Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 154 (2016) 1368 – 1375
Procedia Engineering
www.elsevier.com/locate/procedia

12th International Conference on Hydroinformatics, HIC 2016

# The Relevance of Soil Moisture by Remote Sensing and Hydrological Modelling

Lu Zhuo[a]*, Dawei Han[a]

[a]*Water and Environment Management Research Centre, Department of Civil Engineering, University of Bristol, Bristol BS8 1TR, UK*

**Abstract**

Accurate soil moisture information is critically important for hydrological modelling and natural hazards (landslide & debris flow). However, its effective utilisation in those areas is still in a state of infancy. This paper focuses on exploring the advances and potential issues in current application of satellite soil moisture observations in hydrological modelling. It has proposed that hydrological application of soil moisture data requires two inter-connected components: 1) soil moisture data relevant to hydrology, and 2) appropriate hydrological model structure compatible with such data. In order to meet these two requirements, the following three research tasks are suggested: the first is to carry out comprehensive evaluations of satellite soil moisture observations for hydrological modelling; the second is that the soil moisture representations in hydrological models may need to be modified so that they are more compatible with the real field soil moisture variations; and the third is that a soil moisture product (i.e., soil moisture deficit) directly applicable to hydrological modelling should be developed.


Peer-review under responsibility of the organizing committee of HIC 2016

*Keywords:* Soil moisture; Satellite remote sensing; Hydrological modelling;

## 1. Introduction

The existence of soil moisture information is significant for many application areas such as agriculture, meteorology, climate investigations, and natural hazards predictions. In operational hydrology, soil moisture is an

* Corresponding author. Tel.: +44 117 9289768; fax: +44 117 9289770.
*E-mail address:* lu.zhuo@bristol.ac.uk


Peer-review under responsibility of the organizing committee of HIC 2016
doi:10.1016/j.proeng.2016.07.499

important state variable [1]. Over the past decades, numerous hydrological models have been developed, representing more or less accurately the main hydrological processes involved at a catchment scale [2]. The challenge in forecasting floods in a reliable way stems mainly from the error accumulation of the models, particularly during unusual hydrological events and after a long period of dryness. Solutions such as model state updating and data assimilation have thus been introduced to enhance flood forecasting accuracy by matching the model with the current observations prior to its use in the forecasting mode [3]. Since hydrological models are highly sensitive to the state change of the soil moisture [2], an accurate soil moisture measurement over a catchment should enhance the forecasting performance via correcting the trajectory of the model [4]. Modern satellite remote sensing has shown its potential for providing soil moisture measurements at a large scale [5]. However, existing satellite soil moisture products are calibrated mainly by in-situ measurements, so they are not directly relevant to hydrology. Moreover with all orbiting sensors, only the surface layer soil moisture can be acquired [6, 7]. Conversely operational hydrological models (most often the conceptual hydrological models) consider a much deeper surface soil depth (up to 2 m), which also varies across a catchment.

Clearly there is an incompatible problem between the satellite measured soil moisture and the hydrological model simulated soil moisture, which has caused a commensurate issue for the full utilisation of remotely sensed soil moisture products in operational hydrology. Therefore, the motivation of this study is to review the existing literature and explore the potential issues in current satellite soil moisture application in hydrological modelling, which is topical and timely.

## 2. Soil moisture measuring methods

First, it is important to give a brief introduction on the existing soil moisture measuring methods, based on two major categories: in-situ and satellite remote sensing.

### *2.1. In-situ*

There are several techniques for in-situ soil moisture measurements, which can be sub-grouped into direct and indirect approaches. Here three common types are introduced.

The gravimetric method is the only method that measures soil moisture directly from Earth soil. It is simple and very reliable. However this approach is extremely labour intensive and takes a long time for the soil drying process, hence, it has a low temporal resolution with the best at 1-2 weeks [8]. Moreover, this method is not often considered for developing the soil moisture networks, but rather employed for calibrating other soil moisture sensors such as Time Domain Reflectometry (TDR). Nevertheless, it is useful for long-term climatic studies [9].

