THE REVIEW OF SOIL MOISTURE MULTI-SCALE VERIFICATION METHODS

Zhiguo Pang[1,2]*, Xiangdong Qin[1,2], Wei Jiang[1,2], June Fu[1,2], Kun Yang[1,2], Jingxuan Lu[1,2], Wei Qu[1,2], Lin Li[1,2], Xiaotao Li[1,2]

[1] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water
Resources and Hydropower Research, Beijing, China
[2] Remote Sensing Technology Application Center, Research Center of Flood and Drought Disaster Reduction of the Ministry of
Water Resources, Beijing, China

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ABSTRACT:

Soil moisture is an important physical parameter to investigate water circulation, while it is difficult to be measured with spatiotemporal consistency. During the past several decades, a larger number of soil moisture verification methods were proposed, however, the review of soil moisture verification method from multi-scale perspective is still lacking. This paper investigates the verification method of soil moisture from three scale, such as point-scale, regional scale and remote sensing data verification. The prospect of soil moisture verification is proposed to serve retrieval algorithm validation.

1. INTRODUCTION

Soil water only account for 0.005% of the total world's water storage. Although the proportion of soil water is small, it plays an important role in the exchange of energy and water between the earth's surface and atmosphere (Li, 2012).Soil moisture is widely used in various hydrological models to determine runoff and infiltration rates at different scales. In the land surface model, soil water is also an important parameter to determine the surface evaporation rate and root infiltration rate. Various studies have suggested that the importance of soil moisture in the climate change (H.Douville et al.,2000), surface atmosphere interaction (R.D.Koster et al.,2004), weather prediction (M.Drusch, 2007) and agricultural irrigation (D. W. Shin et al.,2006),.

Currently, it is difficult to measure soil moisture with spatiotemporal consistency (Rajat Bindlish et al., 2006), moreover, because spatial and temporal variability of soil moisture caused by various factors, it is hard to be measured accurately from multi-scale. Most of soil moisture measure at multi-scale cannot be sure, which limits the application of soil moisture product in various fields. Therefore, it is necessary to conduct the investigate soil moisture verification methods. This paper will review the verification method of soil moisture from three scale, such as point-scale, regional scale and remote sensing data verification, and then, the prospect of soil moisture verification method will be discussed.

2. RESEARCH SITUATION

2.1 Process in soil moisture verification at point scale

For point-scale soil moisture verification, it is usually classified according to different measurement data used for verification, such as oven drying data, TDR data, FDR data and Neutron instrument data.

As far as the samples themselves are concerned, the traditional oven drying method has high accuracy of the measured data,

however, it needs complicated operation process, large workload, and time density, thus, it is not enough to meet the larger scale investigate requirements (Chen et al., 2009).Generally, the FDR, TDR and neutron method of calibration and verification method are widely used. Such as Chen et al study, they calibrated GStar-I auto monitor by using the data of oven drying method, and then made correlation analysis from long time sequence between two type data to reduce the error. The results showed that the GStar-I auto monitor method can accurately observe the actual soil moisture.

Both FDR and TDR methods belong to dielectric characteristic method. In verification of TDR data and FDR data, except for Chen et al above mentioned, H. Kirnak et al took several soil gravimetric samples around the instrument in continuous time, the mean value sequence of gravimetric sampling was compared with the sequence of measured values of the instrument, and its consistency index (mean value, variance and fitting degree) was used to analysed the accuracy of TDR data (H. Kirnak et al., 2016a). W. Skierucha used the oven drying data multiplied by a soil refraction coefficient as the reference standard and then, compared the TDR measurement value of different soil texture through a large number of samples to calculate the correction parameters (W. Skierucha, 2000). Wu et al used the artificial soil solution preparation method instead of the traditional oven drying method to calibrate TDR and generated accurate ground soil moisture data for Heihe Remote Sensing Project (Wu et al., 2009a).

Neutron instrumentation method is to determine the soil moisture by measuring the correlation between the density of slow neutron cloud and soil moisture content. Wang et al compared the mean measurement errors of neutron meter method, weight method and TDR method in the long time series, and concluded that the measurement accuracy of neutron meter method in the long time series. The result showed that TDR method can meet measurement standard (Wang et al., 2000a).

The comparison of various soil moisture verification method at point scale are summarized in table 1. Above all,

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* Corresponding author

FDR, TDR and oven drying method have been often used in verification data acquiring, while Neutron instrumentation method is less used due to its cost and radiation hazard.

