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Abstract

Soil moisture is the key state variable from both climate and hydrologic cycle assessment perspectives. Automated measurements of soil moisture were not possible in the past decades. Sensors deployed in the field with real-time monitoring networks such as the Automated Weather Data Network (AWDN) in Nebraska have not only become affordable but enhanced the monitoring capability of the network with valuable soil moisture data added to the existing stream of hourly and daily weather data for precipitation, air temperature, humidity, solar radiation, wind speed, and soil temperature. However, to assure the quality of the data, quality control (QC) tools are needed. Earlier studies lacked the QC of soil water data in general as they were not part of a network that routinely collected soil water measurements. This paper presents a systematic QC analysis and methodology to evaluate the performance of candidate QC techniques using spatially-extenstive soil water dataset available from the AWDN network. The six tests included are based on the general behavior of soil moisture, the statistical characteristics of the measurements, the soil properties, and the precipitation measurements. The threshold, step change, and spatial regression test proved most effective in identifying data problems. The results demonstrate that these methods will lead to early identification of potential instrument failures and other disturbances to the soil water measurements.

Abbreviations

ACIS – Applied Climate Information System
AWDN - Automated Weather Data Network
QC - quality control
R&H SM model - Robinson and Hubbard soil water model
PIB method - precipitation and irrigation based method
PIAB method - precipitation and irrigation amounts based method
SRT - spatial regression test
ND - number of days

Introduction

In the past, quality control (QC) procedures have been applied in a limited way to examine the validity of weather data (Guttman and Quayle, 1990) available from the archives of the National Climatic Data Center. QC generally involved a number of internal consistency tests, a threshold test, and a step change test for detecting potential outliers at a particular station (Wade, 1987; Meek and Hatfield, 1994; Eischeid et al., 1995; Hubbard et al. 2007a;

Durre et al. 2007). Data collected for a given site may also be compared with data from surrounding stations to assess the accuracy of the measurement (Wade, 1987; Gandin, 1988; Eischeid et al., 1995; Hubbard et al., 2005; Hubbard et al. 2007a). An estimate is arrived at for the station of interest, based on the neighboring stations, and the difference between the computed value and the observation for the station of interest is tested to determine the likelihood of it being an outlier. For the inverse distance weighting technique, the estimate is formed by weighting the values at surrounding stations by the inverse of the distance separating the locations (Guttman et al., 1988; Wade, 1987). This does not remove any systematic differences between the stations. Other statistical approaches seek to provide a non-biased estimate (e.g. multiple regression, Eischeid et al., 1995 and Eischeid et al., 2000; bivariate linear regression test, Hubbard et al., 2005). The new Climate Reference Network was designed so that biases due to temperature observation times, station moves, and instrumentation type are eliminated. Examining data from the Climate Reference Network, Gallo (2006) suggests that "microclimate influences on temperatures observed at nearby (horizontally and vertically) stations are potentially much greater than influences that might be due to latitude or elevation differences between stations." Spatial statistical approaches can eliminate systematic bias due to both elevation and latitude differences. With a 24-30 day window for the formation of weighting factors for the spatial statistical approach (Hubbard et al., 2005), any systematic bias due to changing releationships between stations (microclimate) can be removed. An automated procedure for checking the tendency for flags to be grouped geographically is usefull in the event of strong and non-stationary horizontal gradients in the variable (You and Hubbard, 2006).

Recently, the historical climate data has been combined with the near-real time stream of field data to provide an up-to-date analysis in order to draw a comprehensive assessment of site-specific hydroclimatology for both current and historic conditions. The analyses are provided on an interactive basis through the Applied Climate Information System (ACIS, Hubbard et al., 2004) -- a synchronous, distributed system developed by the National Oceanic and Atmospheric Administration's (NOAA) Regional Climate Centers (RCCs). QC procedures have been employed on the historical data regularly however, to be useful the near-real time data requires considerable quality testing as well. Advances in the QC of ACIS data has included the QC of maximum (T_{max}) and minimum (T_{min}) air temperature (Hubbard et al., 2005; Hubbard and You, 2005; Hubbard et al., 2007), and of precipitation (You et al., 2007).

QC of variables using physically-based processes are common. For instance, testing of hourly solar radiation against the estimated clear sky radiation (Allen, 1996; Geiger et al., 2002) and the use of soil heat diffusion theory to determine consistency in the soil temperature profile has shown some degree of success (Hu et al., 2002). These methods apply the physical properties or physically-based estimates or modeling results to help evaluate the validity of measurements.

Soil water is the amount of water held in storage at a given time and is closely related to soil properties, antecedent precipitation, and drainage. Data quality from any sensor is dependant upon three main processes: (1) calibration, (2) installation, and (3) analysis of the collected observations. Hubbard et al., (2008) reported the calibration and installation of the sensors. The focus of this paper is primarily on the third point which deals with the analysis of the collected soil water observations. This will not only aid in improving techniques to add value to field-based observations but also increase confidence in utilizing these observations as has been recognized by Illston et al. (2008) and discussion on this approach is also lacking in the literature..

In this paper, QC tests were developed and their performance was evaluated on a unique soil water dataset. This dataset is unique because the AWDN stations collect soil moisture from multiple depths continuously for over 51 sites spread over eight climate divisions for more than 10 years between 1998-2008. Five tests are included and are based on the properties of soil water, the statistical characteristics of the measurements, the soil properties, and the precipitation measurements. Preliminary tests confirmed that the variability in precipitation and soil types were too high to allow a comparison with neighboring stations. This paper also includes examples of utilization of Robinson and Hubbard Soil Moisture (R&H SM) model (Robinson and Hubbard, 1990) in validating the soil water data. The R&H SM model,with precipitation input from measurements at the soil water monitoring site was applied to provide a reference estimate against which actual observations were compared.

Materials and Methods

Data

The Automated Weather Data Network (AWDN) collects soil water data from 51 locations in Nebraska, at four depths of 0.10, 0.25, 0.50, and 1.00 m for each location. The surface vegetation is predominantly rain-fed native grass of Nebraska. For our study, the focus of the analysis and implementation of automated quality control procedures is on the growing seasons from 1998 to 2005.

The soil water data network has utilized two types of probes: the Vitel (Stevens Hydraprobe) and Theta (model ML2) probes. Both sensors are based on the concept of measuring the dielectric constantof soil and relating it to the volumetric water conent of the soil via acalibration curve. The Vitel probes were installed at 14 stations and the Theta probes were installed at 37 stations thus providing a total of 51 sites for measurement of soil moisture in the state (see Fig. 1 and Table 1). The time period of observations for each station is listed in Table 1. In this study, Dec. 31, 2005 is taken as the end date although data continues to be collected. Calibration curves for the probes were prepared by taking soil samples for each depth at every site. An electronic probe reading was taken f just prior to the collection of a physical soil sample from the field. The samples were then oven-dried and the volumetric water contents were compared to the probe readings. The resulting calibrations are shown in Fig. 2. More detailed information on installation and calibration of soil water probes was provided in Hubbard et al. (2008). One should note that using a single calibration curve would lead to more systematic error thereby propagating uncertainty in the in-situ observations. For example, using the "sand" calibration curve at a signal strength of 700 mv to estimate soil water in silty and clay soils would result in underestimation of soil moisture by 24% and 11% , respectively.

