



INTERNATIONAL CONFERENCE ON WATER RESOURCES, COASTAL AND OCEAN
ENGINEERING (ICWRCOE 2015)

Analysis of Temporal Stability of Observed Soil Moisture under
plantation forest in Western Ghats of India

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Abstract

The recognition of temporally stable location with respect to soil moisture content is of importance for soil water management decisions, especially at watershed scale. And most importantly, the profile soil moisture which play a vital role in generation of runoff in a watershed. In this regard, it is very essential to understand the behavior of soil moisture for their vertical and horizontal stability. To this end, a watershed located in the Western Ghats close to Kodigibail Village, Siddapur Taluk, Uttara Kannada District of Karnataka State, India, was selected for monitoring of soil moisture. The soil moisture was measured at weekly time step for a period of Jan 2006 to Dec 2009. The measured soil moisture values were used for evaluation following issues (a) temporal and spatial variation of the observed soil moisture and (b) stability of soil moisture for both vertical and horizontal scale. The results obtained through the analysis of the observed soil moisture revealed that, the soil moisture content in the watershed exhibit both vertical and horizontal stability and can be considered as representative of the watershed.

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Peer-review under responsibility of organizing committee of ICWRCOE 2015

Keywords: Soil moisture, Temporal Stability, Western Ghats, Plantation Forest, Uttarakannada

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1.0 INTRODUCTION

Soil Moisture, a key variable in the hydrological process, governs bare soil evaporation, crop transpiration, the portioning of rainfall into storm runoff and the replenishment of soil moisture stores, and groundwater recharge. The soil moisture status at a given site is determined by a number of factors. Many researchers have reported that, soil moisture is dependent on topography, geomorphology and metrological factors. Exposed to the rapidly changing atmospheric conditions, surface soil moisture is known to be highly variable in time and space at practically all scales of interest. A better understanding of the surface soil moisture dynamics could be obtained based on the analysis of spatio-temporal soil moisture measurements. One of the best methods of assessing the spatio-temporal behavior of soil moisture is by analyzing the observed data for Temporal Stability of the Soil Moisture values.

Various mathematical models have been developed to predict the catchment responses due to changes in catchment properties (Liu et.al, 2009). Some of the models use the soil moisture as explicit component for computing the water balance of the catchment whether or not the soil moisture values are representative of the catchment. The use of non-homogeneous soil moisture values add to the uncertainty into the model (Roberts and Cranes, 1997) As reported elsewhere, the soil moisture data set are very scarce (Liu et .al., 2009, Qui et al., 2001), and in India it is rarely measured at the watershed scale not at catchment scale (Venkatesh et al., 2011). In view of this, it is pertinent to analyse the existing soil moisture data to examine whether or not they are representative of the area and are they stable over a period of time. This will help in developing a relationship of soil moisture with the other common parameters such as meteorological, soil and land use. These relationships can be used in the process model for the better representation of the soil moisture. Therefore, the present study is aimed at investigating (1) the effect of monitoring frequency of temporal stability and to identify the best location to estimate the area-averaged soil moisture values; and (2) spatio-temporal behavior of observed soil moisture values within the watershed. To this end, a watershed located in the Western Ghats close to Kodigibail Village, Siddapur Taluk, Uttara Kannada District of Karnataka State, India, was selected for monitoring of soil moisture. The measured soil moisture values were used for evaluation following issues (a) temporal and spatial variation of the observed soil moisture and (b) stability of soil moisture for both vertical and horizontal scale.

2.0 STUDY REGION

The Western Ghats, locally called as ‘Sahayadri Mountains’, is a range of mountains in the peninsular India running approximately parallel to the West coast and home to the largest tracts of moist tropical forests in the country. Uttara Kannada district in Karnataka state has the biggest share of moist tropical forests. The district straddles the Ghats, which are at their lowest elevation here (<600m) and are about 20-25 km inland. East of the crest line of the Ghats are rolling hills with forested slopes and shallow valleys with cultivation. This region, locally known as the Malnad, covers most of the Siddapur, Sirsi and Yellapur talukas. The selected watersheds are located in Siddapur taluk.

The geology of the area consists of Dharwar (Chlorite) schists, granitic gneisses and charnockites from the Archana complex (Bourgeon, 1989). Broadly, the soils of this region have been categorized as red sandy or sandy-clay loams (Kamath 1985), or more specifically by Bourgeon (1989) as mainly Ferrallitics (French soil taxonomy) or Alfisols and Inceptisols (USDA soil taxonomy) (USDA, NRCS, 2008).

