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Analysis of observed soil moisture patterns under different land covers in Western Ghats, India

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SUMMARY

An understanding of the soil moisture variability is necessary to characterize the linkages between a region's hydrology, ecology and physiography. In the changing land use scenario of Western Ghats, India, where deforestation along with extensive afforestation with exotic species is being undertaken, there is an urgent need to evaluate the impacts of these changes on regional hydrology. The objectives of the present study were: (a) to understand spatio-temporal variability of soil water potential and soil moisture content under different land covers in the humid tropical Western Ghats region and (b) to evaluate differences if any in spatial and temporal patterns of soil moisture content as influenced by nature of land cover. To this end, experimental watersheds located in the Western Ghats of Uttara Kannada District, Karnataka State, India, were established for monitoring of soil moisture. These watersheds possessed homogenous land covers of acacia plantation, natural forest and degraded forest. In addition to the measurements of hydro-meteorological parameters, soil matric potential measurements were made at four locations in each watershed at 50 cm, 100 cm and 150 cm depths at weekly time intervals during the period October 2004–December 2008.

Soil moisture contents derived from potential measurements collected were analyzed to characterize the spatial and temporal variations across the three land covers. The results of ANOVA ($p < 0.01$, LSD) test indicated that there was no significant change in the mean soil moisture across land covers. However, significant differences in soil moisture with depth were observed under forested watershed, whereas no such changes with depth were noticed under acacia and degraded land covers. Also, relationships between soil moisture at different depths were evaluated using correlation analysis and multiple linear regression models for prediction of soil moisture from climatic variables and antecedent moisture condition were developed and tested. A regression model relating near-surface soil moisture (50 cm) with profile soil moisture content was developed which may prove useful when surface soil moisture contents derived from satellite remote sensing are available. Overall results of this study indicate that while the nature of land cover has an influence on the spatio-temporal variability of soil moisture, other variables related to topography may have a more dominant effect.

1. Introduction

Soil moisture in the uppermost 1–2 m of the earth's surface is recognized as a key variable in numerous environmental studies, including those related to meteorology, hydrology, agriculture and climate change. Although the amount of soil water may seem insignificant when compared to the total quantity of water at the global scale, it is this thin layer of soil that controls the success of agriculture and regulates partitioning of precipitation into runoff and sub-surface water storage. Furthermore, soil moisture content is one of the few directly observable hydrological variables that play an important role in quantifying water and energy budgets necessary for climate studies (Jackson, 1993). The important role played by soil moisture on growth of crops/vegetation (Rodriguez-Iturbe, 2000), groundwater recharge (Hodnett and Bell, 1986) and partitioning of rainfall into runoff and infiltration (Merz and Plate, 1997) are well documented. Unlike discharge or climate variables, soil moisture is not monitored regularly – in spite of its importance. Given the tremendous spatial and temporal variability exhibited by soil moisture (Western and Bloschl, 1999), it is very difficult to observe soil moisture at fine spatial and temporal resolutions while covering even moderately large spatial domains. The complexity of the problem is further compounded by the fact that soil moisture varies both in the lateral and vertical directions.

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Spatial and temporal heterogeneity of soil moisture has been attributed to controls exercised by various factors such as precipitation and climate (Famiglietti et al., 1998), land-cover/vegetation (Mahmood and Hubbard, 2007; Fu and Chen, 2000), soil properties and mean soil moisture content (Bell et al., 1980) and topography (Wilson et al., 2005; Moore et al., 1988; Western et al., 1999; Crave and Gascuel-odux, 1997).

Accurate estimation of soil moisture through conceptual and physically-based models is also rendered difficult due to insufficient knowledge on the exact relationships between soil moisture and these influencing factors, many of which exhibit significant interrelationships (Qiu et al., 2001, 2003). Robust calibration and validation of such soil moisture models is hampered by the non-availability of long-term observations, especially in the humid tropics. In an effort to circumvent the problems posed by ground-based monitoring, efforts are being made to use microwave satellite remote sensing data to map soil moisture over large areas (e.g., Vischel et al., 2008). However, these methods provide information only on near-surface soil moisture thereby necessitating the need for approaches to infer the more important profile soil moisture content (Fernandez-Galvez et al., 2006) from satellite imagery.

The effect of land cover on soil moisture variability has not received sufficient research attention. Although this aspect has been the subject of intense research from the agricultural/agronomic perspective, few field experiments have focused on long-term soil moisture variability under natural vegetation. Exceptions to this are studies carried out by Qiu et al., (2003), Fu et al., (2003) and Longobardi, (2008) in which soil moisture dynamics under various natural land covers was explored using intensive spatio-temporal field monitoring. The non-availability of long-term soil moisture measurements extending over 2 or more years under different natural land covers has prevented a better understanding of the impacts of land cover modifications on the hydrological cycle.

This is especially true of India, where large-scale land cover modifications are taking place to provide land for human activities. In particular, the Western Ghats mountain ranges located in the south-western part of India are undergoing tremendous change in land use/cover due to deforestation on one hand and afforestation of degraded and grass lands by planting the exotic species such as Acacia plants on the other hand (Jha et al., 2000; Bhat et al., 2002). The Uttara Kannada District of Karnataka State, India comprises a portion of the Western Ghats and is one of the forest rich districts of the State. For several decades, the forests in this District have been exploited to meet both fuel and land requirements of the region (Prasad and Hegde, 1986; Priya et al., 2007). Several studies have been taken up to assess the extent of land degradation in this region (Reddy et al., 1986; Mani, 1985; Prasad et al., 1985; Mishra et al., 1985; Gadgil, 1987a,b; Nadkarni et al., 1989) and have confirmed the alarming rate at which forests have been removed. These studies are of the opinion that the degradation has been uni-directional and conversion of forests to agricultural land appears to be the primary cause for deforestation. Livestock grazing, forest fires and widespread extraction of fuel wood and fodder have also contributed to land degradation (Lele et al., 1993; Rai, 2004).

Given that the Western Ghats mountain ranges form the headwater catchments of all major rivers of Peninsular India, there is a growing cause for concern regarding the hydrological impacts of such land cover changes. While the hydrological impacts of deforestation are well known, a few studies have reported that reforestation with exotic tree species may lead to mining of sub-surface water (Vandana and Bondhopadhdyay, 1983; Calder et al., 1992). However, the effect of such exotic species on the soil moisture regime of this hydro-ecologically sensitive region has not been studied through long term field observations. No studies have reported the differences in soil moisture regime under exotic tree species and vegetative covers that occur naturally in the region.

Therefore, the present study was taken up with the following objectives: (a) to understand spatio-temporal variability of soil water potential and soil moisture content under different land covers in the humid tropical Western Ghats region and (b) to evaluate differences if any in spatial and temporal patterns of soil moisture content as influenced by nature of land cover. To this end, experimental watersheds located in the Western Ghats close to Kodigibail Village, Siddapur Taluk, Uttara Kannada District of Karnataka State, India, were selected for monitoring of soil moisture. The selection of these watersheds were done such that they fall within a homogeneous climatic region and possess similar soil type and geology but differ only in the nature of land cover – natural forest, degraded forest and acacia plantation. The field experimentation was taken up to address the following issues: (a) quantification of spatio-temporal variability of soil moisture under different land covers using long-term observations (b) evaluation of depth-wise variations in soil moisture content and exploration of relationships between soil moisture content at various depths with particular emphasis on developing relationships between surface and profile soil moisture content; and (c) development and test of a model for soil moisture prediction using routinely observed climate data and antecedent soil moisture content.

2. Study area

The Western Ghats, locally called as ‘Sahayadri Mountains”, is a range of mountains in the peninsular India running approximately parallel to its west coast and home to the largest tracts of moist tropical forests in the country. The coastal District of Uttara Kannada, Karnataka State straddles the Ghats, which are at their lowest here (<600 m) 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 Malnaad, covers most of the Siddapur, Sirsi and Yellapur talukas. The Siddapur taluk formed the focus of this study.

