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Soil Water and Temperature System (SWATS) Instrument Handbook

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ARM CLIMATE RESEARCH FACILITY

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DR Cook, Argonne National Laboratory

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Acronyms and Abbreviations

ARM	Atmospheric Radiation Measurement
ARS	Agricultural Research Service (USDA)
CF	Central Facility
DOE	U.S. Department of Energy
DQ	Data Quality
DQR	data quality report
EF	extended facility
NRCS	Natural Resources Conservation Service (USDA)
OSU	Oklahoma State University
QC	quality control
QME	Quality Measurement Experiment
RMSE	root-mean-square error
SGP	Southern Great Plains
SHAWMS	Soil Heat And Water Measurement System (USDA)
SST	Site Scientist Team
STAMP	Soil Temperature And Moisture Profile
SWATS	Soil Water and Temperature System
TDR	time-domain reflectometer
USDA	United States Department of Agriculture
VAP	value-added product

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1.0 General Overview

The soil water and temperature system (SWATS) provides vertical profiles of soil temperature, soil-water potential, and soil moisture as a function of depth below the ground surface at hourly intervals. The temperature profiles are measured directly by in situ sensors at the Central Facility (CF) and many of the extended facilities of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility's Southern Great Plains (SGP) atmospheric observatory. The soil-water potential and soil moisture profiles are derived from measurements of soil temperature rise in response to small inputs of heat. Atmospheric scientists use the data in climate models to determine boundary conditions and to estimate the surface energy flux. The data are also useful to hydrologists, soil scientists, and agricultural scientists for determining the state of the soil.

The SWATS system was replaced with the updated sensor and data logger equipment of the STAMP system in early 2016.

2.0 Contacts

2.1 Mentor

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3.0 Deployment Locations and History

Current health and status information for each SWATS instrument can be found at the DQ Explorer website http://dq.arm.gov/dq-explorer/cgi-bin/main/metrics or NCVweb at http://dq.arm.gov/ncvweb/ncvweb.cgi.

New STAMP (Soil Temperature and Moisture Profile) systems were installed at all of the presently operating extended facilities in early 2016, including EF21 Okmulgee Forest, where a SWATS system has not been installed. All SWATS were decommissioned when the STAMP systems were installed, except at EF13, where the SWATS was maintained until early July 2017 for comparison with the new STAMP system.

Table 1 identifies the location of the SWATS instrument systems and the depths at which sensors were installed at each site:

Table 1. SWATS instrument system locations.

Site Location	Depths (cm)	Status
E1 Larned, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Oct 2009
E2 Hillsboro, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Oct 2009
E3 LeRoy, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Oct 2009
E4 Plevna, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Sep 2011
E5 Halstead, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Nov 2009
E6 Towanda, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Oct 2011
E7 Elk Falls, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Nov 2011
E8 Coldwater, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed Nov 2009
E9 Ashton, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed 26 Feb 2016
E10 Tyro, KS	5, 15, 25, 35, 60	Removed Aug 2011
E11 Byron, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 25 Feb 2016
E12 Pawhuska, OK	5, 15, 25, 35, 60	Removed 4 Mar 2016
E13 Lamont, OK	5, 15, 25, 35, 60, 85	Removed 3 Jul 2017
E15 Ringwood, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 1 Mar 2016
E16 Vici, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Jun 2011
E18 Morris, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Nov 2009
E19 El Reno, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Sep 2011
E20 Meeker, OK	5, 15, 25, 35, 60, 85, 125	Removed Nov 2011
E22 Cordell, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Dec 2009
E24 Cyril, OK	5, 15, 25, 35, 60, 85, 125	Removed Nov 2009
E25 Seminole, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Apr 2002
E27 Earlsboro, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed Dec 2009
E31 Anthony, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed 3 Mar 2016
E32 Medford, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 25 Feb 2016
E33 Newkirk, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 23 Feb 2016
E34 Maple City, KS	5, 15, 25, 35, 60, 85, 125, 175	Removed 26 Feb 2016
E35 Tryon, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 2 Mar 2016
E36 Marshall, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 29 Feb 2016
E37 Waukomis, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 269Feb 2016
E38 Omega, OK	5, 15, 25, 35, 60, 85, 125, 175	Removed 1 Mar 2016
E39 Morrison, OK	5, 10, 20, 50, 100	never installed at this site
E40 Pawnee, OK	5, 10, 20, 50, 100	never installed at this site
E21 Okmulgee, OK	5, 10, 20, 50, 100	never installed at this site

4.0 Near-Real-Time Data Plots

See the SGP Quick Looks in the Educational Data Plot Library at http://education.arm.gov/nsdl/Visualization/quicklook_interface.shtml.

In DQ Explorer, select 'ARM site: SGP' and 'Data Streams: sgpswats'.

On NCVweb, select 'sgp' then 'sgpswatsExx.b1'.

In Plot Browser, select 'Search Site - SGP' and 'Datastream - sgpswats'.

5.0 Data Description and Examples

Plots of Reference Temperature, Soil Temperature, Sensor Temperature Rise, Soil Water Potential, and Volumetric Water Content after a precipitation event.

5.1 Data File Contents

5.1.1 Primary Variables and Expected Uncertainty

The system is designed to provide information related to temperature and moisture in the soil profile. The information provided consists of soil temperature, soil-water potential, and volumetric water content. Brief descriptions of these variables, as well as the units of measure, are given below.

Soil Temperature: Soil temperature is the temperature of the sensor/soil water system. Soil temperature is reported in units of degrees Celsius (C).

Soil-Water Potential: Soil-water potential is a measure of the energy state of water in the soil. It can be thought of as the tension with which water is held onto the soil particles, or alternatively, as the amount of work required to remove the water adsorbed to the soil particles. Potential is useful in determining such things as the availability of water for plant uptake, the movement of water within the soil profile, and evaporation of water from the soil surface. Soil-water potential is reported in units of kilopascals (kPa).

Volumetric Water Content: Volumetric water content is the volume of water contained in a given volume of soil. It can be expressed as a depth of water in a given depth of soil by assuming that soil and water are homogeneous over a given surface area. Water content is reported in units of cubic meters of water per cubic meters of soil (m^3/m^3), equivalent to a depth of water per depth of soil (m/m).

Tsoil: A direct measurement of the soil temperature.

