economically and environmentally important processes. From agricultural monitoring, to weather prediction, to drought and flood forecasting, the value of soil moisture metrics is undeniable. At the same time, the means and methods of monitoring soil moisture are undergoing rapid growth and innovation with the advent of new in situ and proximal sensors, new data telemetry methods, and new remote sensing technologies to provide broad and accurate soil moisture estimates. Many nations have established soil moisture sensing networks, including the United States, which has a prolific but uncoordinated collection of monitoring networks at the national, state, and local levels. There is currently no national strategy for the development, deployment, and maintenance of soil moisture monitoring networks. The absence of a coherent strategy leads to a host of problems including many states lacking adequate monitoring, multiple data sets which are not standardized or directly comparable, and no clear plan for how best to target investments to improve the overall monitoring infrastructure. Because of these deficiencies, the United States has not yet capitalized on the transformative potential of nationwide, coordinated in situ soil moisture observations for applications such as improved drought monitoring, water resource management, and fire danger ratings.

In 2013, NOAA's National Integrated Drought Information System (NIDIS) and its partners began an initiative to work towards a coordinated national soil moisture network. The first meeting to discuss this effort with a group of Federal, state, and academic experts was held in November 2013 in Kansas

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[4] Soil moisture is shorthand for soil water content, which has units of m^3 m^{-3} and is represented by the symbol θ.

City, Missouri. The key findings from that meeting[5] included the need for improved metadata, calibration, and validation of soil moisture data, as well as the importance of data integration. The conclusion and recommendations from the meeting included: 1) convening a working group to discuss issues of scale and spatial distribution for monitoring via in situ networks, remote sensing platforms, and modeling efforts; 2) developing a nationwide product from existing soil moisture data to demonstrate the potential usefulness of a coordinated effort; and 3) piloting a soil moisture monitoring system for a small number of regions that would integrate all available soil moisture data types and assess how the data would be used.

As a result of the 2013 workshop, NIDIS funded a series of workshops and a pilot project to advance this goal. The pilot project served as the first proof of concept for a coordinated national soil moisture network by demonstrating that in situ soil moisture data could be integrated in real time from a variety of sources and made accessible both by a web service and a webpage at a common location. This project was led by the U.S. Geological Survey (USGS) and Texas A&M University (Quiring et al., 2016).

In order to continue the progress and discussion on how to better coordinate soil moisture monitoring and perform data assimilation and communication across the federal landscape, and with states and other interests, a second workshop on a National Coordinated Soil Moisture Monitoring Network (NCSMMN) was held in May 2016 in Boulder, CO.[6] The discussion at this 2016 workshop focused on three core elements of a coordinated and integrated national soil moisture network. These included: 1) improving collaboration through incentives and partnerships; 2) developing a consistent methodology for data collection and installation of in situ sensors including metadata standards; and 3) developing a national multi-platform soil moisture gridded product that could serve as a first-order data and information source as well as a platform for the development of derivative or secondary soil moisture products. A third NCSMMN workshop was held in Stillwater, OK, in May 2017 in conjunction with the Marena, OK, In Situ Sensor Testbed (MOISST) workshop. Participants discussed the outcomes of the NIDIS data integration pilot project and refined the vision for the NCSMMN. Desired features for a national gridded soil moisture product were identified, including the need for both surface and root zone soil moisture products and the need for soil moisture data both as absolute values as well as percentiles.

The efforts of creating and formalizing a national coordinated soil moisture network increased significantly in 2018 as a result of some important efforts. Following the 4th NCSMMN meeting in Lincoln, Nebraska in June 2018 (held again in conjunction with the MOISST workshop), an Executive Committee was formed for the network. The NCSMMN Executive Committee (EC) included leaders from Federal agencies and academic institutions, and was charged with clearly defining the goals and framework to bring the NCSMMN concept to fruition (Clayton et al., 2019). Early efforts included a successful project that demonstrated the feasibility of merging soil moisture datasets within the Southern Great Plains, and a NIDIS-funded project by Dr. Trent Ford and Dr. Steven Quiring which showed promise for the generation of a single soil moisture platform of widely available data, including in situ, remotely sensed and modeled data (Zhao et al., 2020). However, there are still challenges that need to be addressed to fully realize the value of the diversity of soil moisture resources available in the United States.

The importance of soil moisture data and a coordinated network garnered further attention of Congress in 2018, in response to the lack of early warning for the 2017 Northern Plains drought and the significant impact it had on the region. The NIDIS Reauthorization Act of 2018 (P.L. 115-423)[7] calls for NIDIS to develop a strategy for a national coordinated soil moisture monitoring network no later than 1 year after the date of enactment of the Reauthorization Act. In addition, the Agriculture Improvement Act of 2018 (P.L. 115-334)[8] (i.e., the "Farm Bill") calls for the U.S. Department of Agriculture (USDA) and NOAA to coordinate with

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[5] *https://www.drought.gov/documents/developing-coordinated-national-soil-moisture-network.*

[6] *https://www.drought.gov/documents/national-soil-moisture-network-workshop-2016-progress-made-future-directions*

[7] *https://www.congress.gov/115/plaws/publ423/PLAW-115publ423.pdf*

[8] *https://www.congress.gov/115/plaws/publ334/PLAW-115publ334.pdf*

the National Drought Mitigation Center (NDMC) to enhance the collection of data (including soil moisture) to improve the accuracy of the U.S. Drought Monitor.

Challenges are common in soil moisture monitoring, and it is important to understand the goal or purpose of a soil moisture network. Very often soil moisture sensors are added to existing networks to enhance their monitoring capability. Or, in the development of a sensor network, a variety of parameters are identified for observation, but siting logistics require a compromise on the different criteria necessary to accurately assess each parameter. A few networks have been developed to specifically monitor soil moisture, including the USDA Soil Climate Analysis Network (SCAN) (Schaefer et al., 2007). However, even if the parameter of interest is ideal, the purpose or use of the network can still impact its applicability for various uses. For instance, the need to monitor soil moisture within an agricultural domain (in-field) requires redeployment during planting and harvesting periods, which results in a discontinuous data record that is not as valuable for long-term research analysis. Also, a soil moisture station for irrigation scheduling is not as valuable for regional monitoring, due to the anthropogenic influence. Remote sensing calibration and validation studies need a different type of network deployment at different depths. Table 1.1 (*below*) lists some of the considerations for network deployment based on the network's primary purpose.

Attempting to satisfy all of these requirements can be difficult, but it is the belief of the community that we are still capable of developing a coordinated soil moisture strategy to address the majority of these considerations, offering a path forward for improved soil moisture monitoring.

The infusion of support from Congress and rising awareness of soil moisture's critical importance in drought prediction and other applications has led the NCSMMN to develop the coordinated strategy that is laid out in this document. The goal of this document is to identify a roadmap forward and the resources needed for implementing the coordinated network; specifically, a network that will provide coordinated, high-quality, nationwide soil moisture information for the public good.

This strategy document was developed as a collaborative effort organized by the NCSMMN EC under the sponsorship of NIDIS and with broad community engagement (see Report Contributors, *page 5*). The document includes: a summary of current networks and remote sensing resources, a discussion on network design considerations, guidance for installation and quality assurance/control, and the implementation strategy for the proposed National Coordinated Soil Moisture Monitoring Network.

Table 1.1: Considerations for network deployment

Purpose of Network	Latency	Duration	Distribution	Depths
Weather Monitoring	X		X	X
Climate Monitoring		X	X	
Agricultural Monitoring	X			X
Forest/Ecological Monitoring	X	X	X	X
Remote Sensing and Model Validation			X	X
Flood Forecasting	X	X	X	X

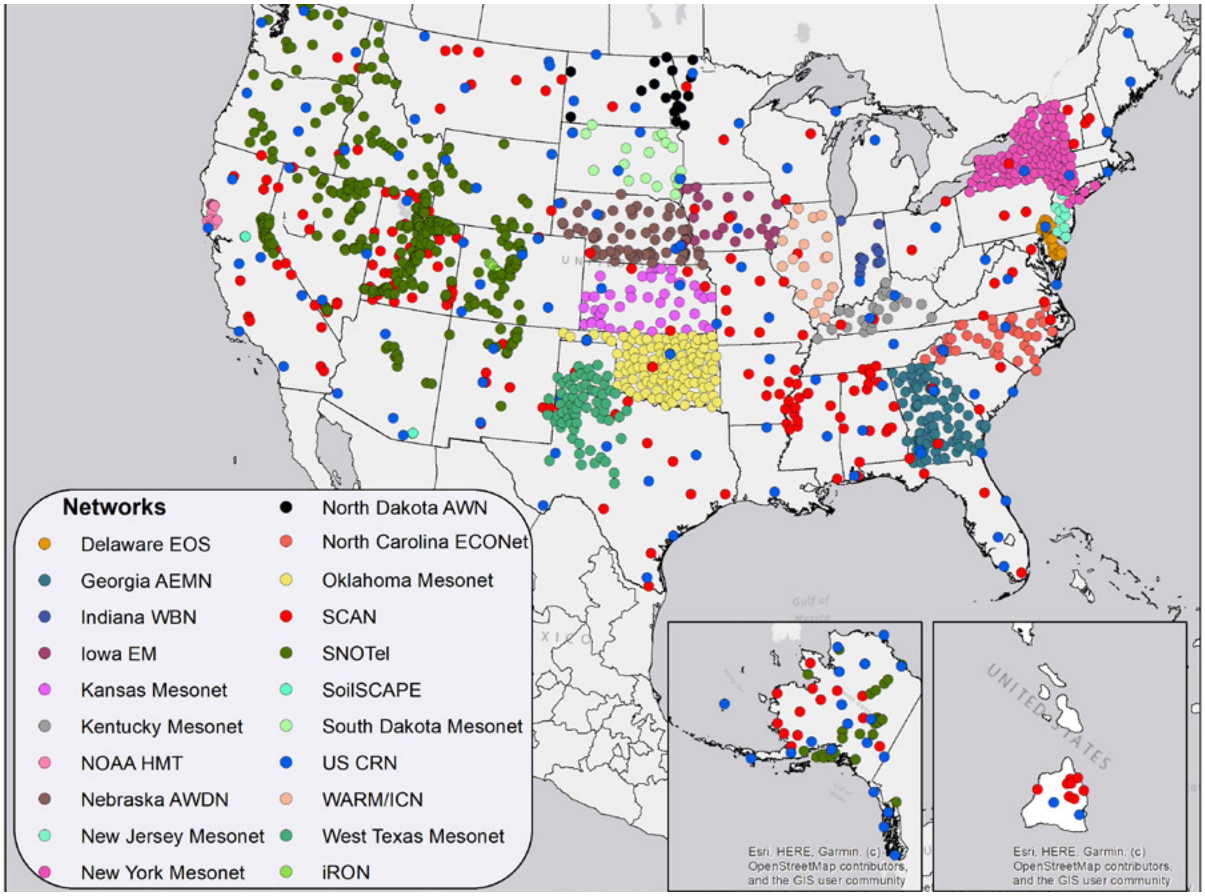

Figure 2.1: Locations of select in situ soil moisture sensor networks across the United States from federal- and state-level networks. (Source: *nationalsoilmoisture.com*)

CHAPTER 2

SUMMARY OF STATEWIDE, REGIONAL, & NATIONAL SOIL MOISTURE MONITORING

2.1 SOIL MOISTURE MONITORING PROGRAMS

The quantity and quality of in situ soil moisture monitoring stations has increased substantially in recent decades. In the United States, most long-term soil moisture monitoring networks are operated by Federal and state agencies. The number of networks that measure soil moisture has continued to expand at both regional and national scales. Figure 2.1 (*above*) provides the location of select Federal and state networks that are currently in operation. The number of networks and stations continues to change, but as of 2019, there are approximately 1,900 stations that estimate soil moisture in public networks in the United States.

Table 2.1 (*next page*) provides an overview of the operational networks that are currently reporting soil moisture in the United States.[9]

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[9] There exist a number of research networks within the United States as well; these are outside the scope of the current effort.

Table 2.1: Description of selected soil moisture monitoring networks in the United States including type of sensor, number of active (automated) stations, period of record and measurement depths.

Network Name	# Active Stations^	Start Year	Sensor Type*	Sensor Depth (cm)
AmeriFlux (AmeriFlux)	60	1996	Various	Varies (5-200)
Atmospheric Radiation Measurement (ARM)	17	1996	CS229-L, Hydra	5, 15, 25, 35, 60, 85, 125, 175
Cosmic-ray Soil Moisture Observing System (COSMOS)	54	2008	COSMOS	Varies (10-30)
Delaware Environmental Observing System (DEOS)	26	2005	CS616	5
Georgia Automated Environmental Monitoring Network (Georgia AEMN)	87	1992	CS616	5, 10, 20
Illinois Climate Network (ICN)	19	2004	Hydra	5, 10, 20, 50, 100, 150
Indiana Water Balance Network	13	2011	CS655/650, EnviroSCAN	Varies (10-180)
Iowa Environmental Mesonet (IEM)	25	1986	CS655	30, 60, 125
Kansas Mesonet	41	2010	Hydra	Varies (5, 10, 20, 50)
Kentucky Mesonet	32	2008	Hydra	5, 10, 20, 50, 100
Michigan Automated Weather Network (MAWN)	80	2000	CS616	5, 10
Montana Mesonet	75	2016	GS3, Teros12	10, 21, 51, 91
National Ecological Observatory Network (NEON)	47	2016	EnviroSCAN	Varies (6-200)
Nebraska Automated Weather Data Network (NAWDN)	51	2006	Hydra, TP	10, 25, 50, 100
New York State (NYS) Mesonet	126	2015	Hydra	5, 25, 50
NOAA Hydrometeorology Testbed Observing Network (NOAA HMT)	25	2004	CS616, Hydra	5, 15
North Carolina Environment and Climate Observing Network (NC ECONet)	36	1999	TP	20
North Dakota Agricultural Weather Network (NDAWN)	23	2016	CS655	10, 20, 30, 50, 75, 100
Oklahoma Mesonet (OKM)	120	1996	CS229-L	5, 10, 25, 60
Plate Boundary Observatory to Study the Water Cycle (PBO H2O)	97	2011	GPS	2.5
Snow Telemetry Network (SNOTEL)	352	2005	Hydra	5, 10, 20, 50, 100
Soil Climate Analysis Network (SCAN)	190	1999	Hydra	5, 10, 20, 50, 100
South Dakota Mesonet	26	2002	Hydra	5, 10, 20, 50, 100
Texas Soil Observation Network (TxSON)	56	2015	CS655	5, 10, 20, 50
Texas Water Observatory	21	2017	CS655, MPS6	5, 15, 30, 75, 100
U.S. Climate Reference Network (USCRN)	114	2009	Hydra, TDR-315	5, 10, 20, 50, 100
West Texas Mesonet (WTM)	59	2002	CS615	5, 20, 60, 75

^ This number only includes active stations with soil moisture sensors within the network; may not reflect total station count.

* Regarding sensor type: CS229-L (Campbell scientific, US) is a heat dissipation matric potential sensor, Hydra (Hydraprobe, Stevens Water, US) and TP (Theta Probe, Delta-T, Inc., UK) are electrical impedance sensors, CS616/655 (Campbell Scientific, US) are transmission line oscillator sensors, EnviroSCAN (Sentek, Australia) is a borehole capacitance sensor, COSMOS is a cosmic ray-based sensor (HydroInnova, US), TDR-315 (Acclima, US) is a time domain reflectometer, MPS6 (Water Potential Sensor, Meter Group, US) and GPS is a generic reflectometer using L-band GPS signals for soil moisture estimation.

Table 2.1 (*previous page*) highlights that there are many existing stations reporting soil moisture and some of them have a period of record >20 years. It also shows that there is a tremendous variability in the depths and type of sensors that are used to estimate soil moisture. These variations will be described in more detail in the following sections of this chapter.

Of these networks, the major national networks are the Soil Climate Analysis Network (SCAN), the Snow Telemetry (SNOTEL) network, and the U.S. Climate Reference Network (USCRN). The SCAN network, operated by the USDA Natural Resources Conservation Service (NRCS), consists of almost 200 stations spanning all 50 states continuously monitoring soil moisture, some for more than 20 years. Soil moisture observations are taken at most SCAN stations at 5-cm, 10-cm, 20-cm, 50-cm, and 100-cm depths using the HydraProbe sensor (Stevens Water Monitoring Systems, Inc.) to estimate soil moisture (volumetric water content, θ in $m^3\ m^{-3}$) at hourly intervals. Soil moisture measurements began between 1997 and 2000 at many SCAN sites. The maintenance cycle is usually as needed, which is typically 2–3 years per site.

The SNOTEL network, also operated by NRCS, is comprised of over 700 stations that monitor meteorological and hydrological conditions across the western United States (Schaefer et al., 2007). HydraProbes are used to estimate soil moisture hourly at 5, 20, and 50 cm at >300 SNOTEL stations. Many SNOTEL stations have continuously reported data since 2005.

The USCRN is a network of climate-monitoring stations maintained and operated by NOAA to provide climate-science-quality measurements. In 2011, sensors were installed at five standards depths (5, 10, 20, 50, and 100 cm). USCRN has a triplicate installation scheme, so there are three separate sets of soil moisture data at each of 114 sites. Data are recorded at the station as dielectric permittivity values in 15-min intervals and then averaged into 1-h values for transmission and storage (Bell et al., 2013). These dielectric permittivity values can be converted to an estimate of soil moisture using empirical calibration equations. The USCRN provides ongoing sensor validation and annual maintenance visits to each site.

2.2 SENSING FREQUENCY, REPORTING INTERVAL, AND PERIOD OF RECORD

Each network has its own sensing frequency. For example, DEOS senses soil moisture every 5 minutes, OKM senses every 30 minutes, SCAN and SNOTEL take instantaneous samples at hourly time step, while other networks like MAWN update their data at a daily time step. If it is desirable to standardize the reporting interval, most stations would be able to report soil moisture measurements every hour. Networks differ in whether reported data are the mean of several data taken at a higher sensing frequency or a singular datum from a sensor.

There is also substantial variability in the period of record for soil moisture data. As shown in Table 2.1 (*previous page*), SCAN and SNOTEL are the two federally operated networks that have been monitoring soil moisture for the longest period of time (1995 and 2005, respectively). In addition, some states also have a long period of record. For example, soil moisture was reported in Iowa from 1954–1983 by gravimetric sampling (Khong et al., 2015) and in Illinois from 1981–2008 by neutron probe (Coopersmith et al., 2016a); however, automated sensors have only been used for long-term soil moisture monitoring networks since the 1990s. Figure 2.2 (*next page*) shows a selection of the stations in the continental United States that have been continuously monitoring soil moisture for either >15 years (*red*) or for <15 years (*yellow*).

Networks that have a longer period of record are better suited for monitoring drought conditions and hydroclimatic change. For example, Figure 2.3 (*next page*) shows soil moisture variations (and drought indices) in the Southern Great Plains of the United States from 2003–2017. The soil moisture data have been converted to percentiles as have the model-derived soil moisture and drought indices that are shown for comparison. One challenge in using in situ soil moisture for monitoring drought conditions is determining whether the period of record is sufficient to produce a stable distribution from which to generate annual percentiles. Ford et al. (2016) found that 6 years of continuous data is sufficient in most conditions to create stable and robust percentiles.

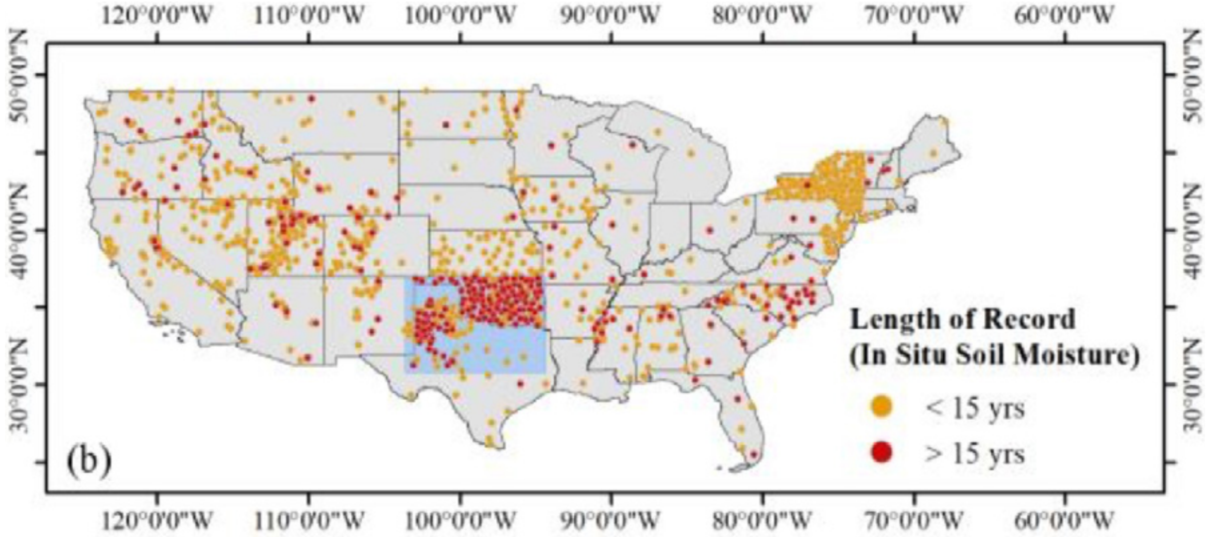
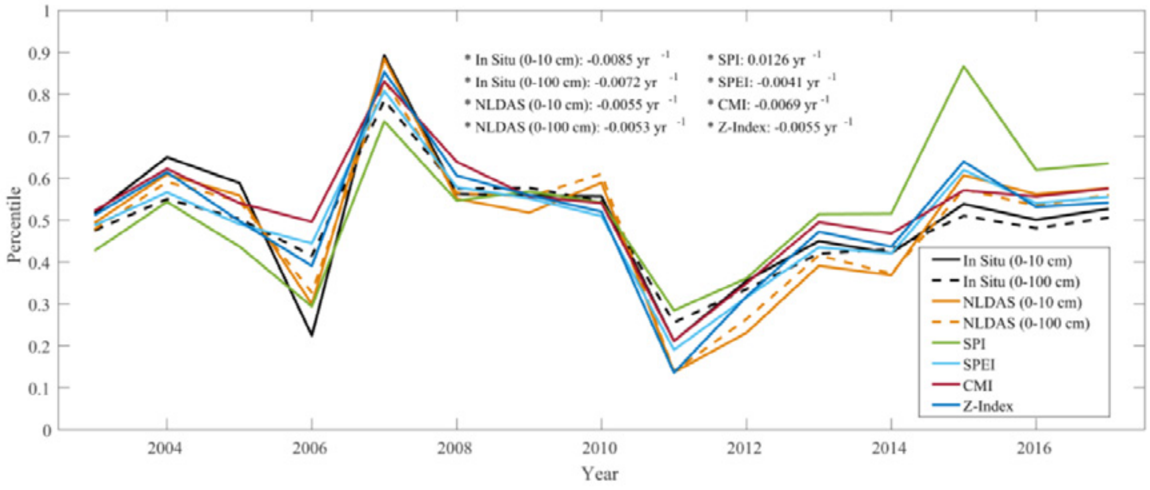


Figure 2.2: Length of record for select stations that monitor soil moisture. Those that have a continuous period of record >15 years are shown in red. Those with a period of record <15 years are shown in yellow. (Source: Yuan et al., 2020; Note: blue box indicates Yuan et al. study area)



"*" denotes statistically significant trend based on the Mann-Kendall test at the 95% confidence level

Figure 2.3: Time series of spatially-averaged percentiles of soil moisture and drought indices in the U.S. Southern Great Plains [region is shown in Figure 2.2 (*above*), *blue box*] from 2003 to 2017. The figure includes soil moisture data at 0–10 cm and 0–100 cm (in situ soil moisture shown in black) and modeled-derived soil moisture at 0–10 cm and 0–100 cm (North American Land Data Assimilation System (NLDAS) soil moisture shown in yellow). Four drought indices are also shown: Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Crop Moisture Index (CMI) and Palmer's Z-index (Z-index). The linear trend in these indices (based on 2003 to 2017) are reported in the figure. (Source: Yuan et al., 2020)

2.3 SENSOR TYPE

One challenge to integrating soil moisture data from a variety of different networks is that there is no universally accepted standard sensor for monitoring soil moisture. Differences between sensors can be substantial (Leib et al., 2003; Yoder et al., 1998), even when they are installed at the same site and depth. Networks have adopted different sensor types for estimating soil moisture, including electrical impedance (e.g., HydraProbe, ThetaProbe), Time Domain Reflectometry (TDR) (e.g., Acclima TDR-315H), transmission line oscillator methods (e.g., Campbell CS-615, CS-616 and CS-655), capacitance (e.g., Sentek TriSCAN sensor, EC-5), heat dissipation (e.g., CS-229), neutron probes, GPS reflectometry, and cosmic ray neutron sensing. Table 2.1 (*page 16*) lists the sensors that have been adopted by some of the networks in the United States. It should be noted that this strategy document is focused on soil moisture (soil water content) as the intended variable to be measured. Soil matric potential sensors, which indicate the attraction of the soil matrix to water, also offer valuable information regarding drought and moisture status, particularly for impacts to plants. Although they are not the focus of the current strategy, they should be regarded as providing useful ancillary data.

There is a clear need to identify best practices for standardizing soil moisture data from different sensors and sensor types to a common standard. This is particularly important for regional and national applications, such as drought and flood monitoring, which necessitate combining soil moisture data from multiple networks (Krueger, 2019). There are initial studies being conducted currently related to the Marena, OK, In Situ Sensor Testbed (Cosh et al., 2016), but this work is ongoing. Ultimately, because new technologies are always being developed, the best practice is to determine for each sensor and installation in a network what the errors are in relation to a true volumetric soil moisture at the location in question. This is the standard used by both the National Aeronautics and Space Administration's (NASA) Soil Moisture Active Passive (SMAP) mission and the European Space Agency's (ESA) Soil Moisture Ocean Salinity (SMOS) mission (Entekhabi et al., 2010; Kerr et al., 2010).