Visual inspection of the raw data indicates that the variation of hourly soil water data measurements from the Vitel probe was considerably higher than those from the Theta probes. This additional noise in the Vitel data may be related toa higher random error in the Vitel soil water measurements and it was one of the reasons to replace all Vitel probes in 2005. The replacement occured at 12 out of the total 14 sites where originally the Vitel probes were installed and the termination dates of the Vitel probes are also included in Table 1. The replacement involved installing the Theta probes at the same depths (10, 25, 50, and 100cm) and retrieving the Vitel probes. At the remaining two sites, Arapahoe and Mead, the Vitel probes were left in place in order for us to operate them concurrently with the Theta probes and to maintain continuity in our measurements.

Methods

The amount of soil water present in the soil column is somewhat limited by the physical properties of the soil apart from other environmental factors including precipitation, solar radiation and vegetation cover. The water content in the soil cannot exceed the porosity of the soil. A lower limit in the soil water content under natural conditions is referred to as the air dry limit. The air dry limit is not usually achieved below a shallow surface layer owing to the time for the process of diffusioin to move the water vapor to the soil surface. A practical lower limit below the surface layer is known as the wilting point below which plant roots can not extract moisture from the soil. The soil properties only provide the upper and lower limits for the soil water content, while precipitation, irrigation, evapotranspiration, drainage, and runoff can cause the water content to fluctuate between these upper and lower limits.

The QC method in this paper uses a time changing statistical confidence interval factor to quantitatively specify the QC results. This method quantifies where the observation falls with regard to the prediction confidence intervals. With time changing confidence interval then statistically based QC procedure can identify a subset of data, if present, which are potential outliers. The magnitude of the standard error of estimate defines the width of the confidence interval (e.g. 98%) and affects the number of bad entries classified as good measurements as well as the number of good measurements classified as potential outliers.

In addition to the traditional QC measures as described in Hubbard et al. (2005), this paper used the modeling results from a soil water model to form a new QC method. Models have been applied in estimating the water balance of the soil layers and as a tool for irrigation scheduling (Qiu et al., 2001; Robinson and Hubbard, 1990). The R&H SM model (Robinson and Hubbard, 1990) has been utilized to estimate the soil water for different crops and different soil types (Carmago, 1993; Camargo et al., 1994; Mahmood and Hubbard, 2003). The estimates from the R&H SM model (Robinson and Hubbard, 1990) serve as reference values against which the actual observations from the soil water dataset are compared. It was recognized that without a detailed fit of the model, systematic differences between the model and measured values would not be completely removed. However, this does not affect the precision of the model or the correlation between measured and model estimated values. The model can be envisioned as a surrogate to the nearest point of measurement in the neighborhood po which is generally highly correlated to the measured values.

R&H SM model

The basic equation for the R&H SM model can be expressed as:

$$\partial S_t / \partial t = P + I - ET - R_0 - D_r, \qquad (1)$$

where S_t (mm) is soil water in the root zone, t is time, P (mm) is precipitation, I (mm) is irrigation, ET (mm) is actual evapotranspiration, R_0 (mm) is runoff, and D_r (mm) is drainage below the root zone. A 24-h time step is used with daily precipitation and irrigation (if applied) as inputs to the model. Runoff is estimated from total precipitation, relative fraction of soil water present, and soil water retention factor (McCuen, 1982). Campbell's equation is used in this model to calculate drainage from each layer (Campbell, 1985). The relationship between S_t and the volumetric water content (θ) for a given layer is $\theta = S_t/\Delta z$ where Δz is the depth of the layer (mm).

The model calculates actual evaporation and transpiration separately and the summation of the two is ET. A modified version of the Penman (1948) combination method for potential ET estimation is applied to derive actual evaporation (E) and transpiration (T). The modification of the Penman method is conducted by including the Kincaid and Heerman (1974) wind function. Actual evaporation is a function of potential ET and the number of days (ND) since the last precipitation occurred. The relationship between E and potential ET is presented as follows:

$$E = ET_p (1/ND)^{1/2} \qquad (2)$$

Where ET_p is potential evapotranspiration based on the modified Penman method. A function of weather conditions and a phenology specific crop-coefficient (K_c), ET_p, and a soil water reduction factor (f) provides actual transpiration. The model assumes that transpiration is not limited when the soil water content falls above the halfway point (from field capacity to wilting point) after e.g. Baier (1969) and Tueling et al. (2006) but decreases linearly with soil water below that point to zero at the wilting point. The soil water reduction factor (f) is the parameter in the model that captures this relationship. Actual transpiration can be expressed as:

$$T = f \cdot K_c \cdot (ET_p - E). \qquad (3)$$

The model was validated and its performance was evaluated for five locations, nine different land uses, a variety of soil conditions (sandy to clay), and for five depths of up to 1.8 m. These sites were located in a cluster of stations: NE(5), SD(2), and WY(2). The overall validation was completed for 20 different land surface conditions. For most cases the model agreed well with observed data with bo the d-index and the $r^2 > 0.9$ (Robinson and Hubbard, 1990; Camargo, 1993; Camargo et al. 1994; Mahmood and Hubbard, 2003). In addition, the soil water model simulates water in each layer, current water stress, runoff, drainage, phenology, actual and potential evapotranspiration, sensible heat flux, and net radiation.

Soil water QC rules

1) Threshold method

The threshold method utilized here is different from the method described in Hubbard et al. (2005) which calculated the upper and lower limits from the historical data. The thresholds for the soil water are the physical bounds of the value instead of the limits defined using the confidence factor together with the statistical characteristics of measurements (mean and standard deviation).

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The degree of saturation (wetness), S, is the proportion of pores that contain water:

$$S = \frac{V_w}{V_a + V_w} = \frac{\theta}{\phi} \tag{4}$$

where V_w is the volume of water and V_a is the volume of air, θ is volumetric water content, and ϕ is the porosity. The volumetric maximum soil water for a given soil is equal to the porosity of the soil. The variable S is physically constrained to values between 0 and 1. Thus, if

$$\theta > \phi, \tag{5}$$

the measurement exceeds its physical limit and S>1. In this case the measurement will be flagged as an outlier for further manual review. The lower threshold applied to the soil water measurements is 0 while the upper limit is the porosity of the soil layer. Physically the soil water in the root zone should not be lower than the water content associated with the wilting point of plants; however, persisting dry conditions may lead to a lower soil water value in the near surface layer. Therefore the lower limit of null value (0) is used in this study. Any measurement falling outside [0, ϕ] will be identified as an outlier.