Soilwatpot: Soil-water potential, also known as 'matric potential,' the binding tension between the soil and water (energy required to remove the water from the soil particles).

Soilwatcont: Volumetric water content, the volume of water in a given volume of soil (depth of water in a given depth of soil); water content is determined from soil-water potential based on laboratory studies using soil samples from each location.

Table 2. Data file variables.

Data file variable	Variable name	Units	Uncertainty
tsoil_W tsoil_E	soil temperature	°C	0.5°C
soilwatpot_W soilwatpot_E	soil-water potential	kPa	4 – 20 kPa
soilwatcont_W soilwatcont_E	water content	m^3/m^3	0.05 m^3/m^3

5.1.1.1 Definition of Uncertainty

We define uncertainty as the range of probable maximum deviation of a measured value from the true value within a 95% confidence interval. Given a bias (mean) error B and uncorrelated random errors characterized by a variance σ2, the root-mean-square error (RMSE) is defined as the vector sum of these,

$$RMSE = \left(B^2 + \sigma^2\right)^{1/2}.$$

(B may be generalized to be the sum of the various contributors to the bias and σ^2 the sum of the variances of the contributors to the random errors). To determine the 95% confidence interval we use the Student's t distribution: tn; 0.025 ≈ 2, assuming the RMSE was computed for a reasonably large ensemble. Then the uncertainty is calculated as twice the RMSE.

5.1.2 Secondary/Underlying Variables

tref: the temperature of the internal reference thermistor.

trise_W, trise_E: the temperature rise measured by each sensor and converted to soil-water potential based on laboratory sensor calibrations.

5.1.3 Diagnostic Variables

serial_numbers_W, serial_numbers_E: serial numbers used to identify individual soil sensors.

5.1.4 Data Quality Flags

-9999 in the datastream means either that particular sensor depth was not installed or the data for that sensor is reporting missing.

Additional information may be found at SWATS Data Object Design Changes for ARM netCDF file header descriptions.

Flag=0: value is within the specified range
Flag=1: value is missing (recorded as '-9999')

Flag=2: value is less than acceptable minimum
Flag=4: value is greater than acceptable maximum
Flag=8: failed delta check (value differs too greatly from previous value)

Data quality flags are used to alert users of bad or questionable data.

For example, the quality control (QC) variable 'qc_trise_W' is actually a diagnostic variable equal to the sum of the data quality flags for the variable 'trise_W.' (There are QC variables for the 'tref,' 'tsoil,' 'trise,' 'soilwatpot,' and 'soilwatcont' variables.)

qc_trise_W = 5

To interpret the QC variable, convert the number to base 2. For example, 5 = 4x1 + 0x2 + 1x1 = 101 [base2].

qc_trise_W = 4 + 1

This means that the QC variable contains the maximum and missing flags.

trise_W = '-9999' > acceptable minimum value

Table 3. Variable acceptable values.

Variable	Acceptable Minimum	Acceptable Maximum	Acceptable Delta
tref	-25°C	50°C	20°C
tsoil	-20°C	50°C	20°C
trise	1	4.5	3.5
soilwatpot	-7000 kPa	0 kPa	7000 kPa
soilwatcont	0 m^3/m^3	0.55 m^3/m^3	0.55 m^3/m^3

5.1.5 Dimensional Variables

Time: a complete file will contain observations for each hour of the day (dimension 'time' equals 24).

Depth: depth (cm) below the surface of the ground (sensor altitude is equal to the value of 'alt' minus the value of 'depth').

5.2 Annotated Examples

Plots of Reference Temperature, Soil Temperature, Sensor Temperature Rise, Soil Water Potential, and Volumetric Water Content after a precipitation event.

Notice how the precipitation (spike seen in the precipitation plot) is followed by a drop in sensor temperature rise values. This happens because the added moisture from the rain increases the effective specific heat of the soil-water system (there is more water in the soil to heat, thus a smaller rise in temperature). The soil-water potential values near the surface become less negative (less energy is required to remove water from wetter soil), and the water content values rise in the top layers of soil. There is also a more subtle effect (reduction) on soil temperature.

5.3 User Notes and Known Problems

See Soil Characterization Studies and Water Retention Curves.

Soil and Physical Characteristics of the ARM Extended Facilities with SWATS.

The range of soil textures is summarized on a soil texture triangle in Figure 1. Descriptions and noteworthy details are briefly summarized by extended facility (EF) below.

Below is a soil texture triangle illustrating the range of soil textures at the ARM SWATS sites.

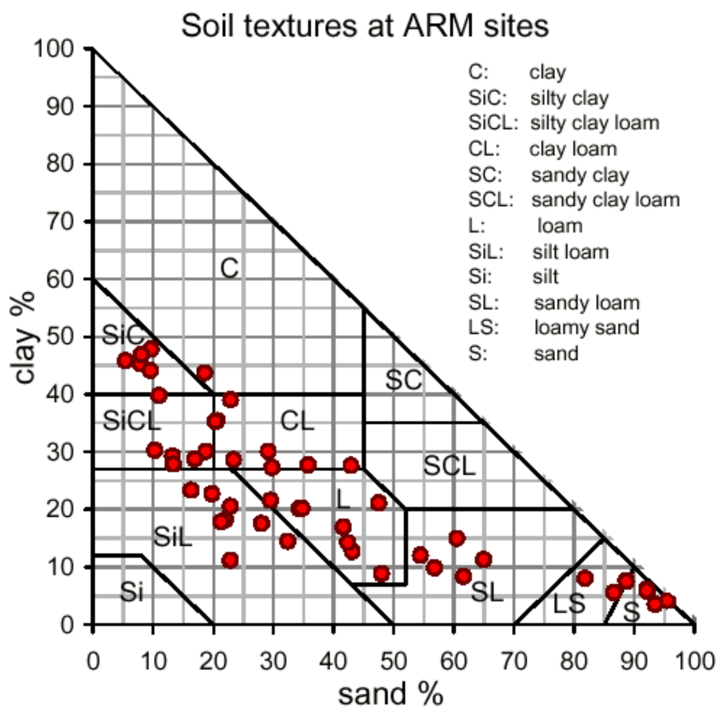

Figure 1. Soil textures at ARM SWATS sites.