2.4 MEASUREMENT DEPTHS

Existing soil moisture monitoring networks measure soil moisture at different depths. Figure 2.4 (*below*) shows the soil moisture measurement depths at 18 selected networks. Many networks, including the federally funded national networks like SCAN, SNOTEL and USCRN, measure soil moisture at 5-cm, 10-cm, 20-cm, 50-cm, and 100-cm depths; however, others measure at site-specific depths based on the soil profile, or only at one depth. This lack of unified measurement depths across different networks impedes soil moisture applications at regional and national scales.

One approach to addressing the lack of uniform measurement depths is to employ methods for vertical interpolation and extrapolation of soil moisture, i.e.,

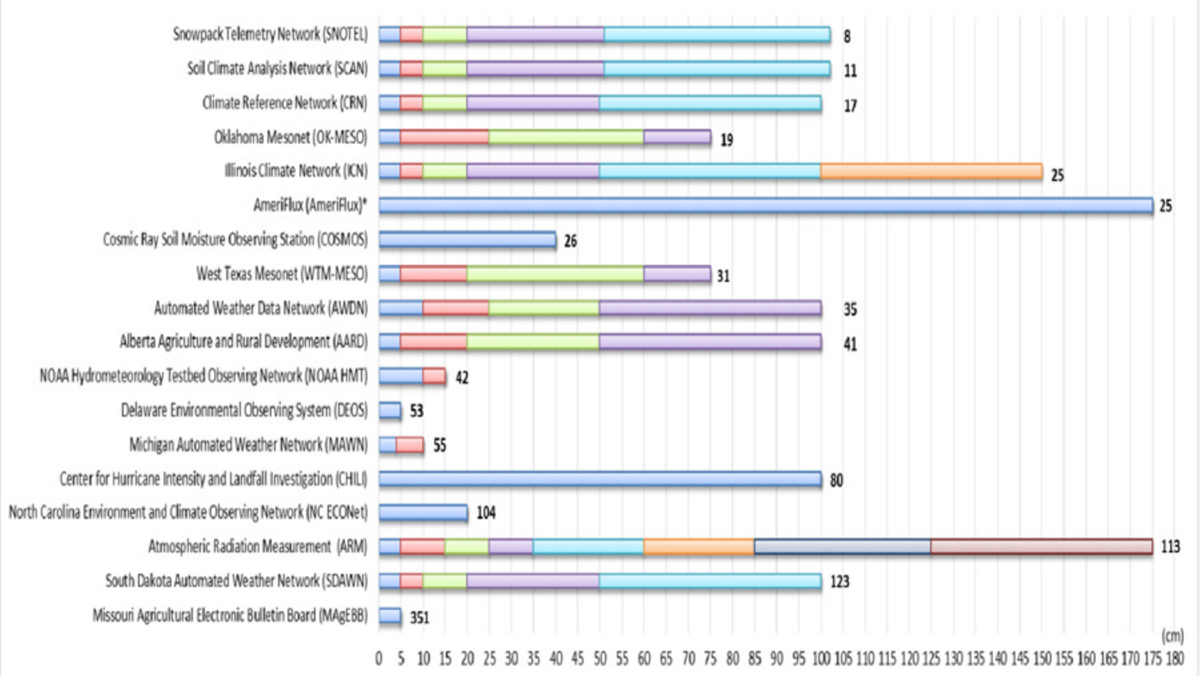


Figure 2.4: Soil moisture measurement depths at 18 of the monitoring networks that are archived in the North American Soil Moisture Database (NASMD) from Jan. 1, 2000 to Dec. 31, 2013. Depths monitored are indicated by depths at which colors change. The greatest depth monitored is indicated by the right end of the color bar. The depths of soil moisture monitoring in AmeriFlux vary from station to station, here we only provide the general range (0–175 cm) of the records. The number indicates the number of stations in each network. (Source: Zhang et al., 2017)

using shallow soil moisture measurements to estimate deeper soil moisture. Such methods could be used to standardize data to a set of common depths. Zhang et al. (2017) compared three methods, artificial neural network (ANN), linear regression (LR), and exponential filter (ExpF), for vertical extrapolation of soil moisture using data from the OKM. They found that all methods had similar performance for near-surface extrapolation of soil moisture (>25 cm), but the ExpF outperformed the other methods at deeper depths.

2.5 DATA QUALITY AND COMPLETENESS

Missing data are a common issue for in situ soil moisture measurements. It is difficult to repair and replace soil moisture sensors because they are often buried in trenches or pits that should not be disturbed after installation. A few sensors do accommodate easier replacement, such as the Sentek EnviroSCAN or the COSMOS systems, but there are other tradeoffs to these technologies. Figure 2.5 (*below*) shows the missing data ratio at each measurement depth (in order) for 18 networks that monitored soil moisture between Jan. 1, 2000 and Dec. 31, 2013 (Zhang et al., 2017). The ratio is defined as the total number of missing observations for that network and depth divided by the total number of observations that would have been collected if every station in the network had no missing data for that depth over the specified time period. It should be noted that "missing" in this study includes cases where stations were not installed until later in the period; the study objective was to examine data availability more so than network performance. The missing ratio tends to range from 10% to 30% for most of the networks that are included in this analysis. There are very few networks that have <10% missing data (only 2 out of 18).

Previous studies have examined the quality of soil moisture measurements at existing networks in the United States using relative error variance and random anomaly error (Ford and Quiring, 2019). Relative error variance indicates the relative proportion of variability from sensing error to real soil moisture variability. Ford and Quiring (2019) calculated relative error variance at eight networks. It was calculated for each station and then averaged by network and depth (Figure 2.6, *next page*). The error bars in Figure 2.6 represent the range of individual station relative error variance values for each network. The results showed that SNOTEL, OKM, and WTM had the lowest relative error variance, with network-averaged values ≤10%, which is a good indicator of network quality. This means that 10% or less of the overall variability in daily soil moisture was attributed to sensing error. The results also indicated that there were statistically significant differences, based on a one-way analysis of variance, in data quality that vary as a function of sensing depth and network. Data from deeper in the soil had smaller random errors.

Ford and Quiring (2019) suggested that the relative error variance and random anomaly error provided

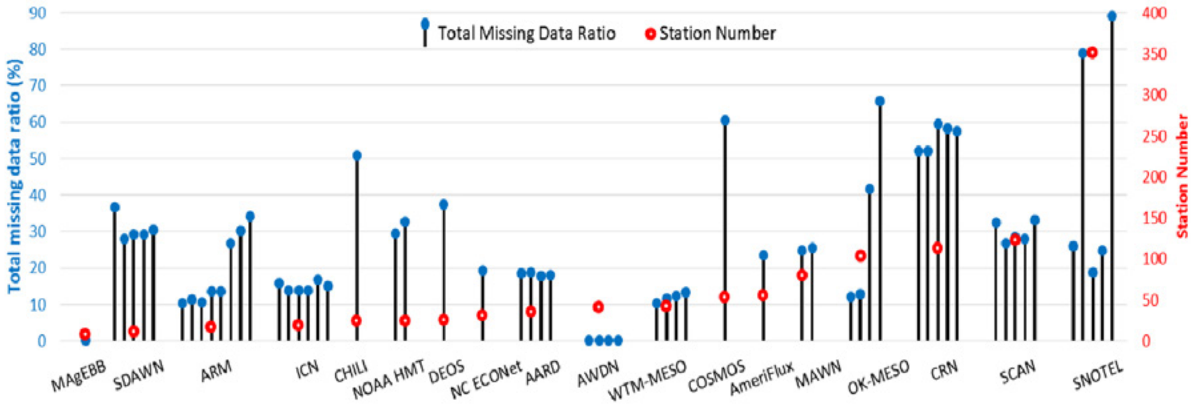


Figure 2.5: Missing data ratio for 18 networks archived in the North American Soil Moisture Database (NASMD) from Jan. 1, 2000 to Dec. 31, 2013. The missing data ratio is defined as the amount of missing data for each network and depth divided by the total number of data that would have been collected if every station in that network had no missing data over the period of record. "Missing" includes cases where stations were not installed until later in the period. (Source: Zhang et al., 2017)

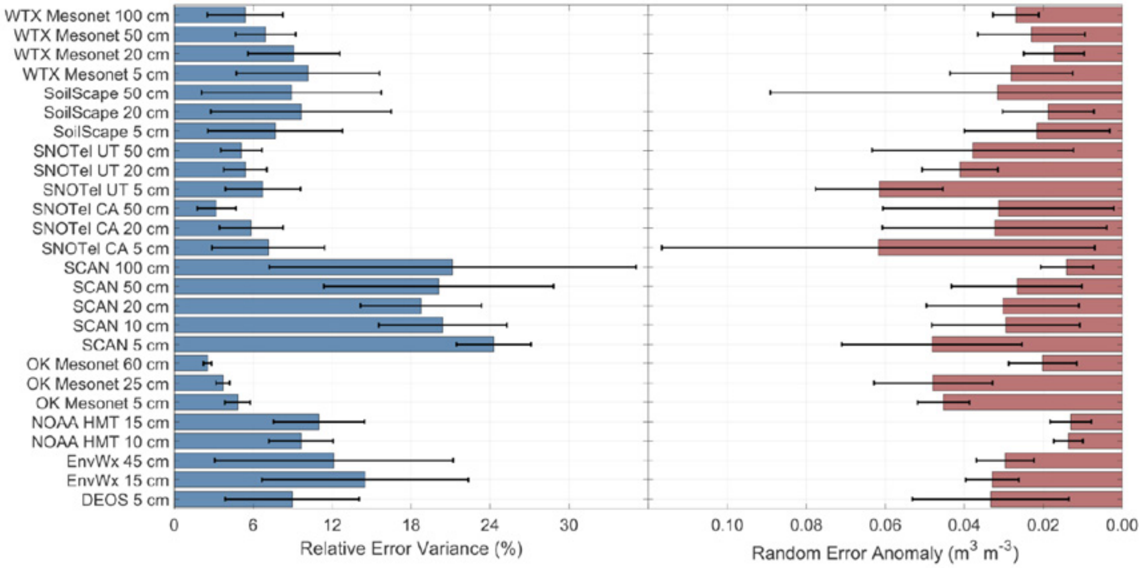


Figure 2.6: Relative error variance (*left*) and random anomaly error (*right*) for soil moisture data from the following networks: West Texas Mesonet, SoilScape, SNOTEL, SCAN, OKM, NOAA HMT, EnviroWeather and DEOS. (Source: Ford and Quiring 2019)

a comprehensive framework for evaluating both the overall quality and spatial representativeness of soil moisture data. These approaches can be used to flag stations and sensors where there are potentially issues with data quality. Overall, Ford and Quiring (2019) found that the majority of in situ stations have high fidelity and they provide high-quality information that is spatially representative.

2.6 INTEGRATION AND SYNTHESIS

Efforts to assemble and homogenize soil moisture data are important for making these data more useful for the scientific community. Robock et al. (2000) developed the Global Soil Moisture Data Bank, which included soil moisture observations from 25 stations in the United States. The Global Soil Moisture Data Bank has been incorporated into the International Soil Moisture Network (ISMN, *www.ipf.tuwien.ac.at/insitu*). ISMN is a global database of in situ soil moisture observations, containing data from 47 networks and more than 1,900 stations located in North America, Europe, Asia, and Australia (Dorigo et al., 2011). Quiring et al. (2016) developed the North America Soil Moisture Database (NASMD), which integrated and quality-controlled in situ measurements from more than 1,600 stations from 33 networks in North America. These past efforts have focused on the collection, quality control, and standardization/homogenization of data, and on developing a consistent set of metadata from all networks. Here we focus on summarizing metadata standards for soil moisture since quality control is covered in Chapter 5 of this report.

Quiring et al. (2016) developed a standard set of metadata that was collected for all stations that were included in the North American Soil Moisture Database (Table 2.3, *next page*). The metadata collected for each station include the: location, county, state, parent observation network, depths at which soil moisture is observed, type of soil moisture sensor, and the sampling frequency. In addition, soil characteristics such as bulk density, texture, percent sand/silt/clay, and hydraulic conductivity are reported at each depth that soil moisture is monitored. Soil texture information from site-specific soil surveys were available for just over 1,000 of the stations included in the NASMD (~69% of the stations). Soil characteristics for the remaining sites were obtained from the NRCS Soil Survey Geographic Database (SSURGO; Reybold and TeSelle 1989). SSURGO provides soil texture and hydraulic parameter information at multiple column depths for the entire contiguous United States. The NASMD also identified land use and land cover (LULC) at each site, based on the land cover classification scheme provided by the Environmental Protection Agency's National Land Cover Dataset (NLCD)

Table 2.3: Description of metadata that was included in the North American Soil Moisture Database for each station. Source: Quiring et al., 2016

Parameter	Unit	Source(s)
Network name		Observation network
Station name		Observation network
City		Observation network
County		Observation network
State		Observation network
Latitude	Decimal degrees	Observation network
Longitude	Decimal degrees	Observation network
First observation year		Observation network
Last observation year		Observation network
Temporal sampling frequency		Observation network
Land use/land cover		Observation network
Number of sampling depths		Observation network
Depth of each sample	cm	Observation network
Percent sand/silt/clay*	%	Observation network/SSURGO
Soil texture class*		Observation network/SSURGO
Saturated hydraulic conductivity*	$\mu m\ s^{-1}$	Observation network/SSURGO
Bult density*	$g\ cm^{-3}$	Observation network/SSURGO
Sampling probe type*		Observation network
Elevation	ft	Observation network
Representative SSURGO polygon		SSURGO

*These parameters are available for all depths at which soil moisture is measured.

2001.[10] Approximately 500 sites (approximately 36% of NASMD sites) provided LULC information. For the remaining sites, LULC was determined by NASDM staff using either site photos or using high-resolution satellite imagery such as Google Earth. Finally, because several authors have concluded that sensor-soil–specific calibration is necessary to obtain a high degree of soil moisture estimation accuracy (e.g., Evett and Parkin, 2005; Leib et al., 2003), sensor calibration functions are sometimes changed in a network. Thus, sensor change or recalibration dates were included in the NASMD metadata if these were available from the observation network.

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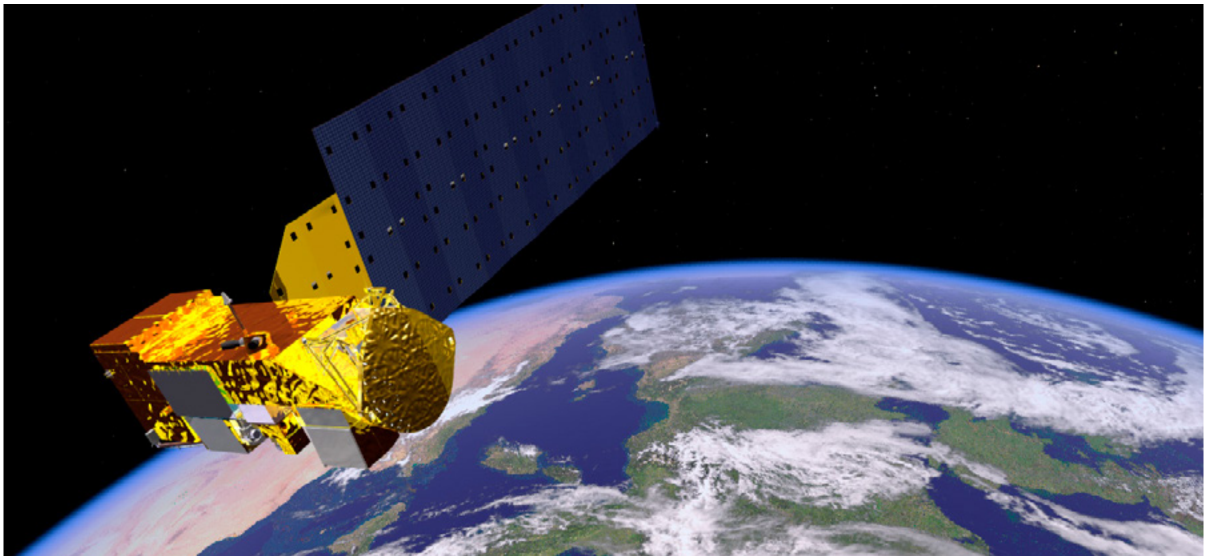
[10] *www.epa.gov/mrlc/classification.html*



An artist's rendering of the Aqua satellite containing AMSR-E. Credit: NASA

CHAPTER 3

MODELING & REMOTE SENSING

3.1 INTRODUCTION

Soil moisture is fundamental to land surface hydrology in many ways. Importantly, it strongly influences the partitioning of precipitation into either runoff or infiltration. Both of these hydrological variables are very important and play critical roles in the transport of water at the land/atmosphere boundary, including providing water for vegetation, and recharge to the ground water table. The surface runoff constitutes the water in the streams, rivers, and other surface water bodies. Infiltrated water is the source for evapotranspiration, which in turn reduces soil moisture and allows more soil water to infiltrate.

In situ soil moisture monitoring networks are important in establishing a baseline for observations. However, for some applications in hydrology, ecology, weather, agriculture and climate, spatially continuous observations are needed. Recent work has demonstrated that spatially continuous soil moisture maps can be produced using data from in situ networks combined with digital soil maps and radar precipitation estimates (Ochsner et al., 2019). However, satellite remote sensing and modeling are two methods by which spatially continuous soil moisture estimates have been more commonly produced.

In this chapter, we review the various methods associated with modeling and satellite remote sensing. In the area of modeling, most hydrological models are intrinsically linked to atmospheric circulation models. Precipitation is input to these models using various sources of observations – rain gages, ground-based radars or satellite sensors. Models estimate various quantities, for example – soil moisture, latent heat flux and streamflow. These variables are also observed using in situ or satellite sensors. Data assimilation is the technique that uses these observations and reconciles their differences with the model simulations and then updates the model states. In this way the model has been "course-corrected" after the assimilation. A model that uses data assimilation typically produces a better estimate of the land surface states compared to a model that does not use data assimilation. There are numerous well-calibrated hydrological models with data assimilation modules that estimate the water and energy balance of the land surface at various temporal and spatial scales (Han et al., 2012; Houser et al., 1998).

Since the 1970s, scientists have leveraged the water sensitivity of microwave frequencies to sense soil moisture. The evolution of microwave sensors has come a long way from tower- and truck-mounted sensors of the 1970s and 1980s, to aircraft sensors and finally satellite sensors. Lower microwave frequencies such as the L band (1 to 2 GHz) are optimal for monitoring of soil moisture as they are less impacted by the water contained in the vegetation canopy. Both passive (radiometer) and active (radar) sensors have been used. Today, there are numerous satellite sensors that offer global soil moisture estimates at different times of the day from space, but the sensing depth is in the near surface, approximately 5 cm. The assimilation of microwave-based soil moisture data with hydrologic models is the key to offering the most accurate representation of the soil moisture across space and time to date. Both models and satellite estimates are calibrated and validated using in situ networks and field experiment observations of soil moisture. Together, these diverse data inputs help us integrate point observations with spatial representation of soil moisture for more reliable applications in hydrology, ecology, weather, agriculture, and climate.

3.2 LAND SURFACE MODELS

Interest in regional and global soil moisture datasets has increased rapidly over the past several decades. One well-established method that permits routine monitoring of soil moisture is applying a land surface water, or water and energy balance, approach. Land Surface Models (LSM) represent a compilation of physically- and statistically-based empirical equations that simulate the flow of water and energy within the soil–vegetation–atmosphere transfer continuum and model water and energy exchange at the land surface–atmosphere interface. The water balance approach applied by LSMs calculates a change in soil water storage (ΔS) as the difference between incoming (i.e., precipitation) and outgoing (i.e., evaporation, runoff and deep ground water storage) fluxes of water (Maidment 1992; Pitman 2003; Singh 2017).

LSMs differ widely with regards to their physical complexity, assumptions and forcing requirements. Chow et al. (1988) subdivides hydrologic models in two broad categories: physical and abstract. The physical models represent the system on a reduced scale, while the abstract models represent the link between the system variables using mathematical equations, where the variables may be probabilistic or random depending on the spatial and temporal behavior of the specific variables. Singh (2017) offers a comprehensive description of some of the available water balance models. Depending on physical complexity, assumptions, number of hydrologic processes captured by the model, and model response or grid unit, the available models can be categorized as a: 1) a simple bucket model, or bucket with a bottom hole model; 2) a simple water balance model; 3) the Soil and Water Assessment Tool (SWAT); and 4) more complex grid-based hydrologic models, (i.e., the Variable Infiltration Capacity model (VIC), the Noah model, the Noah-Multi Physics (Noah-MP) model, the Community Land Model (CLM), and the Catchment Land Surface Model (CLSM)). See Table 3.1 (*next page*) for a general overview of the most commonly used models.

The bucket hydrologic model represents the simplest viable soil water balance model. It typically assumes a single soil layer configuration and one-dimensional water flow, while ignoring the impact of vegetation and energy fluxes. Once the maximum water holding capacity of the soil layer is reached, the extra water added to the system through precipitation is discarded as runoff. The bucket with a bottom-hole model adds upward and downward movement of water through the bottom of the surface layer. The simple water balance model improves the representation of runoff and incorporates additional capabilities that simulate snow accumulation and snow melt. SWAT, VIC, Noah, CLM, and CLSM are examples of more complex models. SWAT was developed as an agricultural water management tool that incorporates numerous models that simulate the complex soil–water–vegetation interactions and processes as well as crop yield and biomass accumulation (Arnold et al., 2012). SWAT is run at a watershed/sub-watershed scale, where each basin can be further subdivided to hydrologic response units based on dominant land, soil type and management practice. VIC, Noah, CLM, and CLSM are multilayer models run at a grid/sub-grid scale that solve for both the water and energy balance and simulate sub-grid heterogeneity in detail. Most models in this tier offer multiple options to simulate

Table 3.1: Overview of Hydrologic Land Surface Models

LSM Model	Basic Characteristics
Bucket with a bottom-hole model Two-layer Palmer model	• One layer • One-way movement of water • Excess water from precipitation is modelled as runoff
Bucket with a bottom-hole model • Two-layer Palmer model	• Multiple layers • Upward and downward movement of water
Simple water balance model	• Improved runoff representation • Snow-related components
Soil and Water Assessment Tool (SWAT)	• Water management tool • Tools that model numerous hydrologic processes and account for various hydrologic components (i.e., irrigation, snowmelt, evapotranspiration, etc.) • Allows the simulation of agricultural yield and biomass
Complex Hydrologic models • Variable Infiltration Capacity Model (VIC) • Community Land Model (CLM) • Catchment Land Surface Model (CLSM) • Noah model (Noah) • Noah-Multi Physics Model (Noah-MP)	• All hydrologic processes are modelled separately within the soil and snow layers • Solves for both the water and energy balance • Multiple soil, canopy and snow layers • Multiple options to model the various hydrologic components

the land, canopy, and snow layers separately (Liang et al., 1996; Lohmann et al. 1998a, 1998b; Koster et al. 2000; Liang, Xie, and Huang 2003; Ek et al. 2003; Mitchell 2005; Niu et al. 2011).

Model-based soil moisture datasets are easily accessible, and provide temporal continuity (e.g., no missing data compared with in situ observations) and continuous spatial distribution. However, models still have several key limitations including limited spatial resolution, which is typically defined by the (often coarse) resolution of the meteorological forcing parameters used to run the models. In addition, LSM performance and accuracy are highly susceptible to the quality of the forcing data, where some of the key forcing datasets necessary to run an LSM include precipitation, temperature, net radiation, humidity, and wind. However, all of these meteorological inputs can now be acquired at a global scale using satellite-based technologies. The large availability of routinely delivered forcing data, along with the long-term trend in computational power, has substantially reduced obstacles for operational, large-scale monitoring of soil moisture using LSMs. For example, Phase-2 of the North American Land Data Assimilation System (NLDAS-2) routinely produces and distributes 0.125-degree resolution North American soil moisture maps[11] with a data latency of approximately 3–4 days. NLDAS-2 soil moisture data have been widely used to support drought monitoring by, for example, the U.S. Drought Monitor (Xia et al., 2014). Such models can be additionally constrained by assimilation of surface soil moisture data available from satellites as noted previously. For a review of regional and global land data assimilation systems, see Xia et al. (2019).

3.3 SATELLITE SOIL MOISTURE

Remote sensors are designed to operate at specific regions of the electromagnetic spectrum according to their intended application. Sensors intended for surface observations operate at frequencies where attenuation and emission by atmospheric gases is low. Sensors intended for global soil moisture sensing must also operate where attenuation by vegetation is low, which implies sensing at low microwave frequencies since vegetation attenuation decreases as frequency decreases. Attenuation by clouds and rain is also lower at lower frequencies. The sensitivity of microwave radiation to soil moisture is governed by the dielectric constant of water, which is greatest at frequencies less than about 5–7 GHz. For the above reasons, satellite soil moisture sensors are designed to operate at microwave frequencies below ~10 GHz (X-band), and preferably close to ~1 GHz (L-band) for highest

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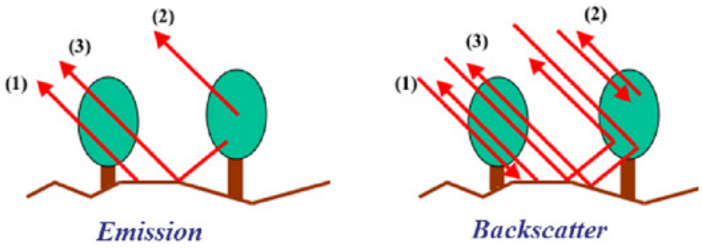
[11] *https://www.emc.ncep.noaa.gov/mmb/nldas/drought/*

accuracy. At frequencies below about 1 GHz, Faraday rotation by the ionosphere becomes a significant problem and there is increased threat from radio frequency interference (RFI) from man-made emitting sources. A final consideration is that wavelengths longer than L-band would present limitations in spatial resolution of the instrument (coarser resolution) because the resolving power of the instrument is related to the ratio of the antenna size (linear dimension) to the wavelength, and large antennae are expensive to deploy in space. Table 3.2 (*page 28*) lists current microwave remote sensing satellites.