The region has a tropical climate with mean monthly temperatures ranging from 20 to 27 °C. The average annual rainfall is 2800 mm with significant intra-annual variability. About 70–80% of the rainfall is received between June and September due to the south-west monsoon phenomenon, while the remaining rainfall is spread over remaining 8 months. The number of rainy days during June to September is about 100–110. The geology of the area consists of Dharwar (Chlorite) schists, granitic gneisses and charnockites from the Archean complex (Bourgeon, 1989). The major soil types found in the study area are red or yellowish-red lateritic soil, with gravely-clay texture. Forest soils are deep to moderately drained, dark brown to dark yellowish brown with sandy-clay to sandy-clayey-loam texture. They are rich in humus, acidic and usually deep. Broadly, the soils of this region have been categorized as red sandy or sandy-clay loams (Kamath, 1985) or more specifically as mainly Ferrallitics (French soil taxonomy) (Bourgeon, 1989) or Alfisols and Inceptisols (USDA soil taxonomy). The forest vegetation of this area is a mixture of semi-evergreen and moist deciduous associations (Pascal, 1986). The latter vegetation type is often the product of intensive human use and therefore may take the form of a tree savanna, heavily pruned trees with grass in the under storey. Pure grasslands occur in small patches and are dominated by *Themeda* sp (Lélé and Hegde, 1997).

2.1. Experimental sites and soil sampling

The watersheds selected for soil moisture studies are located on the leeward side of the mountains (Fig. 1). Three watersheds, one

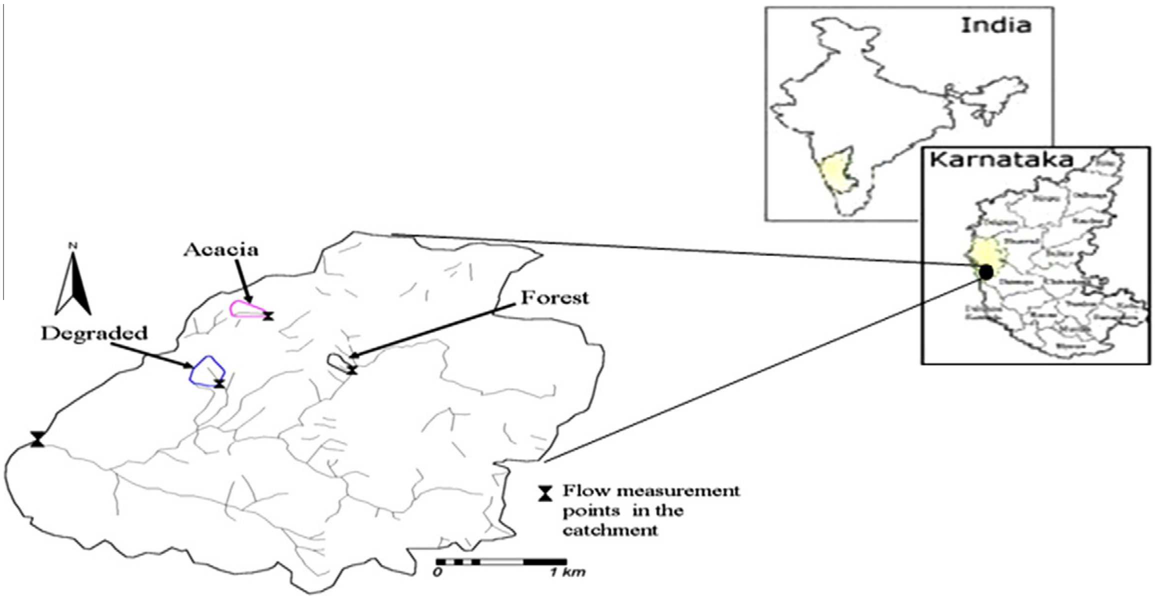

Fig. 1. Index map of study area, showing the location of selected watersheds and the location of meteorological station in the study area.

each under homogenous land covers of acacia plantation (7 ha), degraded forest (9 ha) and natural forest (6 ha) were selected. These watersheds fall between 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. Due to non-availability of radiation and wind speed data, daily records of air temperature and relative humidity were used to compute potential evapotranspiration using the Turc method as recommended by Nandagiri and Kovoor (2006) for sub-humid climates of India. 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'.

Soil samples were collected from the selected watersheds for the textural analysis at an interval of 40 cm up to a depth of 200 cm. The samples were analyzed in the laboratory for their

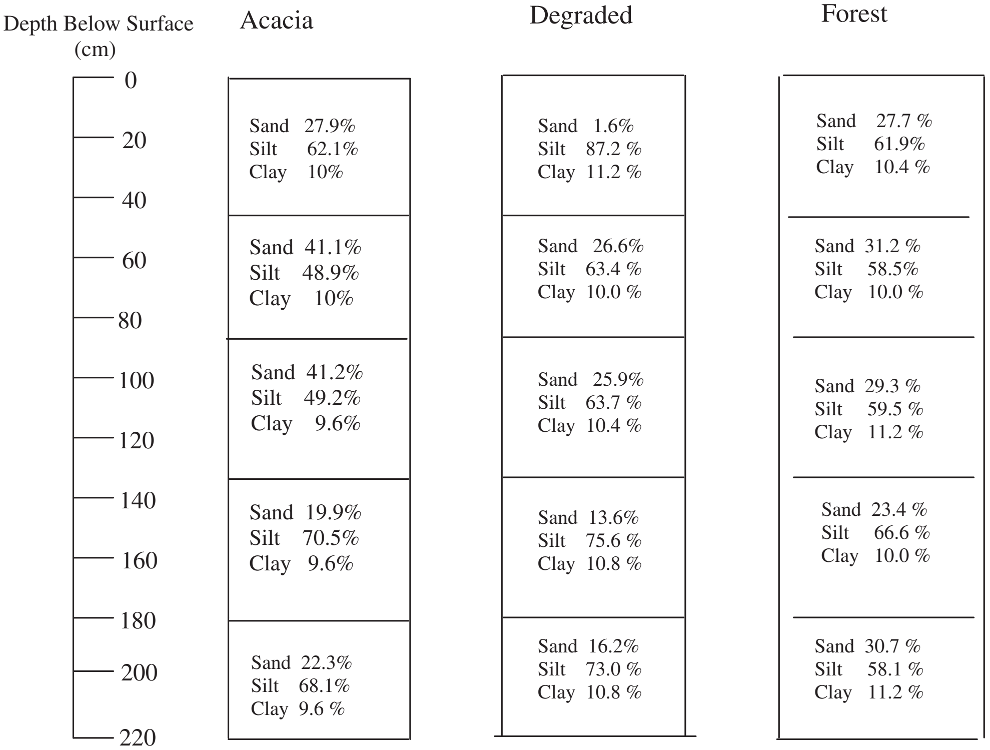

Fig. 2. Representative soil profile in the three watersheds.

texture using the sieve method to quantify the coarse grains and by using the hydrometer method to determine the particle fractions. Most of these samples classified as silty loam as per USDA classification. The depth wise variation of the soil texture in the selected watersheds is presented in the Fig. 2.

Four sampling points were established for measuring the soil moisture content in each of the selected watersheds. These points are spread spatially across the watersheds (Fig. 3) so as to cover both topographic highs and lows. Soil matric potential measurements were made using resistance-type probes developed by Water Mark®. At each sampling point, probes were installed at three depths – 50 cm, 100 cm and 150 cm. 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 2008.