EF1 / LARNED, KS

Relatively flat site in an area with little relief. No landowner information concerning whether or not site has ever been plowed; some indications that it was plowed at some point. There is a wheat field directly south of the site, with several buildings and a cluster of trees several hundred meters to the north, and a U.S. highway 1/8 mile east. Relatively sparse and shallow root layer (density decreased visibly below ~ 10 cm) under thin short pasture. Very good site from a micrometeorological point of view.

EF2 / HILLSBORO, KS

Broad, relatively shallow slope, southern exposure, in an area with gently rolling hills. According to landowner, this site has never been plowed. Substantial sod layer, with roots visible through depth of access pits (65 cm); pasture more than hip deep in a wet year. Good micrometeorological site, with clumps of trees several hundred meters to the east and south.

EF3 / LE ROY, KS

Relatively flat site in an area with little relief. No landowner information concerning whether or not site has ever been plowed. Extremely dense and deep root layer, easily visible through depth of access pits; pasture more than hip deep. Very good micrometeorological site, with a few clumps of trees several hundred meters to the east and north, soybean field immediately to the south.

EF4 / PLEVNA, KS

Relatively flat site in an area with little relief. This is a sandy site, with thin clumps of vegetation at the surface (bare sand showing between), and a mix of flat water-smoothed stones. Unlikely that anyone would have ever plowed this site; few roots, and very little organic matter. Below about 70 cm, there were occasional bands of clay, but the layering is discontinuous between the two access pits. Good micrometeorological site, with significant lines of trees several hundred meters away in all directions except west.

EF5 / HALSTEAD, KS

Relatively flat site in an area with little relief. No landowner information concerning whether or not site has ever been plowed; some indication that it was plowed at some point. Medium-density mixed grass and forb pasture, with roots visible through the depth of the access pits; winter wheat field to the south. Very good micrometeorological site, with a few sparse trees several hundred meters away to the north and west, south of an infrequently traveled gravel road.

EF6 / TOWANDA, KS

Seriously disturbed site in a region of irregular hills, with obvious evidence of terracing in the previous few years; thin layers of sandstone had been broken and strewn across the pasture in the process. System was installed on one shelf of the terraced field on a broad slope with southeast exposure. Soil in the two access holes differed in texture and color. Medium-density pasture, hip deep, with roots visible through the depth of the access pits. Previously cultivated field to the south put into pasture in 1996. Not a good micrometeorological site due to the terrain variations.

EF7 / ELK FALLS, KS

Very flat site in a broad stream valley between irregularly rolling hills. No landowner information concerning whether or not site has ever been plowed; mix of good density “improved” pasture suggests that it has been disturbed to some degree. Roots visible through the depth of the access pits. Installation occurred after an extended dry period; large flat fissures, a couple of centimeters wide and tens of centimeters across, twisted irregularly down through the silt loam and silty clay soil, intersecting the access pits. Very good micrometeorological site, with clumps and lines of trees many hundreds of meters away.

EF8 / COLDWATER, KS

Relatively flat, sandy site with some gravel, in an area with only gentle relief. No landowner information concerning whether or not site has ever been plowed, but some indications that it was plowed at some time. Vegetation is relatively thin and clumpy, about knee deep, with bare soil showing. Roots were relatively thin. The hand-augured access holes (deeper than 85 cm) penetrated into sugar-like sand, pale and extremely dry. Very good micrometeorological site, with only a few trees at distance.

EF9 / ASHTON, KS

High, broad ridge with expansive view to the north. Pasture appears to have never been plowed (no landowner confirmation). There is a dramatic transition in soil texture and color between 60 cm and 85 cm below the surface that was not included in the soil characterization: soils become red and clayey, with red and white soft fragmented sandstone beneath that. Good-quality, knee-deep, dense, mixed-grass-and-forb pasture, with roots through the depth of the access pits. Micrometeorological data will be representative of conditions on the broad hilltop.

EF10 / TYRO, KS

Site located beside a man-made drainage ditch, with about 50 cm of mixed fill on top of the original ground level, in a relatively low area surrounded by higher hills. There is a layer of uneven, lumpy limestone at 55 cm below the SWATS system, varying as much as 15 cm in depth over an area 10 m in diameter, broken at the drainage ditch. Vegetation is hip deep, with roots reaching to the rock layer. The sensors are at 5, 15, 25, 35, and 55 cm, with the 55 cm sensors positioned immediately adjacent to the rock layer. A cultivated field (usually winter wheat) lies south of the drainage ditch. Micrometeorological data will be representative of conditions in the valley.

EF11 / BYRON, OK

Very flat site in a wide, low area, with a few dune-shaped small hills to the far south and east. Proved to be the local low spot: hand auguring hit the water table during installation, with the 125 cm and 175 m sensors installed under water. Since installation, this site has flooded repeatedly. Relatively dense, knee-deep pasture with roots visible through the depth of the access pits. Cultivated pasture to the south, either alfalfa or winter wheat. Very good micrometeorological site.

EF12 / PAWHUSKA, OK

Broad ridge in the Tallgrass Prairie Preserve, a few hundred meters north of the Oklahoma Mesonet Foraker site (http://okmesonet.ocs.ou.edu/). The ground drops sharply several hundred meters north of the EF, and the pasture has never been plowed. There are irregular rock horizons at this location, with a broken layer of shale about 45 cm down, and fractured, increasingly dense sandstone below that. Sensors were installed at 5, 15, 25, 35, and 60 cm. Grazing and fire permitting, the tallgrass can reach heights of several meters here, and roots were thick down to the rock. Micrometeorological data will be representative of conditions on the broad hilltop.

EF13 / LAMONT, OK (CENTRAL FACILITY)

Broad hilltop, a few hundred meters west of a valley. The pasture had been terraced to some degree and "improved" several decades previously, but has returned to a more native mix of grasses and forbs. Vegetation is greater than hip deep (if ungrazed), and roots were visible through the depth of the access pits. A layer of sandstone begins 88 cm below the surface, so sensors are installed at depths of 5, 15, 25, 35, 60, and 85 cm. The original installation in January-February 1996 only included the top five levels due to extremely dry conditions; the lowest depth (85 cm) was added in February 1997. Micrometeorological data will be representative of conditions on the broad hilltop.