Microwave remote sensors can either be passive (receive energy only) or active (transmit and receive energy). Passive remote sensors (radiometers) measure thermally emitted radiation from a medium to determine the emissivity of the surface. The intensity of emitted radiation depends on the dielectric properties, which for the near surface soil layer is a function of the amount of moisture present, and the temperature of the target medium. Active remote sensors (or radars) provide their own illumination source, sending out a transmitted wave and measuring the received reflection back from the target to determine its backscatter cross-section. Radars that employ synthetic aperture processing are known as synthetic aperture radars or SARs. SARs provide higher spatial resolution, allowing finer scale features of the surface to be observed.

Measurements of emissivity and backscatter cross-section (sometimes simply called backscatter) provide complementary information on the soil moisture, roughness and vegetation characteristics of the land surface. Radiometers measures the power of the received radiation, while radars measure both the amplitude and phase of the received signal relative to the transmitted signal. Emission (radiometer) and backscatter (radar) equations are used to model the interactions



$$T^{t}_{Bp} = T^{s}_{Bp} L_{p} + T^{v}_{Bp} + T^{sv}_{Bp} \qquad \text{(Emission)}$$

$$\sigma^{t}_{pq} = \sigma^{s}_{pq} L^{2}_{pq} + \sigma^{v}_{pq} + \sigma^{sv}_{pq} \qquad \text{(Backscatter)}$$

Figure 3.1: Illustration of the passive emission of brightness temperature (TB) and the backscatter measurement technique from remote sensing.

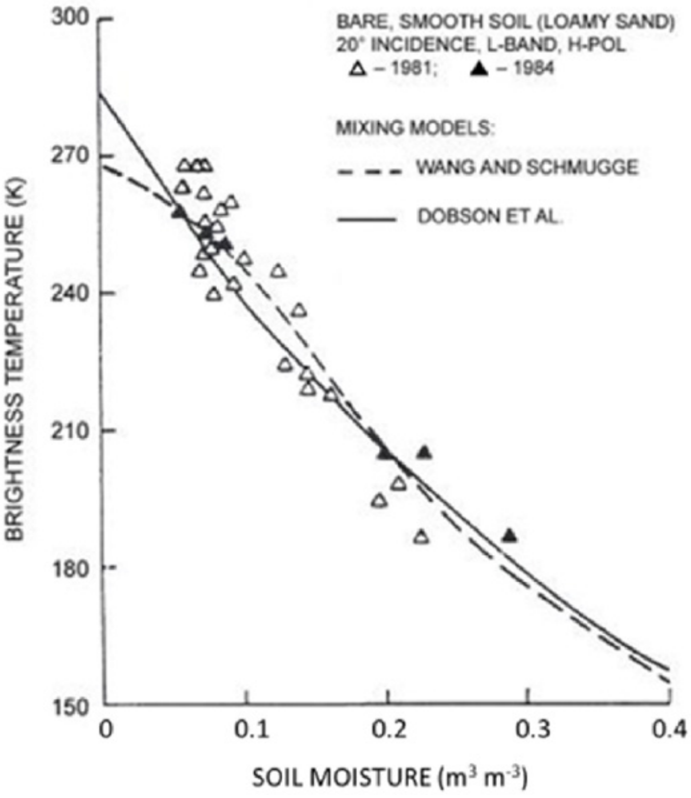


Figure 3.2: L-band brightness temperature response for a bare, smooth soil surface as a function of soil moisture. Soil moisture can range from close to 0.02 m^3 m^{-3} (very dry), to about 0.40 m^3 m^{-3} (near saturation for the soil studied). As soil moisture increases the brightness temperature decreases, changing by about 100 K over the full range of soil moisture. Current microwave radiometers have a precision of about 1 K. Details of theoretical modeling and experimental verification for radiometer and radar measurements of vegetation-covered soils can be found in the literature (e.g., Fung et al., 1986; SMAP Handbook, SMAP ATBD, SMOS ATBD).

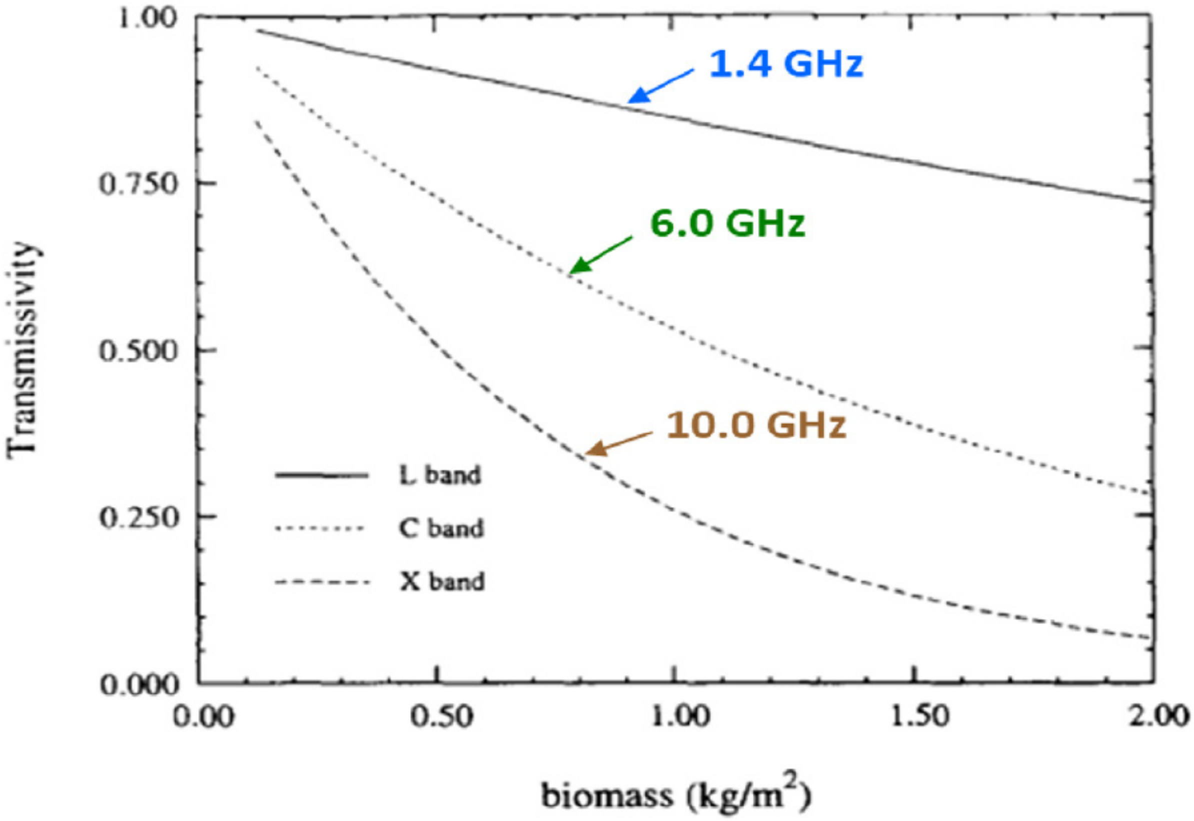


Figure 3.3: The sensitivity of microwave transmission to vegetation biomass.

between microwaves and the vegetation and soil for a typical vegetation-covered landscape. The radiometer measures the emitted radiation intensity or brightness temperature (TB in units of kelvin) and the radar measures the backscatter of the transmitted signal (σ in units of dB).

Each equation models three components of the radiation–surface interaction. Emissions that reach the radiometer come from: 1) the soil directly; 2) the vegetation directly; and 3) from the vegetation after scattering off the soil. Similarly, backscattering interactions from the radar signal come from: 1) the soil; 2) the vegetation; and 3) the vegetation–soil or the soil–vegetation. The radar interactions are more complex because the scattering interactions are more dependent (than emission) on the relative sizes and orientations of the vegetation components. The backscatter signal is also more sensitive (than emission) to the roughness of the soil, the mm-scale variations in soil surface height. The theoretical modeling and experimental verification of the three terms in each of the equations is therefore more complex and difficult for the radar than for the radiometer. Relationships between brightness temperature and volumetric soil moisture are illustrated in Figure 3.2 (*previous page*).

Within the microwave portion of the electromagnetic spectrum, emission from soil at L-band frequencies can be measured through greater amounts of vegetation than emission at higher frequencies. Figure 3.3 (*above*) shows microwave transmissivity as a function of increasing biomass at L-band (1.4 GHz), C-band (6 GHz) and X-band (10 GHz), based upon modeling. The results show that L-band has a significant advantage over the C- and X-band provided by satellite instruments such as the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) and WindSat. Satellite sensors utilizing L-band frequencies, such as NASA's Soil Moisture Active Passive (SMAP) and the ESA's Soil Moisture Ocean Salinity (SMOS), are able to estimate soil moisture globally over the widest possible vegetation conditions. Another advantage of measuring soil moisture at L-band is that the microwave emission originates from deeper in the soil (typically 2 to 5 cm), whereas C- and X-band

Table 3.2: The soil moisture products developed using different microwave satellites. Sun synchronous orbits are described as ascending (asc) or descending (desc).

	Mission duration	SM Spatial Coverage	Temporal Revisit	Orbit	Product Resolution
AMSR-E	2002–2011	Global land	2-3 days	(1:30 pm asc / 1:30 am desc)	25 km
GCOM-W (AMSR2)	2012–Present	Global land	2-3 days	(1:30 pm asc / 1:30 am desc)	25 km
WindSat (DoD)	2004–Present	Global land	2-3 days	Sun synch (6:00 am asc/ 6:00 desc)	25 km
ASCAT	2009–Present	Global land	2-3 days	Sun synch (9:30pm asc / 9:30am desc)	12.5 km/25 km
SMOS (ESA)	2009–Present	Global land	2-3 days	Sun-synch (6am asc / 6pm desc)	25 km
Aquarius	2011–2015	Global land	8 days	Sun-synch (6pm asc / 6 am desc)	100 km
SMAP (NASA)	2015–Present	Global land	2-3 days	Sun-synch (6am desc / 6pm asc)	3 km/9 km/36 km
CYGNSS	2017–Present	Mid-latitudes	Week-Month	Varying overpass time	1-3 km
NISAR	Launch date: Sep. 2022	Global	12 days	6 am /6 pm	200 m

emissions originate from the top 1 cm or less of the soil. The same benefits of longer wavelengths hold for radars. Consequently, the SMOS and SMAP radars also operate within the L-band, and the backscatter observed by SMAP is sensitive to water at a frequency of 1.41 GHz, and the radar operates at adjustable frequencies in approximately the top 5 cm of the soil small range near 1.26 GHz.

A summary of commonly used satellite-based products observation systems and their product resolution are listed in Table 3.2 (*above*). A review of various in situ and satellite-based soil moisture platforms and related issues can be found in Mohanty et al. (2017).

3.4 CALIBRATION AND VALIDATION METHODOLOGY

3.4.1 Validation and Scaling

There is little doubt that satellite observations provide important information regarding the space and time variation of soil moisture. However, the only way to determine the actual value of satellite data is through validation, which can be strictly defined as "… the quantitative determination of the space and time statistical structure of uncertainty." Validation is absolutely necessary before satellite remote sensing can be effectively used to enhance our understanding of the terrestrial water cycle and make predictions: We first need to know the quality of the satellite observations. Validation is simply not possible without acceptably accurate data from in situ soil moisture networks.

There are two main difficulties associated with the validation of remotely-sensed soil moisture observations. First, the resolution limitation imposed by a satellite antenna means that satellite soil moisture observations are spatial averages. The scale mismatch between in situ soil moisture sensors and a satellite sensor can be 10 orders of magnitude (10's of cm^2 versus 100's of km^2). Second, the signal measured (emitted or scattered microwave radiation) is strongly related to soil moisture, but not solely determined by soil moisture. Soil and vegetation temperature, soil texture, soil organic content, the small-scale and large-scale topography of the soil surface, the amount and type of vegetation, and atmospheric conditions also contribute.

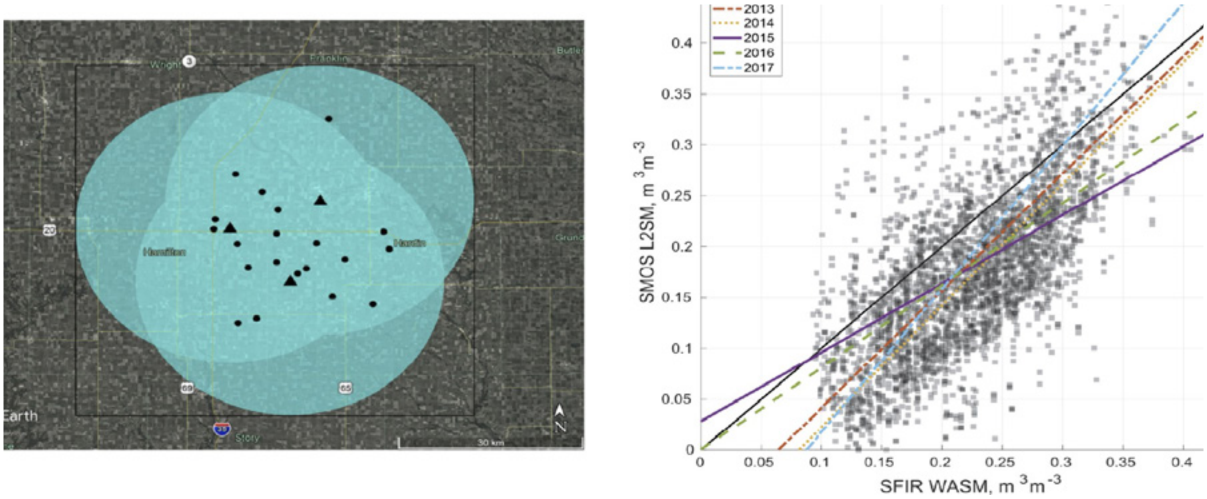


Figure 3.4: (*Left*) The South Fork Iowa River (SFIR) network in central Iowa, an in situ soil moisture network used for validation of satellite soil moisture observations. The black dots mark the locations of the 20 network stations. The black triangles mark the centers of the three Soil Moisture and Ocean Salinity (SMOS) satellite pixels that best match the network. The cyan circles (50 km in diameter) illustrate the approximate area influencing each SMOS pixel. (*Right*) Validation of the SMOS Level 2 soil moisture product in central Iowa, which here is defined as the average soil moisture for these three SMOS pixels (SMOS L2SM) regressed against the SFIR network weighted-average soil moisture (WASM). From Walker et al. (2018).

The first difficulty requires the establishment of a standard for the main quantity of interest (soil moisture) that is valid at the satellite scale. Soil moisture networks are currently the only practical way to upscale, or translate, in situ soil moisture measurements to the scale observed by a satellite. Consequently, network soil moisture is used as “the truth” in satellite validation. The second difficulty (which is, fundamentally, the nature of remote sensing) must be addressed through the use of models and either some type of measurement or estimation of all or at least the most important biogeophysical quantities also affecting the remotely sensed observation. This information can be used to formulate and adjust the models and to explain the validation statistics.

Satellite validation sites have been used by NASA (as well as other international space agencies), often in cooperation with other federal agencies like the USDA who have interest in satellite data. For example, several validation sites built around soil moisture networks were created for NASA’s Soil Moisture Active Passive (SMAP) soil moisture satellite (Entekhabi et al., 2010). These sites have been used to generate the data needed to calculate statistics such as bias (the mean difference between the satellite soil moisture product and the soil moisture derived from the network) and noise (normally some form of the root mean squared difference or RMSD) in order to determine whether SMAP is meeting its mission goals (Chan et al., 2016; Colliander et al., 2017).

Ideally, validation sites should be located in all biomes of interest so that the best estimate of overall satellite performance can be found. Walker et al. (2018) evaluated another soil moisture satellite, the European Space Agency’s Soil Moisture and Ocean Salinity (SMOS) (Kerr et al., 2010), in the U.S. Corn Belt, a large region of extensive row cropping, using a SMAP Core Validation Site established in the watershed of the South Fork Iowa River in central Iowa by the USDA. A map of the South Fork Iowa River (SFIR) soil moisture network in relation to the three SMOS pixels that best match the extent of the network is shown in Figure 3.4 (*above*). Also shown in Figure 3.4 is a comparison between the SMOS soil moisture product (SMOS L2SM) and soil moisture derived from the SFIR soil moisture network (SFIR WASM). This is the classic validation result. Ideally, points in this figure would line up around the black 1:1 line. In this case, it can be seen that SMOS soil moisture values tend to be smaller (drier) than values from the network. Rather than a simple average of the in situ soil moisture measured at each of the 20 SFIR network stations, the network soil moisture in this example is a weighted average,

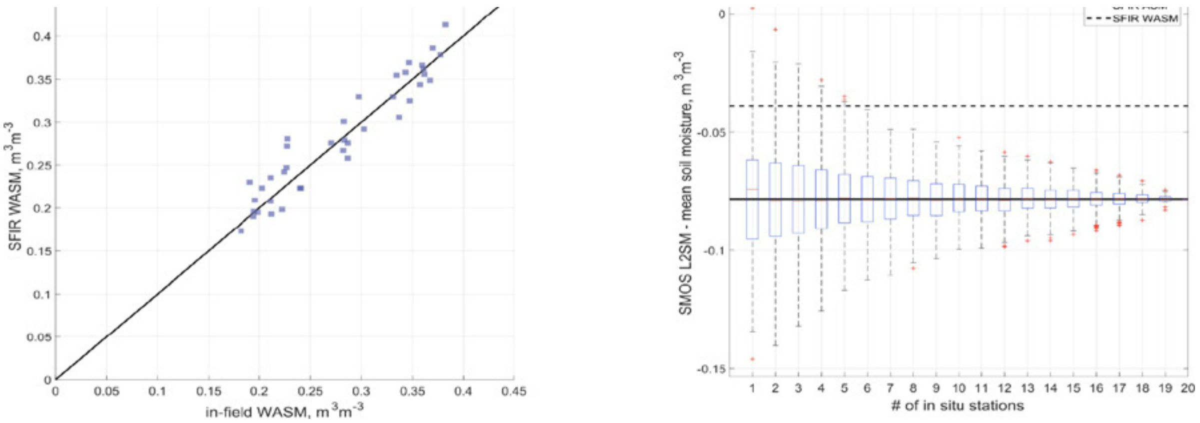


Figure 3.5: (*Left*) South Fork Iowa River (SFIR) network weighted-average soil moisture from 5 cm installed sensors under grass on edges of fields (SFIR WASM) versus in-field soil moisture under row crops measured during a 2014 campaign (in-field WASM). There was essentially no bias between in-field and out-of-field measurements, but there was some noise. (*Right*) the difference between SMOS satellite soil moisture (SMOS L2SM) and SFIR network soil moisture as a function of the number of network stations used to compute a simple average (SFIR average soil moisture or ASM). Also shown is the difference between SMOS L2SM and all 20 stations weighted according pixel area represented (SFIR WASM). Even as few as about five stations clearly indicate SMOS soil moisture is less (drier) than network soil moisture. (Source: Walker et al. (2018))

where stations farther away from neighboring stations receive a larger weight since they represent a larger area of the satellite pixel (weights calculated using a Voronoi diagram, also called Thiessen polygons). This type of scaling function may be appropriate for pixels in which precipitation is the largest source of variability. Scaling functions can also be adjusted using additional in situ measurements obtained during time-limited field campaigns. This can be done using geostatistical techniques (Kathuria et al., 2019) and identifying dominant geophysical factors, i.e. soil, topography and vegetation (Cosh et al., 2004; Gaur and Mohanty, 2013, 2016, 2019).

There are many things to consider when designing a soil moisture network suitable for use in satellite validation. One aspect is representativeness: Do the in situ sensors observe the same quantity of soil moisture as the satellite? In reality, satellites “see” the first few cm of the soil surface, while in situ sensors buried at, for example, 5 cm for long-term robustness observe a different soil layer centered around that depth. These two layers act differently hydrologically: the shallower layer observed by satellites is more dynamic, reacting more dramatically to precipitation events and dry periods. While this circumstance is unavoidable (satellites will always observe from the top-down, and in situ sensors at some depth) these two layers can still share similar statistics (Rondinelli et al., 2015). Hence, soil moisture networks are integral for a remote sensing program.

Another practical matter is the physical location of network stations. In order to have continuous, long-term measurements, in situ sensors must be buried where they will not be disturbed. This location may not be the same as where the soil moisture measurement is desired. Can such compromises be managed? Walker et al. (2018) examined this situation in the Corn Belt. Field operations such as tillage, planting, and harvest make it impossible to install soil moisture sensors directly in fields. Instead, SFIR stations have been installed on the edge of fields, so that in situ sensors are under grass and not the dominant vegetation of the region, row crops. However, this approach leads to a question of whether or not these out-of-field sensors still measure the soil moisture of interest. A field campaign in 2014, during which in-field soil moisture measurements were compared to the SFIR network measurements, found that essentially no bias (but some noise) is introduced into the validation. This result is shown in Figure 3.5 (*above*). From this single study, it appears that these compromises can be managed if fields are rain fed rather than irrigated. In areas where fields are predominantly irrigated (large areas of California, the Great Plains, Mid-South, and Intermountain West) satellite observations of field soil moisture would not be expected to correlate well with data from stations outside of the irrigated area.

Finally, it is necessary to determine if it is realistic to use a limited number of in situ soil moisture measurements (each representing 10's of cm^2) to represent an entire satellite pixel (100's of km^2). The spatial scale of soil moisture can be defined in terms of the spacing, extent, and support of component measurements. Spacing is the distance between measurements or model grid points, extent is the overall coverage or total distance spanned by the measurements, and support is the area integrated by each measurement (Western and Blo¨schl, 1999). The ideal case is small spacing, adequate extent to match the scale of interest, and small support. In situ soil moisture sensors provide small support, and validation networks are designed to span the extent of a satellite footprint. But since this area is so large, necessity dictates that spacing will not be ideal. Further complicating this matter is the fact that stations must normally be located on private land. It is often difficult to identify hosts and make long-term arrangements. In the case of the SFIR, these constraints resulted in 20 network stations.

3.4.2 Data Assimilation

In situ-based soil moisture measurements as well as remote sensing- and model-based estimates are not perfect and do not always directly meet user requirements in terms of their precision, resolution, temporal and spatial coverage, and observation depth (Reichle, 2008). For example, satellite-based retrievals provide an estimate of the soil moisture conditions for only the top 1–5 cm of the soil profile. Many applications require knowledge of the root-zone soil moisture, which cannot be observed directly using remote sensing but could be well simulated by a model informed by forcing data and constrained by data assimilation, some of which data could be derived from remote sensing. The quality of the forcing data plays major role in the accuracy of the model estimates. For example, erroneous precipitation events are directly transferred through model simulations and commonly result in incorrect model soil moisture estimates – especially in data-poor regions of the world (Bolten and Crow 2012; Dong et al. 2019). Data assimilation (DA) offers the opportunity to mitigate these limitations.

Data assimilation is a technique for updating a continuously running model with incomplete and uncertain information acquired from observations. Ideally, this updating should be based on a complete statistical understanding of errors present in both the model and the observations (McLaughlin 1995; Reichle et al. 2004; Reichle 2008; Crow and Reichle 2008; Park and Xu 2009). Direct insertion, optimal interpolation, nudging, Kalman Filter, 3D/4D variational assimilation are all methods that are potentially suitable for land data assimilation (Reichle 2008). Of these, the Ensemble Kalman Filter (EnKF) is generally considered one of the most widely applied data assimilation approaches in hydrology (Evensen 2003). EnKF is a sequential, Monte Carlo–based method that uses a Monte Carlo forecast ensemble to compute the error covariance of the satellite data and the modelled estimates at the time of the update. Therefore, it has two steps: a forecast, where the ensemble is propagated forward in time, and an update step, where the update is performed based on the so called Kalman gain (Reichle, McLaughlin, and Entekhabi 2002). The latter is a function of the forecast error covariance sampled prior to the update from the Monte Carlo ensemble. Essentially, the Kalman gain is a weighing matrix that assigns specific weights to the model and the observations estimates, which reflects our confidence in the model physics and forcing data, and the accuracy of the satellite retrieval algorithm. The Kalman gain also provides a statistical basis for translating updates between observed and unobserved states (e.g., surface soil moisture to root-zone soil moisture).

McLaughlin (1995) summarized that hydrologic data assimilation is "not yet well established." However, substantial progress has been made in the past two decades such that data assimilation methodologies, initially borrowed from the oceanography and atmospheric sciences, have been well-adapted to meet the unique dynamics and requirements of land-based systems. These system have been extensively tested, and the benefits of incorporating satellite-based observations into spatially distributed hydrologic models are well-demonstrated (de Wit and van Diepen 2007; Crow and Ryu 2009; Crow and Van den Berg 2010; Bolten and Crow 2012; Crow, Kumar, and Bolten 2012; Han et al. 2014; Mladenova et al. 2019).

There currently exist multiple land DA systems that operationally ingest remote-sensed soil moisture retrievals (or the satellite brightness temperature observations that underlie these retrievals) to update LSMs and produce a global analysis of surface and root-zone soil moisture (see, e.g., Reichle, De Lannoy, Liu, Ardizzone, et al. 2017; Reichle, De Lannoy, Liu, Koster, et al. 2017; Mladenova et al. 2019). Important advances have also been made towards the development of systems that simultaneously assimilate both satellite- and ground-based soil moisture observations into a unified analysis (Gruber, Crow, and Dorigo 2018).

