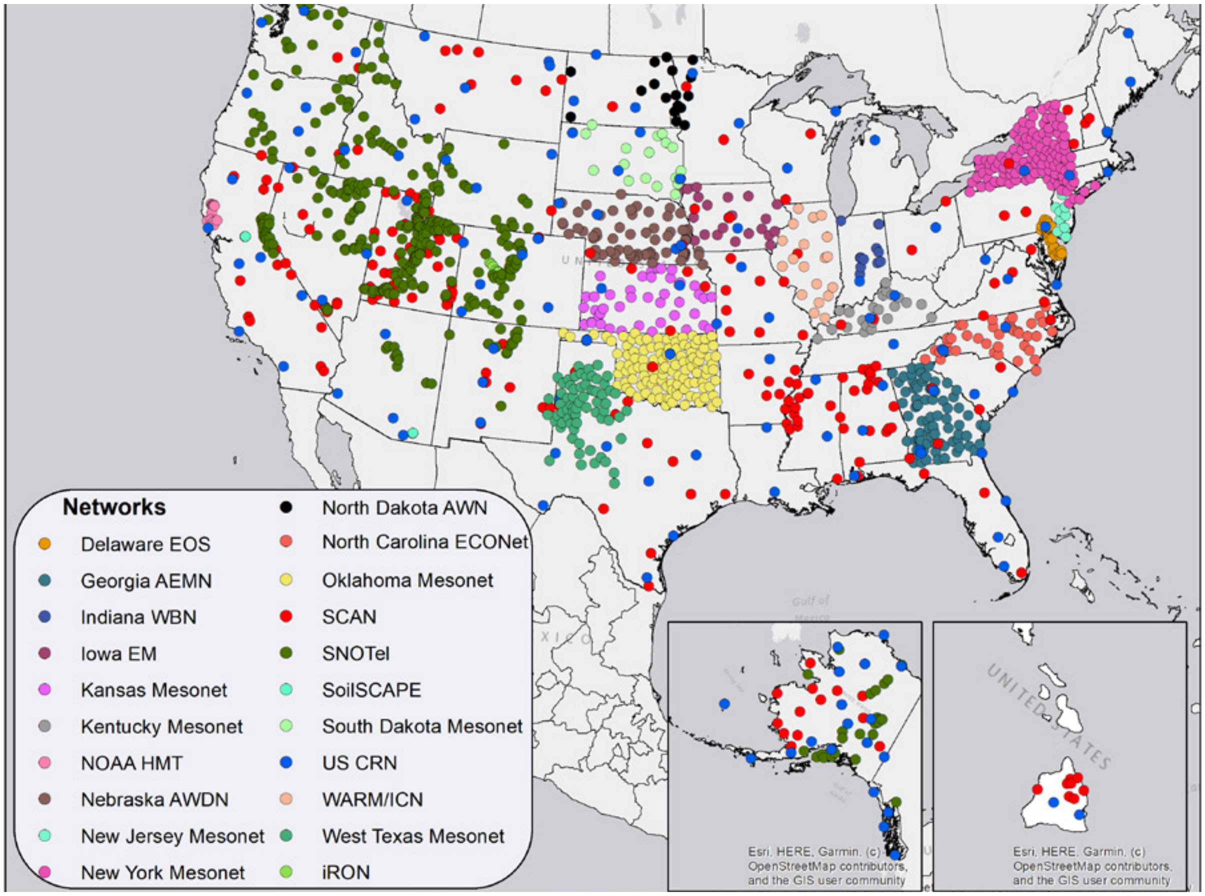

Figure 2.1: Locations of select in situ soil moisture sensor networks across the United States from federal- and state-level networks. (Source: *nationalsoilmoisture.com*)

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]

[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.