EF15 / RINGWOOD, OK

Sandy site, in a relatively uniform area that appears to be grass-covered sand dunes, with tree lines several hundred meters to the north, west, and south. Site appears to have never been plowed (no landowner confirmation). Soil from the deepest two levels (125 cm and 175 cm) was different in texture, with some clay content. Vegetation is knee deep and covers the ground more completely than at the other two sandy sites; roots were visible through the depth of the access pits. Micrometeorological data will be representative of the area.

EF16 / VICI, OK

Relatively flat site, with a slight slope to the north leading to a tree-filled gully. Wheat field to the south has been terraced, so it is possible that this site was disturbed at some time. Vegetation is knee deep and tends to be clumpy, with soil occasionally showing between clumps; roots were visible through the depth of the access pits. Good micrometeorological site.

EF18 / MORRIS, OK

Bermuda hay field, in an extensive area with almost no relief, and a high water table. The hay field is very flat, with a thick tree line to the north, good fetch to the south and west, and a busy state highway due east. During soil sampling and sensor installation, water seeped down the sides of the sampling trench and access pits. Roots were visible through the depth of the access pits. Very good micrometeorological site. The SWATS at this site has suffered repeated lightning damage.

EF19/ EL RENO, OK

Relatively flat site, in gently rolling terrain. Unplowed tallgrass prairie, with a few buildings several hundred meters to the south. Grazing and fire permitting, the tallgrass can reach heights of several meters here, and roots were visible through the depth of the access pits. Good micrometeorological site. This site is collocated or in proximity with several other networks: 1.6 km from the Oklahoma Mesonet El Reno site (http://www.mesonet.org/); co-located with the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) Soil Heat And Water Measurement System (SHAWMS) (site ER01); and co-located with the USDA Natural Resources Conservation Service (NRCS) National Water & Climate Center's Soil Climate Analysis Network (site 2022, http://www.wcc.nrcs.usda.gov/scan/).

EF20 / MEEKER, OK

Broad, north-south ridge in a hilly area, with outcrops of sandstone along the ridgeline. The field has been plowed at some point. The SWATS system is located to the west of the ridge, in an area where the first layer of sandstone is about 130 cm below the surface. There are seven sensors in each profile at this site, lacking the 175 cm depth. When ungrazed, vegetation is knee to hip deep; roots were visible through the depth of the access pits. Micrometeorological data will be representative of conditions on the ridgeline.

EF22 / CORDELL, OK

Gently sloping with southern exposure, in slightly rolling terrain, with a few trees and buildings several hundred meters to the north, and a busy U.S. highway to the east. No landowner information available concerning whether or not the site has ever been plowed. Vegetation is a knee deep when ungrazed, a bit sparse with bare soil showing between clumps; roots were visible through the upper half of the access pits. Good micrometeorological site. Note: the highway is now much closer to the SWATS than when originally installed, approximately 30 m east of the system; the rest of the EF has been moved further west.

EF24 / CYRIL, OK

Gypsum knoll, with a county road on the north edge, surrounded by wheat fields. The sensors are located near the southwest edge of the knoll, in a “hole” in the gypsum filled with soil. The gypsum extends under the wheat field south of the site for less than 10 m south of the EF, so soil moisture measurements will probably not be representative of conditions in the surrounding fields. The installation is non-standard in sensor placement, but does have two sensors at all depths except 175 cm. Vegetation on the knoll is a mix of cacti and opportunistic grasses and forbs. Micrometeorological data will be representative of mixed conditions over the knoll and the surrounding wheat fields.

EF25 / SEMINOLE, OK

Relatively flat site, immediately south of a state highway, with tree lines a few hundred meters in all directions. History of this site is uncertain, as there is some gravel scattered at the surface, with a foundry about 1/4 mile south. Soils appeared to be relatively undisturbed below the topmost 15 cm. Vegetation is relatively dense, and roots were visible through the depth of the access pits. Not the best micrometeorological site.

Sites EF31 through EF41 have yet to be characterized.

5.4 Frequently Asked Questions

Q: (18 November 2002) How many of the Campbell Model 229L Matric Potential Sensors are working and how many have died in the SWATS?

A: For the 19 SWATS facilities in operation (excluding one destroyed by lightning and one being relocated), 270 out of 284 sensors, or 95%, are still working.12 sensors are giving bad readings, and two are just plain dead. There is only one depth at one facility where both sensors are dead and we do not have data for that soil layer. These sensors have been in place since 1996/1997.

Since 2002 (as of August 2015) many more sensors have failed or are producing unreasonable or out-of-range values.

Q: (18 November 2002) Who does the ingest of the SWATS data?

A: ARM's Engineering Group, located at Pacific Northwest National Laboratory, manages the ingest.

6.0 Data Quality

6.1 Data Quality Health and Status

The following links go to current data quality health and status results:

- DQ Explorer http://dq.arm.gov/dq-explorer/cgi-bin/main/metrics.
- NCVweb for interactive data plotting using.

The tables and graphs shown contain the techniques used by ARM's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

For DQ Explorer, select 'ARM site: SGP' and 'Data Streams: sgpswats'.

6.2 Data Reviews by Instrument Mentor

Mentor notes on data quality control procedures:

- **QC frequency**: Once per week
- **QC delay**:
- **QC type**: Graphical plots, data quality metric tables
- **Inputs**: Netcdf data plots
- **Outputs**: data quality reports (DQRs) issued to the site scientist team
- **Reference**:

Data QC procedures for this system are continually being developed.

The instrument mentor inspects SWATS data from all sites at least once per week. The mentor reports data deficiencies via DQRs to the SGP site scientist team (SST) and continually works with Site Operations to issue work orders to fix any problems noted.

The mentor uses several means to inspect the data. Inspection of plots and data quality metric tables at the SGP SST Web site to look for obvious problems and to identify the approximate times of problems.

6.3 Data Assessments by Site Scientists/Data Quality Office

All Data Quality (DQ) Office and most Site Scientist techniques for checking have been incorporated within DQ Explorer and can be viewed there.

Assessments of the SWATS precipitation measurements (supplementary tipping bucket rain gauge data at selected facilities are included in the Data Quality Office's Weekly Data Quality Assessments summaries.)