2*) Test based on the step change*

The step change test has been addressed by Hubbard et al. (2005) and that has been employed in our current study. Mean and the standard deviation of the step change of the soil water data was calculated for the available time series, which was updated continuously with field observations. A confidence interval factor of 3.0 was used in the QC procedure for soil water in this method.

3) Precipitation and irrigation based method (PIB method)

The increases in θ are associated with precipitation and irrigation or the rising water table. Thus the change in θ is zero or negative when there is no rain or no irrigation is applied, under the assumption that the water table does not rise.

$$\partial\theta / \partial t \leq 0, \text{ when } P+I=0. \tag{6}$$

The measurements pass the test if equation (6) is true.. This test identifies those abnormal increases in soil moisture due to the noise of the probe on days when there is no precipitation or irrigation. Note that this test is not useful in areas that have shallow groundwater tables where soil moisture data is subjected to rises in the water level. Using this test, those values that show an increase when there is no irrigation and precipitation are flagged as outliers; however, the measurement will not be changed until additional substantial errors are identified. The results obtained by this method are labeled as the 'PIB method'.

4) Precipitation and irrigation amounts based method (PIAB method)

Equation (1) indicates that the maximum increase of θ in a single time step should not exceed the precipitation plus the irrigation amount. Thus the wetness is limited to the maximum change caused by the precipitation and irrigation, which can be written as:

$$\partial\theta / \partial t < (P+I) / \Delta z, \tag{7}$$

where Δz is the depth of the soil layer. On days when the relationship in equation (7) holds true, we can state that the measurements have passed this test, otherwise the measurements are flagged for further manual review. This test identifies the data regions where those abnormal increases of the soil water content cannot be explained by the observed precipitation and irrigation. In practice the precipitation and irrigation would likely recharge more than one layer but for our purposes we are looking for an upper limit to identify extreme outliers.

The PIAB method can only be applied to the top soil layer owing to the time lag between precipitation and irrigation and drainage to the lower layers. If the soil water content increases more than the precipitation and irrigation amount, the record is flagged for further checking. The underlying assumption here is that the soil structures around the probe are relatively homogenous, and the rise in the water table is neglected for the top layer soil water QC. The results obtained by this method are labeled as the 'PIAB method'.

5) QC based field capacity and permanent wilting point

The decrease in the water content occurs slowly when the water content is less than the field capacity (θ_{fc}), where θ_{fc} represents the water that remains after the soil has been saturated and allowed to equilibrate (drain) for a few days against the force of gravity. The pressure head at field capacity (φ_{fc}) is close to -3.4 m for all soils. In reality, water can be removed from the soil that has reached field capacity by direct evaporation or by plant water uptake leading to transpiration. The plants cannot exert suction strong enough to remove water at the permanent wilting point (φ_{pwp}), a value close to -150 m.

The corresponding water content can be calculated from the pressure head using,

$$\theta = \phi\left(\varphi_s \varphi^{-1}\right)^{b^{-1}}, \tag{8}$$

where φ_s is the pressure head of the soil when the soil is saturated. The wetness can be calculated for both the field capacity and the permanent wilting point using

$$S = \theta\phi^{-1} = \left(\varphi_s \varphi^{-1}\right)^{b^{-1}}, \tag{9}$$

b is one of the empirical parameters of soil following Clapp and Hornberger (1978).

The corresponding water content for field capacity or permanent wilting point (θ_{fc}, θ_{pwp}) can be calculated for the soil from φ_{fc}, φ_{pwp}. If θ is less than θ_{fc} and $\partial\theta/\partial t$ has a relatively large decrease, then we flagged the measurement for further manual checking. For example, the threshold for field capacity test of $\partial\theta/\partial t$ takes an arbitrary value of -0.01 (1 percent decrease). When θ is less than θ_{pwp} and $\partial\theta/\partial t$ <0, we also flagged the measurements for further manual checking. The results obtained using this method has been labeled as "soil properties".

6) *Spatial regression approach based on R&H SM modeling results*

The R&H SM model (Robinson and Hubbard, 1990) has proven to be suitable in modeling the soil water for different crops (Robinson and Hubbard, 1990; Camargo et al., 1994; Mahmood and Hubbard, 2003, 2004). In this study, it is assumed that the value observed at each depth is represented by a corresponding thin layer in the R&H SM model (Robinson and Hubbard, 1990). The thickness of the soil layers in the model were adjusted so that each measurement depth would fall within 2 cm of the prescribed model layers. Time series of modeld soil moisture for the soil layers were in full agreement with the trend in the measured time series and were highly correlated to the measured water content. In this study the spatial regression test (SRT, Hubbard et al., 2005) is adopted to form a QC test fir the soil water data and to provide estimates for the missing value or the reference value for those outliers in the soil water data. The SRT test performed on the soil water data relies on the modeling results obtained using the R&H SM model. It should be noted that the models soil water estimates are based on measures of the the weather variables at each site and are independent of the soil water observation sensor. Research has demonstrated that using a 15-day window with the SRT method can provide good regression results between the model estimates and the measurements (Hubbard and You, 2005).

Results

The quality-control methods were applied to the soil water data collected from the 51 soil water monitoring sites of the Nebraska AWDN. The quality assured dataset contained continuous daily soil water time series for the four depths: 0.1, 0.25, 0.50, and 1.0 m. All tests such as the threshold test, tests based on the precipitation measurements and soil properties were applied for all stations. Irrigation was assumed to be zero for all simulations because all sites were identified to have rain-fed grass as their surface vegetation.

QC results

1) Multi-year Quality-Assurance Record
As with any operational weather data network, some factors cause frequent problems within the system and therefore can lead to erroneous observations. Lightning and animal damage as well as human vandalism can cause a disturbance in and around the sensor that affects the measurements. A low battery also leads to unstable measurements which may cause considerable noise in the measurements. The probability of the latter is greatly reduced if a solar panel and recharging unit are maintained on site. Several significant examples of disturbance include:

- Soon after installation coyotes dug outburied probes, apparently mistaking the fresh digging for gother activity..
- Lightning hit an object nearby the automated weather station. Afterward the measurements by the Theta probe displayed a noisy pattern.
- Gophers burrow across a Vitel probe. The plastic cable cover was chewed off and the probe was damaged.

QC work also identifies subtle effects that result from changes in the environment, rather than instrumental faults. For instance, the Vitel probe installed at 1 m depth at Elgin had zero readings starting from Sep. 1, 2003 and the zero readings continue through Feb. 23, 2004. The readings restarted when a big rainfall event occurred (See Fig. 3); therefore we assumed that the abnormally low readings were caused by the very dry conditions at 1 m, ie. the soil water was between air dry and wilting point

2) Automated QC results for the top layer probe
The flagged fraction of valid measurements for the top layer probe (0.10 m) was mapped for each of the first four QC methods (see Fig. 4). The symbol does not represent the same fraction for all four methods because the fraction of flagged measurements varies significantly for different methods. Discussion of QC results for the SRT method for all layers is presented in SRT QC section and is not repeated in this section.