Although results could have been presented in terms of observed soil matric heads, it was felt that physical interpretations of storage and flow dynamics could be more easily made with equivalent volumetric soil moisture contents. Therefore, undisturbed soil samples were obtained from 50 cm, 100 cm and 150 cm depths in each watershed on 10 different occasions during the study period. On each occasion, the samples were obtained from vicinity of one of the locations where soil matric potential was being monitored. These 30 soil samples were subjected to tests in the laboratory using a pressure plate apparatus. Volumetric soil moisture contents were determined at various pressures starting from 33 kPa and going up to 1500 kPa. Retention data obtained in this manner for each soil sample was used to fit the soil water retention model proposed by van Genuchtern (1980)

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1 + (\alpha * h)^n)^m} \tag{1}$$

where $\theta(h)$ is soil water content ($\text{cm}^3\,\text{cm}^{-3}$) corresponding to soil water pressure h (centibar), θ_r is the residual soil water content ($\text{cm}^3\,\text{cm}^{-3}$), θ_s is the saturation soil water content ($\text{cm}^3\,\text{cm}^{-3}$), α, n and m are the empirical parameters. Van Genucthen proposed use of $m = 1-1/n$. Optimal model parameters α and n were determined using SOLVER Addin in Micro Soft Excel®. Saturation soil water content (θ_s) and residual soil water content (θ_r) were also treated as unknown parameters and their optimal values were determined. A similar procedure was adopted to determine model parameters by pooling the retention data for all soil samples at each depth within each watershed.

The fitted retention curves were used to convert the observed soil matric head values to equivalent values of volumetric soil moisture content (cm^3/cm^3). Uncertainties introduced into inferred soil moisture content values on account of pressure plate measurements and also due to fitting the van Genuchten model are discussed in Section 4.2 of this paper.

3. Methodology

3.1. Soil moisture variables

The overall methodology adopted in this study focused on analyzing the temporal and spatial characteristics of observed soil matric potentials and equivalent soil moisture contents. Given a dataset of soil moisture measurements made at several depths at multiple locations on different occasions, Qiu et al. (2001) proposed computation of the several variables to characterize temporal and spatial variabilities in a quantitative manner. Let soil moisture content of site i, layer j and sampling occasion k be expressed as $M_{i,j,k}$ and let N_p be the number of sites, N_l the number of sampling layers or depths and N_t the number of sampling occasions. Then, the following variables may be defined:

1. Mean soil moisture content of site i. (M_i)

$$M_i = \frac{1}{N_l N_t} \sum_{j=1}^{N_l} \sum_{k=1}^{N_t} M_{i,j,k} \tag{2}$$

2. Mean soil moisture content at soil layer j (M_j)

$$M_j = \frac{1}{N_p N_t} \sum_{i=1}^{N_p} \sum_{t=1}^{N_t} M_{i,j,k} \tag{3}$$

3. Time-averaged soil moisture content on plot i, and at layer j ($M_{i,j}$)

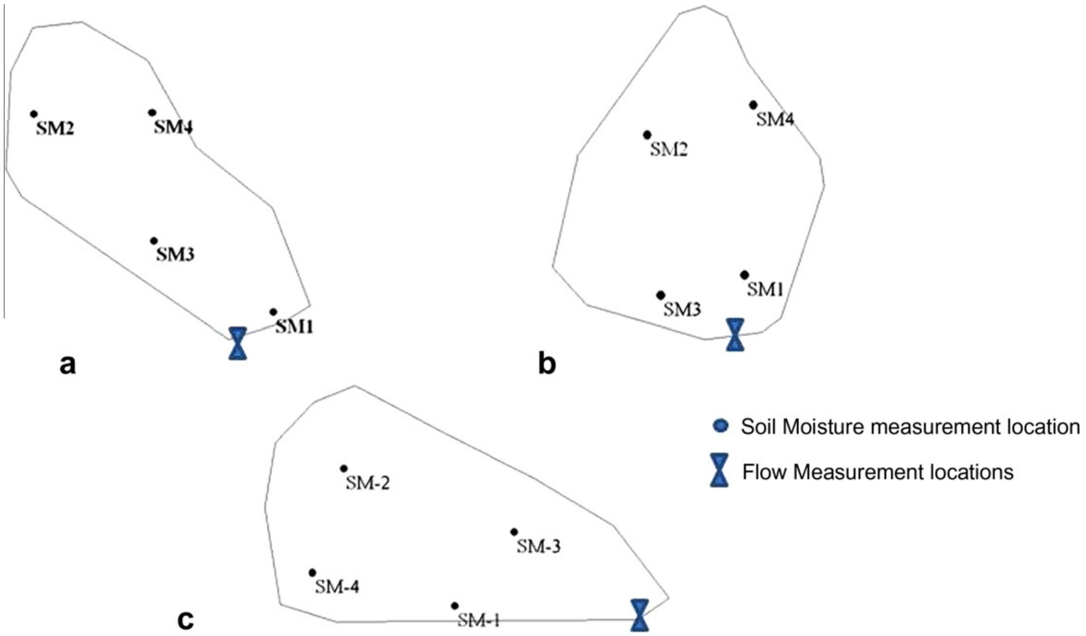

Fig. 3. Locations of soil moisture measuring probes in: (a) forested, (b) degraded and (c) acacia plantation watersheds.

$$M_{i,j} = \frac{1}{N_t}\sum_{k=1}^{N_t} M_{i,j,k} \tag{4}$$

4. Profile Variability of time-averaged soil moisture content on plot, *i*, (VP_i)

$$VP_{i,k} = \sqrt{\frac{N_l\sum_{j=1}^{N_l}(M_{i,j})^2 - \left(\sum_{j=1}^{N_l} M_{i,j}\right)^2}{N_l(N_l-1)}} \tag{5}$$

5. Temporal Variability of layer averaged soil moisture content on plot, *i*, (VT_i)

$$VT_i = \sqrt{\frac{N_t\sum_{k=1}^{N_t} M_{i,k} - \left(\sum_{k=1}^{N_t} M_{i,k}\right)}{N_t(N_t-1)}} \tag{6}$$

6. Spatial variability of layered averaged soil moisture at soil layer *j* (VS_j)

$$VS_j = \sqrt{\frac{N_p\sum_{i=1}^{N_p}(M_{i,j})^2 - \left(\sum_{i=1}^{N_p} M_{i,j}\right)^2}{N_p(N_p-1)}} \tag{7}$$

7. Profile gradient of time-averaged soil moisture on plot *i*, (G_i)

$$G_i = \frac{M_{i,3} - M_{i,1}}{1.5} \tag{8}$$

In the present study, the seven variables defined by Eqs. (2)–(8) were computed for four sites (N_p) in each of the watersheds at three depths (N_l) at 7 day time steps (N_t) during the period October 2004–December 2008.

3.2. Correlation and regression analysis

In addition to characterizing the spatial and temporal characteristics of observed soil moisture contents under different land covers, the study also focused on exploring the relationships between soil moisture levels at different depths using correlation analysis.

An effort was also made to develop a simple regression-based model for prediction of soil moisture from climatic variables and antecedent soil moisture content. Accordingly, the following linear multiple linear regression model was fitted to available observations separately for each watershed.

$$SM_j = a + b*P + c*T + d*RH + e*AMC \tag{9}$$

where SM_j is the soil moisture content with *j* being set to either depths 50, 100 and 150 cm or the soil moisture for the profile as a whole (PM), *P* is rainfall (mm), *T* is air temperature (°C), RH is relative humidity (%) and AMC is antecedent moisture content. *a*, *b*, *c*, *d* and *e* are regression coefficients.

Further, while developing the prediction models for the 100 cm and 150 cm depths, an additional predictor variable in the form of the soil moisture content of the immediate upper layer was included in the model defined by Eq. (9). Also, while developing the model for with soil moisture of the profile as a whole (SM_{PM}), the soil moisture in the surface layer (SM_{50}) was included as an additional predictor in Eq. (9).

All the models described above were calibrated using observed data for the period October 2004–December 2007 and validated with the remaining dataset (January 2008–December 2008). Statistics used to assess model performances in both calibration and validation phases included: the coefficient of determination (R^2), root mean square error (RMSE) and mean absolute error (MAE). In an effort to identify the most parsimonious model, the Akaike Information Criteria was also computed as,

$$AIC = N(\ln SSE) + 2Nv \tag{10}$$

where SSE is the sum of square of error between observed and predicted soil moisture contents, *N* is sample size and Nv is the number of independent variables included in the model. A model with minimum AIC is considered best.