Neutron probe is the first major technological advance in modern soil moisture measuring which has been used widely around the world after the World War II back in Year 1952 [10, 11]. It is able to give volumetric soil moisture reading directly from its designed microprocessor. Although this method is able to measure soil moisture at multi-depth fairly quickly and automatically, it is not capable of providing reliable estimation at shallow depths because some neutrons can escape from the soil surface into the air. Moreover, since the device includes radioactive material, its operation requires extremely strict training and inspection processes [12].

The neutron probe was the dominating method in the market for many years until a soil physicist and two geophysicists from Canada made a significant breakthrough by adopting the dielectric concept for soil moisture estimation [1]. By the 1990s, the TDR method had proven its high value in in-situ soil moisture monitoring [13]. The advantages of TDR include high accuracy within 1 or 2 % of volumetric moisture content, fast response, lack of radiation hazard, and capable of producing continuously automatic soil moisture estimation [14]. However the calibration of the sensor can be difficult and expensive, and the instrument are easy to corrode [15].

*2.2. Satellite remote sensing*

Compared with in-situ methods, satellite remote sensing provides soil moisture observations globally and at larger footprints, so it is more suitable for hydrological usages. A considerable number of studies have shown that near surface soil moisture (~ 5 cm) can be measured by many remote sensing techniques including optical, thermal infrared and microwave [16, 17]. The major differences among them are the region of electromagnetic spectrum employed, the power of the corresponding electromagnetic energy, the signal received by the sensors, and the relationship between the retrieved signal and the soil moisture [16, 18]. The basic knowledge about each technique is introduced as followings:

Optical satellites measure the reflected radiation of the Sun from Earth's surface, known as the reflectance [19]. Its correlation with the soil moisture has long been recognised [20]. Although there are a large number of optical sensors currently serving in orbit, relatively fewer studies have been carried out regarding their application in soil moisture assessment [21].

Thermal infrared satellites measure Earth radiative temperature, which is related to soil moisture. A considerable number of studies have been carried out to assess the accuracy of soil moisture measurements by this technique, such as through the simple thermal inertia approach [22] and the 'Universal Triangle' method [23, 24]. However their accuracy varies across time and meteorological conditions (e.g., wind speed, air temperature and humidity) [25, 26].

The primary theory of microwave soil moisture estimation is based on the large contrast between the dielectric properties of water (~80) and dry soil (<5). Therefore when the soil becomes moist, the dielectric constant of the soil-water mixture rises, and this emission fluctuation is recorded by microwave sensors [27, 28]. For both passive and active sensor types, the measurement efficacy is related to wavelength, where longer wavelengths (> 10cm) penetrate deeper into the soil and have more ability to pass through cloud and some vegetation cover (such as the SMOS satellite with the L-band wavelength (21 cm), which is able to probe about 5 cm into the ground) [27]. Comparatively, microwave bands have more advantages in soil moisture estimation than other spectral bands.

## 3. Hydrological assessment of soil moisture

As aforementioned, satellite remote sensing techniques are a major tool in retrieving soil moisture information on a large scale [5] and are able to provide soil moisture observations globally [29]. In particular, the data acquired by microwave sensors, both active and passive, have been employed to provide detailed soil moisture variability in recent years [30]. With the modern microwave satellites such as the AMSR-E (from 6.9 to 89.0 GHz; [31]) which operated on the AQUA satellite between 2002 and 2011, the SMOS (1.4 GHz) launched in 2009 [29] and the Soil Moisture Active/Passive mission (SMAP; 1.20-1.41 GHz; [32]) which was just launched in early 2015, it is anticipated that more advanced soil moisture measurements would be available in the future.