6.4 Value-Added Procedures and Quality Measurement Experiments

Many of the scientific needs of the ARM Facility are met through the analysis and processing of existing data products into "value-added" products or VAPs. Despite extensive instrumentation deployed at the ARM sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the facility. Conversely, ARM produces some VAPs not to fill unmet measurement needs, but to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces "best estimate" VAPs. A special class of VAP, called a Quality Measurement Experiment (QME), does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks, comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth.

7.0 Instrument Details

7.1 Detailed Description

7.1.1 List of Components

The system consists of several components that enable the system to collect, store, and transmit data automatically. All of the components, with the exception of the sensors, are installed in a weatherproof enclosure located above the soil surface. The components of the system include the following:

- Sensor
  - Model 229L Matric Potential Sensor, Campbell Scientific, Inc.
- Data logger
  - Manages measurement and control functions
  - Campbell Scientific, Inc. Models CR10 and CR10x.
- Multiplexer
  - Allows the connection of up to 16 sensors
  - Campbell Scientific, Inc. Model AM416.

- Constant-current source
  - Provides a regulated current for driving the sensor resistance heater
  - Campbell Scientific, Inc. Model CE8.
- Power supply
  - Provides electrical power for the data logger and telecommunications equipment
  - Campbell Scientific, Inc. Model PS12.
- Storage module
  - Allows long-term, back-up data storage
  - Campbell Scientific, Inc. Model SM192.
- Communications equipment
  - Allows communication with external devices
  - Campbell Scientific, Inc. Model SC32A.

7.1.2 System Configuration and Measurement Methods

Sensors: At a typical SWATS site, sensors are installed at eight different depths in the soil profile: 5, 15, 25, 35, 60, 85, 125, and 175 cm below the soil surface. Two profiles of sensors are installed at each site for replication and redundancy of measurements, resulting in a total of 16 sensors at each site. The two sensor profiles are located 1 m apart from each other. At several of the sites, however, rock or impermeable soil layers prohibited the installation of sensors at the greater depths, resulting in less than eight sensors in each profile.

Installation: At each of the sites, all installation work was performed manually to minimize disturbance of the soil and vegetation at the site, and to minimize safety hazards. Sensors were placed in soil that had been disturbed as little as possible. This was accomplished by minimizing the amount of soil excavated, and by placing the sensors as far away from the excavated area as possible. This resulted in a relatively undisturbed profile of soil in which measurements are made. The electronics enclosure containing the electronic measurement equipment is mounted on a concrete slab placed on the ground surface to minimize the influence of the equipment on the SWATS sensors and on other instrument systems at the site.

The following two figures illustrate the side and top views of a typical installation with sensors installed at all eight depths:

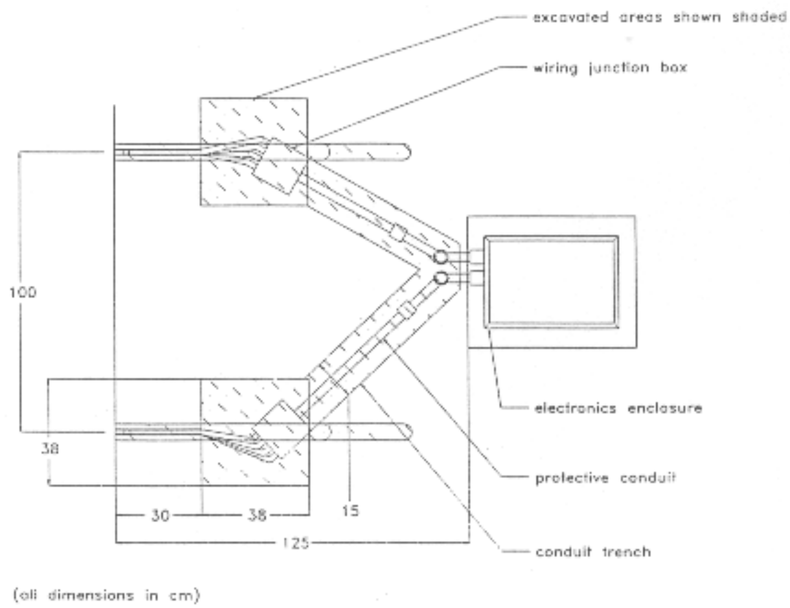

Figure 2. Top view of a typical installation.

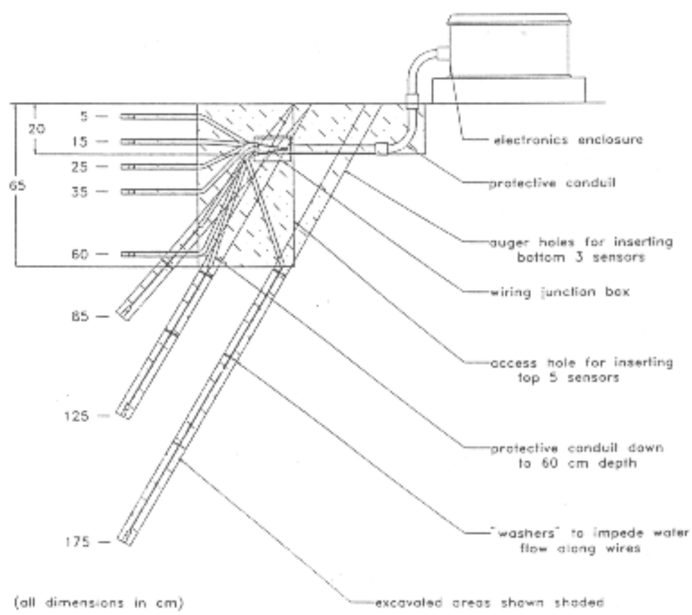

Figure 3. Side view of a typical installation.

Methods of measurements are further described under Section 7.2, Theory of Operation.

7.1.3 Specifications

See Section 7.1.1, List of Components, for details on the sensors.

The Campbell Scientific 229L Soil-Water Potential Sensor

7.2 Theory of Operation

The Model 229L Matric Potential Sensor is designed to provide estimates of matric (or soil-water) potential. The sensor consists of a ceramic matrix, into which a hypodermic needle has been inserted. Inside the hypodermic needle are a thermocouple junction and a resistance heater. A rigid plastic body attaches the hypodermic needle to the ceramic matrix and secures the thermocouple and heater wiring. Figure 4 provides a sketch of the sensor.