Table 2 summarizes the mean fraction of data flagged by each method for all layers. The threshold method detected some outliers in the measurements of several stations. A close examination revealed that, using the threshold test, no outliers were identified for the Vitel probes and some outliers occurred at several sites with Theta probe installations. As shown in Fig. 2, for the Vitel probe the same calibration function was used for all soil types at all stations; while the calibration functions of the Theta probe varied for different soil types (Hubbard, et al. 2008). Thus, potential errors may be more easily detected at the Theta probe sites given that the soil type was not considered in the calibration of the Vitel probe (See Fig. 2). Any misclassifications of the soil sample may also lead to this kind of error.

Mean and standard deviation used in the step change test were obtained from the available time series of the measurements. In the step change test, all stations had a flagged fraction higher than one percent when a confidence interval factor of 3 was used (Fig. 4). The flagged fraction by the step change method was lower than four percent for all stations for all Vitel and Theta probes except for the Theta probes with less than one year of data, e.g. McCook newly installed on July 13, 2005 with a fraction of flagged data of 8.2%. Most stations had a flagged fraction between two percent and four percent, which produced a reasonable number of potential outliers for manual checking by validators.

The QC procedures based on the soil properties also flagged many data entries. A large portion of the flagged data by the threshold approach was also flagged when the measured Theta probe signal was negative, which was below the wilting point. Thus, any negative change of the soil water when a negative soil water value was present would have been flagged as an outlier. This is somewhat similar to resetting all negative solar radiation measurements to null value during nighttime hours, i.e. in both cases the random component around the calibration line can produce non-physically plausible values at the low end of the calibration.

The tests against precipitation and irrigation were actually the tests against only precipitation given that all soil water probes were installed under native, rainfed grass cover at all sites and no irrigation was applied. The QC PIAB method only identified 2 or 3 more flags at two stations than the QC PIB method, hence only the flagged fraction by the PIAB method was shown. As seen in Figure 4, The PIB and PIAB techniques were flagging 10 to 27 % of the data in the top layer, which was higher than those flagged by the other three tests. The results also showed that the fraction of data flagged by the PIB method (or PIAB) was much higher in winter than in summer for both the Vitel and Theta probes due to the difficulties associated with winter precipitation measurements and absence of accounting for snowmelt processes.

3) Automated QC results for the other three layers

The four tests, excluding the test against the precipitation amount, were also conducted for the measurements of the other three depths. Similar to the QC results for the top layer, some values were flagged as failing QC in the lower layers for the same causes noted in the top layer (as listed in Table 2). A notable event was found in measurements of Layer 4 (100 cm) at Ainsworth. A total of 48.4% of the measurements were flagged at the Ainsworth station for the Theta probe and 8.1% for the Vitel probe, with an overall flagged fraction for the time period of 10.7%. The threshold test detected the problem when the measurements exceed the upper limit of the porosity of soil initially judged by visual characteristics of the soil sample. For this location further examination of the soil properties was conducted. Also, the possibility exists that the misclassification of soil type occurred with some, thus the readings were higher than the stated porosity. More analysis is needed to resolve the over-flagging issue at 100 cm depth at Ainsworth.

The QC procedures for the three lower layers also included the direct test against precipitation. However, there was a time lag between the time when precipitation occurred and when the probes at lower layers responded to the precipitation events, which in turn led to the possibility of incorrectly placed flags. The automated review of the lower layer soil water measurements against the precipitation was likely better accomplished by referring to the output from the hydrology model that simulated the essential physical processes. Overall, the PIB and PIAB methods were flagging up to 35 % of the data in the lower layers and this was unacceptably high for manual validation of potential outliers.

4) Modeling results of R&H SM model and SRT results

The R&H SM model (1990) has been validated to North Great Plains (NGP) for different crops (Robinson and Hubbard, 1990; Camargo, 1993; Camargo et al., 1994; Mahmood and Hubbard, 2003). This paper uses an existing set of soil parameters and near surface atmospheric observations to drive the model at sites and the modeling results were referred to in the SRT QC procedures.

The R&H SM model was initialized with field measurements assuming that the growing season began in March every year.. The accumulated growing degree-days were calculated during the model simulations to reflect the phenological development of the grass. The simulation with the R&H SM model was carried out for all stations. In this study, we only report the modeling result at Mead, NE as a typical example for the QC and estimation of the soil water data. Because the layers of the model do not correspond exactly to the measurement depths and because soil water characteristics input to the model were not adjusted by fitting, the wetness at the depth of each probe was regressed using SRT method, as described in Hubbard et al, 2005, against model estimates at corresponding depths. Figure 5 shows the observed and estimated time series for Mead. The correlation between the estimated and measured wetness was high with R^2 of 0.79, 0.93, 0.97 and 0.87 for four probes, respectively. The RMSE between the estimated and measured wetness of the four layers were 0.03, 0.015, 0.008, and 0.01, respectively. The SRT (Hubbard et al., 2005) approach was also conducted to carry out the validity checking for the measurements (see Fig. 6). When the outliers were excluded, the R^2 between the estimated and measured soil water data increased to 0.90, 0.97, 0.99, and 0.99 respectively. The RMSE between the estimated and measured wetness of the four layers were only 0.02, 0.01, 0.005, and 0.006, respectively. The fractions of identified outliers were relatively less for all four layers, which were 6%, 3%, 3%, and 4%, respectively. Many of these identified flags were the result of a time lag between the measured and estimated values, especially for the top layer.

The SRT method was applied in QC of the soil water data (the fraction of flagged data see Fig. 7, Tables 2). The highest fraction of data flagged was about 6% for all layers of all stations. The spatial distribution of the fraction of data flagged did not show noticeable spatial patterns. In addition, the fraction did not strongly relate to the soil types (soils in Nebraska range from mostly clay in the southeast to mostly sand in the northcentral and northwest.) As shown in Figure 6, the SRT method could identify suspect measurements and provide early warnings of potentially bad data.as it is collected.

Discussion and Conclusions

The QC system for measured soil water data is part of the QC system for ACIS. The system applies multiple QC techniques. Each of the techniques has its strengths and weaknesses when applied individually. The combination of the procedures leads to an assessment of the quality of both the past and present soil water data obtained in the AWDN network. As shown in this study, the threshold, step change, and the model/spatial regression techniques performed well. Manual inspection indicated that many of the values flagged by these techniques were outliers. On the other hand, it was discovered that the PIB and PIAB methods were overflagging the data and that only a few of the values flagged were actually outliers. For this reason we recommend automated processes include the threshold, step change, and model/SRT techniques but, exclude the PIB and PIAB techniques. The findings here demonstrated that QC techniques provide the ability to improve and maintain the quality of soil water data sets. Use of different probes and the calibration of the probes appeared to directly affect the quality of the data set. Knowledge gained from the post calibration QC may direct further efforts toward calibration of the probes.