3.5 APPLICATIONS

Remote sensing and hydrological modeling are important tools in the study of both hydrological extremes such as drought and flooding, as well as general weather phenomena. Here are some examples of the distinctive application of these tools:

1. In recent years, floods associated with hurricanes (for example, Hurricane Harvey in Texas in 2017 and Hurricane Florence in South Carolina in 2018) have caused huge disasters. The mapping of these and similar floods using airborne (JPL AIRSAR), and satellite radars (Sentinel), and visible and near infrared (Moderate Resolution Imaging Spectroradiometer – MODIS) have been carried out (Oddo and Bolten, 2019
2. In the case of droughts (and their associated wildfires), the State of California stands out. These droughts have been studied using numerous models (Land Information System, LIS) and observations using satellite sensors.
3. The launch of the Global Precipitation Measurement (GPM) mission in February 2014 and the Soil Moisture Active Passive (SMAP) mission in January 2015 present a big step forward in global monitoring of precipitation and soil moisture. In addition, we have sensors that monitor vegetation, surface temperature and evapotranspiration (MODIS) and the continuation of the Gravity Recovery and Climate Experiment (GRACE) with GRACE-FO (Follow On) that estimates changes in surface and subsurface water storage which together provide a larger picture of the land surface hydrological state. The levels of water in lakes and rivers can be monitored with the SWOT (Surface Water and Ocean Topography) that will be launched in 2021. The NISAR (NASA ISRO Synthetic Aperture Radar) will be launched in 2022 and can monitor the land surface using L and S band SAR (soil moisture).

3.6 FUTURE DIRECTIONS

With rapid advances in computer modeling and observing systems, and the wider adoption of cloud computing technologies, floods, droughts and other weather phenomena are analyzed and forecast with greater precision today than ever before. Land surface models (especially over the continental United States) can map the hydrological cycle at kilometer and sub-kilometer scales. In the case of smaller areas, there is even higher spatial resolution of simulation and the only limiting factor is the resolution of input data. In situ sensors are automated and the data directly relayed to the internet for many hydrological variables such as precipitation, soil moisture, surface temperature and heat fluxes. In addition, satellite remote sensing has advanced to providing twice a day repeat observations at kilometer to 10-kilometer spatial scales.

With remote sensing, we have already mentioned the SWOT and NISAR, two satellite missions that monitor the hydrological state of the land surface. In addition, there are numerous other measurements, for example CyGNSS (Cyclone Global Navigation Satellite System) that was originally launched to monitor cyclones can be used to infer soil moisture on the land surface. Another breakthrough is the downscaling of soil moisture retrieved from L-band brightness temperature to 1 km using MODIS NDVI (Normalized Difference Vegetation Index) and surface temperature and lookup tables (Colliander et al., 2017; Piles et al., 2011). Still, the key to further adopting these technologies and reducing the uncertainty of the aforementioned hydrological models and remote sensing platforms is the development of a robust strategy for characterizing and integrating soil moisture information collected by the National Coordinated Soil Moisture Monitoring Network.

A selection of different soil moisture sensors. Credit: Tyson Ochsner

CHAPTER 4

CONSIDERATIONS IN SOIL MOISTURE NETWORK DESIGN

4.1 DESIGN GOALS AND ASSUMPTIONS

The purpose of this chapter is to identify and review key design considerations for soil moisture networks that may be developed or expanded in the future. Most networks are operated on a local to state level, and as new networks are proposed and developed, it is valuable for the NCSMMN community to provide some background and guidance on network design and to share lessons learned with newer network entrants. Much of this discussion however is applicable to national-scale networks and the NCSMMN as a whole as well. To begin, a clear conception is needed of the design goals and assumptions related to the specific network. Possible design goals include:

1. Quantifying the amount and vertical distribution of water in the root zone;
2. Quantifying the spatial distribution of soil moisture related to weather patterns, topography, vegetation types, land use, and soil types;
3. Documenting the occurrence of natural hazards related to deficit or excess of soil moisture (e.g., drought, flooding);
4. Incorporating data from existing Federal and state monitoring networks;
5. Providing coverage of the United States and its territories;
6. Supporting drought and flood monitoring, water supply forecasting, and fire danger ratings,
7. with many other uses expected;
8. Supporting the creation of gridded national soil moisture maps; and
9. Supporting decisions about Federal drought assistance and other related forms of disaster aid, while minimizing operational cost.

Given the importance of working towards a coordinated national system, this chapter makes three key assumptions about initial network structure. First, this chapter assumes that only permanent monitoring stations will be considered as part of the NCSMMN. Stations which are expected to remain operational in one location for <10 years would not be included because the length of the data record would not justify the time and effort required to include the station in a nationwide system. Stations in which some or all of the sensors are expected to be periodically removed and reinstalled would likewise not be included in the network, regardless of the expected period of record. Such removal and reinstallation are commonly needed, for example, in cropped fields, and the resulting disturbance introduces increased probabilities for discontinuities in the data record. Replacement of failed sensors is necessary for long-term monitoring networks and would not be considered disqualifying.

This chapter also assumes that only automated monitoring stations will be included in the NCSMMN. Monitoring sites that require a person to be present in order to collect data, such as with a neutron probe, hand-held sensors, or by soil sampling, are not likely to be suitable for this network because of the high, long-term labor cost and the inadequate frequency of measurement. Opportunities for non-automated monitoring, such as through citizen science, are one of the recommended areas of future research by the NCSMMN.

Finally, this chapter assumes that the majority of the network will be non-irrigated monitoring sites, but in the future a separate data product from NCSMMN would be produced which specifically addresses data collection from irrigated regions. Irrigated cropland and turf are important land uses, and soil moisture monitoring in these landscapes is a key strategy for improved water management and conservation. Irrigation landscapes are frequently monitored as part of a managed agricultural landscape, operated by the private sector. Irrigated soil moisture stations are also frequently temporary in nature, thus requiring more quality control and human interaction for incorporation into the main data products of the NCSMMN. For these reasons, it is necessary to conduct future research on how soil moisture data from irrigated sites can be used effectively within the NCSMMN framework.

4.2 KEY NETWORK DESIGN DECISIONS

When designing a soil moisture network, there are some key design decisions to be made, including:

1. Where should new stations be added?
2. What depths should be monitored?
3. What types of sensors should be used?

Each of these questions will be considered in turn.

4.2.1 Where should new stations be added?

To determine where new stations are needed, there are several plausible approaches, each with its own pros and cons. The first approach would be based simply on political boundaries. For example, the OKM, one of the oldest automated soil moisture monitoring networks, was designed to have at least one station in each of the state's 77 counties (Brock et al., 1995). The National Research Council has recommended the creation of a nationwide soil moisture and soil temperature observing network with "approximately 3,000 sites" (National Research Council 2009), and while the locations of these sites was unspecified, the total number is similar to the ~3,200 counties and county equivalents (i.e., independent cities, parishes, and boroughs) in the United States.

One benefit of this approach is that it may facilitate linkages with Federal disaster aid payments that have county-based eligibility, such as the Livestock Forage Disaster Program,[12] which provides assistance to livestock producers in counties suffering from drought. One drawback is that counties vary widely in areal extent, from <50 km^2 to >50,000 km^2. Counties in western states are often substantially larger than those in eastern states. From the total of 3,233 counties across all U.S. states and territories, about 22% (725 counties) have a spatial extent greater than 2,500 km^2 and about 4% (126 counties) have an area greater than 10,000 km^2. To observe soil moisture spatial patterns at a mesoscale of about 10,000 km2 (i.e., 100 km x 100 km) using political boundaries, 126 counties would need to be equipped with more than one monitoring station (Figure 4.1, *next page*). At a finer spatial resolution of 2,500 km^2 (i.e. 50 km x 50 km), it would require

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[12] *https://www.fsa.usda.gov/programs-and-services/disaster-assistance-program/livestock-forage/index*

a substantially higher investment in infrastructure, since more than 700 counties would require more than one (Figure 4.2, *middle right*).

Another drawback of using county boundaries is that they may vary vastly in size within a single state or region. The Gini coefficient (Dorfman 1979) was used to quantify the inequality of county sizes within each state. Arkansas, Ohio, and Iowa have the most even county area distribution with Gini coefficients of about 0.1 (Figure 4.3, *bottom right*). California, Maine, and Oregon have the most uneven county area distributions with Gini coefficients of 0.49, 0.47, and 0.45, respectively. Alaska has the highest level with a Gini coefficient of 0.62. Thus, in states with unevenly sized counties, observations of soil moisture might be skewed to the conditions of the smaller counties. For example, the State of Virginia is divided into 95 counties and 38 county-equivalent "independent cities." These independent cities have a small area compared to the counties, resulting in the computation of a large Gini coefficient. Locating stations based on political boundaries could result in an undesirable distribution of stations in this case.

A second approach would be based on spatial gaps in the existing networks. For example, the Kansas Mesonet has adopted a geometric method to select the location of future monitoring stations. The geometric approach consists of finding the largest unmonitored circular area across the network. The centroid of the largest unmonitored circle

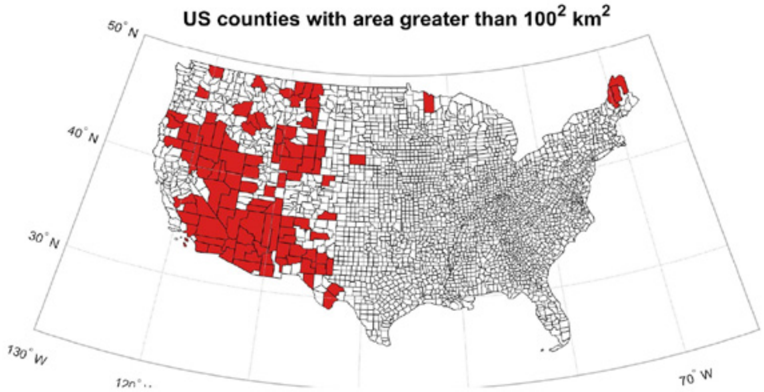

Figure 4.1: Counties in the contiguous United States with an area greater than 1,002 km^2 (or 10,000 km^2).

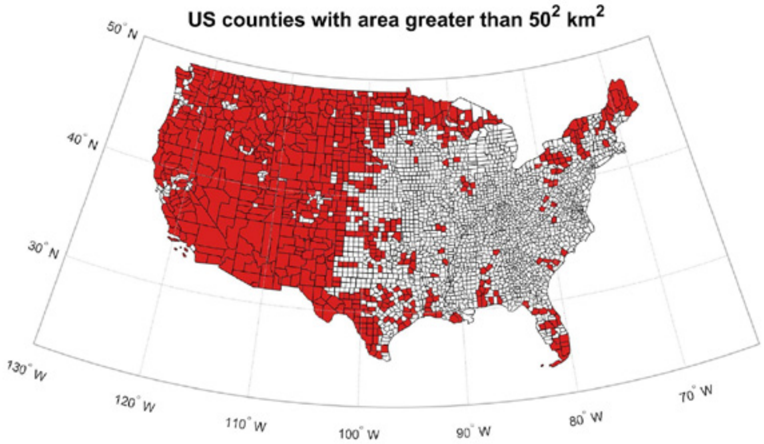

Figure 4.2: Counties in the contiguous United States with an area greater than 502 km^2 (or 2,500 km^2).

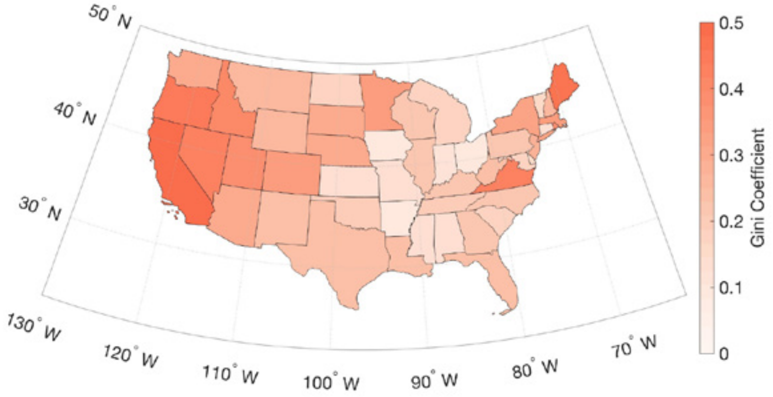

Figure 4.3: Inequality in the county size distribution within each of the 48 contiguous U.S. states. The Gini coefficient was used to represent the degree of inequality in county sizes. The Gini coefficient ranges between zero and one, where zero represents uniformly sized counties and higher values indicate greater inequality of county sizes.

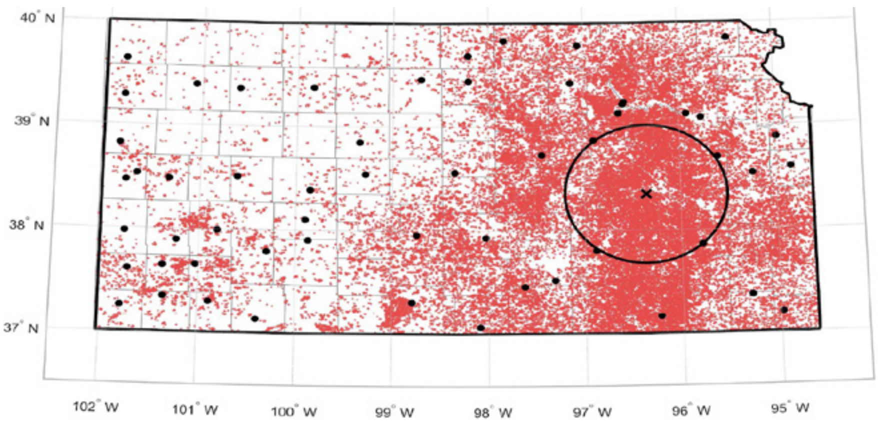

Figure 4.4: Locations of existing monitoring stations in the Kansas Mesonet (*black dots*), the largest unmonitored area (*circle*), and the proposed location of the next additional monitoring station (x). The locations of wildland fires (2000–2018) are shown in red and highlight the potential value of the proposed station for fire danger ratings.

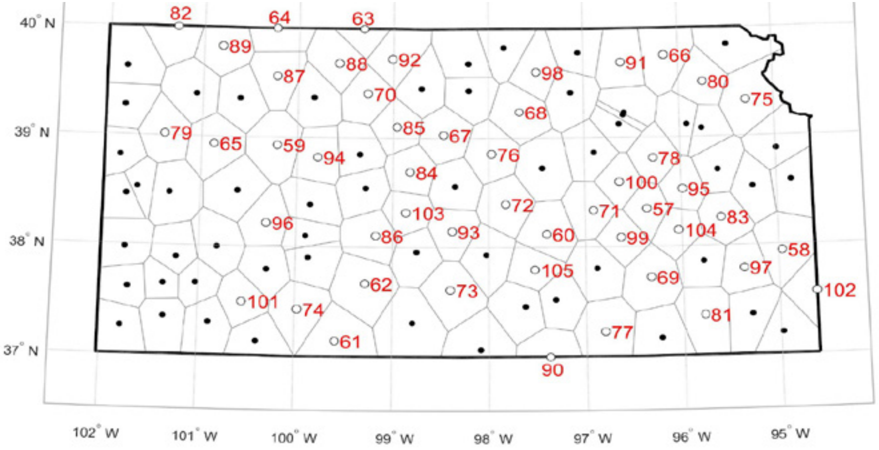

Figure 4.5: Sequence of future monitoring stations for the Kansas Mesonet generated by recursively applying the geometric method. At the time the analysis was run the network had 56 stations represented by the black circles. Thus, the open circle markers represent the locations and sequence of stations 57 to 105. The polygons are Thiessen polygons where every location inside the polygon is closer to the station in that polygon than to any other station.

represents the tentative location for the next future station (Figure 4.4, *above*).

This geometric approach has three main advantages. First, it is simple and only requires the geographic coordinates of the stations and the boundary of the network's domain. This is also an advantage in data-sparse regions places where the spatial structure of soil moisture or rainfall is unknown. Second, it can be easily integrated with the spatial occurrence of natural hazards such as droughts, flooding events, or wildland fires. Figure 4.4 (*above*) represents the largest unmonitored areas with the largest count of wildland fires (prescribed and accidental) in Kansas. Deploying a new soil moisture monitoring station in the selected location has the potential to improve the accuracy of wildfire danger rating systems. Third, the method can be applied recursively to generate a roadmap for future stations, assisting network managers with long-term planning and management of limited resources (Figure 4.5, *above*).

One main drawback of this approach is that it does not consider the spatial structure of soil moisture. The geometric approach may be better suited for multifunctional mesoscale networks that monitor multiple environmental variables with different spatial correlation structures. For application-specific networks that monitor only a few variables, such as soil moisture and rainfall, geostatistical approaches that focus on the minimization of the spatial variance will likely result in more representative locations.

A third approach is based on identifying regions of similarly expected soil behavior. This approach identifies regions of similar soil, climate, and vegetation characteristics that could be expected to produce similar soil moisture dynamics (Coopersmith et al., 2014; Chaney et al., 2015). These regions would

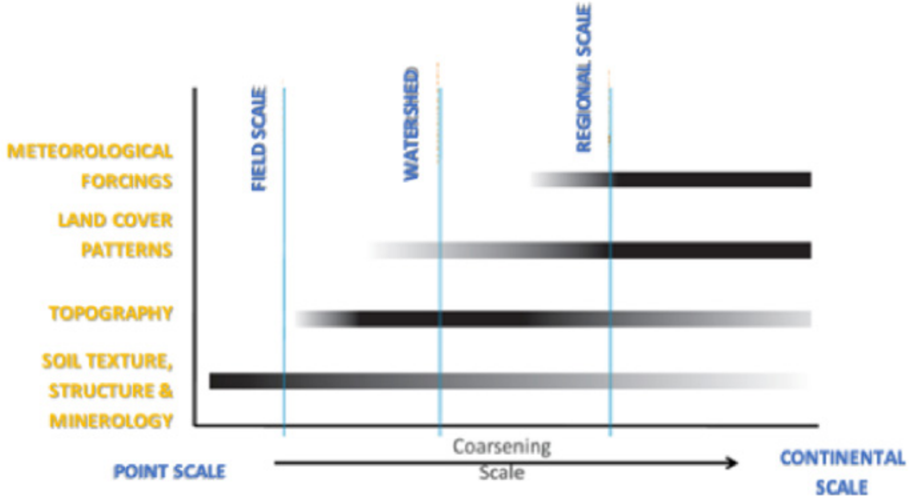

Figure 4.6: Factors controlling soil moisture spatial distribution. Adapted from Jana, 2010

be referred to as soil hydrological response units (SHRU).[13] After identification of SHRUs, the adequacy of existing monitoring stations to represent the different types of SHRUs could be assessed, and the locations of necessary additional monitoring stations could be determined. Given the expected monetary or logistic limitations for the number of sites that can be installed and maintained, one strategy could be to allocate sites between different SHRUs such that the number of sites within each type of SHRU is proportional to the area covered by that type of SHRU across the United States. For example, if a given type of SHRU occupies 4% of the land area and 1000 total sites can be included in the network, then 40 sites should be installed in that type of SHRU.

SHRUs can be identified based on existing information about similarities in hydrologically-relevant attributes such as meteorological conditions, land-cover/vegetation, topography/terrain, and soil type; each of which control soil moisture variability at different spatial scales (Figure 4.6, *above*).

At the continental scale, soil moisture variability may be associated with different hydro-climates which represent the precipitation and temperature patterns of a region. They can be identified using the Koppen classification system (Figure 4.7, *next page*). These hydro-climates may provide a first step towards defining SHRUs for a coordinated National Coordinated Soil Moisture Monitoring Network.

Further refinement in SHRUs can be achieved by incorporating soils, topography and land-use information. SHRU refinement can be done using spatial clustering methods. For example, SHRUs were recently identified in support of a soil moisture monitoring strategy to inform water resources management in California (Curtis et al., 2019; Figure 4.8, *page 39*).

This method identifies SHRUs using principal component analysis and unsupervised K-means clustering. Key input variables include characteristics of the soil (texture, porosity, depth, available water capacity), climate (average annual precipitation, snow water equivalent on April 1, potential evapotranspiration, and climatic water deficit), hydrology (average annual recharge and runoff), vegetation (seasonally integrated NDVI), topography (digital elevation model), and land use (National Land Cover Database).

The main advantages of SHRU based methods are that: 1) they explicitly consider known factors that influence the spatial and temporal patterns of soil moisture; and 2) they can be applied using existing information. A disadvantage of such methods is that they do not explicitly consider the end users of the data. Also, these methods are data intensive and the results will likely vary with the quality of ancillary data available. This method is conceptually appealing but has not yet been used to design and implement a large-scale soil moisture monitoring network, so its real-world effectiveness remains to be seen.

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[13] Other physical characteristics could also be used as the basis of siting decisions. For example, one option for forestry and ecological applications would be to use ecologically-based land classifications, such as the U.S. Forest Service's Terrestrial Ecological Unit Inventory (TEUI) system. Another option is to use Hydrologic Unit Codes (HUCs).

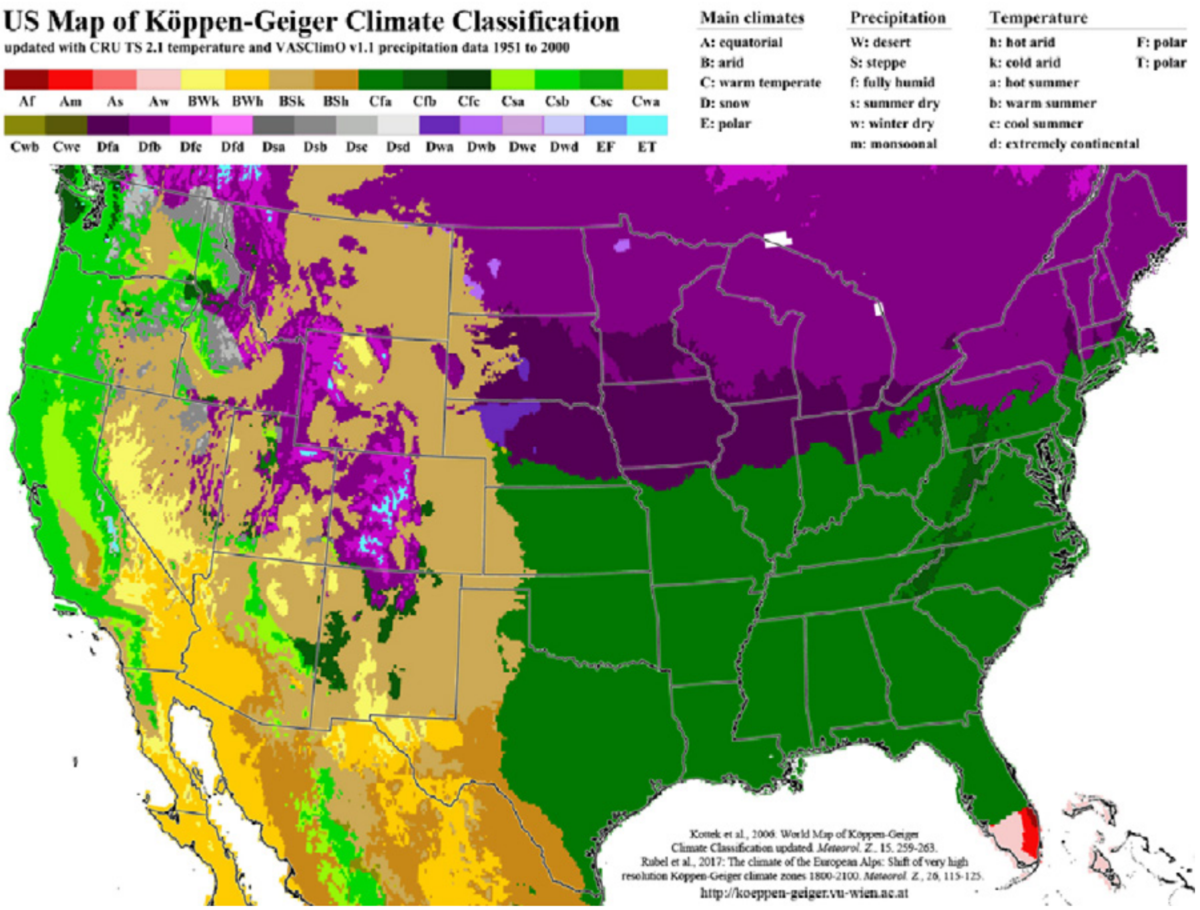

Figure 4.7: Köppen-Geiger hydro-climate map. (Source: *http://koeppen-geiger.vu-wien.ac.at/usa.htm*)

4.2.2 What depths should be monitored?

The selection of the sensor installation depths in the soil profile influences the accuracy of monitoring the soil moisture content in both individual soil horizons and the total soil water storage in the root-zone. The decision to monitor deep layers of the soil profile typically requires substantial additional hardware and labor costs. Each additional monitoring depth in a network can meaningfully impact the network's long-term budget. A key part of that added cost is the labor required for the initial installation and the removal and replacement of failed sensors at depth. Installing soil moisture sensors has traditionally involved digging a trench or pit and installing sensors into the exposed face of the soil profile followed by careful repacking of soil. With the advent of new soil profile sensors (e.g., Campbell Scientific SoilVue, Sentek Drill and Drop) and borehole installation tools (e.g., Meter Environment TEROS Borehole Installation Tool), the installation process can be less physically demanding. However, these labor-saving technologies have yet to be widely tested for long-term monitoring networks.

Another relevant point when choosing installation depths for soil moisture sensors is compatibility with existing networks. This is particularly important when deploying soil moisture sensors within the scope of a coordinated NCSMMN that will integrate observations from multiple networks. One of the most common sets of sensor depths is that adopted by the NRCS Soil Climate Analysis Network, which has sensors at 5, 10, 20, 50, and 100 cm. These depths are also used by the NOAA Climate Reference Network. Some networks, like the Kansas Mesonet, have partially adopted this layout with the exception of the sensor at 100 cm. The OKM, which initially adopted a layout with sensors at 5, 25, 60, and 75 cm depth, decommissioned the sensors at 75 cm due to maintenance costs. More recently, the OKM has added sensors at the 10 cm depth.