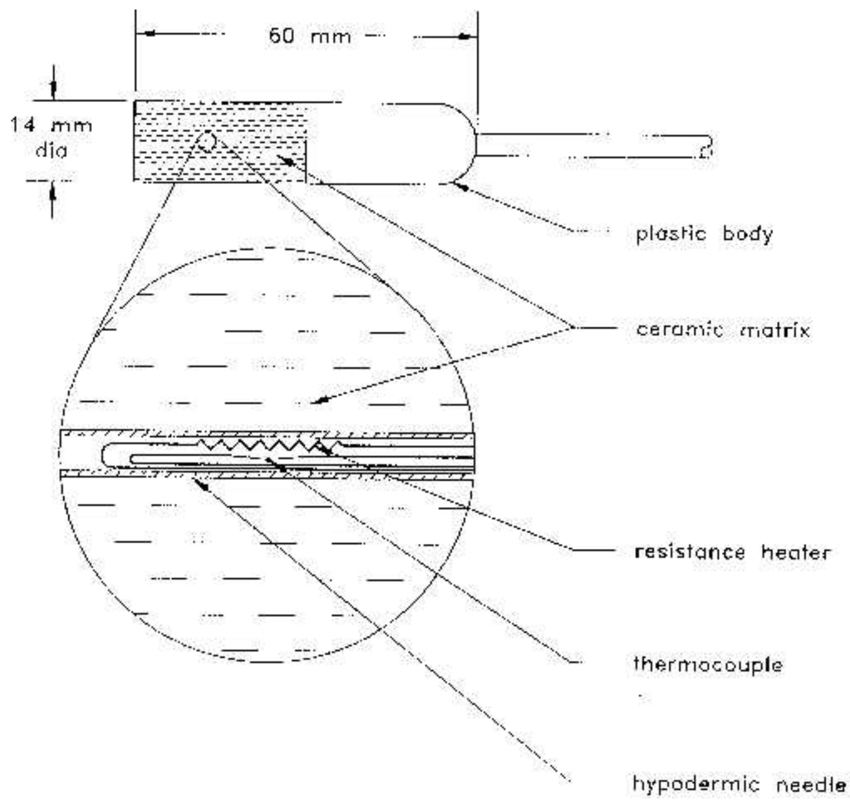

Figure 4. Sketch of the SWAT sensor.

The sensor operates on a heat-dissipation principle. A heat pulse is generated by supplying an electrical current for a short time to the resistance heater inside the sensor. Heat is dissipated by water held in the pore spaces. The temperature rise resulting from the heat pulse and subsequent dissipation of some of the heat is measured with the thermocouple junction inside the sensor. If the pore spaces contain much water, a large amount of heat can be dissipated and the temperature rise will be small. If the pore spaces contain little water and mostly air, the air acts as an insulator, little heat is dissipated, and a large temperature rise results.

A calibration curve relates water potential to temperature rise. The calibration curve returns a water potential value based on the temperature rise reported by the sensor.

To obtain an estimate of the volumetric water content of the soil, the water-holding characteristics of the soil must be known. The soil-water retention curve, also referred to as the water release curve or moisture characteristic curve, relates the water content to the water potential of the soil. This relationship is unique for each soil, and is a function of physical properties, such as soil particle size distribution, organic matter content, and compaction. Knowing this relationship, an estimate of water content can be made based on a value of water potential.

The process by which temperature, water potential, and water content values are obtained is as follows:

1. Measure the initial sensor/soil temperature with the thermocouple.
2. Introduce a heat pulse into the sensor by supplying a current to the resistance heater for a specified length of time.
3. Turn off the heating current and measure the heated-sensor temperature.
4. Calculate the sensor temperature rise by subtracting the initial temperature from the temperature after heating.
5. Convert the sensor temperature rise into an estimate of soil water potential by applying a sensor calibration function.
6. Convert the water potential estimate into an estimate of soil water content by applying a moisture characteristic function.

Sensor measurements are made and recorded at 1-hour intervals throughout the day. Each sensor reports the following information at each measurement interval:

- initial sensor/soil temperature
- sensor temperature rise (difference between after-heating and initial temperatures)
- soil-water potential estimate
- volumetric water content estimate.

All 16 sensors (8 sensors in each of two profiles) at each site are read within a 6-minute period. Data are stored in the data logger internal memory, which will accommodate approximately 3 days of data storage before any data are overwritten and lost. Data are also stored in the storage module, which will accommodate approximately 15 days of data storage before any data are overwritten and lost.

7.3 Calibration

7.3.1 Theory

The SWATS calibration is sufficiently complicated to justify a brief review as precursor for this report. Recall that the calibration for the 229-L heat dissipation sensors in the SWATS is a two-step process. The first step produces a matric potential value ("suction") from the raw measurement of temperature change over a heating cycle (delta T). This is related to the amount of work required to move water in the soil, with units of kPa. The second step produces an estimate of volumetric water (m^3/m^3) from the potential, using the unique soil water retention curves measured by Oklahoma State University (OSU) for each soil horizon at all the SWATS sites. This report is in reference to a proposed change in the first step of this two-step process. NO change is currently recommended for the second step.

After considerable laboratory work, Ken Fisher issued a recommendation to revise the matric potential calibration. This laboratory work has been in the "wet" end of the range of observation to date, from 0 to about 160 kPa. Dr. Fisher has confirmed that the 229-L sensors do not respond to changes in water between 0 and about 10 kPa; i.e., their porous ceramic wick does not begin to drain until the suction reaches that level. The revised calibration takes this behavior into account. The first one did not. Due to the improved performance in very wet conditions, and the simpler form of the calibration equation, the Oklahoma Mesonet has decided to use this revised calibration for their 229-Ls. We recommend that ARM follow suit, calling the original calibration “First-Generation”, and the new one “Second-Generation,” because subsequent revisions may be developed in the future. It is imperative to maintain the original data during any revision of the SWATS data in the ARM Data Center, in particular the soil temperature and the raw measurement of temperature change over a heating cycle (DeltaT).