This paper provides rules to review the soil water data relying on physical processes of water transfer and the physical properties of the soil. The results obtained using the described methods will lead to early detection of potential instrument failures and unpredictable disturbances. We recognize that procedures and refinements of the techniques presented here may add value, however, further study on QC procedures and estimation of the soil water through the soil water models, e.g. the R&H SM model (Robinson and Hubbard, 1990) is warranted.

The probes still need improvements in several respects. The noise in the probe measurements resulted in a higher frequency of errors in the QC procedures. The noise may be reduced using filtering tools like the Fourier filtering technique; however, this calls for investigation because filtering may contaminate the data by smoothing the real variations of soil water.

The estimated time series based on the R&H SM model (Robinson and Hubbard, 1990) corresponded well with the time series of measurements for the different observation depths. The bias between the modeled and measured soil water data were caused by the complex processes involved in the plant activity and local water balance processes. Any systematic bias can be accounted for by the regression process hence the SRT QC technique is suitable if the observed values and model estimates have a high correlation.

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Table 1. Probes and measurement period for each station

Station name	Probe	Start	Retired	End
Ainsworth	Vitel	1/1/1998	6/29/2005	12/31/2005
Alliance North	Theta	8/27/2004		12/31/2005
Alliance West	Vitel	1/26/1999	8/23/2005	12/31/2005
Arapahoe Prairie	Vitel	1/1/1998	6/8/2005	12/31/2005
Arthur	Theta	9/29/2004		12/31/2005
Barta	Theta	11/22/2002		12/31/2005
Beatrice	Theta	9/26/2002		12/31/2005
Brunswick	Theta	7/17/2004		12/31/2005
Cedar Point	Theta	9/30/2004		12/31/2005
Central City	Theta	4/15/2004		12/31/2005
Champion	Theta	6/27/2002		12/31/2005
Clay Center(SC)	Theta	5/20/2004		12/31/2005
Concord (NE)	Vitel	1/26/1999	5/27/2005	12/31/2005
Cozad	Theta	5/30/2004		12/31/2005
Curtisunsta	Theta	6/28/2002		12/31/2005
Dickens	Theta	9/28/2004		12/31/2005
Elgin	Vitel	1/26/1999	5/26/2005	12/31/2005
Gordon	Theta	8/26/2004		12/31/2005
Gothenburg	Theta	8/16/2002		12/31/2005
Grand Island	Theta	4/17/2004		12/31/2005
Gudmundsens	Vitel	5/8/1998	7/28/2005	12/31/2005
Halsey	Theta	9/5/2002		12/31/2005
Higgins Ranch	Theta	7/14/2004		12/31/2005
Holdrege	Vitel	1/1/1998	7/14/2005	12/31/2005
Holdrege 4N	Theta	9/25/2004		12/31/2005
Indian Cave St Park	Vitel	7/20/1999	3/28/2005	12/31/2005
Kearney	Theta	5/27/2004		12/31/2005
Lexington	Theta	10/22/2004		12/31/2005
Lincoln 82E 20S	Theta	3/20/2004		12/31/2005
McCook	Vitel	1/1/1998	7/13/2005	12/31/2005
Mead	Vitel	1/1/1998	3/31/2005	12/31/2005
Mead Agrofarm	Theta	3/20/2004		12/31/2005
Merna	Theta	6/18/2004		12/31/2005
Merritt	Theta	7/27/2004		12/31/2005
Minden	Theta	9/18/2004		12/31/2005
Mitchell Farms	Vitel	1/26/1999	8/24/2005	12/31/2005
Monroe	Theta	4/20/2004		12/31/2005
Nebraska City	Theta	4/1/2004		12/31/2005
Nebraska City 2N	Theta	3/26/2004		12/31/2005
Newport	Theta	8/13/2004		12/31/2005
North Platte	Theta	10/1/2004		12/31/2005
O,Neill	Vitel	1/1/1998	6/30/2005	12/31/2005
Ord	Vitel	1/26/1999	6/28/2005	12/31/2005

Station name	Probe	Start	Retired	End
Red Cloud	Theta	6/20/2002		12/31/2005
Scottsbluff	Theta	8/28/2004		12/31/2005
Shelton	Theta	10/23/2004		12/31/2005
Sidney	Theta	8/22/2002		12/31/2005
Smithfield	Theta	10/1/2004		12/31/2005
Sparks	Theta	7/29/2004		12/31/2005
West Point	Vitel	1/26/1999	6/16/2005	12/31/2005
York	Theta	7/18/2002		12/31/2005

Notes: All Vitel probes were replaced by Theta probes at the noted dates

Table 2. Flagged fraction of measurements using QC approaches

Station name	Probe type	Threshold	Step change	Soil properties based	PIB method	PIAB method	SRT	Total1	Total2
Layer 1	Theta	0.0004	0.024	0.011	0.185	0.185	0.028	0.054	0.233
	Vitel	0.0013	0.022	0.009	0.211	0.211	0.026	0.051	0.255
	Both	0.0013	0.022	0.009	0.211	0.211	0.026	0.051	0.254
Layer 2	Theta	0.0008	0.024	0.011			0.192	0.192	
	Vitel	0.0002	0.021	0.006			0.203	0.203	
	Both	0.0000	0.024	0.012			0.184	0.184	
Layer 3	Theta	0.0008	0.024	0.009			0.192	0.192	
	Vitel	0.0004	0.023	0.008			0.203	0.203	
	Both	0.0000	0.024	0.017			0.185	0.185	
Layer 4	Theta	0.0008	0.024	0.010			0.194	0.194	
	Vitel	0.0006	0.023	0.009			0.203	0.203	
	Both	0.0000	0.025	0.016			0.177	0.177	

Notes: PIB - precipitation and irrigation based; PIAB - precipitation and irrigation amount based; Total1 - fraction of data flagged by methods other than PIB and PIAB; Total2 - fraction of data flagged by all methods