SMOS is the first mission dedicated to monitoring direct surface soil moisture and sea surface salinity on a global scale [33], therefore this paper focuses on discussing the issues related to its hydrological applications (nevertheless, the result is general and applicable to other satellites). SMOS soil moisture is calculated from the multi-angular and fully polarised L-band passive microwave measurements [34]. A number of studies have reported SMOS soil moisture retrieval, downscaling, assimilation and its validation against point based in-situ measurements over different regions [35-42]. However, in-situ measurements are not directly relevant to hydrological modelling because they cannot be directly placed into a state variable of a hydrological model. On the other hand, some attempts have been made on hydrological evaluations of SMOS soil moisture, such as the ones carry out by [38, 43-45]. The results show the SMOS soil moisture are not accurate enough for direct hydrological modelling usage and additional work such as using separated algorithms for high- and low-vegetated seasons is needed [45]

## 4. Satellite descending and ascending overpasses

SMOS makes both ascending and descending overpasses, however the performance of those retrievals remains unclear [42, 46-48]. Based on the literature review, previous studies mainly focused on the downscaling, assimilation, and evaluation of the SMOS ascending overpass in order to minimise the observation error caused by the daytime soil drying effect and the impact of vertical soil-vegetation temperature gradients [31, 37, 38, 42, 45]. It is expected that satellite soil moisture measurements are more accurate in the hours near dawn when the soil profile has the most time to return to an equilibrium state from the previous day's fluxes [49]. Hence, based on this hypothesis, it is more likely to be true that ascending soil moisture measurements would have better performance than their descending counterparts [42]. In addition, based on evaporation demand, it is expected that soil would be wetter at night and drier during the day; in other words, the ascending pass should hold higher soil moisture values than the descending pass if there is no rainfall during the day [40]. However it is found by [50] the SMOS descending orbit shows a stronger potential for improved hydrological predictions in a medium-size cropland catchment. This outcome contradicts the previous hypothesis from other studies that ascending soil moisture measurements should have better performance than their descending counterparts. Additionally in [50], it is explored that SMOS retrievals from the descending overpass are consistently wetter (about 11.7% by volume) than the ascending retrievals, which is again not expected. Based on the mixed results from the published literature, it is encouraged to carry out more research on this topic, with extended spectrum of catchment types and satellite products, so that a look-up table could be established.

## 5. Error distribution modelling of satellite soil moisture measurements

Since satellite soil moisture measurements can be affected by several error sources (e.g., algorithms, sensors, and physical processes) [51]. Quantification of such uncertainties is particularly important for applying the soil moisture datasets in real-time flood forecasting systems [52]. More importantly, this is the foundation to the optimal modelling performance in using such soil moisture datasets. Although there are many studies on exploring the uncertainty of satellite soil moisture estimates in hydrological applications, they are mainly represented as summary statistics (such as RMSE, NSE) [35-40, 45, 53-55], and there is a lack of attention on the error distribution model (such as probability density function, spatial and temporal correlation, nonstationarity).

A paper by [56] demonstrates the first attempt in modelling satellite soil moisture error distribution in hydrological applications. It uses the SMOS soil moisture product [29] and a hydrological model called XAJ [57] as a case study. In this study four commonly used probability distributions (Gaussian, EV, GEV, and Logistic) are adopted to describe the uncertainties of satellite soil moisture data, which are extensively evaluated by using the chi-square statistical test and the bootstrapping resampling technique. From the analysed results, it is concluded that GEV is the best curve in describing the uncertainty of the SMOS soil moisture estimates. During its second-order error distribution modelling, Gaussian is the most suitable curve for describing the uncertainty of the GEV error distribution model. These results are rather useful for satellite soil moisture data assimilation in operational hydrology, because hydrological models need ensemble inputs based on them for sensitivity analysis and uncertainty analysis.

In the future research of this area, more detailed studies such as the spatial and temporal dependence analysis should be conducted. Studies are also needed to consider soil moisture information from other satellite missions over a wider range of catchment conditions with different hydrological models in order to find generalisation patterns of the error distribution models (this is especially important for ungauged catchments).

## 6. New hydrological model development

As aforementioned in most conceptual hydrological models, the soil moisture variable is misrepresented. The soil moisture misrepresentation can significantly reduce the model's capability in data assimilation during the operational mode, because of its incompatibility with the observed soil moisture information. [58] presented that coarse-resolution remotely sensed soil moisture data added little or no extra value for runoff prediction. Interestingly [58] raised an open research question in the study of whether the assimilation results could mainly be attributed to errors in the soil moisture estimates, or it was mainly related to the hydrological model itself.