Verification method	Advantage	Disadvantage	Reference
Oven Drying Method	Accurate at point sample; Low cost; Flexiblity at measure site, etc.	Low monitor frequence; difficult in sampling deep soil; heavy workload etc.	Chen et al.,2009 Zhao,Wang,2017
Neutron Instrumentation Method	Continous monitor; Little destroy on original soil	Calibration necessary; expensive on instrument; Radiation hazard	Wang et al.,2000 Zhao,Wang,2017
FDR Method TDR Method	Continous; little destroy; Safety; Relative cheap	Calibration necessary; Temperature affect accurate	Gao L et al.,2010 Wu et al.,2009

Table 1. Comparison of point scale measure method

2.2 Progress in soil moisture verification at regional scale

Soil moisture verification at regional scale contain ground penetrating radar (GPR) method and cosmic rays neutron (CRS) method. Both of them are no harm and non-contact. They will not destroy the original soil texture, density, salt and so on. Thus, GPR and CRS are suitable for dozens of hectares of regional scale soil moisture observation.

The principle of GPR soil moisture measurement can be divided into four steps: firstly, using radar record profile of measure area from instrument, secondly, extracting the propagation velocity of radar waves in underground media from profile, thirdly, calculating the dielectric constant of soil through electromagnetic wave propagation theory, finally, the relationship model between soil dielectric constant and soil moisture will be established to determine soil moisture. Currently, for GPR soil moisture measure, Hu et al compared the calculation results of low-frequency ground penetrating radar with the results of gravimetric measurement, the result showed that there was a significant functional correlation between the dielectric constant of reclaimed soil and the moisture content, which suggested that the method of measuring the moisture content of reclaimed soil by GPR was feasible (Hu et al., 2005a). Zhou et al used high frequency ground penetrating radar to detect different soil moisture conditions to acquire GPR information, then extracted characteristic parameters of electromagnetic spectrum and analysed the quantitative relation between soil moisture content and the parameter. The result showed that the determination coefficient R^2 of the soil dielectric constant detected by 1 GHz and 2 GHz frequency GPR and the measured soil moisture fitting model were 0.94 and 0.97, the results indicated that the high frequency GPR technique is feasible to predict the soil moisture of silty clay loam (Zhou et al., 2016a).

For cosmic-ray neutron soil moisture measurement, hydrogen atoms play a crucial role in slowing down fast neutrons and it mainly exist in the soil moisture. Thus, the soil moisture is the sensitivity factor influencing the fast neutron intensity. Therefore, as long as the strength of near-surface fast neutrons

is measured passively, the soil moisture can be calculated. In study of cosmic rays neutron method to measure soil moisture, Jia et al used cosmic rays neutron method for soil moisture measurement on the experimental station of China Agricultural University in suburban areas of Beijing and analysed the main affecting factors. The temporal data of multipoint sampling value was taken using oven drying method and the fitness and the root mean square error between the raw value and the correction data were calculated and compared. Finally, the cosmic-ray neutron method can observe the changes of soil moisture on the underlying surface of the study area. Moreover, it is necessary to correct the effects of air pressure and air moisture in the application process (Jia et al., 2014a). Jiao et al used the wireless sensor network with cosmic ray neutron method to verify the observation data. The result showed that the consistency of the two type data is well when the effect of water accumulation in the study area is removed, which suggested that the cosmic ray neutron method can effectively measure soil moisture in the farmland area under the condition of high heterogeneity(Jiao et al., 2013a). Cai et al conducted fitting analysis between CRS, oven drying and FDR data in Inner Mongolia desert grassland area, respectively. Four methods, including uniform weighting method, geometric weighting method, discretizing the cumulative fraction of count method and the neutron intensity-based weighting method, are compared. The compared result showed that the fitness of the neutron intensity-based weighting method is best, which indicated that the spatial characteristics represented by neutron intensity-based weighting method are closest to the actual spatial characteristics of CRS soil moisture measurement footprint(Cai et al., 2018a).

Verification Method	Advantage	Disadvantage	Reference
GPR	Measure scale flexiblity	Restrict in low electrical conductivity area,	Klotzsche et al.2018
CRS		Sensitive to air pressure, air moisture and rainfall	Pang et al,2019

Table 2 Comparison of region scale verification method

The comparison of two kinds of regional scale verification method (GPR and CRS) are summarized in table2. It can be concluded that: the cosmic ray neutron method and ground penetrating radar are similar in long time series. The difference is that the cosmic ray neutron method is generally insensitive to soil texture, while GPR is mostly restricted to areas with relatively low electrical conductivity (Klotzsche et al.2018). Thus, GPR is not suitable for application in very sticky soil and heavy saline-alkali soil areas. Moreover, the cosmic ray neutron method need to be corrected by multiple correction parameters, and the accuracy of the measurement before and after the revision is quite different. However, the GPR can obtain relatively accurate data after calibration. In terms of the flexibility of measuring scale, the cosmic-ray neutron method has a fixed measuring range, while GPR is relatively flexible.