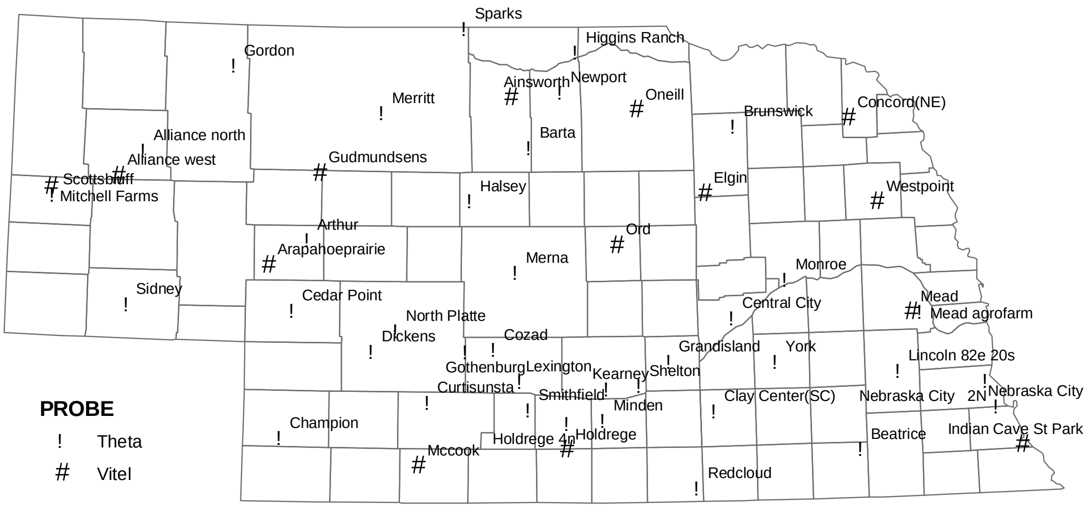

Figure 1. Locations and probe types used for soil moisture measurements

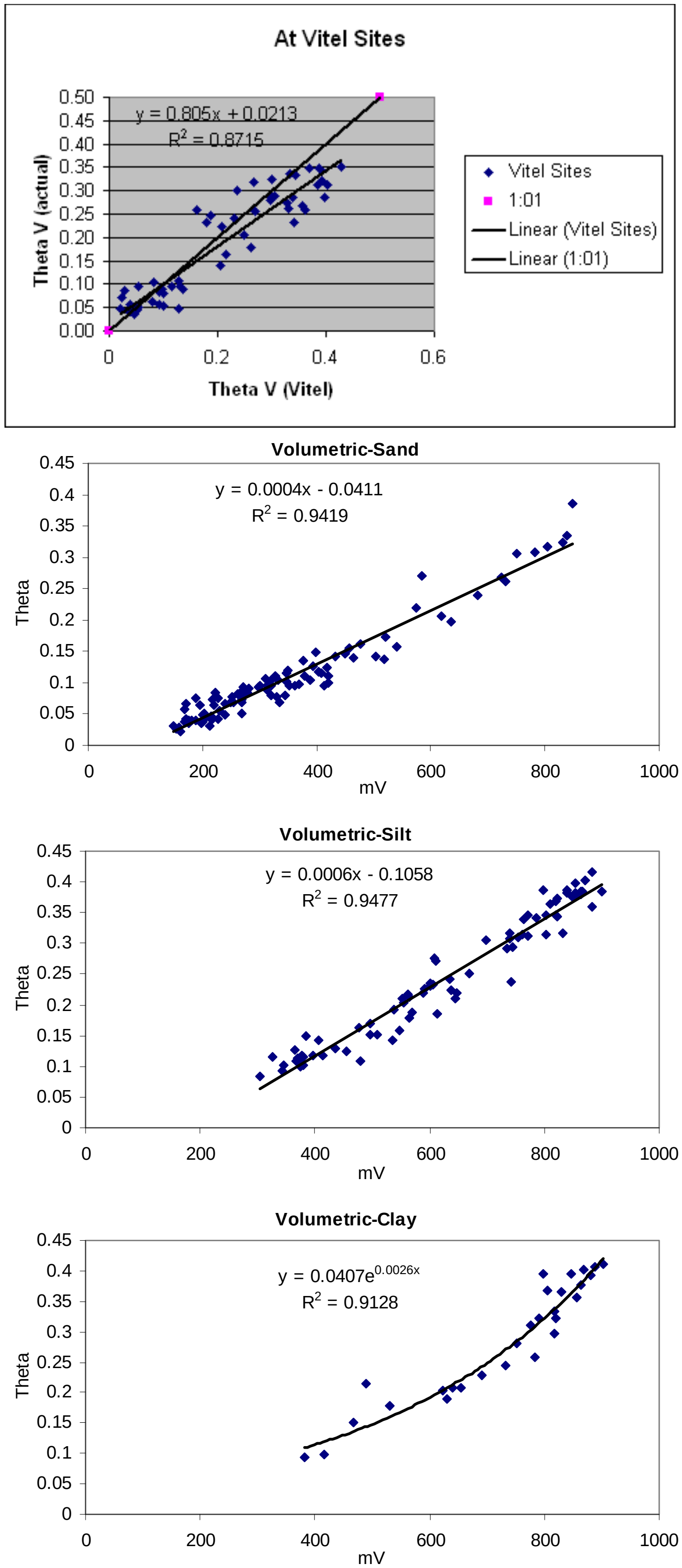

Figure 2. A comparison of readings taken by Vitel and Theta probes at the same site (top panel) and the calibration for Theta probes in sandy, silty, and clay soils (lower panels).

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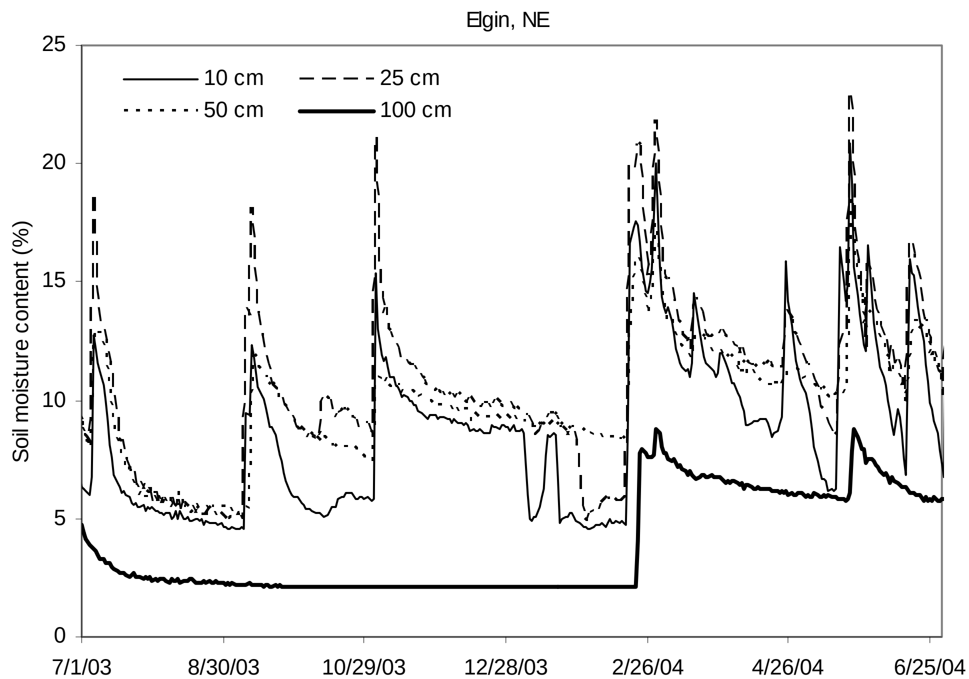

Figure 3. Example of problematic readings for the 100 cm sensor at Elgin.