4. Results and discussion

4.1. Variations in observed soil matric potentials

As mentioned earlier, the primary measurements in the present study consisted of soil matric potentials recorded at weekly time steps at three depths at four locations and in all the three watersheds. As an example, the temporal variations in soil matric potentials at three depths in the forested watershed are plotted in Fig. 4. Significant seasonal variations can be seen with matric potential values going from 10 kPa during the rainy season to values as high as 200 kPa during the dry season. Substantial differences in potential values between the three depths can be seen, especially during the dry season.

The utility of observed soil matric potentials in computing water fluxes under the three land covers has been demonstrated in Venkatesh et al. (2010). Since the focus in this paper is to understand the spatio-temporal characteristics of soil water storage, equivalent soil moisture contents were calculated using water retention curves.

4.2. Soil water retention curves

Results of the pressure plate retention tests are shown in Table 1 for each depth under each land cover. In an effort to quantify the uncertainty in inferred volumetric soil moisture contents derived from matric potentials using these measurements, the mean moisture content and the standard deviations for 10 samples for each pressure are shown in Table 1. It can be seen that the standard

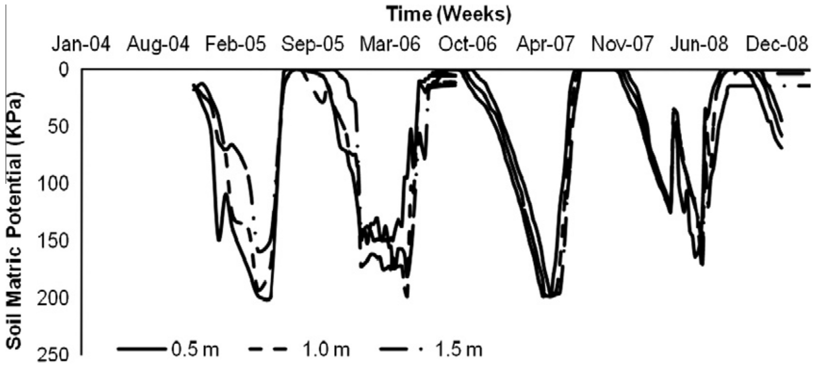

Fig. 4. Plot of observed soil matric potential under forested watershed.

Table 1
Statistics of soil moisture release curves developed for soils at different depths under selected watersheds.

Land cover	Soil matric potential (kPa)	Mean soil moisture content ± standard deviation (cm^3/cm^3)		
		50 cm	100 cm	150 cm
Forest	33	0.290 ± 0.091	0.289 ± 0.056	0.286 ± 0.064
	300	0.183 ± 0.043	0.121 ± 0.025	0.167 ± 0.030
	500	0.171 ± 0.045	0.161 ± 0.027	0.155 ± 0.026
	700	0.165 ± 0.034	0.163 ± 0.030	0.147 ± 0.016
	1000	0.162 ± 0.033	0142 ± 0.022	0.149 ± 0.025
	1500	0.151 ± 0.035	0.141 ± 0.022	0.155 ± 0.067
Degraded	33	0.338 ± 0.066	0.314 ± 0.056	0.284 ± 0.059
	300	0.201 ± 0.040	0.203 ± 0.028	0.172 ± 0.032
	500	0.166 ± 0.045	0.184 ± 0.020	0.162 ± 0.024
	700	0.172 ± 0.025	0.180 ± 0.018	0.158 ± 0.028
	1000	0.165 ± 0.027	0.167 ± 0.020	0.153 ± 0.027
	1500	0.160 ± 0.032	0.165 ± 0.020	0.137 ± 0.032
Acacia	33	0.245 ± 0.069	0.252 ± 0.067	0.361 ± 0.015
	300	0.167 ± 0.036	0.151 ± 0.029	0.198 ± 0.056
	500	0.157 ± 0.035	0.142 ± 0.024	0.186 ± 0.049
	700	0.149 ± 0.030	0.137 ± 0.027	0.179 ± 0.044
	1000	0.142 ± 0.027	0.131 ± 0.021	0.177 ± 0.044
	1500	0.136 ± 0.024	0.125 ± 0.033	0.108 ± 0.048

deviations are reasonably low and also consistent between the three land covers.

Table 2 on the other hand shows optimal parameters of the fitted van Genuchten model (Eq. (1)) by combining the pressure plate retention data of 10 samples for each depth under each land cover. As an example, the optimal van Genuchten water retention curves for three depths in the degraded watershed are shown in Fig. 5. Soil matric potentials measured in the field were converted to volumetric moisture contents using such optimal curves for each depth under each land cover. Table 2 also shows the range of R^2 and RMSE values obtained while fitting the van Genucthen model to the 10 samples for each case. These error statistics are indicative of the uncertainties introduced into inferred moisture contents on account of the model used. It can be seen from Table 2 that the values of RMSE in almost all cases are quite low thereby indicating that the uncertainties due to use of the model are small. Reasonably high R^2 values support this conclusion.

Table 2
Optimal parameters of van Genucthen model for soil water retention curve and error statistics.

Land cover	Parameter	Optimal parameters[a] and statistics		
		50 cm	100 cm	150 cm
Forest	Θ_r	0.126	0.116	0.145
	Θ_s	0.569	0.457	0.483
	α	0.395	0.0325	0.0054
	n	1.475	1.512	1.947
	Range of R^2	0.99–0.93	0.99–0.767	0.99–0.955
	Range of RMSE (cm^3/cm^3)	0.0012–0.000013	0.0051–0.000027	0.0063–0.000023
Degraded	Θ_r	0.158	0.121	0.112
	Θ_s	0.348	0.557	0.697
	α	1.11×10^{-6}	0.794	0.503
	n	2.79	1.139	1.455
	Range of R^2	0.999–0.941	0.999–0.917	0.996–0.719
	Range of RMSE (cm^3/cm^3)	0.0092–0.0000076	0.0092–0.000013	0.022–0.0014
Acacia	Θ_r	0.092	0.109	0.158
	Θ_s	0.342	0.4105	0.494
	α	0.0566	0.023	0.044
	n	1.334	1.583	1.739
	Range of R^2	0.998–0.82	0.999–0.957	0.999–0.92
	Range of RMSE (cm^3/cm^3)	0.0038–0.000012	0.00064–0.0000085	0.0041–0.000018

[a] Optimal values of parameters of van Genucthen model for the water retention curve (Eq. (1)).

In any case, it must be reiterated that since the major focus of this study is to distinguish temporal and spatial variations in soil moisture between the three land covers considered, relative differences and not absolute values of moisture contents, are more important. Since the uncertainties due to measurements and modeling of retention data are more or less similar for the three watersheds, it is expected that the inferences drawn on the basis of soil moisture contents will remain unaffected.

4.3. Overall soil moisture variability

Table 3 shows the soil moisture variables computed using Eqs. (2)–(8). Considerable differences were found in the mean soil moisture contents across the three land covers. Also, the mean soil moisture content of individual sites within each land cover recorded different values. This could be due to the fact that these points are located at different slopes within the watershed. In addition, mean soil moisture content appears to increase with 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 2, that the profile variability is higher when the profile gradient is high. This is in line with the observation made by Qiu 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.

Large differences in the temporal variability between the different sites within each of the land covers are observed. Not much spatial variability is observed between the four sites at different depths in acacia and forested watershed. However, degraded watershed exhibits greater spatial variability across all the points at different depths. These differences could be attributed to the vegetation cover (mainly grass) and proximity of the measuring point to the tree. Whereas, uniform distribution of trees and accordingly uniform utilization of soil moisture across all the depths has resulted in less spatial variability in acacia and forested watersheds. A similar observation has been reported by Qiu et al. (2001), Zhou et al. (2001) and Teuling et al. (2006). It is also, observed that, the spatial variability is greater during the recession period than that of soil moisture accumulation period and this in line with the observations reported by Brocca et al. (2007).