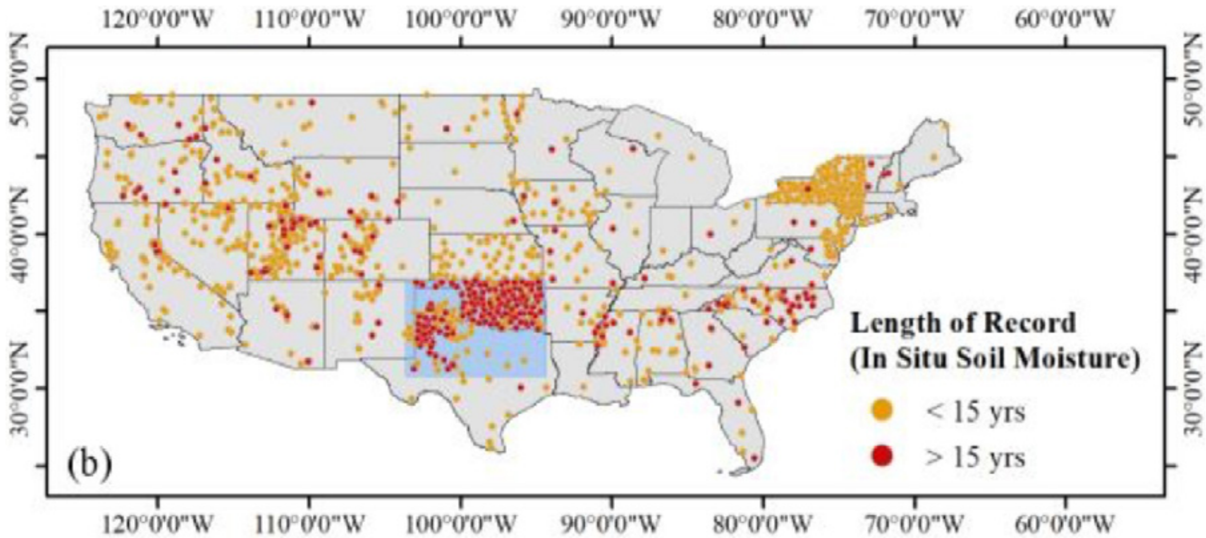

Figure 2.2: Length of record for select stations that monitor soil moisture. Those that have a continuous period of record >15 years are shown in red. Those with a period of record <15 years are shown in yellow. (Source: Yuan et al., 2020; Note: blue box indicates Yuan et al. study area)

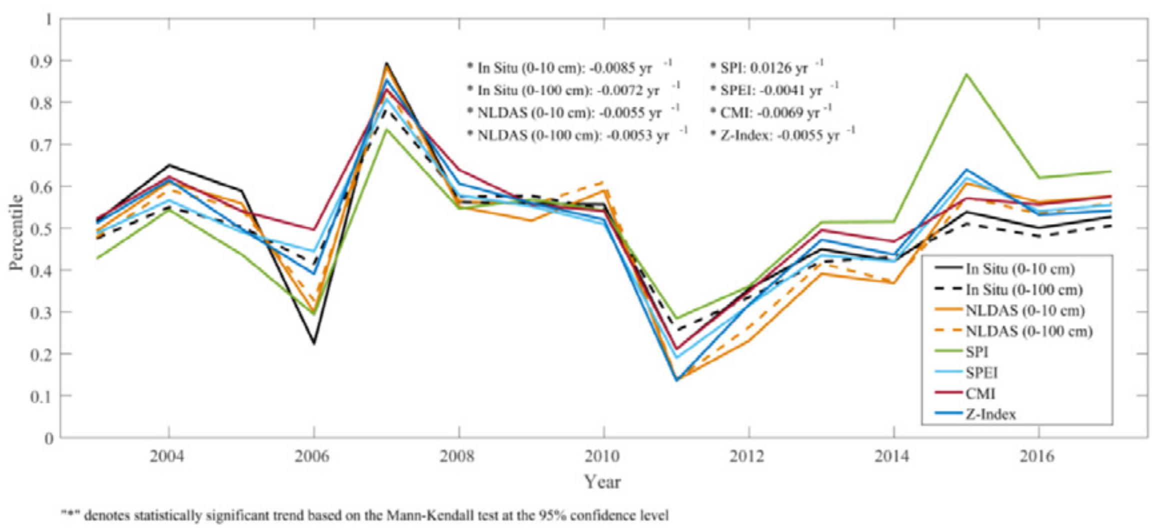

Figure 2.3: Time series of spatially-averaged percentiles of soil moisture and drought indices in the U.S. Southern Great Plains [region is shown in Figure 2.2 (*above*), *blue box*] from 2003 to 2017. The figure includes soil moisture data at 0–10 cm and 0–100 cm (in situ soil moisture shown in black) 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.,