2.1 Experimental Site

The watersheds selected for the study (Fig. 1) are situated on the leeward side of the Sahayadri Mountains (Malnad area of Karnataka). The present consider only acacia plantation, which is one of the dominant land cover of the area having an area of 6 ha. This watershed located at 74° 47' 20" to 74° 52' 30" E Longitude and 14° 22' 20" to 14° 22' 30" N Latitude.

A meteorological observatory was established close to the acacia watershed in the study area. The observatory is equipped with a recording and a non-recording rain gauge to measure rainfall. Air temperatures (maximum and minimum) and wet and dry bulb temperatures were also measured. The measurements were initiated from October 2004 and continued up to December 2008. Meteorological observations were assumed to be representative for all three watersheds. Average monthly water balance of the region was computed using the Thornthwaite-Mather approach and yielded climatic class of ‘Humid climate with rainfall deficit during summer and winter’ (Thornthwaite and Mather 1957).

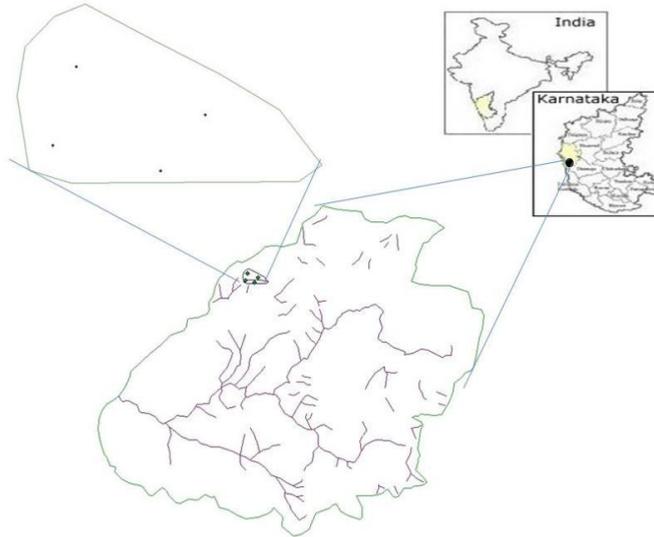


Fig 1. : Index map of the study area along with location of soil moisture measurement points

The analysis of at-site climatic variables monitored between 2004 and 2008 revealed that mean monthly temperature range between 20° – 27° C. The average annual rainfall is 2800 mm with significant intra-annual variability. About 70-80% of the rainfall occurs between June to September (south-west monsoon), while the other 20-30% is spread over the remaining 8 months of the year. The number of rainy days during June to September is about 100-110. The net result is an effective dry season of almost 8 months.

2.2 Soil Moisture Measurements

Four sampling points were established for measuring the soil moisture content in the selected watershed. These points are spread spatially across the watersheds (Fig.1) so as to cover both topographic highs and lows. Most of these samples are classified as clay loam as per USDA classification. Soil matric potential measurements were made using resistance-type soil moisture probes developed by Water Mark[®]. At each sampling point, probes were installed at three depths – 50 cm, 100 cm and 150 cm so as to monitor soil moisture variations in the zone of maximum plant root activity. A roving instrument (handheld read-out unit) was used to record matric potential (KPa) and expressed as soil matric head (cm). Measurements were made at weekly time steps starting from October 2004 till the end of December 2009. Undisturbed soil samples were obtained from all three depths from each watershed and soil moisture retention curves were determined experimentally in the laboratory using pressure plate apparatus. The developed retention curves (Venkatesh et al., 2011) were used to convert the observed soil matric head values to equivalent values of volumetric soil moisture content (cm^3/cm^3).

3.0 METHODOLOGY

Spearman's rank correlation coefficient (R) was used to assess the time stability of vertical patterns (or horizontal patterns) of θ between measurement dates with the whole datasets of θ (Vachaud et al., 1985). The closer R is to 1, the more stable the vertical (or horizontal) patterns of θ between different dates will be. For differentiation, R will be expressed as R_v (or R_h) in terms of vertical (or horizontal) direction.

The whole datasets were roughly divided into two even groups in terms of measurements span, i.e., calibration and validation groups. The calibration datasets were used to identify the MTSD using the MABE. The validation datasets were used to test the possibility to use soil water measurements at certain depth to estimate mean θ of a soil profile at a point or at a hillslope scale.