2.3 Progress in soil moisture data verification of remote sensing

The existing soil moisture product can be divided into optical remote sensing products and microwave remote sensing products according to spectral response mechanism and most of them are microwave remote sensing products.

Optical remote sensing soil moisture products including MODIS dataset, is mainly retrieved by apparent thermal inertia model using surface temperature daily range data. Although the spatial resolution is high, it is limited due to the low penetration depth of the earth's surface, the impact by the cloud, vegetation and atmosphere factor.

Microwave remote sensing product include active microwave data and passive microwave data. Active microwave data are provided by the ERS and METOP satellites, etc., which use Synthetic Aperture Radar (SAR) to measure the backscattering coefficients to retrieve soil moisture. Passive microwave data is mainly provided by advanced microwave scanning radiometer (including AMSR-E and AMSR-2), Soil Moisture and salinity observation satellite (SMOS) and Soil Moisture Lord Passive detection satellite (SMAP). The light temperature data from FY-3 microwave radiometer was used to retrieve Passive microwave product. Compared with optical remote sensing, microwave remote sensing has the characteristics of all time observation, ground-penetrating depth is deeper than the former, and the temporal resolution is higher (especially the passive microwave radiometer), which is more suitable for soil moisture inversion.

The verification methods of remote sensing retrieve data is by coupling regional observation stations and various remote sensing data. There are three forms of validation for using ground observation sites. Firstly, node to site, it is a comparison between single node value and single observation sites value. Cui et al employed one observation sites data directly compared with time series relevant pixel retrieve value to analyse the fitness (Cui et al., 2015). Secondly, node to average, it is a comparison between single node value and weighted value for multiple sites. Bai et al adopted Kriging method, inverse distance interpolation method, Tyson polygon method and mean value method to calculate pixel reference values on the ascending scale of ground monitoring station data and compare different on time series by using error index, including root mean square error, unbiased root mean square error, deviation and correlation coefficient, to evaluate the accuracy of SMOS and SMAP inversion data (Bai et al, 2012). Thirdly, average to average, it is a comparison between mean pixel value and mean sites value in same region. Based on the mean values of the four observation networks in the United States, the stability of the four inversion algorithms is evaluated by data fitting (Zhao et al, 2012). Moreover, the accuracy of soil moisture retrieved by microwave imager in the Tropical Rainforest Observation Mission was evaluated by comparing the fitting degree of the station mean value in the southern Great Plains test site (Rajat Bindlish et al., 2003a).

For verification using regional observation data, Cai et al used the neutron intensity-based weighting method to establish scale transformation model and converted the pixels data to the same region of the CRS measurement footprint, and then, the remote sensing product was verified through this model (Cai et al, 2017). Pang et al used CRS data and FDR data to analyse the accuracy of the remote sensing data in different pixel scales, and found that the accuracy of CRS verification in soil moisture retrieve data of 30 m, 1 km, 3 km and 9 km resolution was higher than that of FDR method(Pang et al., 2019a).

As for verification using multiple retrieve data, Triple-Collocation model is widely used, which is a case where the real value of the measurement is unknown, assuming that all three sets of data have independent random errors and a linear relationship with the truth value, a new variable is introduced to eliminate the truth value and calculate the TC error of each dataset to evaluate the authenticity of the data. Pierdicca used the improved point-by-point TC method and global TC method to analyse the errors of simulated data of ASCAT, SMOS site and ERA model in Europe and North America, respectively. The result showed that the error of soil moisture in ERA was the smallest within the study area, and SMOS was slightly better than that of ASCAT (Pierdicca, 2015a). Shen et al collected China observation sites data from 1991 to 2003, active and passive microwave data before synthesis from the ESA Climate Change Initiative Soil Moisture Data Set (ESACCISM) to evaluate the accuracy in TC method, and found that the performance of the active microwave products are better than that of passive microwave products based on each statistic index comparison (Shen, An, 2017). Someone sample the study area and use the correlation degree of multiple sample pairs to evaluate the accuracy of the overall product. For example, Leng et al employed the fitting analysis of 300 sample point pairs to evaluate the accuracy of the whole sky surface soil moisture data products, and the reference data is meteorology data, which is resampled to the same resolution (Leng, 2019a).