Papers by [59, 60] present a modification scheme to improve conventional conceptual hydrological models to better utilise the satellite soil moisture observations. XAJ model is used as a representative hydrological model in their studies. As a result, the amended XAJ model is as effective as its original form in flow modelling, but represents more logically realistic soil water processes. In addition, a term called the holding excess runoff has been introduced to illustrate the computational runoff mechanism in the XAJ and other similar models, which helps to clarify the difference between the runoff in reality and the modelled runoff. Another term called Soil Moisture Deficit to Saturation (SMDS) is proposed to replace the conventional Soil Moisture Deficit (SMD). The study shows that SMDS is hydrologically more realistic than SMD based on general soil water movement principles. The methods discussed in [59, 60] are only a first step towards a comprehensive soil moisture modification procedure. Therefore, more studies with longer time periods, a larger number of catchments should be carried out in the future.

## 7. The need for new soil moisture products development

Despite there have been significant investments by various organisations such as ESA, NASA, United States Department of Agriculture in a wide range of soil moisture observational programs (e.g., satellite missions such as ASCAT, SMOS, and SMAP (note: SMAP's radar can no longer return data, however the mission continues to produce high-quality soil moisture measurements [61]); ground-based networks such as Soil Climate Analysis Network, U.S. Surface Climate Observing Reference Networks, and COSMOS), they are not sufficiently used in hydrology mainly because they are calibrated by in-situ soil moisture measurements or airborne retrievals which have significant spatial mismatch (both horizontally and vertically) to catchment scales and are therefore less applicable to hydrological modelling [62].

In order to retrieve accurate soil wetness information that can be directly used in a hydrological model and avoid aforementioned shortcomings, a need for a data-driven model is desirable, which can effectively link the inputs to the desired output and is not computationally intensive. Works carry out by [55, 63] are good foundations for future hydrological soil moisture product development. For example, in [55] three artificial intelligence techniques along with the generalised linear model are used to improve the spatial resolution of the SMOS derived soil moisture. The land surface temperature data retrieved from MODIS satellite is used for the data downscaling, and SMD data calculated from a hydrological model called PDM is selected for performance evaluation. The results show that all the downscaled soil moisture products surpass the original SMOS soil moisture estimation, which are more useful for hydrological modelling. Further research on employing satellite brightness temperature data for direct SMD estimation is highly encouraged.

## 8. Conclusions

This paper aims to explore in different aspects the potential issues existing in current satellite soil moisture utilisation in hydrological modelling. Two major problems are addressed: the first is that current satellite soil moisture products are mainly calibrated by in-situ soil moisture observations, and they may not be directly relevant to catchment hydrological modelling. Therefore a soil moisture product that can be directly linked with hydrological models is desired. The second is that the existing hydrological model is not compatible with the soil moisture observations, so an improvement to the hydrological model is required. Only breakthrough in these two areas will lay a good foundation for future data assimilation of soil moisture observations in the real-time flood forecasting. Furthermore it is hoped this study will attract attention from the hydrological community on those problems and encourage more research to solve them at deeper levels.

**Acknowledgements**

This study is partially supported by Resilient Economy and Society by Integrated SysTems modelling (RESIST), Newton Fund via Natural Environment Research Council (NERC) and Economic and Social Research Council (ESRC) (NE/N012143/1).