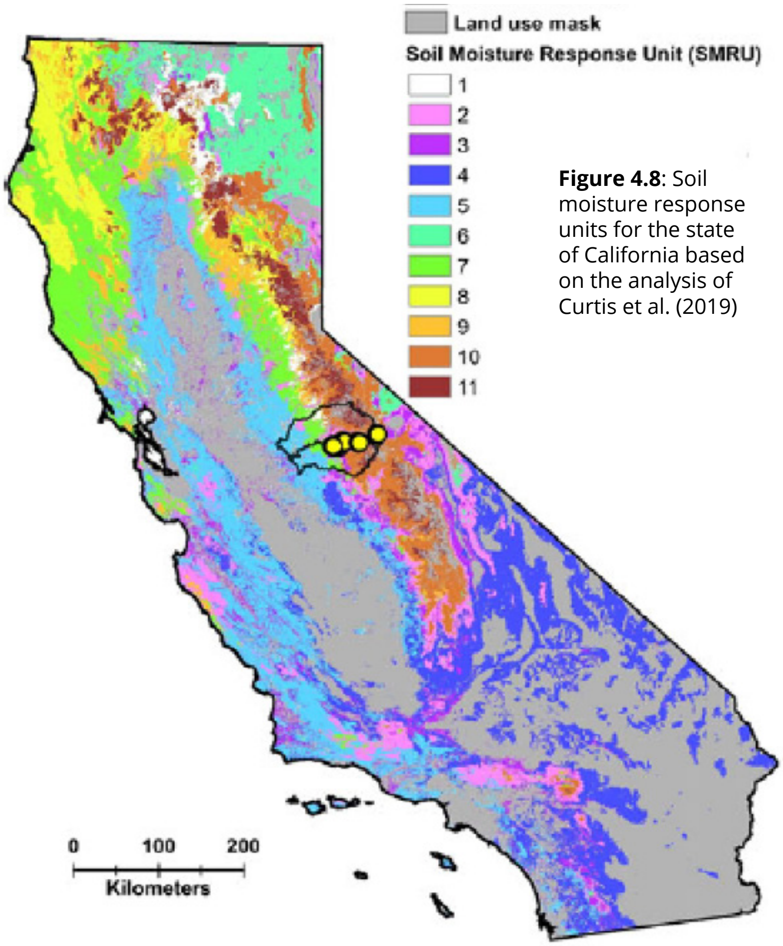

Figure 4.8: Soil moisture response units for the state of California based on the analysis of Curtis et al. (2019)

Often soil moisture measurements at discrete depths are integrated to calculate the total soil water storage in the profile. If the sensor depths are such that each sensor can be treated as measuring at the center of a soil layer, then the soil water storage of the layer is simply estimated as the value reported by the sensor times the thickness of the soil layer. This approach is the most logical approach from a hydrological and soil water balance perspective. This approach also facilitates comparisons between in situ soil moisture observations and land surface or hydrologic models, which typically simulate soil moisture for discrete soil layers, e.g. 0–10 cm. Thus, this installation approach is also well-suited for assimilation of soil moisture observations into such models. An example of a network using this approach is the OKM, where sensors deployed at 5 cm represent the 0–10 cm layer, sensors deployed at 25 cm represent the 10–40 cm layer, and sensors deployed at 60 cm represent the 40–80 cm layer.

In contrast, if the sensor depths are such that each sensor can be treated as measuring at the boundary between two layers, then estimating the soil water storage requires a numerical integration procedure. An example would be any network using depths such as 5, 10, 20, 50, and 100 cm. The soil water storage in the soil layer between each pair of successively deeper sensors (e.g., 5 and 10 cm) could be estimated as the average of the soil moisture values from the two sensors times the thickness of the soil layer. Some extrapolation procedure is needed to estimate the soil water storage for the 0–5 cm layer. A third approach, seldom used, consists of deploying sensors at site-specific depths dictated by the different soil horizons. While this approach respects the morphology of the soil, it creates varying sensor depths across the network, complicating maintenance and end-user applications.

Sensors at 5-cm depth are present in most existing networks. This sensor depth has often been used in the calibration and validation of remotely-sensed soil moisture products. Although shallower placements might provide a better match with the sensing depths of many microwave-based remote sensing techniques, sensors placed at depths shallower than 5 cm can be easily exposed due to soil erosion. Also, the accuracy of soil moisture sensors may be negatively influenced by the soil–air interface if placed at depths <5 cm. The World Meteorological Organization (2014) recommends 10-cm as the standard depth for soil temperature measurement. Recommendations for some agricultural management decisions, such as when to plant warm-season crops, have traditionally been based on soil temperature measurements at the 10-cm depth under bare soil. However, because a limited number of sensors are typically available for monitoring soil moisture throughout the root zone, placing two of those sensors only 5 cm apart (at 5 and 10 cm) is not optimal. New approaches are needed to strategically coordinate soil moisture and soil temperature observation systems for maximum efficiency under resource constraints. Other common depths among existing networks in the United States are sensors at 20 or 25 cm depth, 50 or 60 cm depth, and 100 cm depth (Zhang et al., 2017).

Another approach to choosing sensor depths and numbers is to fit the vertical distribution of sensors to the known or expected extent of the active root zone, defined by the soil thickness and the predominant vegetation in the area. In grasslands or annual croplands, this could lead to sensors more closely spaced near the surface and extending down to approximately 100 cm. In woodlands or perennial crops, this could lead to much deeper sensor profiles. If NCSMMN data were used to assess the severity of hydrologic drought, then soil water contents down to 200 cm or more might be warranted. Additional data-driven approaches, such as a robust decision-making approach (Clutter and Ferre, 2019), can further help identify the specific depths of value to a decision process. A broader understanding of the applications intending to use the NCSMMN is necessary to help narrow the scope of depth selection as well as other parameters. This requires a consensus from both the scientific community and the local stakeholders within each network.

4.2.3 What sensors should be used?

4.2.3.1 Available sensor types

There are a number of sensor options, operating at various depths, ranges and spatial-scales, with which to monitor soil moisture within a network. Most technologies rely on electromagnetic (EM) techniques (see Robison et al., 2008) that use various travel-time, capacitance and impedance-based approaches for sensing volumetric soil water content. Options we focus on here come in the form of: i) commonly deployed point-scale insertable sensors; ii) bore-hole sensors; iii) larger-scale neutron-based sensors; and iv) sensing capabilities using global positioning satellite systems.

The seminal work of Topp, Davis and Anaan (Topp, Davis, and Annan 1980) demonstrated the amazing potential of time domain reflectometry (TDR) for nondestructive, nonradioactive determination of soil moisture. Since then electromagnetic (EM)-based sensor designs that take advantage of various travel-time and impedance-based approaches for sensing volumetric water content are continuing to be developed. Decades of research have shown that measurement frequency (i.e., between MHz and GHz), is a significant factor affecting the accuracy of EM-based water content sensors. There is substantial evidence showing low frequency measurements are more susceptible to secondary effects (e.g., from temperature, salinity, polarization, relaxation, etc.) on dielectric permittivity determination than are measurements made at higher frequency. Correcting for these secondary effects can be challenging given the complexity and variety of circuit designs and the compounding of these environmental effects in materials being measured (Bogena et al., 2007). Low frequency devices (e.g., <100 MHz) were initially built due to their simpler design and low cost, however in the past decade cellular technology has lowered the cost of higher frequency components, resulting in competitively priced GHz frequency devices, which are less susceptible to these secondary effects (Chen and Or 2006). Dozens of commercially-available, EM-based soil moisture sensor designs can now be found worldwide with more being conceived of and developed every year (Figure 4.9, *next page*).

For developers or consumers of EM sensors, there is currently little information available that provides standardized sensor performance measures or evaluation criteria. Most of the literature on EM sensor comparison has focused on comparing several EM sensors in one or more porous media, generally in soils of varied texture. Some of the misinformation generated from such studies arise when evaluators are not aware of, or ignore, characteristics such as the sensor sampling volume. Standard testing criteria are needed to better inform developers and consumers. Jones et al. (2005) proposed standardized testing in liquids to characterize and compare EM sensing systems. Ideal standard liquids would be globally available and provide a homogeneous background as opposed to heterogeneous natural materials. The frequency dependent permittivity of the material under test (i.e., soil) can be used to estimate the apparent measurement frequency of a given sensor (Robinson et al., 2003). This can also be an indicator of the sensor measurement quality given the tendency of higher frequency measurements to be less sensitive to phase configuration, salinity and other secondary effects on permittivity.

Figure 4.9: Array of electromagnetic-based bore-hole (left) and insertable soil water content sensors.

Nonetheless, the plethora of sensor evaluations in the literature lead to some conclusions about the existing fundamental sensor technologies (e.g., Evett and Parkin, 2005; Evett et al., 2012). As pointed out by Evett et al. (2012) most of the existing EM sensor technologies use one of two physical approaches to sensing. One approach, and the most common one due to its relevant simplicity and lower cost, is to measure the resonant frequency of an oscillating electrical circuit composed of capacitors, inductors, resistors and a power source. In this approach, the EM field of one of the capacitors is coupled with the soil matrix either by inserting electrodes of the capacitive element into the soil or by placing the capacitive element in a plastic tube inserted into the soil. In the latter case the fringing EM field of the capacitive element pass through the tube wall and into the soil surrounding the tube. The various sensors based on capacitance principles relate the soil water content to some function of the resonant frequency. The geometry of the sensor's electromagnetic field strongly determines the value of capacitance and, therefore, the resonant frequency. Unfortunately, the geometric factor is not well defined for some capacitance-based soil water sensors, leading to both bias and scatter in the soil water data (Evett et al., 2005, 2008, 2012, etc.).

The other major electromagnetic approach to soil water sensing is time domain reflectometry or TDR. In the TDR approach, the travel time of an electronic pulse in a waveguide surrounded by soil (i.e., electrodes inserted into the soil) is related to the apparent relative permittivity of the soil. Although the electromagnetic field in the soil surrounding the TDR electrodes is subject to the same factors that influence the electromagnetic field of a capacitance sensor, there is no geometric factor in the equations, and the travel time is not influenced by the geometry of the electromagnetic field. Therefore, data from TDR sensors is often more accurate and less influenced by the small-scale soil structure, water content, and bulk electrical conductivity variations than the data from sensors based on capacitance principles.

Beyond the EM-based sensors commonly used in weather stations and sensor networks, there are newer, noninvasive technologies providing larger footprint estimates of soil moisture (Bogena et al., 2015). Among these is the cosmic ray neutron probe (CRNP, Figure 4.10, *next page*), which is a noninvasive technique to sense the areal averaged soil moisture with an effective depth typically between 10 and 50 centimeters and a circular footprint with a radius on the order of 200 hundred meters (M. Zreda et al., 2012; Marek Zreda et al., 2008; Köhli et al., 2015). Cosmic rays interact with nuclei of atoms in the atmosphere, water, vegetation and soil, leading to the emission of fast neutrons in the atmosphere, and those fast neutrons are mainly slowed or moderated by hydrogen atoms. The probe, typically

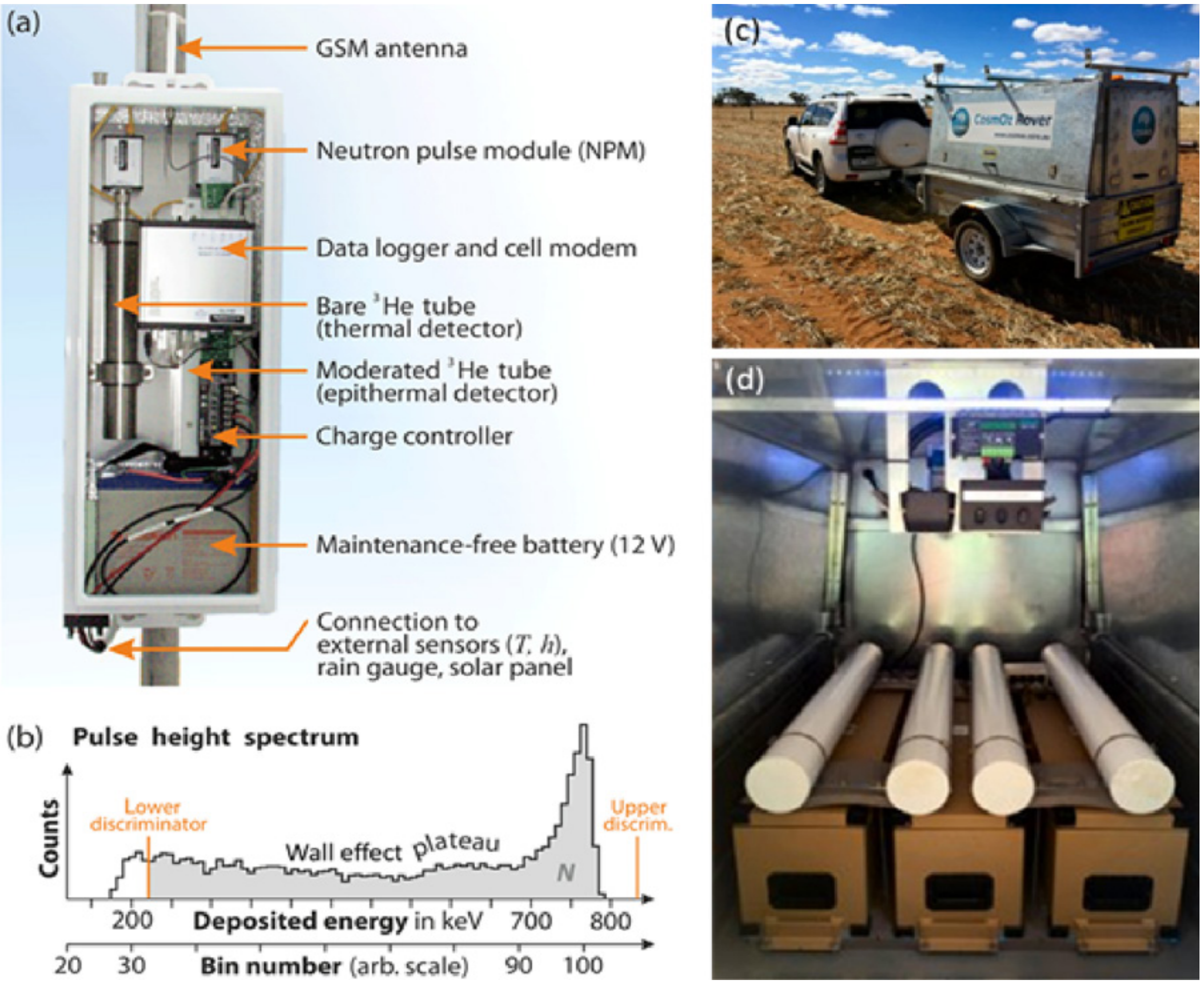

Figure 4.10: (*a*) Cosmic-ray neutron sensor system illustrating the basic components, (*b*) A typical, measured pulse height spectrum shows the deposited energy in the gas tube (Schrön et al., 2018b), (*c*) Mobile CRNP Rover, and (*d*) sensor array used for spatial mapping of soil moisture (CosmOz, 2019, October 21).

installed ~1 meter above the land surface, determines the count rate of these fast neutrons, and that count rate is inversely correlated with the soil water content. Several studies have characterized the response of the CRNP to soil moisture determined by direct sampling and by networks of soil water sensors installed at various depths. These studies have led to advances in the modeling of the neutron scattering and attenuation processes (Köhli et al., 2016), to improved understanding of spatial sensitivity (Martin Schrön et al., 2017) as well as better understanding of the influence of nonsoil constituents, such as vegetation (Lv et al., 2014; Baatz et al., 2015), roadways (M. Schrön et al., 2018a), etc. Networks of CRNPs are growing worldwide, with the original COSMOS network in the United States (COSMOS, 2019, October 23) and with Europe, the UK, China, and other countries building additional networks.

Another relatively new and noninvasive soil moisture sensing capability comes from Global Navigation Satellite System (GNSS) reflectometry. In this approach, near-surface soil water content can be estimated based on the interference pattern observed by a GNSS receiver positioned a few meters above the ground. Early work using the GNSS sensors showed promising relationships between this interference pattern and the soil moisture of the surrounding area on the order of 300 m2 (Larson et al., 2008). The GNSS interference reflectometry approach can potentially take advantage of existing GNSS receiver networks at sites where there are no trees or other verticals obstacles in close proximity to the receiver. For example, the National Geodetic

Survey (NGS), an office of NOAA's National Ocean Service, manages a Continuously Operating Reference Stations (CORS) network that provide GNSS data in support of three-dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States. The CORS network is a multipurpose cooperative endeavor involving over 230 government, academic, and private organizations managing sites that are independently owned and operated. Each agency shares their data with NGS who in turn analyze and distribute the data free of charge. The CORS network provides data from more than 2,000 active sites as of August 2018.

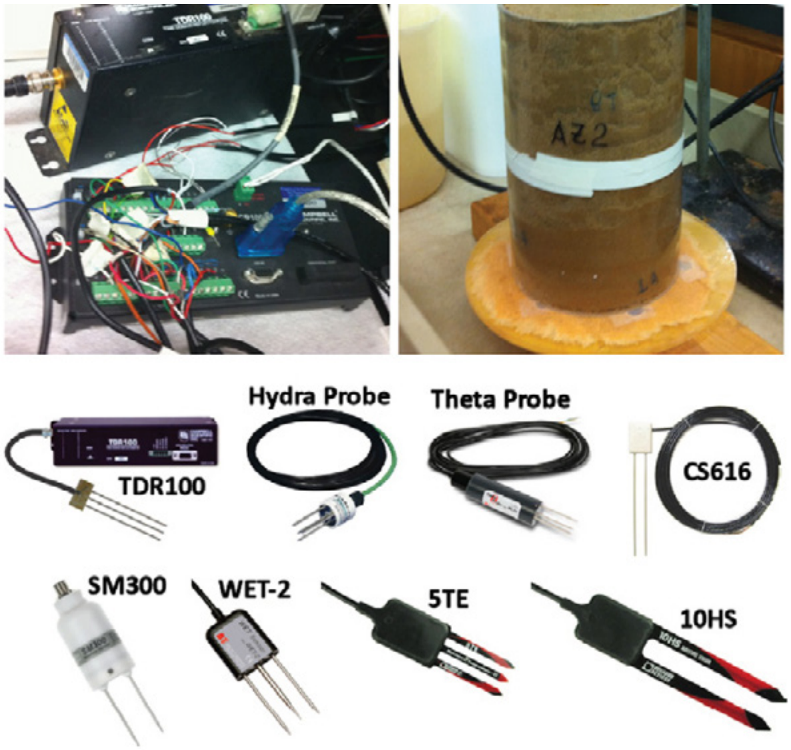

Figure 4.11: Eight electromagnetic soil moisture sensors evaluated by Vaz et al. (2013)

4.2.3.2 Approaches to sensor selection

Three possible approaches to sensor selection are: 1) precedent-based; 2) performance-based; and 3) feature-based approaches. Networks may also utilize some combination of these various approaches to guide sensor selection.

A precedent-based approach means that when a new network is established, the sensor is chosen to match the sensors in pre-existing networks. This has the obvious advantage of facilitating similarity across networks and consistency over time. A disadvantage is that it creates a bias against newer, and possibly better performing technologies. For example, USDA Agricultural Research Service (ARS) researchers in Durant, OK, evaluated commercially available sensors for long-term, automated soil moisture and temperature monitoring in the Little Washita River Watershed in 1994, and selected a heat dissipation sensor (CS-229, Campbell Scientific) as the best available option (Schneider et al., 2003). Soon thereafter, the OKM and the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program's Southern Great Plains Cloud and Radiation Testbed (CART) site followed this precedent and selected the same sensor for their networks. The OKM has used these heat dissipation sensors continuously since 1996, which is also the year in which the first peer-reviewed paper describing their performance was published (Reece, 1996).

Separate from these developments in Oklahoma, USDA NRCS staff in multiple states began to collaborate on a Soil Moisture and Soil Temperature Pilot Project in 1991 (NRCS, 2004). Soil moisture measurements were initially made using granular matrix sensors (Watermark, Irrometer), but the sensors were changed to impedance-based sensors (HydraProbe, Vitel) beginning in 1994. These sensors were developed based on the approach of Campbell (1990), and the first peer-reviewed papers including HydraProbe measurements appeared in 1998 (e.g., Nelson et al., 1998; Miller et al., 1998). Based on the Soil Moisture and Soil Temperature Pilot Project, the NRCS Soil Climate Analysis Network was established in 1999 and the HydraProbe sensors were selected for this first nationwide network. Based on this precedent, HydraProbes and the second generation HydraProbe II have subsequently been selected for use in other networks such as the NRCS SNOTEL network, the

Table 4.1: Soil water content accuracies provided by sensor manufacturers and root mean squared difference (RMSD) obtained by Vaz et al. (2013) for mineral soils with factory-supplied and soil-specific calibrations.

Sensor	θ accuracy, UM†		θ-RMSD‡	
	Factory	Soil specific	Factory	Soil specific§
	m^3m^{-3}			
Wet2	±0.050	±0.030	0.034	0.025
5TE	±0.030	< ±0.020	0.040	0.026
10HS	±0.030	±0.020	0.073	0.013
SM300	±0.025	–	0.037	0.014
Theta Probe	±0.050	< ±0.020	0.029	0.015
Hydra Probe	±0.030	–	0.048	0.028
CS616	±0.025	–	0.129	0.025
TDR100	±0.030	±0.020	0.023	0.022

† UM: from user manuals.
‡ From this study for mineral soils AZ2, AZ6, AZ9, AZ11, and AZ18.
§ Average soil-specific calibrations obtained for the mineral soils in this study (Table 6).

NOAA USCRN,[14] multiple USDA ARS experimental watersheds, and multiple state Mesonets.

A performance-based approach selects a soil moisture sensor based on evidence of its acceptable performance, where performance may include factors such as accuracy, precision, and durability. Sensor performance may be evaluated through laboratory testing in standard test media (Jones et al., 2005; Blonquist et al., 2005) or natural soils. Less commonly, sensor performance may be evaluated through testing in the field. Laboratory evaluation of soil moisture sensor performance is exemplified by the work of Vaz et al. (2013) who evaluated eight types of commercially-available electromagnetic soil moisture sensors (Figure 4.11, *previous page*). Such laboratory studies facilitate sensor evaluations in diverse soil types in a controlled environment and sensor accuracy can be summarized by statistical measures such as the root mean squared difference (RMSD) between the estimated and known soil moisture values (Table 4.1, *above*).

Field evaluations and inter-comparisons provide another valuable way of assessing soil moisture sensor performance. A benefit of field evaluations is that they provide better opportunities than lab experiments to learn about between-sensor differences in ease of installation, site disturbance, and durability. Sensors in field evaluations are also confronted with the real-world challenges of structured soil, soils with coarse fragments, and the inherent spatial variability of soil in situ. These challenges are a benefit in terms of providing a rigorous test, and they are also a drawback because they make it more difficult to know the true value of soil moisture for the sake of quantifying sensor errors. One such field evaluation is the Marena, OK, In Situ Sensor Testbed (MOISST) site (Cosh et al., 2016). Twelve different types of soil moisture sensing technologies have been intercompared at this field site, with seven of the sensor types replicated in four profiles installed in different soils (Figure 4.12, *next page*). As with laboratory evaluations, field evaluations like this also allow quantification of sensor accuracy when soil moisture can be independently determined by some standard method, typically by soil sampling and oven drying (Table 4.2, *next page*).

A third approach to sensor selection is feature-based in which a sensor type is selected because it inherently possesses a certain feature deemed necessary to the objectives of the measurements. For example, in 2004, during the planning phase for the National Ecological Observatory Network (NEON), it was decided that the soil moisture sensors must be "... retrievable to allow for regular calibration and maintenance" (Roberti et al., 2018). At the time, the only commercially-available, automatable sensors that offered this feature were tube-type capacitance sensors (e.g., EnviroSCAN, Sentek Pty.). This sensor type was then selected for deployment across NEON; however, subsequent laboratory testing showed an unacceptable root mean square error (RMSE) at 33 sites of 0.123 cm^3 cm^{-3}, necessitating the development of unique calibration functions for each site and depth (Roberti et al., 2018). Another example of feature-based sensor selection is the increasing

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[14] USCRN has now switched to Acclima TDR-315 for new installations.

use of CRNPs selected for monitoring networks such as the COSMOS network in the United States (Zreda et al., 2012) and the CosmOz network in Australia (Hawdon et al., 2014). Yet, there are no perfect sensors, and the CRNPs have a sensing depth that varies substantially with soil moisture, complicating interpretation of the data.