4.4. Spatial variation of soil moisture under different land covers

An analysis was carried out to understand how soil moisture varies across the different slopes within the watershed (the spatial location of soil moisture measuring points are shown in Fig. 3a). Fig. 6 shows change in mean soil moisture content at different spatial points within the selected land uses. It is noticed from Fig. 6, that the soil moisture increased from top to bottom of the slope. The acacia and degraded watersheds register a higher water content of 35% and 32% respectively at the bottom (close to watershed outlet) of the watershed. A similar pattern was observed by different authors elsewhere (Fu et al., 2003; Kim et al., 2007). In the present case, forested watershed shows higher soil moisture content of 36% at the top and 34% at the bottom. The changes observed across the different slopes may be due to continuous inflow of water from the upper zone to the lower zone after every rainfall events. This may be the only possible explanation for higher soil

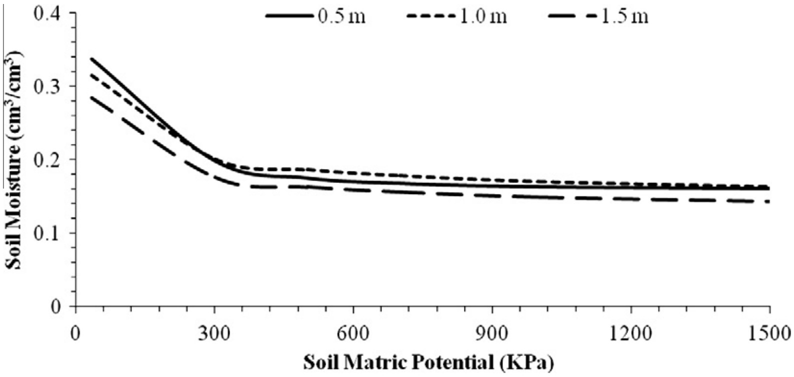

Fig. 5. Fitted Soil Water Retention curves for degraded watershed.

Table 3
Statistics of the time averaged observed soil moisture at various depths under different land cover types.

Land cover	Site	$M_{i,j}$, j = 50 cm	$M_{i,j}$, j = 100 cm	$M_{i,j}$, j = 150 cm	Mean, M_i	Profile variability, VP_i	Profile gradient, G_i	Temporal variability, VT_i
Forest	1	26	30	32	29	2.830	0.036	3.380
	2	24	31	33	30	2.820	0.0365	3.360
	3	28	36	35	33	3.600	0.078	1.700
	4	30	33	34	31	3.540	0.0400	1.703
	Mean, M_j	27	32.5	33.5	30.75			
	Spatial variability, VS_j	1.22	2.64	1.45	1.77			
Degraded	1	29	30	33	30	0.966	0.0121	3.390
	2	28	31	32	31	0.742	0.0077	3.340
	3	33	32	35	34	0.599	0.0077	1.789
	4	35	36	38	37	0.248	0.0031	1.774
	Mean, M_j	31.25	32.25	34.5	33			
	Spatial variability VS_j	4.06	3.68	2.75	3.49			
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, M_j	31.75	34	35	34			
	Spatial variability, VS_j	2.66	2.21	2.50	2.44			

moisture in the bottom layer than that of other two layers. As it has been reported by many researchers (Montgomery et al., 1997; Uchida et al., 2002; Asano et al., 2002; Freer et al., 2004), the contribution of flow from bedrock to the soil may be another possible explanation for the persistence of soil moisture in the bottom and middle zones of these watersheds.

4.5. Temporal variability of soil moisture under three land covers

The temporal variation of mean soil moisture content within 0–150 cm under three land covers is shown is Fig. 7. Also shown is the accumulated daily rainfall over weekly time steps for the entire study period. The seasonal variation of the mean soil moisture in all the land covers is apparent. As expected, increase or decrease of mean soil moisture is associated with the occurrences of high and low rainfall amounts. Also three peaks in soil moisture content are exhibited since the data period covers the monsoon season of four years. Similarly, four troughs are observed corresponding to the dry season of each year.

In general, the peak moisture content value corresponds to the heaviest rainfall in the season. However, for smaller rainfall events, there are differences in the response of soil moisture under different land covers. For example, in the acacia and forested watersheds the build up of soil moisture is at a slower rate compared to that in the degraded watershed. The accumulated amount of rainfall which is responsible for building up the soil moisture during the study period under the selected land covers is tabulated in Table 4. It can be seen from the results shown in Table 4 that, this amount varies year to year and layer to layer. This could be due to antecedent moisture available in the soil. The influence of antecedent moisture on soil moisture build up is clearly evident during the years 2007 and 2008 under degraded and acacia watersheds. The response in the degraded watershed is relatively steep and soil moisture peak is attained rapidly. The peak (field capacity) soil moisture at the 50 cm layer was attained for lower amount of rainfall (834 and 915 mm for 2007 and 2008 respectively). Similarly, recession in the degraded watershed is faster in comparison to the other two watersheds. The recession is quite higher at 50 cm depth in comparison to the other two layers. The average rate of soil moisture drying at this depth varies from 0.028 to 0.0342 per week by volume in the year 2006–2007 and 2007–2008 respectively. During the same period, a lower rate of drying was observed at 150 cm depth. A similar process is observed under the acacia watershed. This clearly implies that, the use of moisture under these watersheds is mostly confined to the first layer (up to 50 cm depth) on account of plant water use. This result is only to be expected since Acacia does not have a deep rooting system (Kallarackal and Somen, 2008).

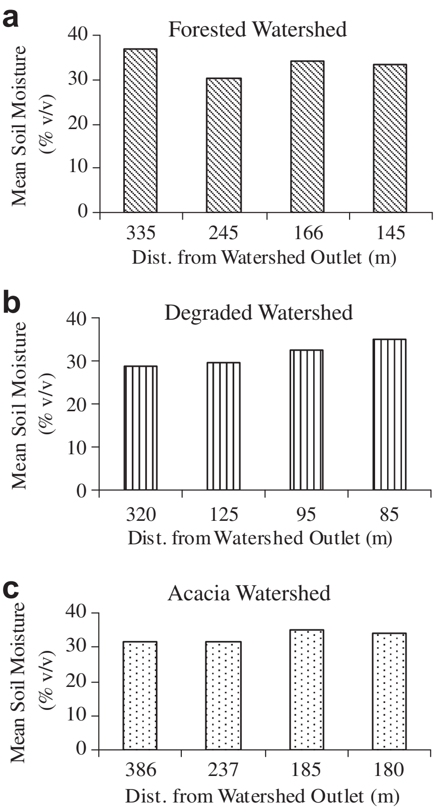

Fig. 6. Measured soil moisture at different slopes within each of the selected watersheds.

On the other hand, forested watershed required higher amount of rainfall (1485 and 993 mm respectively for 2007 and 2008) to reach the maximum soil moisture level. As observed by Lin et al. (2006), the antecedent soil moisture can influence the distribution of soil moisture and its build up in the forested watersheds. The recession in the watershed is quite higher at 150 cm depth. This is due to the presence of roots, which use the moisture for their physiological activities especially during the post monsoon season when water is freely available (Kallarackal and Somen, 2008). This is further supported by the presence of higher mean moisture content at this depth in the selected watershed. Similarly, Lin et al. (2006) reported consistently higher moisture content in deeper soil layers (0.91–1.09 m) of a forested watershed in central Pennsylvania State, USA.

An ANOVA test was done to verify the influence of land cover on the soil moisture at $p < 0.01$ significant level. The result indicated no significant differences across the land covers. This may imply that parameters other than land cover may have an influence on the soil moisture regime (e.g., Pellenq et al., 2003; Freer et al., 2004; Wilson et al., 2004). Similarly, ANOVA test was carried out for soil moisture between different layers (i.e., 50–100 cm, 100–150 cm and 50–150 cm) to evaluate the impact of land covers at these depths. The results (Table 5) show that there is no significant difference in the mean soil moisture across the depths under Acacia and Degraded watersheds. However, the forested watershed showed a significant difference ($p < 0.01$, LSD) in observed mean soil moisture at these depths.