**References**

[1] Ochsner TE, MH Cosh, RH Cuenca, WA Dorigo, CS Draper, Y Hagimoto, et al. State of the art in large-scale soil moisture monitoring. Soil Science Society of America Journal. 77 (2013) 1888-919.
[2] Aubert D, C Loumagne, L Oudin. Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall–runoff model. Journal of Hydrology. 280 (2003) 145-61.
[3] Christian RJ. Validation and intercomparison of different updating procedures for real-time forecasting. Nordic Hydrology. 28 (1997) 65-84.
[4] Ottlé C, D Vidal-Madjar. Assimilation of soil moisture inferred from infrared remote sensing in a hydrological model over the HAPEX-MOBILHY region. Journal of Hydrology. 158 (1994) 241-64.
[5] Engman ET, N Chauhan. Status of microwave soil moisture measurements with remote sensing. Remote Sensing of Environment. 51 (1995) 189-98.
[6] Oh Y. Retrieval of the effective soil moisture contents as a ground truth from natural soil surfaces. Geoscience and Remote Sensing Symposium, 2000 Proceedings IGARSS 2000 IEEE 2000 International. IEEE2000. pp. 1702-4.
[7] Ulaby FT, PC Dubois, J van Zyl. Radar mapping of surface soil moisture. Journal of Hydrology. 184 (1996) 57-84.
[8] Seneviratne SI, T Corti, EL Davin, M Hirschi, EB Jaeger, I Lehner, et al. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews. 99 (2010) 125-61.
[9] Robock A, KY Vinnikov, G Srinivasan, JK Entin, SE Hollinger, NA Speranskaya, et al. The global soil moisture data bank. Bulletin of the American Meteorological Society. 81 (2000) 1281-99.
[10] Evett S. Exploits and endeavours in soil water management and conservation using nuclear techniques. Nuclear techniques in integrated plant nutrient, water and soil management. 16 (2000) 151.
[11] Gardner W, D Kirkham. Determination of soil moisture by neutron scattering. Soil Science. 73 (1952) 391-402.
[12] California Uo. Neutron moisture meters. Division of Agriculture and Natural Resources, University of California, http://ucmanagedrought.ucdavis.edu/PDF/DROUGHT_WEB_NEUTRON_PRB.pdf, 2015.
[13] Baker J, R Allmaras. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. Soil Science Society of America Journal. 54 (1990) 1-6.
[14] Jones SB, JM Wraith, D Or. Time domain reflectometry measurement principles and applications. Hydrological processes. 16 (2002) 141-53.
[15] Mukhopadhyay SC. Intelligent sensing, instrumentation and measurements. Springer Berlin Heidelberg, 2013.
[16] Walker JP. Estimating soil moisture profile dynamics from near-surface soil moisture measurements and standard meteorological data [PhD]. New South Wales, Australia: the University of Newcastle; 1999.
[17] Petropoulos GP, G Ireland, B Barrett. Surface soil moisture retrievals from remote sensing: Current status, products & future trends. Physics and Chemistry of the Earth, Parts A/B/C. (2015), doi: doi:10.1016/j.pce.2015.02.009.
[18] Wang L, JJ Qu. Satellite remote sensing applications for surface soil moisture monitoring: A review. Frontiers of Earth Science in China. 3 (2009) 237-47.
[19] Sadeghi A, G Hancock, W Waite, H Scott, J Rand. Microwave measurements of moisture distributions in the upper soil profile. Water Resources Research. 20 (1984) 927-34.
[20] Ångström A. The albedo of various surfaces of ground. Geografiska Annaler. (1925) 323-42.
[21] Muller E, H Decamps. Modeling soil moisture–reflectance. Remote Sensing of Environment. 76 (2001) 173-80.
[22] Schmugge T. Remote sensing of surface soil moisture. Journal of Applied Meteorology. 17 (1978) 1549-57.
[23] Carlson TN, RR Gillies, EM Perry. A method to make use of thermal infrared temperature and NDVI measurements to infer surface soil water content and fractional vegetation cover. Remote Sensing Reviews. 9 (1994) 161-73.
[24] Gillies R, W Kustas, K Humes. A verification of the'triangle'method for obtaining surface soil water content and energy fluxes from remote measurements of the Normalized Difference Vegetation Index (NDVI) and surface e. International journal of remote sensing. 18 (1997) 3145-66.
[25] Smith R, B Choudhury. Analysis of normalized difference and surface temperature observations over southeastern Australia. Remote Sensing. 12 (1991) 2021-44.
[26] Czajkowski KP, SN Goward, SJ Stadler, A Walz. Thermal remote sensing of near surface environmental variables: application over the Oklahoma Mesonet. The Professional Geographer. 52 (2000) 345-57.
[27] Njoku EG, JA Kong. Theory for passive microwave remote sensing of near-surface soil moisture. Journal of Geophysical Research. 82 (1977) 3108-18.
[28] Dobson MC, FT Ulaby, MT Hallikainen, MA El-Rayes. Microwave dielectric behavior of wet soil-Part II: Dielectric mixing models. Geoscience and Remote Sensing, IEEE Transactions on. (1985) 35-46.
[29] Kerr YH, P Waldteufel, J-P Wigneron, J Martinuzzi, J Font, M Berger. Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) mission. Geoscience and Remote Sensing, IEEE Transactions on. 39 (2001) 1729-35.