The MABE value at depth (or location) i is calculated by

$$MABE = \frac{1}{m} \sum_{j=1}^m \left| \frac{\theta_j(i) - \bar{\theta}_j}{1 + \bar{\theta}_j} \right| \quad (1)$$

Where 'm' is the number of sampling dates in the calibration period. $\theta_j(i)$ is the relative difference of θ at depth (or location) i at time j and $\bar{\theta}_j$ is the mean relative difference (MRD) calculated as the temporal mean of $\theta_j(i)$. $\theta_j(i)$ is calculated by (Vachaud et al., 1985)

$$\theta_j(i) = \frac{\theta_j(i) - \bar{\theta}_j}{\bar{\theta}_j} \quad (2)$$

Where $\theta_j(i)$ is the θ measurement at depth i (or mean of a soil profile at location i) at time j and $\bar{\theta}_j$ is the spatial mean of a soil profile at the point (or hillslope) scale. Note that $\bar{\theta}_j$ of a soil profile was the soil thickness weighted mean of θ . Lower values of MABE indicate stronger time stability of a depth (Hu et al., 2010:2012). Following Hu et al. (2010), a critical value of 0.005 or 0.1 for MABE can be used to identify a time stable depth (or location). The MTSD (or MTSL) was defined as that with the minimum MABE value. For differentiation, MRD and MABE will be expressed as MRD_v (or MRD_h) and $MABE_v$ (or $MABE_h$) in terms of vertical (or horizontal) direction.

During the validation period, mean θ of a soil profile at a point (or hillslope) scale at time j , $\bar{\theta}_j$ is obtained by (Grayson and Western, 1998)

$$\bar{\theta}_j = \frac{\theta_j(i)}{1 + \bar{\theta}_j} \quad (3)$$

where the $\bar{\theta}_j$ was obtained from the calibration period. Note that for predicating mean θ of a soil profile at a hillslope scale, the $\theta_j(i)$ is not mean θ of a soil profile measured but predicted from a certain depth at location i with Eq. (3). In the order to assess the possibility of various depths (or sampling location) besides the MTSD (or MTSL) in predicating mean θ of a soil profile at a point (or hillslope) scale, mean θ of a soil profile was predicted from all depths (or sampling locations).

The absolute bias relative to mean (RBIAS) was used to assess the mean prediction error, which is calculated by

$$RBIAS = \frac{1}{q} \sum_{j=1}^q \frac{\bar{\theta}_j - \bar{\theta}_j}{\bar{\theta}_j} \quad (4)$$

Where, q is the number of sampling dates in the validation period. The lower value of RBIAS indicates better prediction. Usually, a prediction with RBIAS less than 0.05 or 0.1 is acceptable in the hydrology community (Peterson and Wicks 2006; Hu et al 2009). For Differentiation, we use $RBIAS_v$ and $RBIAS_h$ to represent RBIAS in the vertical and horizontal directions, respectively.

4.0 RESULTS AND DISCUSSION

The measurements on soil moisture carried out in Acacia plantation for the period of January 2006 to December 2009 has been subjected the various analysis. Various variables describing the behavior of the observed soil moisture were computed and are tabulated in Table 1. Considerable differences were found in the mean soil moisture contents across individual sites. This could be due to the fact that these points are located at different slopes within the watershed. In addition, mean soil moisture content of individual layer increase with increasing of soil depth. The profile gradient is defined as the difference in soil moisture from the bottom most layer to the uppermost layer and divided by the profile thickness. Most of the sites across the land cover recorded positive values indicating the increasing trend of soil moisture within the profile. This variation within the profile is defined by the profile variability. It can be seen from Table 1 that the profile variability has been higher when the profile gradient is high. This is in line with the observation made by Qui et al., (2001). The authors have used these values to classify the profile into the decreasing, increasing and waving type using the values of profile gradients. Most of the higher values pertain to the increasing type and lower values are for the decreasing type of soil moisture profile.

Table 1: Statistics of the time averaged observed soil moisture at various depths

Land Use	Site	0-50 cm	50-100 cm	100-150 cm	Mean	Profile Variability	Profile Gradient	Temporal Variability
Acacia	1	28	30	32	30	0.884	0.0114	3.550
	2	30	34	33	33	1.670	0.022	3.560
	3	34	36	37	36	1.003	0.0124	1.896
	4	35	36	38	37	1.790	0.0172	1.893
	Mean	31.7	34	35	34			
	Spatial Variability	2.6	2.2	2.5	2.4			

Further, the temporal variations of depth-wise soil moisture are shown in Figure 2. It is noticed that the soil moisture at all the layers is responsive to rainfall events. The wetting and drying of soil moisture is in agreement with rainfall occurrences. The increase in the soil moisture at different layer shows a lag, which indicates the movement of water through the soil layers. This process suggests that the water infiltrated after the rainfall event moves faster through the soil profile to augment the soil moisture at lower soil layers (i.e., at 100 cm and 150 cm). The lower soil layer (at 150 cm) holds the maximum soil moisture. This can be due to lower rate of water movement to the next soil layer under these land covers, or may be contribution from lateral flow within the soil layer from the upslope due to change in the properties of saturated hydraulic conductivity.