The revised calibration ensures proper values of matric potential at the wet end, but leaves the dry end unresolved at present. The difference in matric potential between the two calibrations is dramatic as the soils dry beyond 300 kPa (see Figures 1 and 2). At this time, Dr. Fisher has no definitive data on the behavior of the sensors in the 300 to 2000 kPa range. Published work by Reese on six earlier-model 229-Ls reported accurate response out to 1200 kPa, so there is reason to believe that a useful calibration could be developed. Until such work is performed, we have no definitive means to choose between the two. One of us (Jeanne Schneider) expects that a “Third-Generation” matric potential calibration will be shaped like the revised calibration, but closer to the “First-Generation” calibration at the dry end, approaching an asymptote of about 1500 kPa as the volumetric water approaches the residual volumetric water for that particular soil.

The impact of the “Second-Generation” potential calibration on the estimate of volumetric water is much smaller, and primarily at the wet end. Figure 1 gives an example of the impact at two different levels over a two-month period. During wet conditions in a silt loam soil (potential < -50 kPa), the “Second-Generation” volumetric water is almost 3% drier. During dry conditions (late July in the plot), the difference is only about 1%.

If you are unfamiliar with the shape of the relationship between potential and volumetric water (the soil water release curve), it may seem irrational that a large change in potential equates to such a small change in volumetric water. At both the extremely wet and dry ends of the distribution, small changes in volumetric water content produce huge changes in potential. The dynamic response range for a soil (where one can differentiate drying from either dry or wet) is usually between about 5 kPa and 500 kPa. [There is an exception: sand or loamy sand soils tend to be either dry or wet, changing rapidly between the two states; in these sandy soils, there is no useful dynamic response range for relating potential and volumetric water. Further, the 229-Ls do NOT respond to wetting and drying in a manner similar to the sand. The sensors wet more slowly and only partially, and then retain water long after the sand has dried. This is why the SWATS soil water data at EFs 4, 8, and 15 will never be representative of the soil state.]

In summary: we have an improved calibration available for the matric potential in the wet end of the range of observations; calibrations issues remain for the dry end of the range of observations; adjustment of individual sensor response to <u>“reference” sensor response (NO CHANGE)</u>

$$dT_{ref} = m * dT_{sensor} + b$$

Removes sensor-to-sensor variability; coefficients m and b are unique for each individual sensor.

Where

dT_{ref} = “reference” sensor response (C)
dT_{sensor} = individual sensor response (C)
m = slope b = intercept

“Reference” Sensor Calibration Equation

***********FIRST-GENERATION CALIBRATION**********

Estimates potential as a function of reference sensor response; coefficients dT_d, dT_w, a, n are constant for all sensors.

$$\psi = \frac{1}{a}\left[\frac{dT_w - dT_d}{dT_{ref} - dT_d} - 0.9\right]^{\frac{1}{n}}$$

Where

Ψ = potential (kPa)
dT_d = 4.00 (C) dT_w = 1.45 (C)
a = -0.01 (kPa) n = 0.77

***********SECOND-GENERATION CALIBRATION***********

$$\psi = c * \exp\left(a * dT_{ref}\right)$$

Where

a = 1.788
c = 0.717

Soil Water Retention Curve (NO CHANGE)

$$\Theta = \Theta_r + \frac{\Theta_s - \Theta_r}{\left[1 + \left(\alpha\left(\frac{-\Psi}{100}\right)\right)^n\right]^{\left(1 - 1/n\right)}}$$

Estimates water content as a function of potential; coefficients Q_r, Q_s, a, n are unique for each different soil layer at each site.

Where

Θ = volumetric soil water content (m^3 / m^3)
Θ_r = residual water content (m^3 / m^3)
Θ_s = saturated water content (m^3 / m^3)
α, n = empirical constants Ψ =potential (kPa)

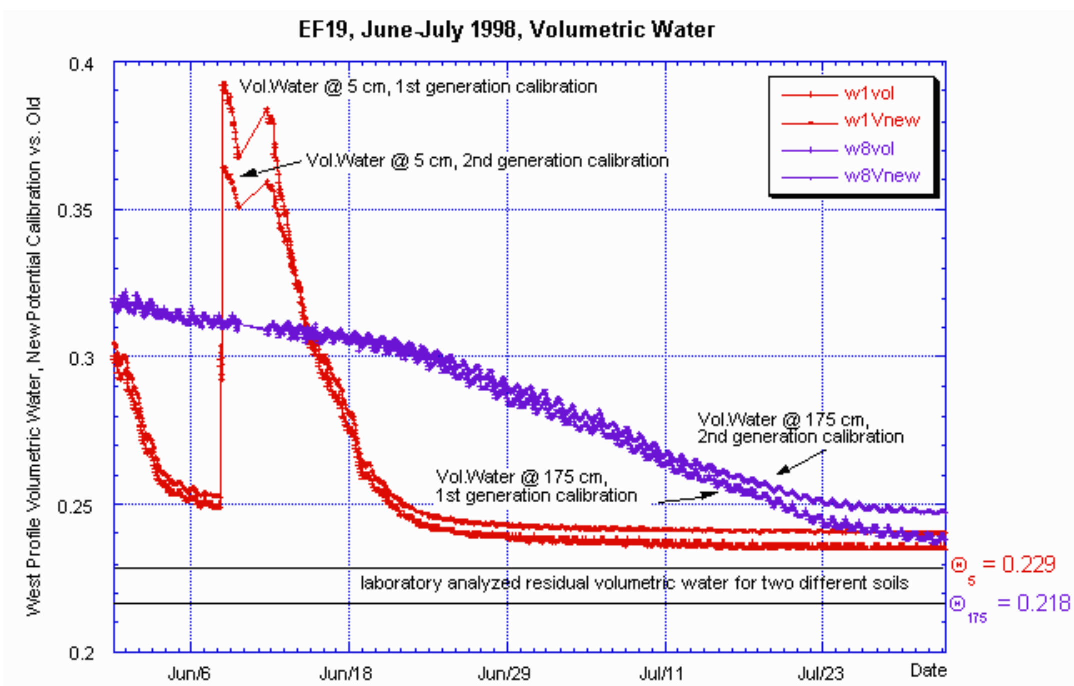

Figure 5. Volumetric water content for both First- and Second-Generation calibration techniques.