[30] Calvet J-C, J-P Wigneron, J Walker, F Karbou, A Chanzy, C Albergel. Sensitivity of passive microwave observations to soil moisture and vegetation water content: L-band to W-band. Geoscience and Remote Sensing, IEEE Transactions on. 49 (2011) 1190-9.
[31] Njoku EG, TJ Jackson, V Lakshmi, TK Chan, SV Nghiem. Soil moisture retrieval from AMSR-E. Geoscience and Remote Sensing, IEEE Transactions on. 41 (2003) 215-29.
[32] Entekhabi D, EG Njoku, PE Neill, KH Kellogg, WT Crow, WN Edelstein, et al. The soil moisture active passive (SMAP) mission. Proceedings of the IEEE. 98 (2010) 704-16.
[33] Kerr YH, P Waldteufel, J-P Wigneron, S Delwart, FO Cabot, J Boutin, et al. The SMOS mission: New tool for monitoring key elements ofthe global water cycle. Proceedings of the IEEE. 98 (2010) 666-87.
[34] Kerr YH, P Waldteufel, P Richaume, J-P Wigneron, P Ferrazzoli, A Mahmoodi, et al. The SMOS soil moisture retrieval algorithm. Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1384-403.
[35] Albergel C, P de Rosnay, C Gruhier, J Muñoz-Sabater, S Hasenauer, L Isaksen, et al. Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations. Remote Sensing of Environment. 118 (2012) 215-26.
[36] Panciera R, JP Walker, JD Kalma, EJ Kim, JM Hacker, O Merlin, et al. The NAFE'05/CoSMOS data set: Toward SMOS soil moisture retrieval, downscaling, and assimilation. Geoscience and Remote Sensing, IEEE Transactions on. 46 (2008) 736-45.
[37] Piles M, A Camps, M Vall-Llossera, I Corbella, R Panciera, C Rudiger, et al. Downscaling SMOS-derived soil moisture using MODIS visible/infrared data. Geoscience and Remote Sensing, IEEE Transactions on. 49 (2011) 3156-66.
[38] Lacava T, P Matgen, L Brocca, M Bittelli, N Pergola, T Moramarco, et al. A first assessment of the SMOS soil moisture product with in situ and modeled data in Italy and Luxembourg. Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1612-22.
[39] Albergel C, E Zakharova, J-C Calvet, M Zribi, M Pardé, J-P Wigneron, et al. A first assessment of the SMOS data in southwestern France using in situ and airborne soil moisture estimates: The CAROLS airborne campaign. Remote sensing of environment. 115 (2011) 2718-28.
[40] Collow TW, A Robock, JB Basara, BG Illston. Evaluation of SMOS retrievals of soil moisture over the central United States with currently available in situ observations. Journal of Geophysical Research: Atmospheres (1984–2012). 117 (2012).
[41] Singh VP. Computer Models of Watershed Hydrology. Water Resources Publications, 2012.
[42] Jackson TJ, R Bindlish, MH Cosh, T Zhao, PJ Starks, DD Bosch, et al. Validation of soil moisture and ocean salinity (SMOS) soil moisture over watershed networks in the US. Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1530-43.
[43] Srivastava PK, D Han, MAR Ramirez, T Islam. Appraisal of SMOS soil moisture at a catchment scale in a temperate maritime climate. Journal of Hydrology. 498 (2013) 292-304.
[44] Srivastava PK, D Han, MA Rico-Ramirez, P O'Neill, T Islam, M Gupta. Assessment of SMOS soil moisture retrieval parameters using tau–omega algorithms for soil moisture deficit estimation. Journal of Hydrology. 519 (2014) 574-87.
[45] Srivastava PK, D Han, MA Rico Ramirez, T Islam. Appraisal of SMOS soil moisture at a catchment scale in a temperate maritime climate. Journal of Hydrology. 498 (2013) 292-304.
[46] Dente L, Z Su, J Wen. Validation of SMOS soil moisture products over the maqu and twente regions. Sensors. 12 (2012) 9965-86.