4.6. Variation of soil moisture at different depths

The temporal variations of depth-wise soil moisture for the selected land covers are shown in Fig. 8. It is noticed that the soil moisture at all the layers is responsive to rainfall events. The

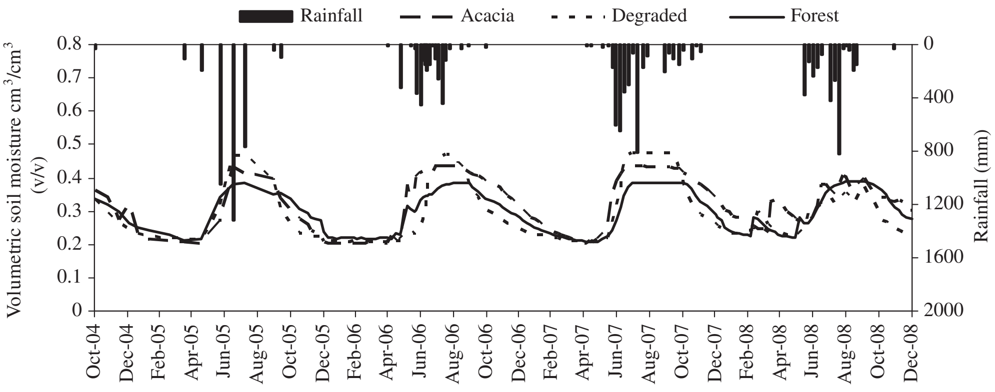

Fig. 7. Comparison of mean soil moisture content of three land-use types.

Table 4
Salient features of the soil wetting and drying under different land covers.

Land cover		Natural forest			Degraded			Acacia		
Depth in cm		50	100	150	50	100	150	50	100	150
Accumulated rainfall up to attaining peak soil moisture (cm)	2005	1351	2673	2673	1351	1673	1351	1351	1351	2473
	2006	1459	2628	2628	1645	1951	1951	1451	1792	2343
	2007	1485	3031	3031	834	1485	2048	814	1485	2148
	2008	993	2505	2575	915	993	2505	949	1416	2538
Average drying rate of soil moisture/week (cm^3/cm^3)	2005–06	0.0093	0.0234	0.0288	0.0341	0.0246	0.0159	0.0271	0.021	0.02
	2006–07	0.0042	0.0179	0.0368	0.0288	0.0095	0.0076	0.0284	0.0074	0.0087
	2007–08	0.0053	0.0131	0.0303	0.0285	0.0185	0.0133	0.026	0.007	0.0077

Table 5
Comparison of mean soil moisture content across the soil layers through ANOVA test.

Land cover type	Soil layer (cm)	Difference in mean soil moisture content between layers (% v/v)
Forest	50–100	−3.99[a]
	100–150	−5.412[a]
	50–150	−1.423
Degraded	50–100	−0.0480
	100–150	−1.3784
	50–150	−1.3303
Acacia	50–100	−1.528
	100–150	−0.9008
	50–150	−2.429

[a] Mean soil moisture values are significant at $P < 0.01$ significant level.

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). Also, Fig. 8 depicts that the soil layer at 100 cm holds the maximum moisture under degraded and forested watershed. Whereas, in the acacia watershed, 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. A similar observation was reported by Kroner and Jahr (2005) under a conifer forest in Thuringia, Germany. Zhou et al. (2001) reported that soil moisture under Eucalyptus and mixed forest was lower than the bare land catchment. The statistics shown in Table 6 indicates that the lower most layer holds the maximum moisture with higher standard deviation in acacia and forested watersheds. On the other hand, the degraded watershed shows a higher standard deviation in the middle layer.

The field capacity of the soil was superimposed on the plot of temporal variation of layer-wise soil moisture (Fig. 8). This permits visualization of the resident time of the soil moisture at field capacity under the selected watersheds. From this plot it can be seen that soil moisture in the deeper layer (150 cm) under forested watershed is maintained at a higher level for longer time duration in comparison to the degraded watershed, where the moisture recession is quite faster. Whereas under the acacia plantation, it is noticed that soil moisture in entire profile have similar resident time but lesser than that of forested watershed. The most important observation made is that, soil moisture in the upper layer (at 50 cm) of forested watershed did not reach the field capacity during the study period.

4.7. Relationship between soil moisture at various depths

Soil moisture is an important component and a key mediator between land surface and atmospheric interactions. The variation of soil moisture across different land covers under varying climatic conditions needs to be probed for better understanding how this quantity varies over different time-scales and at different depths. These variations may be assessed by the strength of correlations and cross-correlations between soil moisture content in the top-layer (0–50 cm) and moisture content in the other layers under in each land cover. Such analyses may provide an opportunity to determine the lag for attaining maximum correlation and how these correlations and lags vary across the land covers. The results obtained are tabulated in Table 7. It is found that a strong correlation exists between all the layers across all the land covers. The highest correlation is observed in acacia between soil moisture at the 100 cm depth with that at 150 cm depth. The lowest correlation is exhibited between moisture contents at 50 cm and 150 cm depths in the degraded watershed.

Soil moisture levels are also modified by the movement of water in and out of the layer, and due to root uptake from each layer. Therefore, an analysis was undertaken to establish time-lag relationships by lagging the soil moisture time series between any two depths by 1 week, 2 weeks and so on. The lag duration which yielded highest correlation coefficient between the two time series was identified. The results shown in Table 7 suggest that the correlation between soil moisture content in 50 cm and 100 cm depths is highest under all the land covers and no lag was needed. This suggests, in the first few soil layers, the movement of water is faster. A similar analysis between 50 cm and 150 cm suggests that, there is a lag varying between 1 and 2 weeks, indicating the slower movement of water below 100 cm depth in these watersheds. The results obtained here are in agreement with the observations made by Mahmood and Hubbard (2007) under varying land covers and climatic conditions of USA. Similarly Lin et al. (2006) reported that in humid tropical forested watersheds, the sub-surface soil moisture is mostly dependent on the combined effect of topography and soil characteristics. Since these monitoring points are located on slopes, the water moving from upper slope to lower levels may contribute to soil moisture at 100 cm and 150 cm. This phenomenon may be responsible for not showing any lag-time between the 50 cm and 100 cm layers and between the 100 cm and 150 cm layers. Also, the soil moisture augmentation in these watersheds may be more due to the lateral movement of water within the soil layer than the vertical movement of water.

4.8. Development of soil moisture prediction models

An attempt was made to relate the soil moisture observed at 4 spatial locations under acacia, degraded forest and natural forest with at-site meteorological parameters and soil moisture variables in the respective watersheds. As described in Article (3.0), a linear model (Eq. (9)) was used for the purpose. Table 8 shows regression coefficients of the independent variables for the prediction models at three soil depths and for the profile mean along with R^2 and RMSE values. Values of R^2 greater than 0.9 and small values of RMSE for all cases indicate that the performance of all the developed models is reasonably good. From the regression coefficients it can be seen that the influence of rainfall, relative humidity and air temperature on the soil moisture at different depths is small. The largest values of coefficients are associated with the antecedent moisture condition (AMC) variable, thereby indicating its importance. Also, both R^2 and RMSE values show some improvement with the inclusion of soil moisture of the immediate upper layer. However, the relationship developed for 150 cm depth under acacia showed no significant impact of soil moisture observed at 100 cm. Whereas for the same depth under forest show a greater significance in the relationship. This clearly indicates that the soil moisture at the 150 cm depth is augmented by the movement of water from upper soil layer under forested watershed. The signs (positive or negative) associated with the regression coefficients of the variables reflect the nature of relationship with soil moisture. For example, the negative coefficient for relative humidity may be indicative of the processes of evapotranspiration which is directly related to the wetting and drying up of soil.