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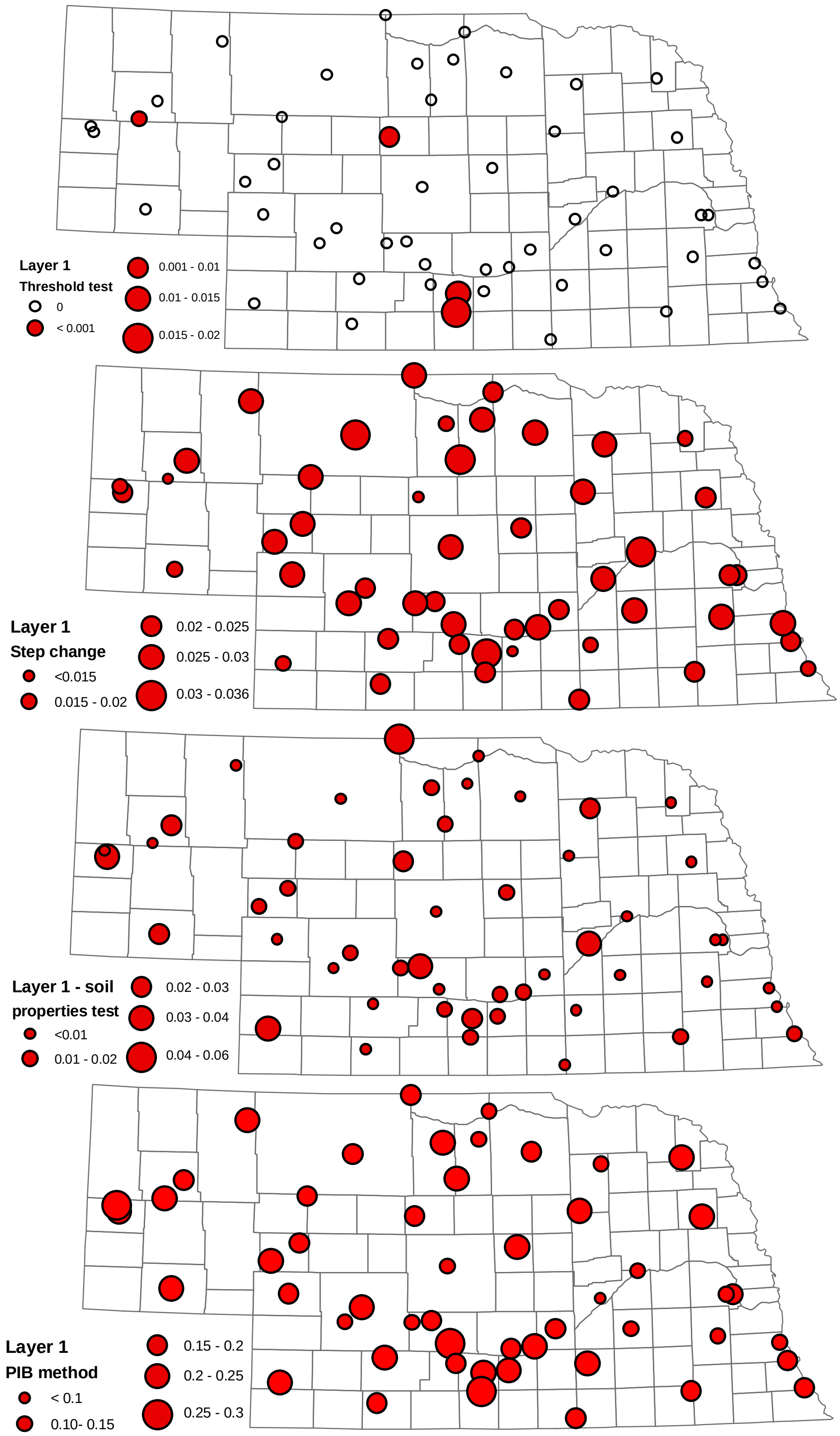
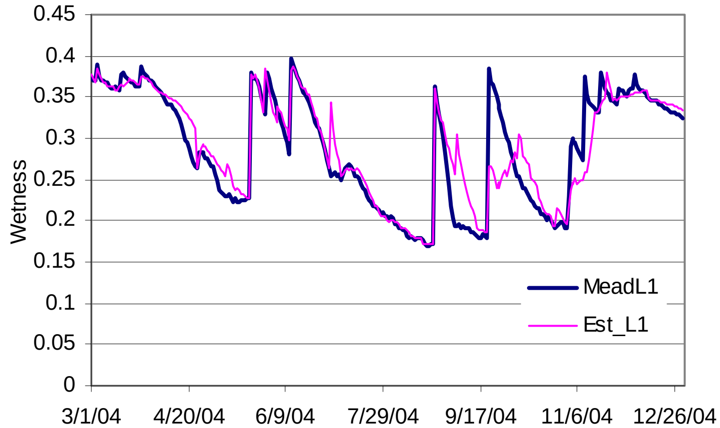


Figure 4. Flagged fractions of valid measurements using four different methods for top layer data (0.1 m depth).



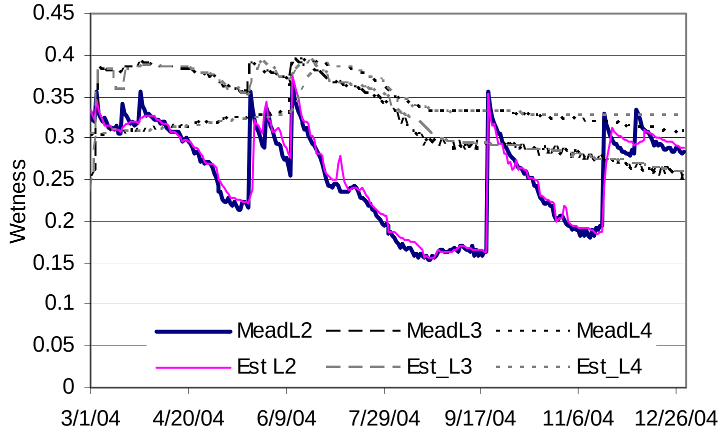


Figure 5. Comparisons of measured and estimated wetness for different layers at Mead, NE. “MeadLx” represents the measurements of the “x” layer at Mead. “Est_Lx” represents the estimated soil moisture for the “x” layer using SRT method based on modeling results from R&H SM model (1990).