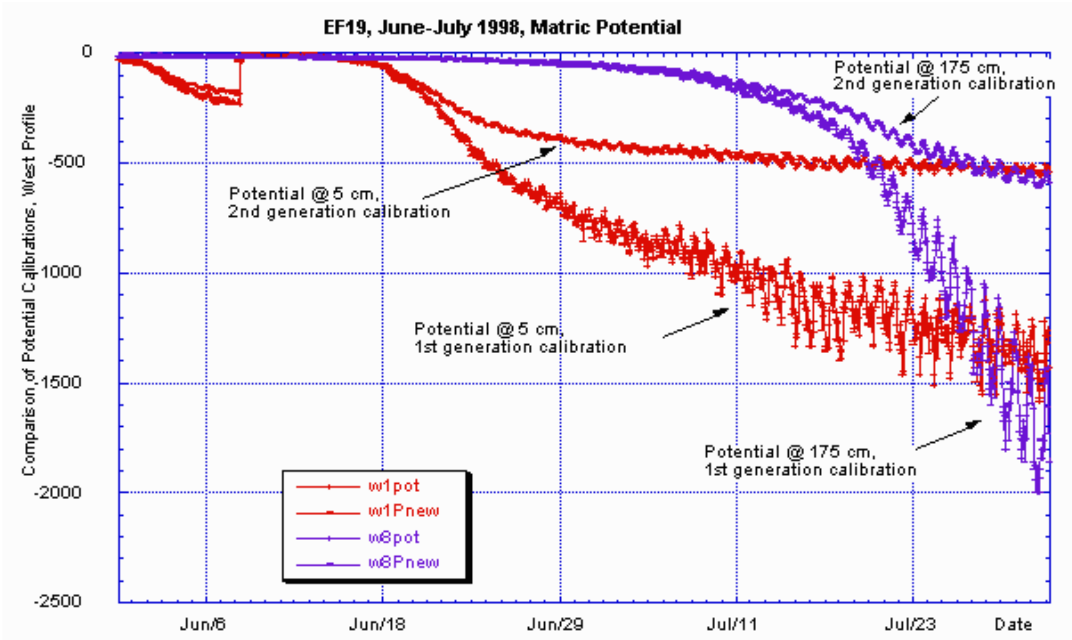

Figure 6. Matric potential (soil water potential) for both First- and Second-Generation calibration techniques.

7.3.2 Procedures

7.3.2.1 Sensor Calibration

The sensors were calibrated to yield a soil-water potential value in response to a temperature rise in the sensor. The resulting calibration equation gives soil water potential as a function of sensor temperature rise.

Early analysis of sensor performance indicated that response varied from sensor to sensor, but that the shape of the response curves was similar for all sensors. Two points on each sensor curve, when the sensor was wet and when the sensor was completely dry, were used to reduce the sensor-to-sensor variability. Linear regression was used to adjust the response of each sensor to that of a “reference” sensor.

The method used in calibrating the 229L sensor involved correlating measurements of potential made with thermocouple psychrometers to temperature-rise readings made with the 229L sensor. A set of 229L sensors and thermocouple psychrometers were placed together in a soil container. The soil was initially saturated and allowed to dry slowly. Readings were taken concurrently from the thermocouple psychrometers and the 229L sensors as the soil dried. A calibration equation was then developed from the concurrent readings.

7.3.2.2 Soil Analyses

A number of physical analyses for the soils at each of the ARM EFs were performed by the Oklahoma State University Biosystems and Agricultural Engineering Department. At each site, a trench was dug

0.5 m deep to visually characterize the soil profile and to identify different soil layers. Multiple soil samples were collected from each distinct soil layer, and were returned to the laboratory for analysis. The samples were analyzed to determine: a) the particle size distribution; b) sand, silt, and clay fractions; c) textural classification; d) organic matter content (in the near-surface layer only); and e) the soil-water retention curve.

The soil water retention curves allow estimates of volumetric water content to be made based on water potential values obtained from the 229L sensors. The van Genuchten form of the water content versus potential equation was fit to the water retention laboratory data from each soil layer, resulting in unique relationships for each soil layer at each site.

7.3.3 History

Comparisons of the water content estimates made with the 229L sensors involves comparing sensor estimates to estimates or measurements of water content made independently of the 229L sensors. Independent water content estimates may be determined from gravimetric analysis of soil samples collected at each site, or from water content measurements made with neutron meters or time-domain reflectometer (TDR) instruments. This work is ongoing, with work being performed by the OSU Biosystems and Agricultural Engineering Department and the Oklahoma Climatological Survey located at the University of Oklahoma.

24 July 2001

Latest Report on SWATS Calibrations

26 July 2000

Status Report on SWATS Calibrations

Jeanne M. Schneider, Ken Fisher and Chad Bahrmann

The SWATS calibration is sufficiently complicated to justify a brief review as precursor for this report. Recall that the calibration for the 229-L heat dissipation sensors in the SWATS is a two-step process. The first step produces a matric potential value ("suction") from the raw measurement of temperature change over a heating cycle (delta T). This is related to the amount of work required to move water in the soil, with units of kPa. The second step produces an estimate of volumetric water (m^3/m^3) from the potential, using the unique soil water retention curves measured by OSU for each soil horizon at all the SWATS sites. This report is in reference to a proposed change in the first step of this two-step process. No change is currently recommended for the second step.

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In summary:

- we have an improved calibration available for the matric potential in the wet end of the range of observations
- calibrations issues remain for the dry end of the range of observations.

7.4 Operation and Maintenance

7.4.1 User Manual

Please contact the mentor (Section 2.1) for a copy of the SWATS User Manual.

7.4.2 Routine and Corrective Maintenance Documentation

Preventative Maintenance Procedures

Corrective maintenance generally entails reconfiguring the wiring in the above-ground electronics box and/or replacing electronics components as deemed necessary during troubleshooting. Corrective maintenance documentation is in draft form: please contact the mentor (See Section 2.1) to obtain documentation.

7.4.3 Software Documentation

ARM netCDF file header descriptions may be found at SWATS Data Object Design Changes.

7.4.4 Additional Documentation

See the Preventative Maintenance Procedure Summaries for the SWATS at the Southern Great Plains (SGP) observatory.

The Campbell Scientific 229L Soil-Water Potential Sensor

8.0 Citable References

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Schneider, JM, DK Fisher, RL Elliott, GO Brown, and CP Bahrmann. 2003. “Spatiotemporal variations in soil water: First results from the ARM SGP CART network.” *Journal of Hydrometeorology* 4(1): 106-120, doi:10.1175/1525-7541(2003)004<0106:SVISWF>2.9.CO;2.

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