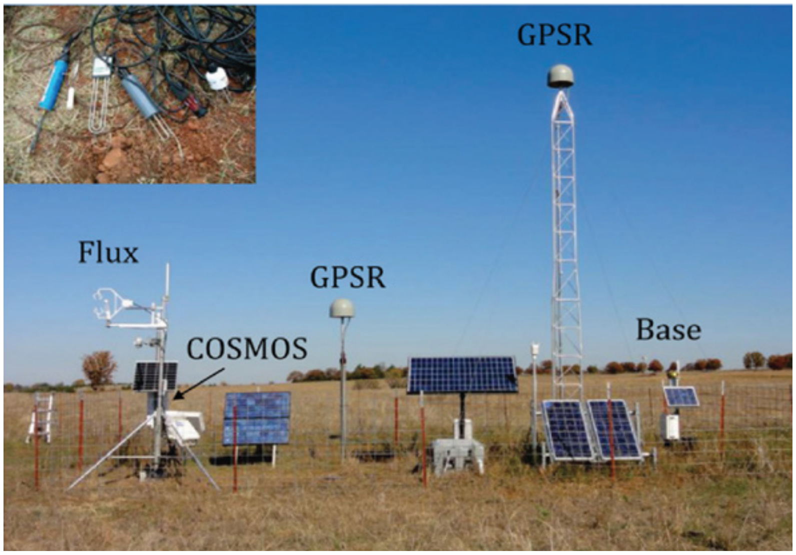
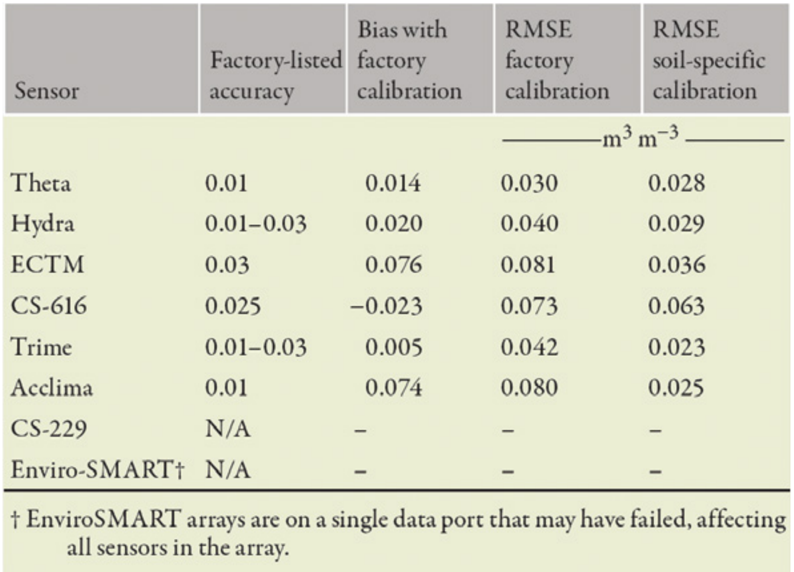


Figure 4.12: One of four sensor installation sites in the Marena, OK, In Situ Sensor Testbed (MOISST). The inset in the upper left shows several of the types of soil moisture sensors evaluated. Labeled in the main photograph are an eddy covariance system (Flux), a cosmic-ray neutron detector (COSMOS), and an antenna used for GPS reflectometry (GPSR), and one of four base stations to which the below-ground sensors are connected (Base).

4.3 ENGAGING USERS IN NETWORK DESIGN

In designing a network, there are often trade-offs because it is difficult to develop a network which meets all objectives efficiently. The design criteria detailed in the previous sections are based on the approach of providing a robust observation set that can generically define the amount of water in the soil. In addition to this approach, it may also be worth considering application-specific network designs. These approaches consider the expected value of observations at certain spatial, depth, and temporal resolution to support specific anticipated decisions.



Sensor	Factory-listed accuracy	Bias with factory calibration	RMSE factory calibration	RMSE soil-specific calibration
			$m^3 m^{-3}$	
Theta	0.01	0.014	0.030	0.028
Hydra	0.01–0.03	0.020	0.040	0.029
ECTM	0.03	0.076	0.081	0.036
CS-616	0.025	−0.023	0.073	0.063
Trime	0.01–0.03	0.005	0.042	0.023
Acclima	0.01	0.074	0.080	0.025
CS-229	N/A	–	–	–
Enviro-SMART†	N/A	–	–	–

† EnviroSMART arrays are on a single data port that may have failed, affecting all sensors in the array.

Table 4.2: Bias and root mean squared error (RMSE) for soil moisture estimated using factory calibrations and RMSE values for soil-specific calibrations for soil moisture sensors at the MOISST site (Cosh et al., 2016).

The first step to designing a monitoring network to support current and anticipated uses of soil moisture data is to review current uses of available soil moisture observations. Key user groups at the national level include the authors of the U.S. Drought Monitor and other USDA and NOAA (and non-Federal) entities responsible for producing conditions reports and forecasts. Key user groups to consult with at the state level include agricultural agencies, water resource managers, and other natural resource decision-makers. More details on the user community are provided in Chapter 6.

Ideally, users would be polled to determine the locations and depths of soil moisture information that have been found to be most useful to inform their decisions. Data may be used directly, as for drought monitoring, or indirectly by constraining a model that informs anticipated wildfire activity, explores biological activity, or that projects the impacts of climate change on groundwater availability. A similar exercise could be completed to ask those whose decisions are most affected by soil moisture data to identify gaps in data that would best support their decision-making process. Finally, it is worth considering how to identify and survey key potential data users. One example is foresters, who currently do not often consider soil moisture in their assessments.

A survey of current and anticipated soil moisture data needs may uncover that some proposed observation locations or depths will be highly valued by an already-identified user group. This should imply prioritizing these elements within the network design. The survey may also indicate that the user groups do not foresee the value of some proposed soil moisture observations. This should guide network designers to carefully consider their rationale for including such observations. More likely the user group will identify needs for more station locations or measurement depths than are planned in the initial design. This may include higher spatial and/or temporal resolution, seasonal observations, or episodic observations.

In the likely event that users request more information than can be supported by the monitoring budget, a formal analysis can be completed to identify the most broadly useful subset of observations. These analyses can be based on reducing redundancy by, for example, replacing some generic elements (e.g., a single observation at a location) with a higher resolution local network (e.g., a set of observations designed to answer a question that requires high resolution near-surface observations). Similarly, regularly timed observations can be included as part of short duration surveys with higher temporal resolution. This redundancy reduction can serve both the regular data stream and question-specific data needs.

Even after forming a hybrid regular/focused network, it is likely that the number of observations will not be economically viable and fewer stations than desired will be available for deployment. At this stage, an approach like robust decision-making under uncertainty (RDM) can be applied. These approaches essentially require soil moisture data users to consider second and third best options for data to support their decision-making (Clutter and Ferré 2019). The full data set, comprised of all requested observations, forms the full set of hypothetically available observations. Users are tasked with describing how their selected alternative data subsets could be used to support their analyses and with predicting the impact of using these alternative data on the quality and/or costs of their decisions. RDM or similar approaches can then be used to explore the data space to describe the cost of measurement subsets. Ultimately, the network design will represent a trade-off decision that attempts to equitably provide sub-optimal data to all users with the greatest utility under given budgetary restrictions.

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

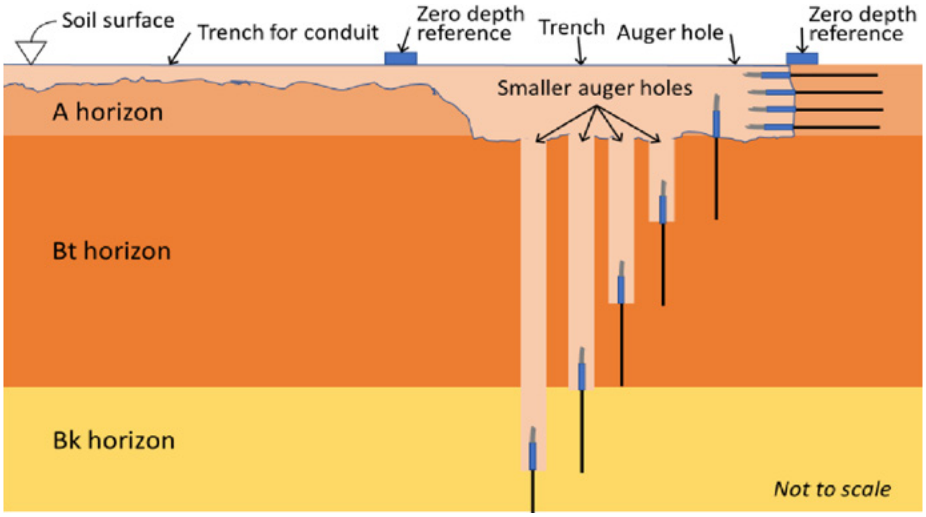


Figure 5.1: Installation of sensors horizontally into the side and vertically into the bottom of a trench pit and vertically into auger holes made in the bottom of the trench. The zero depth references span the trench and rest on the soil surface on either side.

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.

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[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.

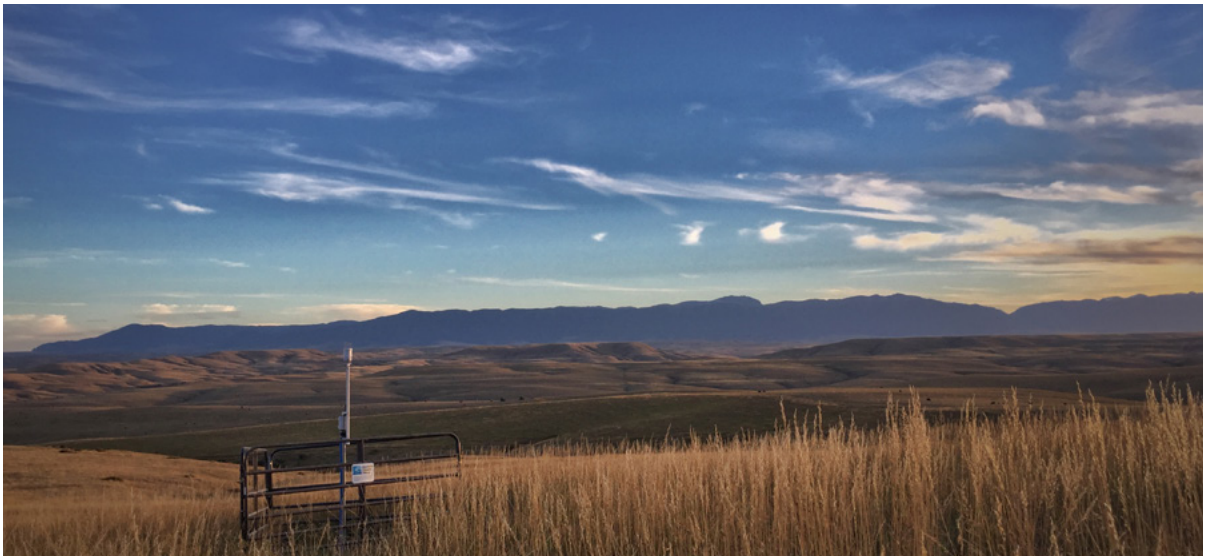
5.6.4 Spatial Coherency

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.



Montana Mesonet Station above Cooney Reservoir, Stillwater County, MT. Credit: Kevin D. Hyde

CHAPTER 6

IMPLEMENTATION OF THE NCSMMN: THE PATH FORWARD

6.1 NATIONAL NETWORK DESIGN

The work of the NCSMMN will leverage, collaborate with, and support existing Federal, state, multistate, and local monitoring efforts for soil moisture. The point-based (i.e., in situ) soil moisture data from participating networks will be enhanced by aggregating and integrating the datasets in one place, and by creating end products that add value by, for example, visually showing the current spatial status of soil moisture across the entire United States. The NCSMMN will support efforts to develop standardized and consistent metadata for monitoring networks, including sampling and characterization of soil physical properties necessary for quality assurance and interpretation of soil moisture observations. The NCSMMN effort will also continue to explore ways to merge the in situ soil moisture data with remotely-sensed and modeled soil moisture products in order to create real-time, high-resolution, gridded national soil moisture maps and other meaningful products and services. The NCSMMN does not replace existing monitoring programs, rather, it is focused on coordinating and improving the status of soil moisture monitoring efforts nationwide for the benefit of applications such as drought and flood monitoring, groundwater recharge estimation, streamflow forecasting, and fire danger ratings.

The overriding mission of the NCSMMN is to provide "… coordinated, high-quality, nationwide, soil moisture information for the public good." What follows in this implementation chapter are a set of steps or recommendations to allow NCSMMN to fulfill this mission.

The first step in the process of developing a national network is to continue to expand the community of experts schooled in the different aspects of soil moisture monitoring. Annual National Soil Moisture Workshops have brought together experts from across the United States to discuss the latest science research and technical innovations regarding soil moisture monitoring and applications.

These workshops provided the initial formation of a community of practice. As the implementation of this Strategy begins, a key recommendation is to support an annual meeting dedicated to improved soil moisture monitoring and new uses for soil moisture information. This would include information from in situ sensors, remote sensing, and modeling. These technologies interact and improve each other, building a better national coordinated network. The recently renamed, community-led, annual National Soil Moisture Workshops, which were initiated by Oklahoma State University and the USDA Agricultural Research Service in 2011, have evolved to a nationwide audience with close to 100 attendees annually. Recent workshops were held in Lincoln, NE (2018), and Manhattan, KS (2019), with the 2020 workshop already in planning and slated for Beltsville, MD, in August.

A near-term goal of the NCSMMN is to engage in situ monitoring networks to improve the availability of their data to user groups across the United States, as well as to improve the quality of soil moisture data by providing standards and quality assurance recommendations. This activity requires outreach to the current state and regional mesonets, some of which must generate their own revenue, in part through data fees. Securing Federal or encouraging sustained state funding is one possible means to encourage participation in the broader network. Since each mesonet is unique, individual discussions should be held with each mesonet, with a goal of being equitable across the national landscape. As a part of this process, an evaluation of current data quality is necessary to determine whether the data being collected is suitable, accurate, and representative for drought monitoring purposes, as this is one of the key objectives of the NCSMMN. The approach of Ford and Quiring (2019) provides one way to complete this evaluation.

There is an obvious need for more accurate, abundant, and real-time soil moisture information, which has led the NCSMMN to prioritize making real-time, high-resolution, gridded national soil moisture maps and other meaningful products available for user groups and other stakeholders across the country. The potential to create daily 800-m resolution soil moisture maps for multiple soil depths using data from in situ monitoring networks has already been demonstrated in Oklahoma (Ochsner et al., 2019). Creating similar maps at the national level may include developing new soil moisture products or operationalizing or increasing the visibility for high-quality products that already exist. The data sources for the products may include in situ, remotely-sensed, or modeled data, or merged product(s) that combine multiple sources of data.

A longer-term goal of a NCSMMN is to develop a process to guide the initiation and development of future in situ resources to maximize the societal benefits of soil moisture monitoring across the United States. An early case study of this process in the Upper Missouri River Basin has demonstrated a rapid expansion of in situ stations specifically to address data scarcity in that region (highlighted in Appendix A). This guidance will be ongoing and require a significant amount of representation and engagement with state mesonets, regional networks, commercial and private interests, and citizen science consortiums. The formation of an NCSMMN committee or board with the specific goal of maintaining broad engagement with individual partners is one possible pathway to achieving this goal.

6.2 NETWORK ESTABLISHMENT

6.2.1 Existing Networks

One immediate action of the NCSMMN is to establish working relationships with existing and emerging networks to provide soil moisture data to a central repository. Once agreements are in place, necessary hardware, software, and human oversight procedures must be put in place for the automated ingest, standardization, and integration of data from the networks and for creation of consistent nationwide in situ soil moisture data sets. This will be of immediate benefit to efforts such as the U.S. Drought Monitor. As such, a mechanism must be established to encourage participation in the National Coordinated Soil Moisture Monitoring Network, either via funding or additional resources.

Ideas and recommendations relating to incorporating data from existing networks were formed in collaboration with state mesonets listed in Table 6.1 (*next page*) through two different opportunities for feedback and discussion. The first opportunity was during an in-person meeting at the American Association for State Climatologists on June 26, 2019, in Santa Rosa, CA, and the second was a virtual meeting on July 8, 2019.

Table 6.1: Opportunities for state mesonets to participate in NCSMMN discussions specific to NCSMMN-mesonet collaboration occurred on June 26, 2019, at the American Association for State Climatologists Meeting in Santa Rosa, California and virtually on July 8, 2019.

List of State Mesonets that Participated in NCSMMN Discussions

South Alabama Mesonet (AL)	Delta Agricultural Weather Center (MS)
California Irrigation Management Information System (CA)	Montana Mesonet (MT)
Colorado Agricultural Meteorological Network (CO)	North Carolina ECOnet (NC)
Delaware Environmental Observing System (DE)	North Dakota Agricultural Weather Network (ND)
Florida Automated Weather Network (FL)	New Jersey Weather and Climate Network (NJ)
Georgia Weather Network (GA)	New Mexico Climate Network (NM)
Iowa Soil Moisture Network (IA)	New York State Mesonet (NY)
Indiana Water Balance Network (IN)	Ohio Agricultural Research and Development Weather Network (OH)
Purdue Automated Agricultural Weather Stations (IN)	Oklahoma Mesonet – University of Oklahoma/ Oklahoma State University (OK)
Illinois Climate Network (IL)	Pennsylvania Mesonet (PA)
Kansas Mesonet – Kansas State University (KS)	South Dakota Mesonet – South Dakota State University (SD)
Kentucky Mesonet – Western Kentucky University (KY)	West Texas Mesonet – Texas Tech University (TX)
Michigan Enviro-Weather (MI)	

6.2.2 Data Aggregation

The primary goal of the NCSMMN is the aggregation of data from existing soil moisture monitoring networks into a curated, spatially representative database for the production of real-time, high-resolution, gridded national soil moisture maps and other meaningful products and services, the need for which is discussed in Section 6.4. Existing monitoring networks were created for a variety of purposes and provide data that are not uniform with respect to monitoring depth, sensor type, or accuracy, and are disparate with respect to metadata about the monitoring locations. Consequently, the NCSMMN must determine, in partnership with the data providers across the country, the most efficient, logical, and collaborative way to aggregate and mediate data from the various networks.

One potentially useful platform for data ingest, archiving and delivery, is NOAA's Meteorological Assimilation Data Ingest System (MADIS). MADIS, as its name implies, is a meteorological ingestion system, and it has the ability to bring together data from NOAA sources, other Federal sources, and non-Federal sources. Ingest, quality control, and archiving are done in near real-time. Data are homogenized by removing dissimilarities in time resolution, timestamps, units, and variable names, and data can be retrieved through a variety of channels, including: ftp/LDM (netCDF), API, web services, etc.[16] Gridded products for certain atmospheric variables are available as well. Finally, MADIS' observation portfolio of hydrometeorological variables related to soil moisture (soil temperature, precipitation, atmospheric variables for calculating evapotranspiration, etc.) further strengthen the case for using MADIS.

The portion of hydrometeorological data collected by non-Federal entities like state mesonets and commercial entities is increasing. NOAA's National Mesonet Program[17] (NMP) manages contracts with a coalition of mesonets to offset the costs of operation, while at the same time saving taxpayers by only paying for the data rights needed to produce derived products such as gridded data sets. The program has been very successful for NOAA, and has made large amounts of data available from a wide

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[16] ftp and LDM are internet data transfer protocols; API or "application program interface" allows for direct application programming; and web services would include web-based data access.

[17] *https://madis.ncep.noaa.gov/national_mesonet.shtml*

variety of sources at reduced expense.[18] Acquisition of rights to soil moisture data is already a part of the mission of the NMP, and agreements stipulate delivery of the data to MADIS. It is noteworthy that the majority of quality stations in the country with soil instrumentation are non-Federal and mostly state mesonets.

The NMP grew from a National Academy of Sciences report that established the need for a nationwide "network of networks" for a Weather-Ready Nation. This report focused on the need to acquire high-resolution, lower-latency data from all available observational datasets, both Federal and non-Federal.[19] The NMP provides the National Weather Service (NWS) with data from approximately 35,000 real-time weather stations, including surface and upper-air data from mobile platforms such as vehicle- and aircraft-mounted sensors. Since its inception in 2009, the NMP has become an expansive network of 40+ partners nationwide including participants from the public, private, and academic sectors. By leveraging observations from these partners, the NMP is able to fill large temporal and spatial data gaps across the country for a fraction of the cost of establishing and maintaining stations. More high-quality data leads to more accurate forecasts and more well-informed decision-making during critical weather situations. A majority of the current state networks that measure soil moisture are partners of the NMP and are routinely providing data to this effort for other measured variables like temperature and precipitation.

6.2.3 Data Ownership

An important topic for the NCSMMN and its data aggregation and product development efforts is acknowledging that the existing monitoring networks will always own their data. The NCSMMN can serve as a national clearinghouse for NCSMMN-derived data products (e.g., a standardized nationwide in situ data set, gridded maps) and metadata from all contributors, but all data provenance and maintenance will be the responsibility of the data providers. Therefore, a set of protocols will need to be instituted that protect data ownership and manage other aspects of organizational engagement. As one example of such protocols, in order to ensure data consumers understand the proper authority for the data, source statements should be included in a consistent format for every distribution of data from the NCSMMN.

Many state monitoring networks rely on subscriptions (pay-for-data) to subsist, and for several, soil moisture data is the highest source of data income. Due to this, the NCSMMN will not distribute the raw data from the state monitoring networks unless the state network elects to do so.

6.2.4 Resources and Technical Assistance Needed for Monitoring Network Partnerships

For robust participation in the NCSMMN by non-Federal monitoring networks, financial compensation is required. Network operators have noted that this compensation would help support the following: network operations and maintenance in order to gather, disseminate, and sustain data collection, purchasing and installing new sensors to either start or expand soil moisture monitoring, personnel time to facilitate the automated data transfer process, and soil characterization expenses. The compensation might also be used to offset additional costs to meet NCSMMN requirements.

Networks have also requested technical assistance in siting stations, soil characterization, data interpretation, sensor selection and calibration, installation, QA/QC, and data management guidance, and communication. Partnerships with programs such as USDA's NRCS for necessary soil characterization (i.e., data by depth on soil type, bulk density, texture, wilting point, field capacity, etc.) at the monitoring sites would provide important information that would aid both the networks and the NCSMMN in data interpretation and communication. Communication of the value of their data, and useful ways to share data and educate others is an important topic for networks, and one which the NCSMMN and networks could explore together. The technical assistance described in this paragraph could provide benefits to the participating networks beyond financial compensation, as well as to the broader NCSMMN community.

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[18] It should be noted that the NMP allows mesonets to constrain the use of their data to within NOAA.

[19] Further impetus for collaborating with non-Federal partners comes from the Weather Research and Forecast Innovation Act of 2017 (P.L. 115-25), which directs NOAA to seek out opportunities to enlist non-Federal partners to provide supplemental data services.

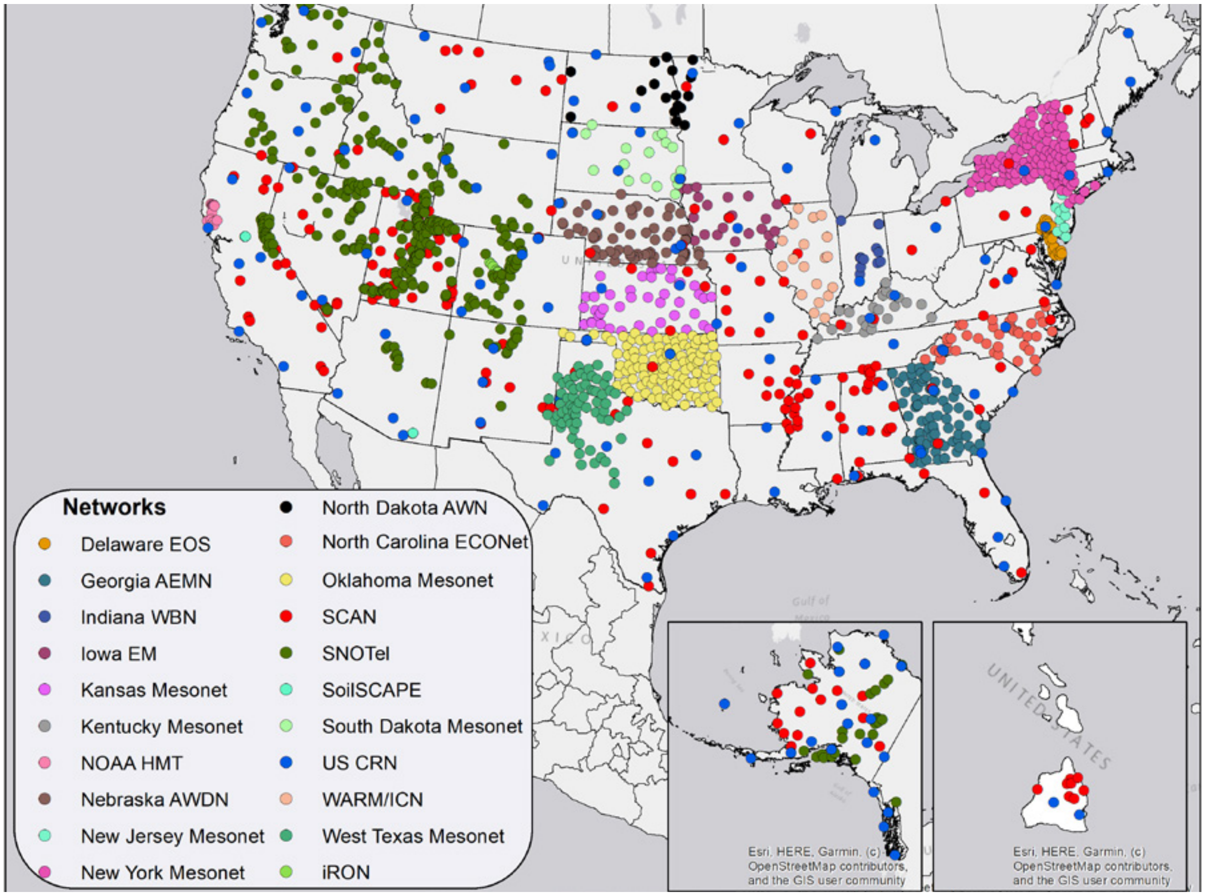

Figure 6.1: Locations of select in situ soil moisture sensor networks across the United States from federal- and state-level networks. (Source: *nationalsoilmoisture.com*)

6.2.5 Expanded Monitoring

The effort to standardize and integrate soil moisture data from existing monitoring networks is a necessary but not sufficient step for fulling the NCSMMN mission. There must be a strategic and coordinated increase of in situ soil moisture monitoring stations across the United States. New monitoring stations are essential because large areas of the United States have either no soil moisture monitoring stations or an inadequate density of stations (Figure 6.1, *above*). The roughly 2,000 long-term soil moisture monitoring stations in the United States today will need to be increased by 50% to reach the National Research Council's target of approximately 3,000 stations (National Research Council, 2009). Furthermore, the unequal distribution of the existing stations implies that the actual number of stations needed may be substantially higher than that target. Chapter 4 in this document describes approaches for determining where additional stations should be located.