[47] Rowlandson TL, BK Hornbuckle, LM Bramer, JC Patton, SD Logsdon. Comparisons of evening and morning SMOS passes over the Midwest United States. Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1544-55.
[48] Sanchez N, J Martinez-Fernandez, A Scaini, C Perez-Gutierrez. Validation of the SMOS L2 soil moisture data in the REMEDHUS network (Spain). Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1602-11.
[49] Jackson TJ. Profile soil moisture from surface measurements. Journal of the Irrigation and Drainage Division, American Society of Civil Engineers. 106 (1980) 81-92.
[50] Zhuo L, Q Dai, D Han. Evaluation of SMOS soil moisture retrievals over the central United States for hydro-meteorological application. Physics and Chemistry of the Earth, Parts A/B/C. 83-84 (2015) 146–55.
[51] Dorigo W, K Scipal, R Parinussa, Y Liu, W Wagner, R De Jeu, et al. Error characterisation of global active and passive microwave soil moisture datasets. Hydrology and Earth System Sciences. 14 (2010) 2605-16.
[52] Brocca L, F Melone, T Moramarco, W Wagner, V Naeimi, Z Bartalis, et al. Improving runoff prediction through the assimilation of the ASCAT soil moisture product. Hydrology and Earth System Sciences Discussions. 7 (2010) 4113-44.
[53] Al-Bitar A, D Leroux, YH Kerr, O Merlin, P Richaume, A Sahoo, et al. Evaluation of SMOS soil moisture products over continental US using the SCAN/SNOTEL network. Geoscience and Remote Sensing, IEEE Transactions on. 50 (2012) 1572-86.
[54] Srivastava PK, D Han, MA Ramirez, P O'Neil, T Islam, M Gupta. Assessment of SMOS soil moisture retrieval parameters using tau-omega algorithms for soil moisture deficit estimation. Journal of Hydrology. 519 (2014) 574-87.
[55] Srivastava PK, D Han, MR Ramirez, T Islam. Machine learning techniques for downscaling SMOS satellite soil moisture using MODIS land surface temperature for hydrological application. Water resources management. 27 (2013) 3127-44.
[56] Zhuo L, Q Dai, T Islam, D Han. Error distribution modelling of satellite soil moisture measurements for hydrological applications. Hydrological Processes. (2016), doi: 10.1002/hyp.10789.
[57] Zhao R. The Xinanjiang model, . Hydrological Forecasting Proceedings Oxford Symposium, IASH 129. 351-356 (1980).
[58] Matgen P, F Fenicia, S Heitz, D Plaza, R de Keyser, VR Pauwels, et al. Can ASCAT-derived soil wetness indices reduce predictive uncertainty in well-gauged areas? A comparison with in situ observed soil moisture in an assimilation application. Advances in Water Resources. 44 (2012) 49-65.
[59] Zhuo L, D Han. Misrepresentation and amendment of soil moisture in conceptual hydrological modelling. Journal of Hydrology. 535 (2016) 637-51.
[60] Zhuo L, D Han. Could operational hydrological models be made compatible with satellite soil moisture observations? Hydrological Processes. (2016), doi: 10.1002/hyp.10804.

[61] NASA JPL. NASA Soil Moisture Radar Ends Operations, Mission Science Continues. NASA, http://www.jpl.nasa.gov/news/news.php?feature=4710, 2015.

[62] Pierdicca N, L Pulvirenti, C Bignami, F Ticconi. Monitoring soil moisture in an agricultural test site using SAR data: design and test of a pre-operational procedure. Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of. 6 (2013) 1199-210.

[63] Srivastava PK, D Han, MA Rico-Ramirez, D Al-Shrafany, T Islam. Data fusion techniques for improving soil moisture deficit using SMOS satellite and WRF-NOAH land surface model. Water resources management. 27 (2013) 5069-87.