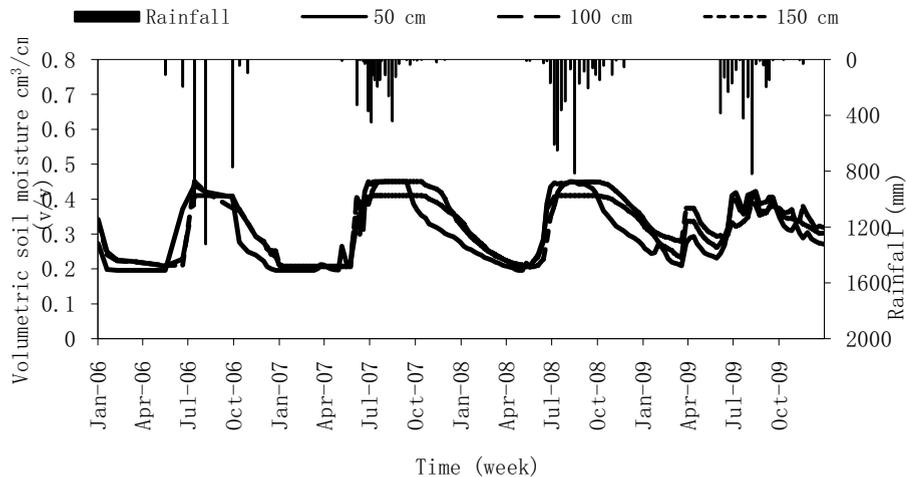


Figure 2. Depth-wise soil moisture content and rainfall during the period of observation

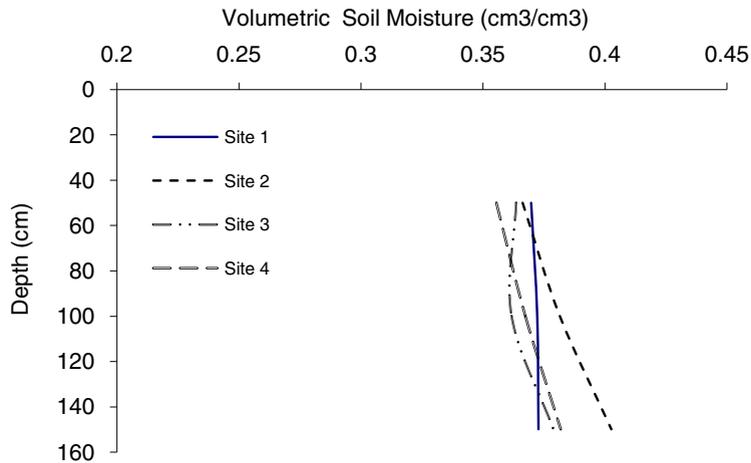


Figure 3. Soil moisture variation along the depth

The Figure.3 shows the variation of the soil moisture in the vertical profile. It is noticed from Figure.3, that, at site no. 1, there is no variation in the soil moisture with the depth, whereas at site 3, the mean soil moisture decreases within 50-100 cm and there after it increases.

4.1 Temporal Stability of soil moisture at specific plot

The purpose of the parameter Mean Relative Difference (MRD) was to measure how a particular sampling location is compared to the average soil moisture over the watershed considered for the analysis. Also, it indicates the sampling location is wetter or drier than the mean of the watershed. This analyses serves also as an indicator of the infield variation of surface soil moisture. In this regard, the results obtained for the selected watershed show that, there is a spatial variation of -3% to +3% at 50cm depth and -14% to 16% at 150 cm across the measuring plots (Table.2). Similarly, the MRD falls within the range between -6% to 3% and -9% 10% across the depth at the measurement plots (Table 3). These observations indicate that, the relative differences are not larger and thereby the observed values of these plots are closer to each other and may be homogeneous in nature.