New soil moisture monitoring stations are also needed because existing networks do not adequately represent the various major land cover types across the United States. Two notable deficiencies are forests and cropland. Few, if any, of the stations in the existing long-term monitoring networks are located under forest canopies, outside of the NEON network. Some may be located in clearings in a forest, but unless the sensors are directly beneath the forest canopy, the resulting soil moisture values may not be representative of the forest landscape. Under-canopy stations face a combination of logistical challenges, including power, connectivity, and access for maintenance. In concert with the U.S. Forest Service as well as state forest managers, the NCSMMN should develop plans for implementing soil moisture monitoring stations for beneath forest

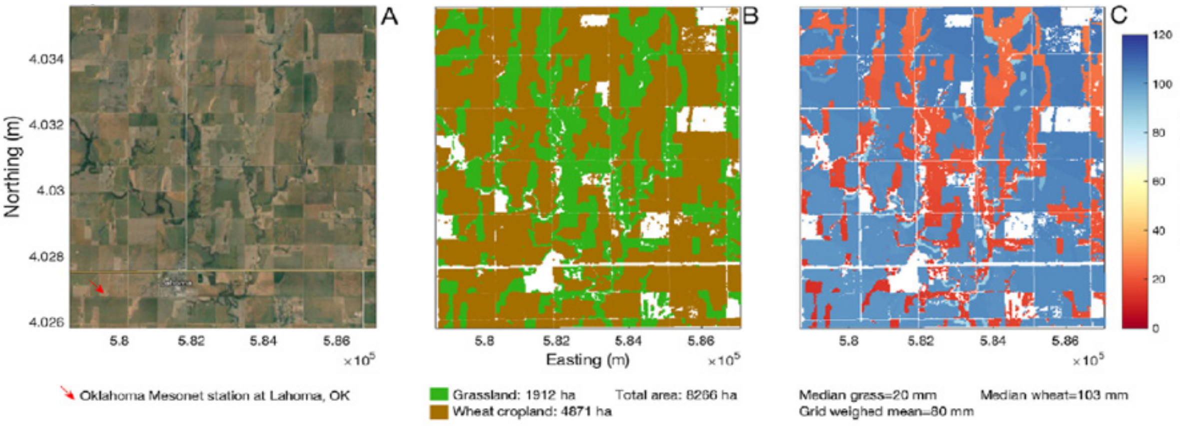

Figure 6.2: (*A*) Orthophoto, (*B*) grassland and winter wheat cropland area, and (*C*) estimated plant available water (PAW) in the top 0.8 m of the soil profile for a SMAP grid cell (FID: 153137, row: 329, column: 877) on 15 Oct 2011 near the Lahoma Oklahoma Mesonet station. Reproduced from Patrignani and Ochsner, 2018.

canopies. The data from such stations could have tremendous value for forest drought monitoring, fire danger rating, and water supply forecasts in forested regions.

The lack of long-term soil moisture monitoring stations in cropland is commonly overlooked and is surprising to many people. Long-term monitoring stations are not placed in cropland because normal agricultural operations such as tilling, planting, spraying, and harvesting all have potential to damage the monitoring equipment. Many soil moisture monitoring stations are adjacent to cropland, but research has proven that strong and temporally unstable differences exist between the soil moisture in cropland versus that in the adjacent uncultivated landscape (Han et al., 2012). For example, in the fall of 2011 the soil moisture under pasture and rangelands in northwestern Oklahoma was severely depleted while the soil moisture under adjacent winter wheat cropland, which had been fallow during the summer, was near field capacity (Figure 6.2c, *above*; Patrignani and Ochsner, 2018). Such contrasts between cropland and the adjacent uncultivated land cannot be represented by any of the existing in situ monitoring networks. There is a clear need for the NCSMMN to work with the USDA to develop and deploy long-term monitoring stations that are suitable for the unique challenges of cropland monitoring. This is particularly true because of the often-severe impacts of drought on crop production, and the large role of the Federal Government in crop insurance and disaster payments. It should also be noted that separate from long-term monitoring, there may also be a role for temporary, periodic monitoring efforts designed to inform model-based approaches.

6.3 DATA QUALITY STANDARDS AND ASSESSMENT

A frequent assumption within the applications and end-user scientific communities is that collecting in situ soil moisture data starts and ends with putting a sensor in the ground; whereas, it is widely understood within the mesonet community that putting sensors in the ground is somewhere in the middle of the never-ending process of in situ data collection. Landscape scouting, ancillary data set analysis (soil properties representation), dominant climate and weather patterns, as well as macro- and micro-topography are just some of the initial steps in the process, all before sensor installations. Other steps in the process include sensor selection, installation using best practices, calibration, maintenance, scaling studies, quality assurance, and data curation. Occasional reassessment of network function can help to refine and optimize the effort required to keep a large-scale network operating. Equipment replacement and recalibration are normal. These steps are all a part of a rigorous installation and maintenance protocol that the NCSMMN hopes to establish and evolve with changing technologies.

On the topic of sensor performance, as noted in Section 4.2.3, there are currently no common standards among sensor manufacturers pertaining to sensor performance and verification/evaluation, with each manufacturer using their own procedures. The NCSMMN will work to promote the adoption of common standard testing criteria so sensors can be more easily compared.

Collecting high-quality soil moisture data can be a complicated and time-consuming process, but it is ultimately necessary if the value of soil moisture data is to be fully realized. Another assumption often made by data end-users is that all data in a data archive is of good quality, but it is too often the case that in situ sensors are not well calibrated and/or are not representative of the larger landscape. A related issue is that some networks have had soil moisture sensors added after siting and installation of the station has been completed with another set of observation variables as the focus. What is needed for the NCSMMN is a verifiable soil moisture dataset that can be used by operational decision makers to demonstrate that value that soil moisture information adds to their process.

Therefore, it is proposed that a protocol or set of criteria be established to assess and categorize the quality of in situ soil moisture networks. These criteria will have clear minimum threshold for quality control practices that lead to networks being categorized as producing high (versus moderate- or provisional-) quality soil moisture data. These categories will help guide data users as to their appropriateness for different applications. Meeting the high-quality standard will require items such as adequate metadata, calibration information, an appropriate site maintenance schedule, and post installation soil sampling to determine data accuracy and representativeness. To initiate this activity, it will be necessary to coordinate evaluations of networks against this set of criteria. Once established, regular reviews of network qualifications as well as evaluating new networks will need to be managed by dedicated personnel. A pilot study of this type could be initiated to demonstrate the process and form the initial set of NCSMMN sites.

To focus efforts on data quality and representativeness, one consideration is to provide financial compensation to contributing networks on a sliding scale, based upon the degree to which the network meets the agreed upon quality criteria. In initial discussions with mesonet operators, this idea was supported by many. Those quality criteria could be based on factors such as:

- Completeness of the soil moisture data;
- Accuracy of soil moisture data quantified by post-installation sampling;
- Data latency;
- Measurements of not only soil volumetric water content and soil temperature, but also other meteorological variables such as precipitation and potential evapotranspiration;
- Characterization and documentation of relevant soil properties for the site;
- Availability of site photos;
- Length of observational record; and
- Location in a relatively unmonitored region.

Other criteria for high quality are also worth considering. One example (discussed in 5.6.2) is whether the network has triplicate sensors rather than single ones. Triplicate installation provides redundancy that supports data quality and the identification of failure; however, this would mean less spatial distribution for the same capital outlay, and for many networks data gaps might be more of a priority to address. Thus, this type of consideration might be characterized as an eventual goal, rather than a near-term quality criterion.

The quality of a network (and of each individual station within a network) can change over time, so regular evaluation of network quality should be a part of the NCSMMN effort. Networks that do not meet the standards to be labeled as “high quality” can be accepted into the NCSMMN, but at a lower grade or status. Operators of such networks are encouraged to meet these standards to the degree possible. Another consideration is to make funding available for networks to improve and/or expand their soil moisture monitoring.

6.4 NATIONAL SOIL MOISTURE PRODUCTS FROM THE NCSMMN

6.4.1 The Value and Uses of NCSMMN Soil Moisture Products

The creation of near real-time, meaningful, and easy-to-understand soil moisture products from the NCSMMN is crucial to reduce societal risks from hazards such as drought, flood, and fire. These products will help contribute to better hazard early warning systems, improve characterization of national water budgets and climate models, boost crop production and resilience, and benefit many additional user groups.

To promote utilization of NCSMMN data in different applications (e.g., drought or flood monitoring, planting guidance, water management), research needs to be conducted to determine the data accuracy and impact of the data. Decision-makers need to partner with soil and mesonet scientists to understand the metrics involved in the estimates of soil moisture and how to best use the data in the decision process. The uncertainties of soil moisture estimation have many nuances that cannot be evaluated with a single metric.

One of the key user groups are the authors for the U.S. Drought Monitor (USDM),[20] and an important early goal of the NCSMMN is creating products that will increase the availability and accuracy of soil moisture data to the authors as they determine drought status for this highly referenced national product. The Agriculture Improvement Act of 2018 calls for USDA and NOAA to coordinate with the director of the National Drought Mitigation Center (NDMC) to enhance the collection of data to improve the accuracy of the USDM. In addition, it states that USDA should, to the maximum extent practicable, develop standards to allow the integration of meteorological or climatological data into the USDM, and it specifically identifies in situ soil moisture monitoring.[21]

Another user group is the USDA National Agricultural Statistics Service (NASS), which conducts weekly national top and root zone soil moisture surveys and publishes weekly cropland soil moisture statistics at the state level in the Crop Progress and Condition Report,[22] and the Crop Weather Report. Currently, the assessment is conducted manually by visual observation and tactile sensing without instrumentation, and the assessments are qualitatively classified into four categories of very short, short, adequate, and surplus for both top and root-zone soil moisture. In the future, NASS could utilize NCSMMN soil moisture data to improve their soil moisture assessment, particularly if the data also incorporated crop type information. Another USDA agency, the Risk Management Agency (RMA), could use the soil moisture data and products to refine yield validation models, and it would also be useful in developing environmental models that would complement RMA's existing daily data stream of precipitation, temperature, and vapor pressure deficit data at an 800-meter spatial resolution.

Within NOAA, the River Forecast Centers (RFC) also utilize soil moisture data and would welcome additional products and sources of data. Soil moisture data has been incorporated as a qualitative check on their hydrologic models at the North Central RFC as a part of a recent NASA project. This effort could be expanded to other RFCs. In addition, soil moisture products that put the soil moisture state at a particular time in a historical perspective are helpful in messaging anticipated flood and/or drought threat. Finally, actual soil moisture data along with soil temperature at different depths can be used when the RFCs analyze the effects of frozen soils on runoff.

Two potential Federal user groups include the U.S. Forest Service (USFS) and the U.S. Environmental Protection Agency (EPA). The USFS is increasingly focused on soil moisture as an indicator of forest health and wildfire risk. And the EPA is interested in soil moisture data to enhance modelling of carbon stock changes in soils, and potentially nitrous oxide emissions as well, as part of the national Greenhouse Gas inventory.

Other user groups on the local and regional level include local NOAA National Weather Service Weather Forecast offices, local USDA offices, NIDIS' Regional Drought Early Warning Systems (DEWS), USDA Regional Climate Hubs, NOAA's Regional Climate Centers, the U.S. Army Corps of Engineers (USACE), the Department of Interior's Climate Adaptation Science Centers, state and local agencies, and others.

Finally, one emerging user group worth mentioning is the public health sector. Public health agencies and health researchers are increasingly recognizing the connections between human (and animal) health and soil disease vectors. There are many soil-borne diseases, and changes in soil moisture can have a direct relationship to disease outbreak

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[20] *https://droughtmonitor.unl.edu/*

[21] *https://www.ers.usda.gov/agriculture-improvement-act-of-2018-highlights-and-implications/*

[22] *https://www.nass.usda.gov/Statistics_by_State/index.php*

for such diseases as valley fever, crop diseases, Toxoplasmosis, and Hantavirus (see for example: Coopersmith et al., 2017). Federal as well as state or local health agencies are therefore potential user groups.

The indisputable need for more accurate, abundant, and real-time soil moisture information has led the NCSMMN to prioritize making more soil moisture products that provide information for the needs described above available for stakeholders across the country. This may include developing new soil moisture products or operationalizing or increasing the visibility for high-quality products that already exist. While the focus is primarily on in situ observations, other data sources would also be utilized including remotely-sensed or modeled soil moisture estimates. The NCSMMN will also support the development of merged product(s) that combine multiple sources of data.

6.4.2 User-Specific Needs for National Soil Moisture Products

In order to determine user-specific needs for national soil moisture products, the NCSMMN has had discussions with several user groups, which have included the USDM authors, state-based mesonet operators, USDA Risk Management Agency, USDA National Agricultural Statistics Service, and NOAA River Forecast Centers.

The following list describes user needs identified thus far:

Accessibility of Products

- The suite of NCSMMN soil moisture products should be made available free online to all users. Many users also prefer some sort of interactive map/products as well, ideally with the option of creating a URL that automatically zooms into a specific area.
- Product(s) should be available in standard formats like CSV, txt, GeoTiff, machine readable, and common GIS formats. It would also be ideal if there are multiple layers of data that could be toggled on and off.
- Product(s) should be a form that can be pushed to users or that is accessible via automated downloading programs or scripts.

Format of Products

- There is a desire to have product(s) in the form of absolute values and their associated uncertainties, anomalies, and percentiles (with percentiles represented according to the same scheme used by the USDM).
- Products should be available in the form of time series for specific locations as well as gridded maps at the state and national levels.
- Soil moisture data is most helpful when it includes data from various depths, including both topsoil (top ~10cm) and root-zone (~10 cm to ~100cm) soil moisture.
- Due to inconsistency of density of in situ data, a product with point data should be made available. It might be helpful to have clickable points to bring up more information, like moisture availability at different depths. An example of how this could be displayed is from the South Dakota Mesonet[23] (see Figure 6.3, *next page*).
- It would be helpful to have a product expressing the soil moisture level in terms of crop water availability according to the scheme used by NASS (i.e., very short, short, adequate, and surplus).
- Soil temperature is a popular companion alongside soil moisture data for many users. For example, it is critical to see soil temperature data alongside soil moisture data for those concerned about the effect of frozen ground.

Frequency of Release

- Weekly or more frequent products and/or observations are needed for drought monitoring. For the USDM in particular, the cutoff time for data for inclusion in weekly map is 12z Tuesday, so products need to be available by early afternoon on Tuesday every week (though earlier products would be useful for first drafts).
- Other uses of soil moisture data require daily, or in some cases, hourly data.

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[23] *https://climate.sdstate.edu/*

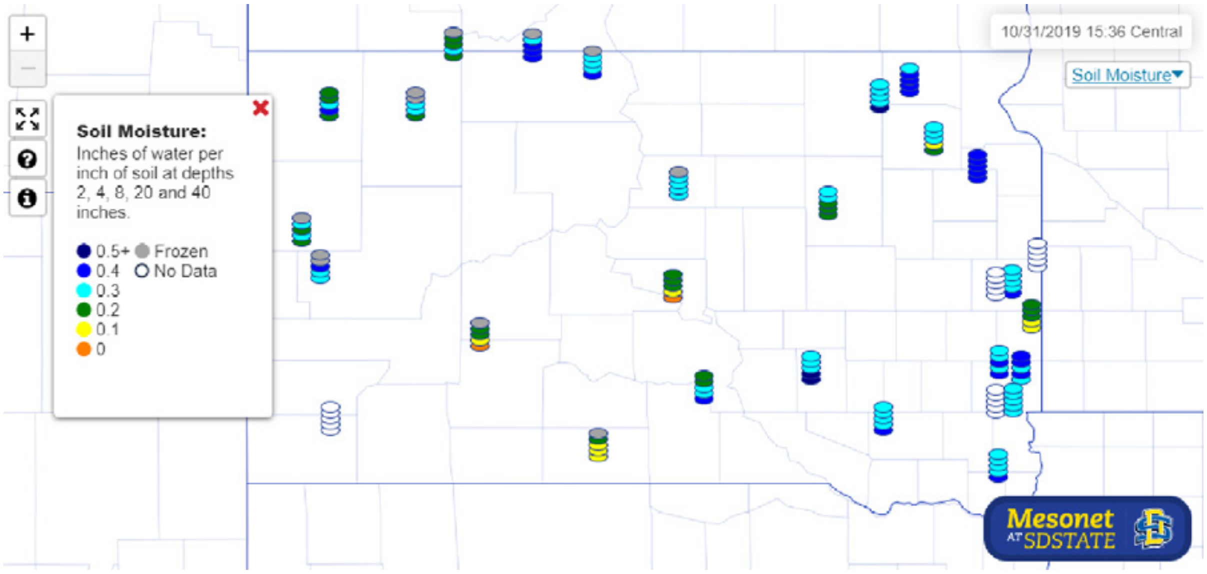

Figure 6.3: Example of displaying soil moisture data at various depths from the South Dakota Mesonet.

Spatial Coverage

- Preferred resolution for gridded data is at a maximum 4-km, but preferably 800-m spatial resolution.
- Since the USDM covers not only the contiguous United States but also Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands, and the Pacific Islands, the USDM authors would like to see products covering these other areas as well.

6.4.3 Creating and Hosting a Suite of NCSMMN Soil Moisture Products

The NCSMMN aims to create a suite of real-time, meaningful, and easy-to-understand soil moisture products. The data sources within this suite of products will focus primarily on in situ observations and may be complemented by remotely sensed or modeled soil moisture estimates to produce merged products.

One of the first steps is to determine what entity will host the suite of NCSMMN national soil moisture products. One logical possibility is to have a NOAA program host this suite of products. Primarily, housing the suite of products within NOAA significantly increases the amount of data that is available for use in those products, due to the existing structure and agreements within NOAA's National Mesonet Program. NOAA programs have access to NOAA-only data within MADIS in addition to public domain data. While this NOAA-only data cannot be redistributed outside of NOAA, derivative data—such as an NCSMMN gridded product—could be. Other Federal agencies that could logically be involved or serve as the NCSMMN host include USDA, because it has a long history of soil moisture monitoring and the largest Federal monitoring networks, and USGS, because it is already tasked with monitoring surface water and groundwater. Soil water is the logical missing piece that is intrinsically linked to surface water and groundwater.

Another key step is to begin developing new soil moisture products, supporting the necessary research, and leveraging new collaborations through the NCSMMN effort. As discussed in section 6.2.2, it is recommended that aggregation of in situ data from monitoring networks be done through collaboration with the NOAA's National Mesonet Program and its existing database, MADIS. From there, the data will be used to develop a set of products, based on in situ soil moisture data. Necessary products include:

1. Standardized and combined daily, nationwide, multidepth (minimally surface and root zone) soil moisture observation set from all NCSMMN stations; this is product 1.
2. Daily, nationwide, soil moisture anomaly observation set based on product 1.

3. Daily, nationwide, soil moisture percentile observation set based on product 1.
4. Daily, nationwide, multidepth, gridded soil moisture data set at high resolution (4 km or better) derived from supplementing product 1 with digital soil maps, gridded precipitation data, and other beneficial supporting data layers in a geostatistical and/or machine learning-based mapping algorithm; this is product 4.
5. Additional products will be created that merge the in situ data with remotely-sensed soil moisture products and/or soil moisture estimates from land surface/hydrologic models.

Although preliminary research and demonstration projects have shown the feasibility of all these products, further research will be required to enable the creation of these products at the national scale and to rigorously quantify the uncertainty in those products. In particular, more research is needed: 1) to develop proven methods for standardizing data across differing sensor types and measurement depths; 2) to determine the best way to provide a historical context for soil moisture data with a short period of record; and 3) to develop effective methods for generating gridded soil moisture products from in situ observations at the national scale. Such research by Federal agency staff and university researchers should be supported through the NCSMMN effort.

As the necessary supporting research is completed, product development teams including personnel from one or more Federal agencies and university researchers could lead the work to create the operational systems and products. If the host agency is NOAA, it is important for the product development teams to have NOAA status in order to have full access to public domain, noncommercial only, and NOAA-only data within MADIS.

6.4.4 Research Needed to Enable Creation of NCSMMN Soil Moisture Products

Soil moisture measurement depths and sensor types vary between networks, which can impede interpretation of large-scale soil moisture conditions. Several approaches have been developed for extrapolating soil moisture data across depths, particularly from the surface to deeper depths, and perhaps the most successful approach has been the exponential filter. However, this method is effective mainly for extrapolating soil moisture values that have been normalized (i.e., from 0 to 1) and can have large biases when extrapolating absolute soil moisture values (Zhang et al., 2017). More research is needed to determine an effective approach for interpolating absolute soil moisture values across depths, accounting for temporal dynamics and soil property variation with depth. Similarly, normalized soil moisture data have been successfully combined for drought monitoring across networks using different sensor types (e.g. Krueger et al., 2019), but an accurate method to combine absolute soil moisture values across sensor types still needs to be developed. One possible approach is coordinated, post-installation soil sampling at each station to be included in the NCSMMN to quantify the accuracy of each network's soil moisture data and to facilitate correction/recalibration of absolute soil moisture values as needed. This approach has already been successfully applied to the OKM (Scott et al., 2013).

Based on user group feedback described in 6.4.2, the suite of NCSMMN national soil moisture products will strive to provide current soil moisture data in a historical context when possible (see products 2 and 3). However, not all in situ monitoring stations have a long period of record, and the accuracy and precision of anomalies and percentiles increase as the data record becomes longer. There is some evidence that seasonally standardized percentiles can be accurately characterized within 3–6 years of consistent data collection using bootstrapping methods (Ford et al., 2016). However, more research is needed to determine the best way to provide a historical context for soil moisture data with a short period of record, particularly as new networks and stations become available.

In addition to point-based soil moisture products, spatially interpolated gridded products will be created based on the in situ soil moisture measurements ingested from the various networks. Spatial interpolation of in situ soil moisture is challenging because there are many factors that may influence how soil moisture varies at regional scales (soil properties, topography, land use/landcover, climate, etc.). An automated regression kriging methodology was recently developed for the Oklahoma Mesonet[24] to create daily gridded soil moisture maps at 800-m resolution for three depths across the State of Oklahoma (Ochsner et al., 2019). This method uses digital soil maps from USDA NRCS and gauge-corrected radar precipitation data from the National Weather Service with in situ soil moisture observations in a simple geostatistical framework. The resulting maps show detailed spatial patterns in soil moisture reflecting variations in landscape properties and meteorological forcings (Figure 6.4, *right*).

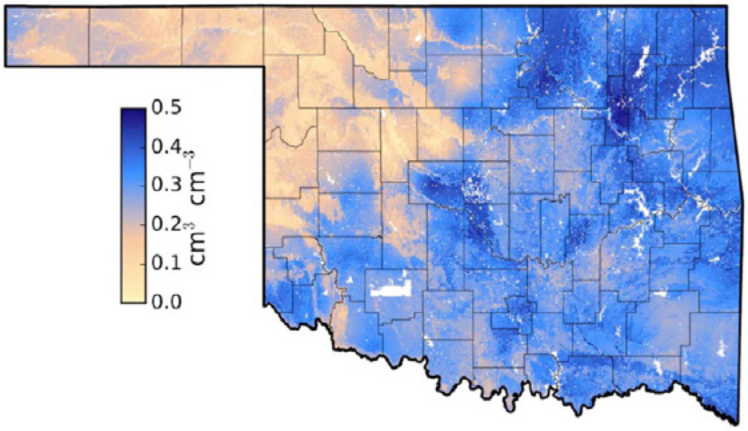

Figure 6.4: Map of volumetric water content for the 5-cm soil depth across Oklahoma at 12:00 a.m. CST, 9 March 2016. This map was produced using in situ soil moisture observations, digital soil maps, and radar-based precipitation data. Reproduced from Ochsner et al. (2019).

Work is ongoing to expand this approach to a national level as part of the National Soil Moisture Network, a first-generation, NIDIS-sponsored research effort to explore the feasibility of combining in situ, satellite, and modeled data into an operational product, currently found at *http://nationalsoilmoisture.com*. Percentiles based on in situ soil moisture observations are being interpolated at a 4 km spatial resolution across the contiguous United States (Zhao et al., 2020). The methodology has been tested in an operational environment and has been shown to outperform other methods for national-scale soil moisture interpolation. Fine resolution gridded soil moisture can be served in raster (GeoTiff, netCDF) format for direct ingestion to spatial analysis software used by U.S. Drought Monitor authors and for other uses.

A few additional key research needs include: 1) Developing an effective method to create gridded national data sets of absolute soil moisture values as required in many applications, not only percentiles; 2) Developing ways to account for the important effects of differing vegetation/land cover characteristics when producing these gridded data sets; and 3) Developing ways to upscale each of the NCSMMN stations so that the data are representative of the station's immediate surroundings and not only a single point. Thus, despite many promising developments, important research needs remain before the gridded products necessary to fulfill the NCSMMN vision can be fully created.

6.5 COMMUNICATION, COORDINATION, AND COLLABORATION

6.5.1 Collaboration and Coordination for NCSMMN Soil Moisture Products

There are several efforts within the NCSMMN that will require significant collaboration and coordination with agencies and other entities across the country. Many of these collaborations have been discussed throughout this chapter, including formalizing a financially supported collaboration between the NCSMMN partners at NOAA's National Mesonet Program and existing monitoring networks across the country. In addition, collaboration is needed with product developers for the existing and new soil moisture products that will be a part of the suite of NCSMMN products.