4.9. Relationship between near-surface soil moisture and profile soil moisture

In an effort to aid estimation of profile soil moisture content from near-surface soil moisture derived from satellite remote

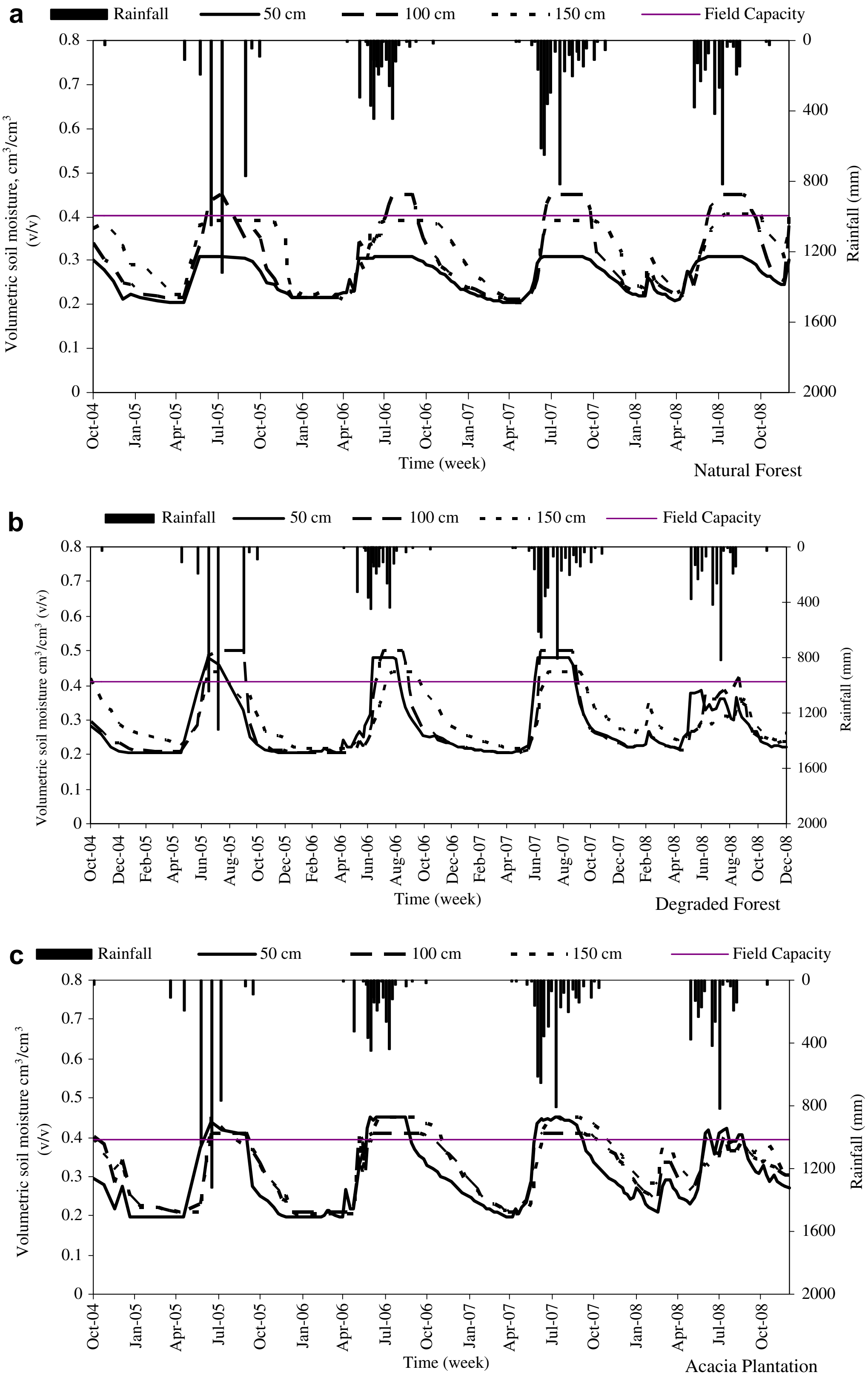

Fig. 8. Depth-wise soil moisture content and rainfall during the period of observation in the selected watersheds under (a) forest, (b) degraded and (c) acacia land cover.

sensing, an effort was made to establish the relationship between these two variables with the current dataset. As mentioned earlier, this was achieved by including the soil moisture content at the 50 cm depth along with the other climatic variables while considering the profile soil moisture content as the dependent variable in the linear regression model. Results are tabulated in Tables 8 and 9 from which a clear dependency of the near-surface soil moisture on the profile soil moisture content is evident from the favourable

Table 6
Temporal variations of soil moisture in selected land uses.

Land cover	Depth (cm)	Mean (cm^3/cm^3)	Standard deviation (σ)
Forest	50	27.00	4.12
	100	32.50	8.68
	150	33.50	7.29
Degraded	50	31.25	10.16
	100	32.25	10.93
	150	34.50	8.27
Acacia	50	31.75	9.69
	100	34.00	8.39
	150	35.00	9.78

Table 7
Relationship between soil moisture at various depths.

Land cover	Statistic	50 cm vs 100 cm	50 cm vs 150 cm	100 cm vs 150 cm
Forest	Correlation	0.926[a]	0.840[a]	0.830[a]
	Cross-correlation	0.926(0)	0.851(1)	0.830(0)
Degraded	Correlation	0.908[a]	0.694[a]	0.851[a]
	Cross-correlation	0.908(0)	0.784(2)	0.875(1)
Acacia	Correlation	0.916[a]	0.904[a]	0.984[a]
	Cross-correlation	0.916(0)	0.926(1)	0.984(0)

Values in parenthesis are lag time in weeks.

[a] Values are significant at $p < 0.01$ significant level.

Table 9
Performance indices of soil moisture prediction models in validation phase.

Land cover	Depth (m)	Previous layer		Performance statistics			
		0.5	1.0	RMSE	MAE	AIC	R^2
Forest	0.5	–	–	0.0111	0.0068	−246.37	0.951
	1.0	–	–	0.0218	0.0139	−181.27	0.967
	1.0	Included	–	0.0292	0.0261	−149.85	0.972
	1.5	–	–	0.0290	0.0165	−90.24	0.614
	1.5	–	Included	0.2419	0.238	−63.71	0.792
	PM	–	–	0.0184	0.0112	−198.69	0.953
	PM	Included	–	0.0216	0.0189	−182.63	0.953
Degraded	0.5	–	–	0.0274	0.0145	−148.99	0.876
	1.0	–	–	0.0186	0.0136	−185.20	0.958
	1.0	Included	–	0.0197	0.0138	−177.78	0.953
	1.5	–	–	0.0198	0.0122	−179.89	0.804
	1.5	–	Included	0.0176	0.110	−188.31	0.853
	PM	–	–	0.0211	0.0131	−173.57	0.777
	PM	Included	–	0.0210	0.0144	−172.14	0.838
Acacia	0.5	–	–	0.0231	0.0158	−170.80	0.934
	1.0	–	–	0.0241	0.0141	−166.31	0.858
	1.0	Included	–	0.0157	0.0104	−208.32	0.947
	1.5	–	–	0.0213	0.0128	−178.49	0.778
	1.5	–	Included	0.0215	0.0129	−177.42	0.780
	PM	–	–	0.0207	0.0128	−180.90	0.891
	PM	Included	–	0.0140	0.0099	−219.47	0.965

values of performance statistics. A *t* test was carried out to check the significance of the coefficients of the equation and showed no significant change in the values of the coefficients at $p < 0.001$.

4.10. Validation of soil moisture prediction models

This section describes the performance of the regression models in predicting the soil moisture content for data which was not used in calibration (i.e., data for January 2008–December 2008). Performance indices of MAE, RMSE, AIC and R^2 computed for the validation phase shown in Table 9. The variations of these indices are shown in Fig. 9. It can be seen that RMSE constantly increases with the depth in the forested watershed (Fig. 9a), whereas it decreases with depth in the degraded watershed. RMSE values in the acacia watershed are initially low and increase up to 100 cm depth and then converge to the value for degraded land cover at 150 cm depth.

MAE values decline with depth under the acacia and degraded covers (Fig. 9b). However, estimates under forested watershed show a steady increase in the values. Similarly, the values of R^2 steadily (Fig. 9a) decreased with the increase with the depth under all the land covers. The estimates of AIC (Fig. 9b) follow the same trend as MAE.

Overall, the performance of all the models in the validation is reasonably good. They can be used with confidence in conditions that are similar to the ones in the study area.

Table 8
Multiple linear regression models developed for the prediction of soil moisture content at different depths.