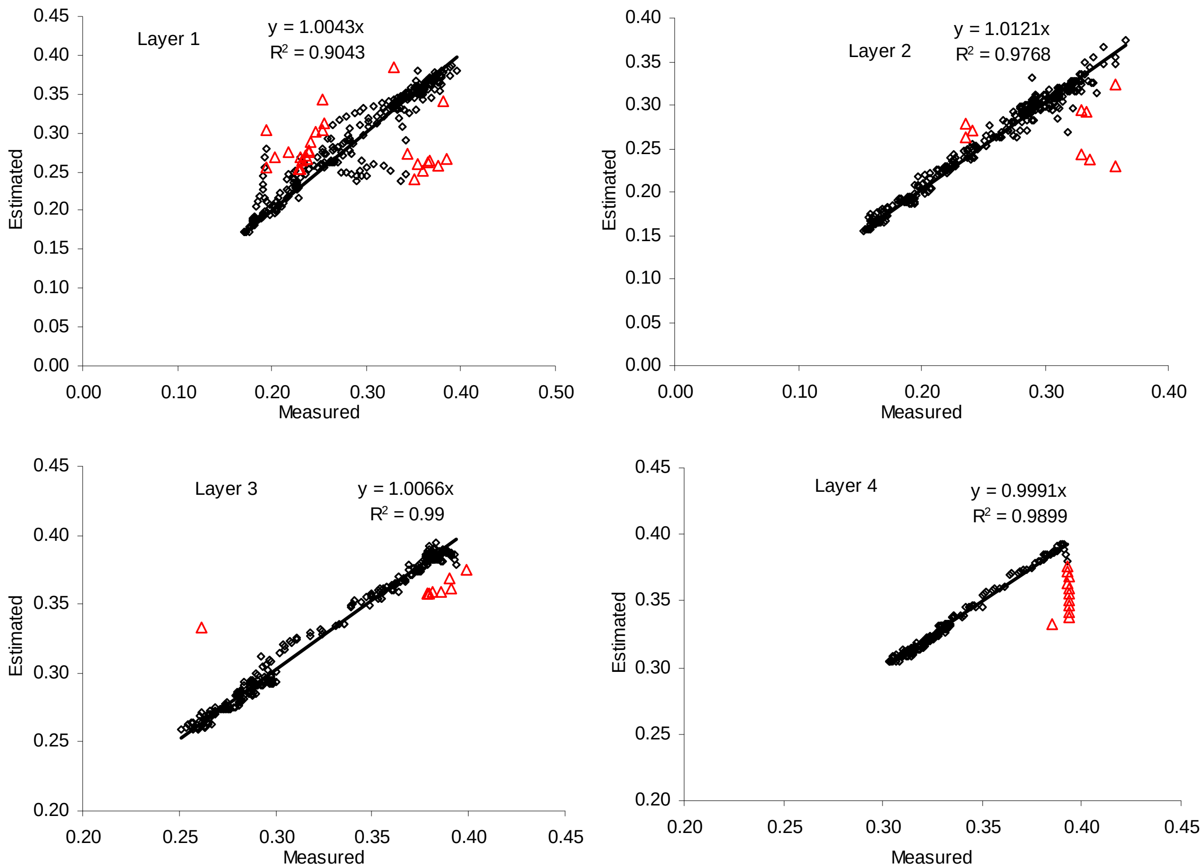


Figure 6. Scatter plot of measured and estimated wetness for four different layers and the test results at Mead, NE. The triangles are outliers identified using SRT method.

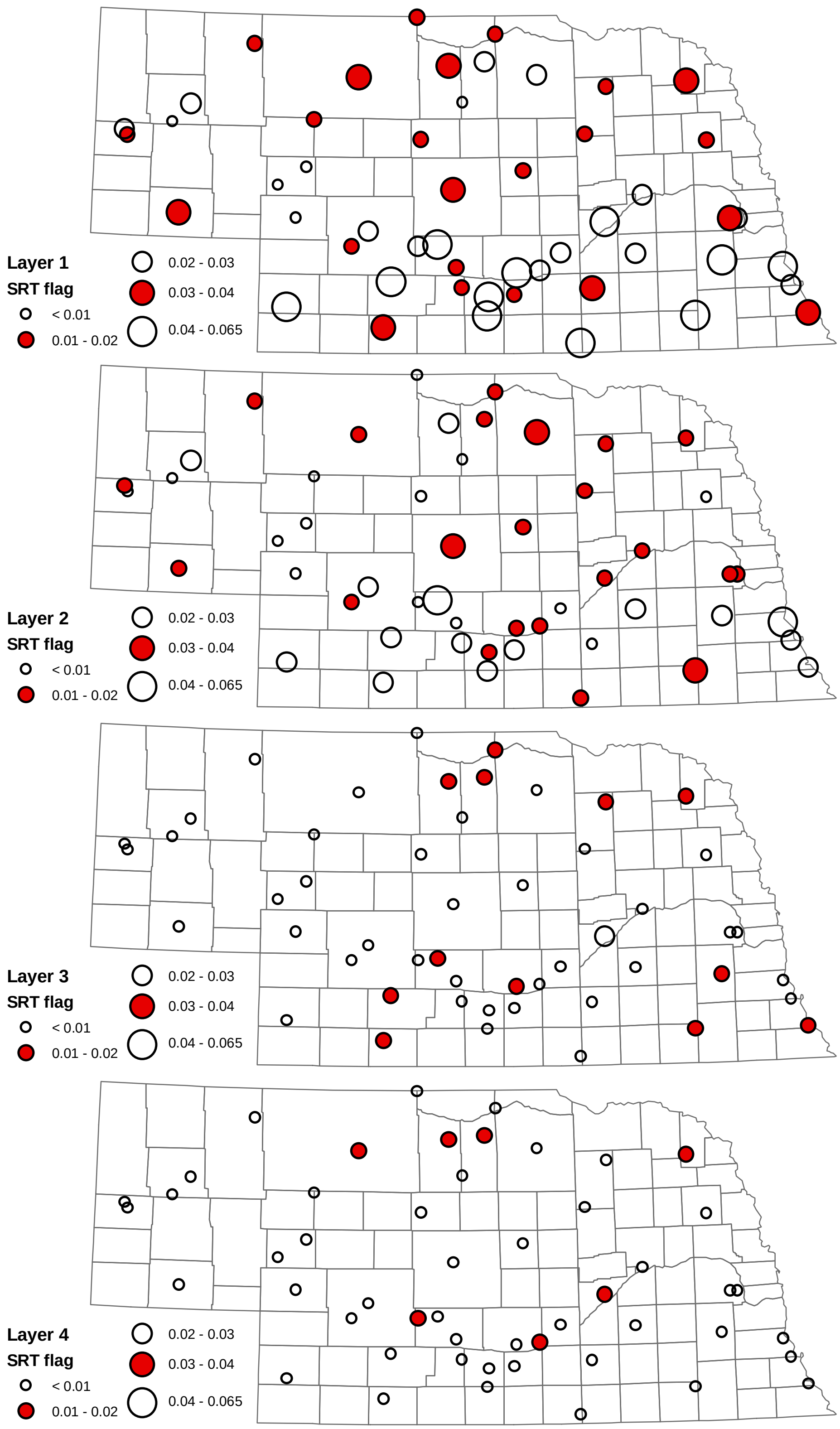


Figure 7. Fraction of flagged data by SRT method for four measurement layers.