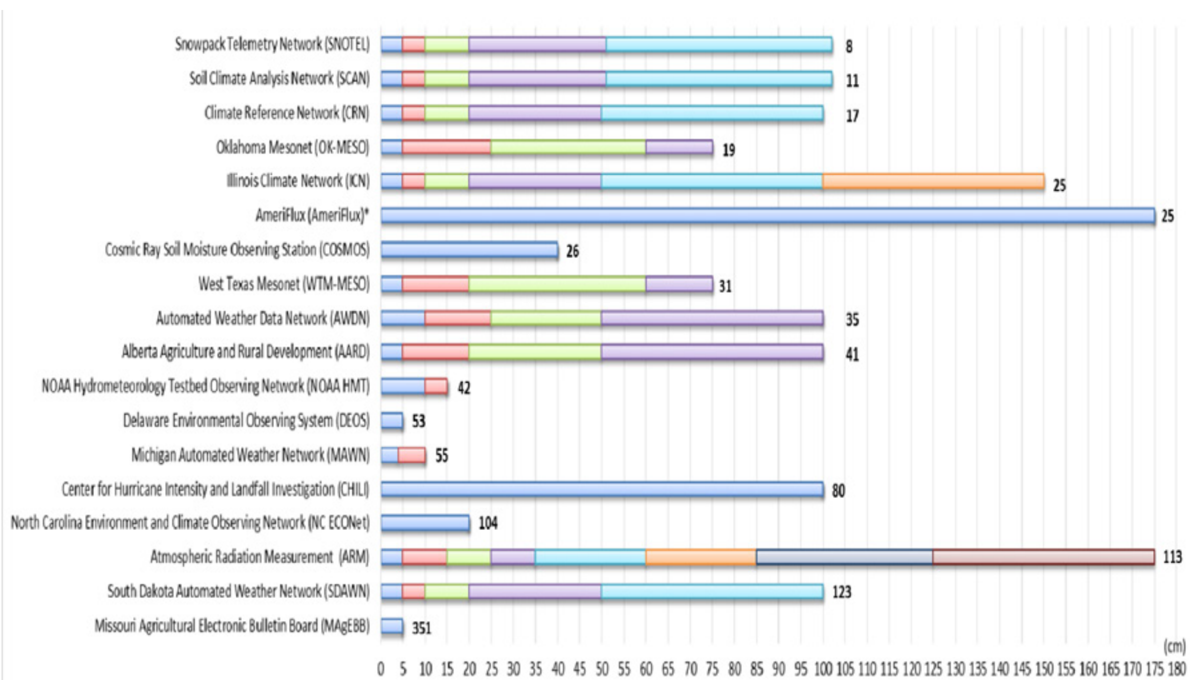

Figure 2.4: Soil moisture measurement depths at 18 of the monitoring networks that are archived in the North American Soil Moisture Database (NASMD) from Jan. 1, 2000 to Dec. 31, 2013. Depths monitored are indicated by depths at which colors change. The greatest depth monitored is indicated by the right 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