6.5.2 Citizen Science Collaboration

Another collaboration opportunity for the NCSMMN is to invite the participation of citizen science to the network. Citizen science is gaining in popularity across various disciplines as advances in both measurement technologies as well as web-based data platforms make engagement easier. In addition, the aforementioned Agriculture Improvement Act of 2018 and NIDIS Reauthorization of 2018 both include mandates for USDA and NOAA to engage and utilize data from citizen scientists. The NCSMMN

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[24] *http://soilmoisture.okstate.edu/*

could explore ways to use data collected by citizen scientists as a means of filling in gaps from in situ data collected by state and Federal networks.

While it is desirable to include citizen scientists in an effort such as the NCSMMN, for the uninitiated citizenry, the path forward is not immediately obvious. Due to expense, it is unlikely that large numbers of citizens would invest in high-quality soil moisture monitoring equipment and the equipment needed to telemeter data into the NCSMMN portal. The utility of hand-collected data depends on: (a) if site metadata is available, (b) if the collection method is consistent with expected protocols, and (c) if data can be uploaded to a central portal via Web tools. A project to develop the protocols and Web tools to support an effort like this should be considered before commitment is made to include the use of citizens as a component of the formalized data-collection effort.

One possible approach would be to give participating citizen scientists the option to file either a quantitative or qualitative soil moisture report. Quantitative reports would likely be gravimetric measurements[25] of soil moisture, which is a sampling technique to obtain volumetric water content reading, for example for the top layer of soil. The NCSMMN could provide documentation which explains, as simply as possible, how to take a gravimetric sample. Qualitative reports can be provided by filling out a short form as is done with the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) Condition Monitoring[26] program where soils could be ranked on a scale from "severely dry" to "severely wet" based on anecdotal experiences. The volunteer would be asked to report local impacts of the dry/wet soils, and to give a brief written synopsis of the situation. A similar system has been developed by the Crowd Water[27] team which uses a phone application for people to enter soil moisture status among other parameters of interest. Qualitative reports such as this could provide useful ancillary information to the network, for example by extending the range of observations, or by providing confirmation of quantitative metrics.

In order to execute any citizen science efforts, a collaboration with CoCoRaHS would be a logical path forward. CoCoRaHS is a unique, nonprofit, community-based network of volunteers of all ages and backgrounds working together to measure and map precipitation (i.e., rain, hail and snow). Recently, CoCoRaHS also added the option for their observers to sign up to take soil moisture measurements as well.[28] CoCoRaHS already has the needed infrastructure in place for collecting both quantitative and qualitative soil moisture reports, and CoCoRaHS could easily share these reports directly with the NCSMMN.

NOAA's NWS Cooperative Observer Program (COOP) is another potential partner for expanding the network of community-based monitoring. In the COOP program, volunteers take daily weather observations at more than 8,000 set locations across the country, including both urban and more dispersed natural settings (public lands, agricultural areas, etc.). COOP data usually consist of daily maximum and minimum temperatures, snowfall, and 24-hour precipitation totals, but also can include additional hydrological or meteorological data such as evaporation or soil temperatures. It is worth investigating the possibility of soil moisture measurement being added to some of these locations. The opportunity to leverage COOP program expertise as part of the NCSMMN should be explored.

6.5.3 External Communication

There are several aspects of communication that need to be discussed for the NCSMMN including outward communication to increase awareness of NCSMMN efforts and products, communication regarding the information and uncertainties associated with the suite of NCSMMN soil moisture products, and internal communication among the NCSMMN community.

An important first step for NCSMMN communication is to establish a website for the effort, and this website can also serve as the home for the suite of NCSMMN soil moisture products. It will be important for stakeholders across the country to be able

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[25] *https://www.globe.gov/documents/352961/353769/Soil+Moisture+-+Gravimetric+protocol/cbca34da-fcc7-4e5b-a8d9-eae745c7c17d*

[26] *https://www.cocorahs.org/maps/conditionmonitoring/about.html*

[27] *https://crowdwater.ch/en/app-2/*

[28] *https://www.cocorahs.org/Content.aspx?page=soilmoisture*

to easily find information about the NCSMMN, particularly for those who are interested in starting a monitoring network that might want to participate in a larger network and contribute data to the NCSMMN. It is crucial for these emerging networks to be aware of the NCSMMN and to know that the NCSMMN will be developing standards for monitoring that they can incorporate into their efforts, along with other technical assistance resources. As part of this effort, it will be important to clarify the identity and branding of the overall NCSMMN along with its various research component parts, including the proof-of-concept National Soil Moisture Network website (currently found at *http://nationalsoilmoisture.com*).

In order to increase the awareness of NCSMMN efforts across the country, it will also be important to do outreach to and collaborate with entities across the country that have a regional or local footprint. These partners may include NOAA NWS Weather Forecast Offices, local USDA offices, NIDIS' Regional Drought Early Warning Systems (DEWS), USDA Regional Climate Hubs, NOAA's Regional Climate Centers, the U.S. Army Corps of Engineers, the Department of Interior's Climate Adaptation Science Centers, state and local agencies, and others. These local or regional programs can tie local stakeholders interested in soil moisture data, monitoring, or other information into the larger NCSMMN efforts.

6.6 NETWORK MANAGEMENT

The existing management of the NCSMMN includes an ad hoc NCSMMN Executive Committee (EC), which was organized in 2018, and the broader community contributing to the NCSMMN that includes Federal, state, local, academic, private sector, and other partners. The entire NCSMMN community has been instrumental in bringing the NCSMMN to what it is today, and will continue to be instrumental in the future.

The current NCSMMN EC includes leaders from Federal agencies and academic institutions, and is the group that has been working with NIDIS to define the goals and develop a framework to bring the NCSMMN concept to fruition. This Strategy proposes to continue with a similar approach to managing the NCSMMN; however, with a more formalized structure in place. Work to develop such a management structure will be key to the implementation of the NCSMMN strategy, and should incorporate a means by which the broad range of Federal, state, local, academic, private sector, and other partners can continue to participate and provide ongoing consultation.

In terms of organizational "home," NIDIS will continue to shepherd progress toward the implementation of the NCSMMN strategy, per the NIDIS Reauthorization Act of 2018. As of December 2019, an NCSMMN Coordinator position has been created within NIDIS to provide organizing and management support to the NCSMMN, and to facilitate implementation of the NCSMMN Strategy. Ultimate residence of the NCSMMN management structure can adapt and migrate over time as needed to other appropriate agencies.

While a more formalized structure for the NCSMMN is being determined, meetings and webinars of the NCSMMN community will continue to be held, including the annual National Soil Moisture Workshop which grew from a series of annual workshops started in 2011. Associated communication efforts will include developing a web presence, developing brochures and other outreach materials, and creating an email listserv and/or newsletter to keep stakeholders up-to-date on activities that are happening, products that are being developed, and other NCSMMN news that might be of interest. Finally, because broad engagement is a priority of the NCSMMN, specific outreach will be conducted with both current and potential stakeholders across data provider, research, and user groups.

Much can be learned in managing such a network from similar, existing networks, and a key near-term task is to investigate models and best practices across the Federal Government. For example, the USGS hosts the National Ground Water Monitoring Network (NGWMN), which follows a three-tiered structure for network management. The NGWMN is a product of the Subcommittee on Ground Water (SOGW), which is part of the Federal Advisory Committee on Water Information. The NGWMN has a Program Board whose key role is to provide input to the USGS (the lead agency) and the SOGW on issues related to network growth, development, and operation from the perspective of data providers. The Program Board's duties and responsibilities are to provide input on the NGWMN Program's scope, priorities and overall direction, evaluate funding proposals, and to communicate with current and potential data providers. More details about the board, and membership requirements, are laid out in the Structure and Operating Principles document. The NGWMN also has a USGS manager who oversees day-to-day operations of the NGWMN on a full-time basis. A network structure for the NCSMMN that utilizes governance protocols similar to the GWMN is worth considering, particularly given the fact that several elements of the NCSMMN will require formal decision-making, such as formalizing partnerships with data providers, funding research and product development, and ensuring general management and representation.

6.7 FUNDING FOR THE NATIONAL COORDINATED SOIL MOISTURE MONITORING NETWORK

Financial resources required for a robust NCSMMN will support a variety of activities. Of particular importance are: the integration of high-quality, in situ soil moisture data from existing and new monitoring networks, the evaluation and development of the suite of NCSMMN soil moisture products, and the sustained management of the NCSMMN.

While networks vary widely in size, quality, and capability, the typical high-quality, hydrometeorological station that reports soil moisture with relevant variables (soil temperature, precipitation, and atmospherics needed to calculate evapotranspiration) costs approximately $20,000 to $65,000 to install and $5,000 to $15,000 annual to operate. Expenses include personnel (engineer, technician, student help, IT professionals), travel, equipment and supplies, communications, and administrative overhead (i.e., indirect cost).

Often times, the original creation of a network is well funded, but over time operational funding may not keep pace. The remedy sought by many local and state networks is to find financial resources via fundraising, sponsorship, or sales of data records, necessitating an exclusivity of the data being collected. The biggest threat to any data provider's sustainability is to have their identity stripped from that data before it gets to the end user. NCSMMN's flexibility with contributors to permit them to retain their rights to ownership of their raw data, their right to restrict redistribution of data, and their right to demand attribution will be key to getting access to more data at lower cost. This model has precedent in the NMP, which has been a success story for data acquisition for NOAA. Many state mesonets are utilizing a business model that treats these data as a commodity to maintain network operations.

Soil moisture has applications from flash flood forecasting and fire weather, to agriculture and reservoir management. Consequently, there is a wide range of Federal agencies with a stake in having more accessible and accurate soil moisture data. Given the breadth of impact of this collective data, it is clear that inclusion of multiple agencies in some capacity would benefit the overall network and would enhance the ability to create diverse applications and respond to diverse stakeholders. Going forward, implementation of the NCSMMN strategy will need to consider these issues of inclusion.

6.8 RECOMMENDATIONS AND NEXT STEPS

Based on the discussion in this and previous chapters, there are several recommendations and next steps for moving forward the development of a coordinated NCSMMN. These recommendations include both organizational steps to solidify the NCSMMN program structure, as well as research and operational steps to advance soil moisture monitoring and data assimilation. The recommendations are listed in a roughly logical flow of activities, but many steps could and indeed should occur in parallel.

1. **Determine Home Agency and Management Structure for the NCSMMN.** NIDIS should work with the leadership of the participating Federal agencies to determine the ultimate management structure for the NCSMMN. In the interim, it is recommended that NIDIS continues as the near-term "home" for the NCSMMN. The reasons for this recommendation are threefold: this Strategy was called for in the 2018 NIDIS Reauthorization Act, NIDIS has a specific mandate for cross-agency collaboration, and as a part of NOAA, NIDIS is well-positioned to solidify partnerships with NOAA's National Mesonet Program. This Strategy further proposes reviewing models and best practices across the Federal Government

to inform the choice of a formalized management structure for the NCSMMN.

2. **Establish a Web Presence and Formalize Communication & Outreach Planning for the NCSMMN.** The success of the overall network depends in part upon partners and stakeholders being able to easily find information online about the network's efforts. Developing a visible, user-friendly website for the NCSMMN will be important for both communication and product delivery. The website can also serve as the host for the suite of products, as well as other resources such as technical assistance materials and standards documents, as they are developed. An Open Science Framework webpage[29] has been serving as a public repository for NCSMMN related documents; going forward, the NCSMMN will need to determine the most effective platform. In addition to a website, the NCSMMN will need to do broader communications planning, including developing appropriate branding, determining additional materials (e.g., newsletter) and channels (e.g., listserv) with which to engage stakeholders and the public, and developing plans for ongoing outreach.

   As a cornerstone engagement activity, the NCSMMN will continue to host the annual National Soil Moisture Workshop, which will bring together experts from across the United States to discuss the latest science and innovations in soil moisture monitoring. These meetings have been held since 2011 and initially were focused on in situ soil moisture monitoring but since have evolved to include remote sensing, modeling, and soil moisture applications. An annual meeting will be an important means to continue developing the NCSMMN, to communicate within the NCSMMN Community, and to make progress on implementing this Strategy. Going forward, this meeting should also include outreach to user groups, with the aim to build better collaboration between researchers, data providers, and users.

3. **Formalize Partnerships with the National Mesonet Program and Existing Monitoring Networks.** In order to obtain in situ soil moisture data from existing monitoring networks across the country, the NCSMMN should formalize a partnership with NOAA's NMP, which already has established partnerships with many mesonets throughout the country. In addition, MOUs will be needed with MADIS and with networks outside of the scope of NMP, including NRCS SCAN and SNOTEL, NOAA USCRN, and others. These partnerships should include financial compensation for networks contributing high-quality soil moisture data and options for technical assistance to networks on issues such as siting stations, soil characterization, data interpretation, sensor selection and calibration, installation, QA/QC, data management, and communication.

4. **Develop a Set of Criteria for High-Quality Data Sources.** Collecting high-quality soil moisture data can be a complicated and time-consuming process, but it is ultimately necessary if the value of soil moisture data is to be fully realized. What is needed for the NCSMMN is a verifiable soil moisture dataset that can be used by operational decision-makers, providing value in their decision-making process. Therefore, it is proposed that a set of criteria be established to qualify an in situ soil moisture network as producing high-quality versus moderate- or provisional-quality data. These criteria will be developed in coordination with the research, data provider, and user communities, and will include both standard metrics of data quality (e.g., random error rates), as well as other metrics of relevance, such as operational uptime and the existence of good metadata.

5. **Support Research Necessary to Develop or Improve NCSMMN Methodologies.** Although preliminary research and demonstration projects have shown the feasibility of the envisioned NCSMMN products, further research is required to enable the creation of these products at the national scale and to rigorously quantify the uncertainty in

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[29] *https://osf.io/56gsj/*

those products. In particular, more research is needed: 1) to develop proven methods for standardizing data across differing sensor types and measurement depths; 2) to determine the best way to provide a historical context, i.e., anomalies and percentiles, for soil moisture data with a short period of record; and 3) to develop effective methods for generating gridded soil moisture products from in situ observations at the national scale.

6. **Increase In Situ Soil Moisture Monitoring Nationwide.** There is a clear need to increase the number of long-term, high-quality, in situ soil moisture monitoring stations across the United States. An initial milestone will be to meet the National Research Council (2009) goal of 3,000 monitoring stations across the continental United States. The NCSMMN will work with partners from across the country to optimize locations of new monitoring stations to meet Federal and state goals, following one or more of the approaches described in Chapter 4 and targeting spatial gaps in the existing in situ soil moisture monitoring infrastructure. In siting new locations, priority will also be given to increased monitoring in vegetation/land cover types that are underrepresented in the current monitoring infrastructure, especially forests, grazing land, and cropland.

7. **Explore Increasing Partnerships with the Private Sector.** The private sector operates a large number of weather and soil monitoring stations for a variety of purposes, such as irrigation scheduling, but the data from these stations are not readily available to the broader community. A concerted effort must be made to engage with the private sector not only to expand the impact of monitoring efforts from all sources, but also to provide feedback to the private sector with regards to methodologies and validation protocols, so that these efforts can benefit from the scientific advancements propagated by the NCSMMN community. Outreach can include engagement at meetings, joint presentations, and targeted workshops for private sector audiences.

8. **Engage with the Citizen Science Community.** One potential way to increase in situ soil moisture monitoring, and public support for such monitoring, is to invite the participation of citizen science. There are ideas to explore, including the quantitative and qualitative measurement methods by citizen scientists, and a pilot project should be considered to develop the protocols and web tools to support an effort like this. In order to execute any citizen science efforts, exploring collaborations with NOAA's COOP program and CoCoRaHS would be a logical path forward.

9. **Develop, Release, and Promote NCSMMN Products.** The primary aim of the NCSMMN effort is to provide coordinated, high-quality, nationwide soil moisture information for the public good. To date, there has been good progress on proof-of-concept and first-generation products, such as the National Soil Moisture Network (*http://nationalsoilmoisture.com*). A more comprehensive and fully developed platform will require developing, releasing, and promoting new, nationwide point-based and gridded soil moisture data products that meet the needs of diverse end user groups. These products, including absolute soil moisture values, anomalies, and percentiles, will be freely and publicly available in the form of maps and time series. They will be delivered in formats designed to maximize their public value for crucial applications such as drought and flood monitoring, fire danger ratings, and streamflow forecasting.

   While this recommendation is the most fundamental objective of the NCSMMN, its success will depend on most (if not all) of the preceding steps. Through efforts to: 1) develop a strong organizational home; 2) engage in communication and outreach; 3) establish partnerships and build out the network; 4) conduct needed research; and 5) develop and refine data collection, integration, and quality standards, the NCSMMN will be positioned to deliver transformative soil moisture products to the Nation.

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APPENDIX A

REGIONAL CASE STUDY: THE UPPER MISSOURI RIVER BASIN SOIL MOISTURE AND PLAINS SNOW MONITORING NETWORK

A.1 Background

After the historic 2011 flood, and in response to one of the six recommendations from the Independent Review Team, the U.S. Army Corps of Engineers (USACE) and various Missouri River Basin agencies developed a framework in 2013 for the establishment of an Upper Missouri River Basin Soil Moisture and Plains Snow Monitoring Network (UMB Monitoring Network). The USACE is collaborating with Federal and state partners to update the 2013 recommendations. The USACE uses plains snowpack and soil moisture data in its runoff forecasting for operations, and along with other Federal agencies, has found limitations with the plains snow and soil moisture data that is currently being collected.

A.2 Federal Support

The Water Resources Reform and Development Act of 2014[30] included a requirement that the Secretary of the Army, in coordination with other specified agencies, carry out snowpack and soil moisture monitoring in the Upper Missouri Basin. The Water Infrastructure Improvements for the Nation Act of 2016[31] Section 1179(b) designated the USACE as the lead agency for that effort.

A.3 Value to the USACE and the Upper Missouri River Basin

The data obtained from the network will be available for all federal, state, and local agencies to use in their betterment of existing products and/or the development of new products (e.g., NWS river forecasts and flood outlooks, U.S. Drought Monitor, NOAA Climate Prediction Center outlooks, U.S. Bureau of Reclamation (USBR) and USDA-NRCS water supply forecasts, and various Federal and state fire hazard reports). Specifically for the USACE, the data will be used by the NWS-National Operational Hydrologic Remote Sensing Center (NOHRSC) office to better their plains snow map. The map is direct input into the river and runoff models used by the NWS and the USACE, respectively. Those river and runoff models also use soil moisture data to model the impacts of melted plains snow and rainfall to estimate the inflows into the USACE's reservoir projects.

A.4 Network Goals

The plains area of the Upper Missouri River Basin (above Sioux City, Iowa) in the United States totals 270,000 square miles, as shown in Figure A.1 (*next page*). Ongoing discussions with soil moisture experts (e.g., state mesonet operators, NRCS and NRCS-National Soils Lab) and plains snow and river forecasting experts (NWS-NOHRSC and NWS-Missouri Basin River Forecast Center (MBRFC)) has revealed that a soil moisture and plains snow monitoring site should be installed in every watershed (*see Figure A.1*) at a density of 1 in every 500 sites, meaning a goal of 540 monitoring sites total.

A monitoring site includes the following sensors: soil moisture and temperature at five depths, snow depth, wind speed and direction, solar radiation, relative humidity, precipitation, and air temperature. In addition, during the December–March period, onsite weekly snow depth and snow water equivalent measurements should be taken at each site and conveyed to the USACE, NWS-NOHRSC, and NWS-MBRFC offices for integration into their models.

There are approximately 180 existing soil moisture sites in the Upper Missouri River Basin. These sites do not include plains snow monitoring equipment. Of these 180 sites, 156 are owned and operated by five state mesonet offices (Montana, Wyoming, North Dakota, South Dakota, and Nebraska), the other 24 are owned and operated by the USBR (AgriMet). The USACE is actively working with the

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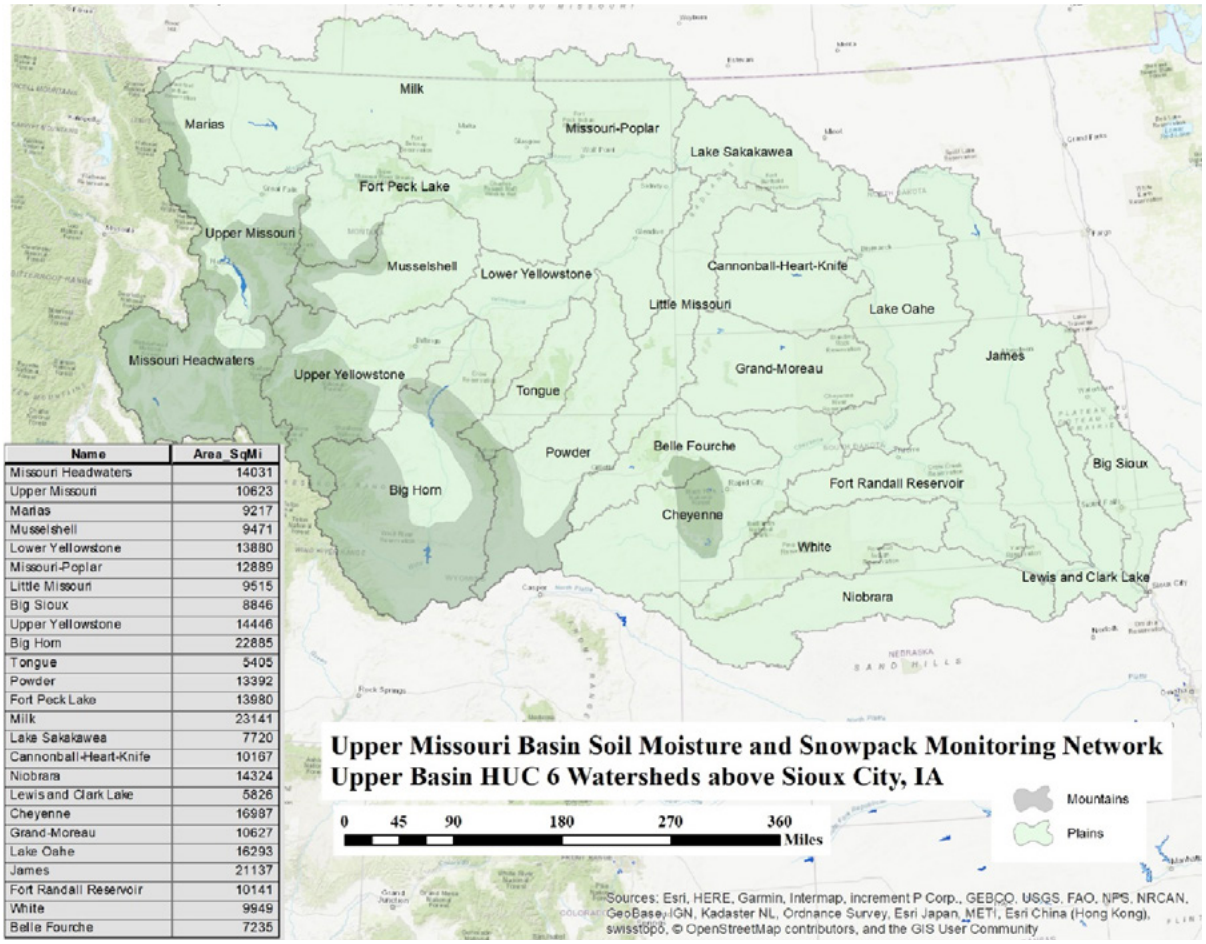
[30] *https://www.congress.gov/113/bills/hr3080/BILLS-113hr3080enr.pdf*

[31] *https://www.congress.gov/114/plaws/publ322/PLAW-114publ322.pdf*



Name	Area_SqMi
Missouri Headwaters	14031
Upper Missouri	10623
Marias	9217
Musselshell	9471
Lower Yellowstone	13880
Missouri-Poplar	12889
Little Missouri	9515
Big Sioux	8846
Upper Yellowstone	14446
Big Horn	22885
Tongue	5405
Powder	13392
Fort Peck Lake	13980
Milk	23141
Lake Sakakawea	7720
Cannonball-Heart-Knife	10167
Niobrara	14324
Lewis and Clark Lake	5826
Cheyenne	16987
Grand-Moreau	10627
Lake Oahe	16293
James	21137
Fort Randall Reservoir	10141
White	9949
Belle Fourche	7235

Upper Missouri Basin Soil Moisture and Snowpack Monitoring Network
Upper Basin HUC 6 Watersheds above Sioux City, IA

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure A.1: The geographical extent of the UMB Monitoring Network.

Mesonet offices and the USBR to modify their existing sites to be part of the UMB Monitoring Network. The USACE is also working with the NRCS and NWS-NOHRSC to develop a site selection methodology for new sites for each watershed. To complete the 540-site network, 360 new sites will need to be installed.

A.5 Funding Structure

The USACE is paying for the purchase and installation of all equipment for all sites (existing and new) as well as soil characterization. Specific costs for installing the equipment are still be being determined, as well as the determination for what agency will assume ongoing operation and maintenance once the network is installed.

A.6 Completed and Ongoing Work

An instrumentation test bed at South Dakota State University with the South Dakota Mesonet is complete. The report was furnished to the USACE in August 2019, and established the equipment needs for the network. The USACE and NRCS National Soils Lab have established a methodology to select the new (roughly 360) sites. Work is ongoing to complete the following: 1) complete a Programmatic Environmental Assessment to meet National Environmental Policy Act (NEPA) requirements; 2) establish interagency agreements with the NRCS or NOAA and the state offices operating the Mesonet networks for the installation of new sites and annual maintenance of the entire network; 3) finalize the agreement with the NRCS National Soils Lab regarding the soil characterization effort; 4) establish an agreement for a Mesonet Coordinator, which is a liaison between USACE and the state mesonets to facilitate land use agreements, NEPA, reporting, etc.; and 5) complete an implementation guide that outlines all roles and responsibilities for all offices/agencies involved in the establishment and maintenance of the network.

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