Table 2. Values of Mean Relative Difference (MRD) of Soil moisture content for different depths

Depth	S1	S2	S3	S4
50 cm	-0.006	0.037	-0.0056	-0.0306
100 cm	0.034	0.089	-0.027	-0.096
150 cm	0.006	0.168	-0.028	-0.146

Table 3. Values of Mean Relative Difference (MRD)of Soil moisture content for different plots

Plot	50 cm	100 cm	150 cm
S1	-0.060	0.030	0.030
S2	-0.096	-0.004	0.101
S3	-0.026	-0.002	0.028
S4	0.032	-0.006	-0.026

Further, Spearman rank correction coefficients were estimated for each of the plot and cross the depths (Table 4). The lower values of the Spearman rank correlation coefficient are indicator of the spatial stability of the soil moisture of a plot. Jia et al.,(2013), reported an increase in temporal stability of the soil moisture with the depth. This observation seems to be valid in this analysis except for site 2 where the computed very lower values indicating the in-stability of the soil moisture content at that point. This could be either due change in the type of

trees grown closer to the site 2. However, when paired test was carried out to evaluate the variation of average soil moisture values across the sites. The analyses showed (Table 5) a larger variation at the 150 cm depth compared with other depth. This suggest that soils at 150 cm suggest that soil moisture will not necessarily reflect profile conditions considering the rapid process of water infiltration within the soil profile.

Table 4. The Spearman's correlation coefficients among values of mean soil water content determined at different depths under plots

Plots		100 cm	150cm
S1	50 cm	0.950	0.806
	100 cm		0.883
S2	50 cm	0.85	-0.181
	100 cm		0.052
S3	50 cm	0.85	0.545
	100 cm		0.756
S4	50 cm	0.601	0.486
	100 cm		0.865

Table 5. The Spearman's correlation coefficients among values of mean soil water content determined at different depths.

Depth		S2	S3	S4
50 cm	S1	0.889	0.851	0.932
	S2		0.732	0.836
	S3			0.877
100 cm	S1	0.922	0.984	0.477
	S2		0.912	0.497
	S3			0.572
150 cm	S1	-0.127	0.90	0.302
	S2		-0.036	0.45
	S3			0.395

4.2 Standard deviation of relative difference (SDRD) and mean absolute bias error (MABE)

The standard deviation of relative difference is widely used to describe the temporal stability of soil water content (Table 6). For this study, SDRD varied across space for various soil depths. At site 1, the values are very low for all the depths. The higher values are obtained for other sites. As Hu et al., (2010) report that, the lower values of SDRD represents the drier sites/layer. This may be true in the present case, as the acacia tress reported to have the maximum density of roots around this depth. As the density decrease with the depth, the higher value of moisture. Conversely, the lower values of mean absolute bias error were computed for most of the sites. The combined results will further strengthen that, the sites which are being used for measuring the soil moisture content are more or less representative of the watershed and can be relative be used for generalizing the soil moisture across entire watershed. The SDRD and MABE values obtained for vertical profile (i e., depth wise) revealed that, the values are more or less in the same range and more representative at each of the measurement location (Table 7). Further, the lower values of MABE and SDRD at 100 cm depth across the measurement sites in the watershed indicates that there is uniform use of the moisture content by the trees and are more of a stable in nature.

Table 6. Mean Absolute Bias Error (MABE) and their standard deviation (SDRD) for the observational plots

Site	50 cm		100 cm		150 cm	
	MABE	SDRD	MABE	SDRD	MABE	SDRD
S1	0.076	0.089	0.040	0.056	0.061	0.089
S2	0.143	0.143	0.060	0.074	0.136	0.184
S3	0.108	0.132	0.046	0.058	0.101	0.141
S4	0.125	0.163	0.072	0.083	0.099	0.124

Table 7. Mean Absolute Bias Error (MABE) and their standard deviation (SDRD) for the observational Depth

Depth (cm)	S1		S2		S3		S4	
	MABE	SDRD	MABE	SDRD	MABE	SDRD	MABE	SDRD
50	0.042	0.055	0.075	0.115	0.071	0.108	0.055	0.066
100	0.072	0.088	0.078	0.098	0.068	0.083	0.156	0.168
150	0.125	0.154	0.154	0.216	0.129	0.152	0.167	0.176

5.0 CONCLUSION

This study assessed time stability of vertical and spatial pattern of soil moisture profile at point scales in a watershed covered by acacia trees. The major observations of the study are;

1. The SDRD values can be used for identifying the drier points among the measurement points, while MABE can be used for wetter points

2. Comparison of SDRD and MABE estimation among different depths showed that soil moisture content at 100 cm is more stable than at 50 cm depth.

Finally it can be concluded that, the soil moisture content in the watershed exhibit more or less a stable condition and can be considered as more representative of the watershed.

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