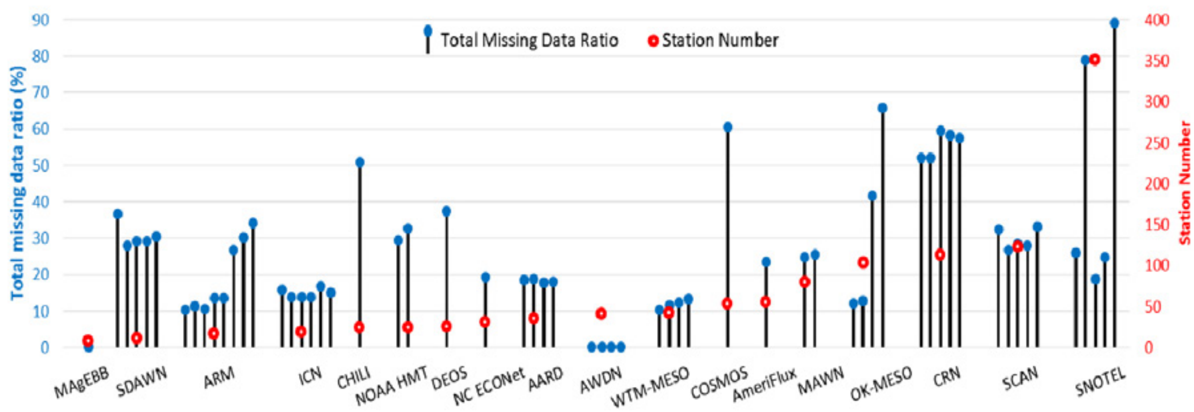

Figure 2.5: Missing data ratio for 18 networks archived in the North American Soil Moisture Database (NASMD) from Jan. 1, 2000 to Dec. 31, 2013. The missing data ratio is defined as the amount of missing data for each network and depth divided by the total number of data that would have been collected 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)

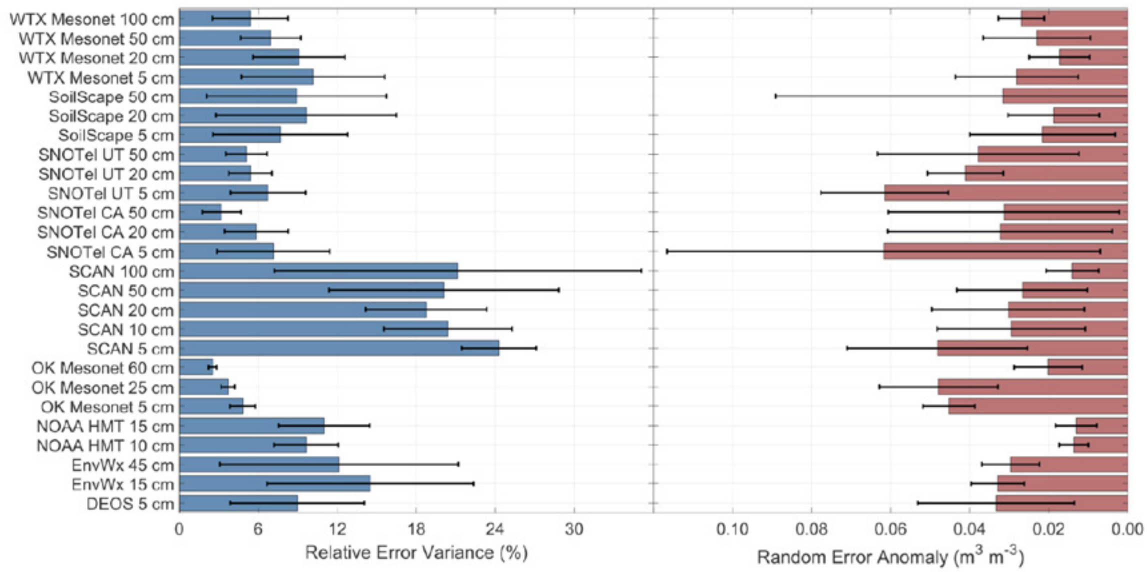

Figure 2.6: Relative error variance (*left*) and random anomaly error (*right*) for soil moisture data from the following networks: West Texas Mesonet, SoilScape, SNOTEL, SCAN, OKM, NOAA HMT, EnviroWeather and DEOS. (Source: Ford and Quiring 2019)

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.

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