Summarizing and analysing above verification methods, Somethings can be found. For verification based on ground observation sites, the main drawbacks are the limited effective coverage of site data and the uncertainty caused by data scale transformation. Firstly, it is not accurate for remote sensing products to evaluate the accuracy of the whole product with the fitting analysis of a few pixel. Secondly, the lack of spatial representation of point scale data on large spatial scale may be the main reason for the anomalies in fitting analysis. The advantage is that the site data have high accuracy on its own scale. For verification with regional observations data, the mainly limitation is that the regional data need to calibrate and verify using the point scale data for many times and the truth value of its own data cannot be accurately measured due to the observation scale. The advantage of this method is that the verification efficiency is higher, the uncertainty of scale transformation is smaller than that that of ground observation site verification, and the spatial representation of regional data on large spatial scale is stronger than that of the former. For verification with multiple retrieval data, the main limitation is that the truth value of the reference data cannot be determined. This because that the benchmark itself carries some uncertainty. The advantage of this method is that it has a good match with the data to be verified in terms of data format, observation scale and coverage range, and the process of acquiring and verifying the benchmark data is relatively simple.

3. TREND OF FUTURE DEVELOPEMENT

According to the summary and comparative analysis of the above methods, soil moisture verification may develop in two aspects. Firstly, the reference data need to be more accurate and abundant, which mainly depends on the density of soil moisture station observation and the establishment of a reasonable observation network. It makes the data cover more widely in the time dimension, more representative and reasonable in the large scale distribution and more convenient in the data storage and invoking. Secondly, a more objective verification method needs to be extended. Instead of using a single scale data for verification, it is considered to use a variety of scales data for comprehensive verification analysis. This method use point scale data to calibrate and verify the regional data, and then use the regional scale data to verify remote sensing data. Finally,

the results with data verification using point scale data need to be compared. Considering the spatial heterogeneity of soil moisture, the causes of fitting anomalies can be further analyzed, which can improve the accuracy of data evaluation. Although the specific verification effect of this method remains to be verified and the quantitative analysis lacks high accuracy, it provides a possibility for accurate evaluation of the accuracy of soil moisture products.

3.1 The precision and richness of soil moisture reference data

The data amount of traditional point scale verification is small, with spatial and temporal continuity insufficient. The original observation network takes a long time to collect and transfer data, which cannot meet the time accuracy requirements of soil moisture verification. To improve the quality of the reference data and verification efficiency, it is a good idea to establish a soil moisture monitoring system based on wireless sensor network. The system consists of three parts: sensor node, base station and computer control center. The moisture sensing node is responsible for collecting moisture data regularly, the base station is responsible for temporarily saving and uploading the data collected by the node, and the computer control center is responsible for analysing and managing the data from the base station. Chang et al have demonstrated the system stability through the experimental monitoring result, which suggested that the system can be widely used in other agricultural environmental monitoring fields (Chang, 2011a). This method not only reduces the complexity of obtaining soil moisture verification reference data, its automatic monitoring also provides a great convenience for long temporal soil moisture validation. It not only improves the spatial and temporal continuity and efficiency of soil moisture verification, but also provides a more comprehensive and accurate data basis for remote sensing data and regional data verification.

3.2 Multi-scale comprehensive cross-validation of remote sensing

Before remote sensing product using, the key issue in the verification of their accuracy. Only after objective and quantitative evaluation, the remote sensing product can be reliable information sources for earth system science and global change research(Wu, 2015a).As a complex heterogeneous system, it is inevitable that there is great uncertainty between the soil water distribution and the actual situation of the whole surface through the finite point observation. In the case of sufficient reference data, the multi-scale comprehensive cross validation analyse the difference of the verification result using different scale data and decompose this uncertainty to improve the accuracy of the verification evaluation. This method usually adopted point scale data to calibrate and verify the regional monitoring data, the verified regional data is then used to verify the remote sensing data and the verification result of stepwise scaling are compared with point verification result. Finally, the spatial heterogeneity of soil moisture can be simply analysed to explore the reason of some point scale data fitting anomalies, which can furtherly improve the accuracy of data evaluation.

For multiscale comprehensive cross-validation of remote sensing, although the rapid development of regional soil moisture measurement technology (CRS and GPR method) provides a certain data basis for it, however, it is not enough to improve the retrieve precision of low-resolution data through multi-scale verification. Therefore, the multi-scale ground automatic monitoring network should be established to enrich the ground verification benchmark data in the future, the space-sky-land collaborative observation technology may be developed to make up monitoring means at different scales. Moreover, the multiscale comprehensive cross-validation method may be improved to provide a theoretical basis for large-scale soil moisture verification.

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