Land cover	Variables	Intercept	Regression coefficients for						R^2	RMSE
			SM_{50}	SM_{100}	Rainfall (P0) mm	RH (%)	Temp. (°C)	AMC		
Natural forest	SM_{50}	0.0036	–	–	2.84×10^{-5}	5.54×10^{-7}	0.00072	0.905	0.950	0.0123
	SM_{100}	0.0224	–	–	7.17×10^{-5}	2.04×10^{-6}	−0.0002	0.922	0.969	0.0213
		−0.0010	0.1672	–	6.26×10^{-5}	2.1×10^{-6}	−0.0002	0.859	0.970	0.0208
	SM_{150}	0.2181	–	–	6.7×10^{-6}	1.01×10^{-6}	−0.0045	0.626	0.848	0.0375
		0.221	–	0.468	7.28×10^{-5}	2.54×10^{-6}	−0.0054	0.273	0.913	0.0288
	SM_{PM}[a]	0.0104	–	–	4.99×10^{-5}	1.23×10^{-6}	0.00023	0.929	0.967	0.0153
		−0.0048	0.260	–	3.526×10^{-5}	1.22×10^{-6}	−0.00022	0.794	0.976	0.0136
Degraded	SM_{50}	0.0140	–	–	7.84×10^{-5}	0.00033	−0.00024	0.853	0.959	0.0258
	SM_{100}	0.0248	–	–	8.17×10^{-5}	0.000565	−0.00168	0.877	0.965	0.0258
		−0.00435	0.3678	–	2.72×10^{-5}	0.000266	−0.00091	0.646	0.978	0.0206
	SM_{150}	−0.01178	–	–	4.64×10^{-5}	0.000526	−0.0003	0.906	0.970	0.0175
		−0.00325	–	0.162	2.88×10^{-5}	0.000317	2.1×10^{-7}	0.755	0.978	0.0150
	SM_{PM}[a]	0.00819	–	–	6.79×10^{-5}	0.000457	0.00071	0.884	0.977	0.0176
		0.00231	0.370	–	1.93×10^{-5}	0.000209	−0.0002	0.597	0.992	0.0164
Acacia	SM_{50}	0.0378	–	–	7.6×10^{-5}	1.93 × 10–6	−0.00092	0.890	0.957	0.0257
	SM_{100}	0.0493	–	–	5.8×10^{-5}	-1.4×10^{-6}	−0.00076	0.890	0.937	0.0275
		0.0508	0.421	–	$--1 \times 10^{-5}$	-2.3×10^{-6}	−0.00097	0.518	0.960	0.021
	SM_{150}	0.0237	–	–	6.81×10^{-5}	1.59×10^{-6}	-4.2×10^{-5}	0.911	0.939	0.029
		0.0176	–	0.0925	6.58×10^{-5}	9.88×10^{-7}	4.53×10^{-5}	0.834	0.939	0.029
	SM_{PM}[a]	0.0327	–	–	6.58×10^{-5}	-8.1×10^{-7}	−0.00038	0.910	0.956	0.0235
		0.0422	0.5005	–	-2.6×10^{-6}	-1.6×10^{-6}	−0.00082	0.454	0.981	0.0155

RMSE: root mean square error. AMC: antecedent soil moisture content at weekly time step.

[a] Represents the relation between the near-surface soil moisture with the profile mean soil moisture.

5. Summary and conclusions

An experimental study was carried out to understand spatio-temporal variability of soil moisture under different land covers (acacia, degraded forest, forest) in watersheds located in the Western Ghats mountain ranges of Karnataka State, India. Results indicated that there is no significant difference in the mean soil moisture content between the three land covers considered. This clearly indicates that soil moisture is not only influenced by land cover but also by other parameters. Also, an attempt was made to understand the relationships between soil moisture in different layers within each of the selected land covers through correlation

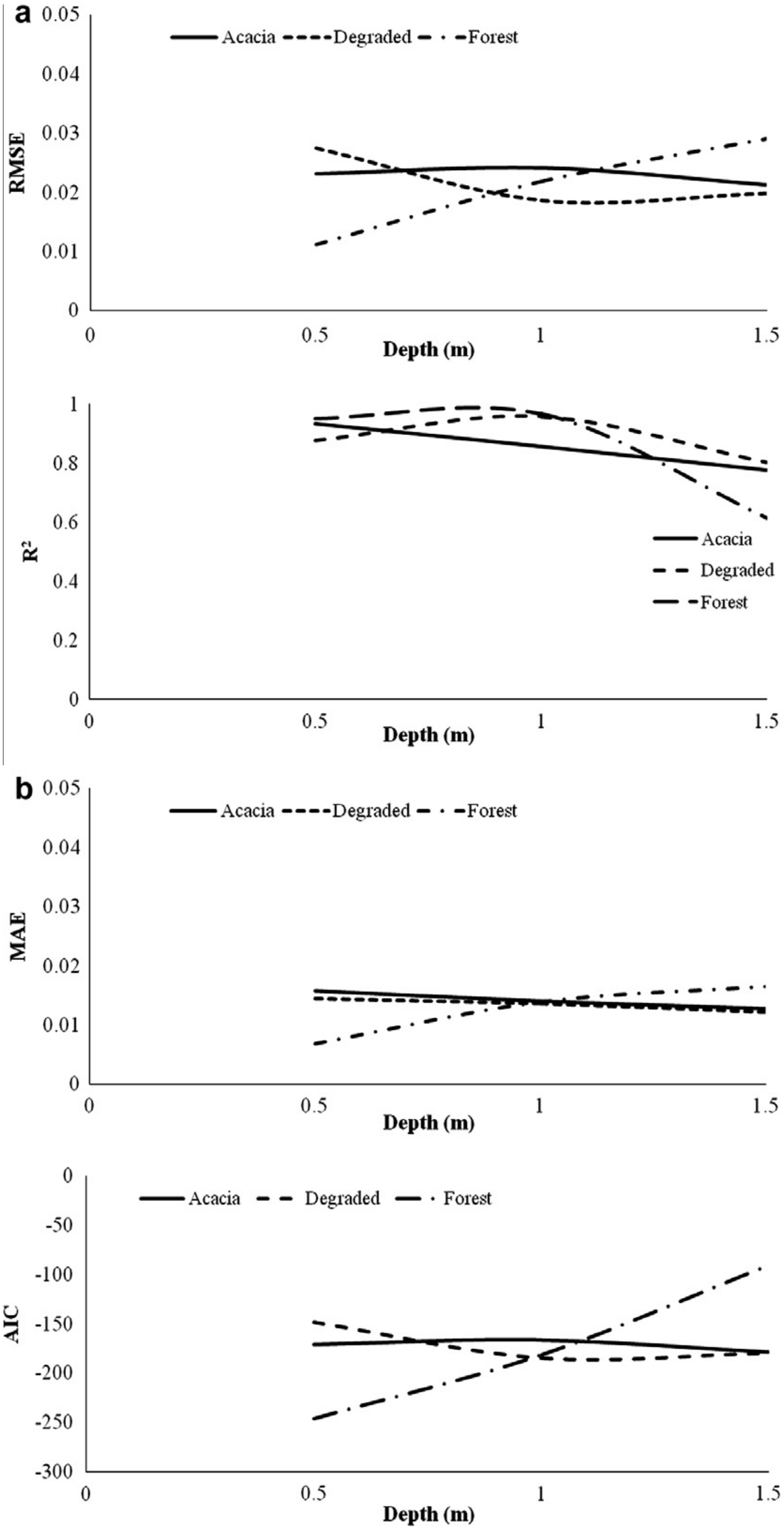

Fig. 9. Plot of performance indices used for validating the soil moisture prediction models.

analysis. The prominent finding of this analysis is the existence of strong correlation and cross correlation between soil moisture at different depths. The lag influence of rainfall on soil moisture was found only in the degraded watershed.

Multiple linear regression models were developed for prediction of soil moisture from climatic variables, antecedent moisture and moisture in the adjacent upper layer and found to perform reasonably well both in calibration and validation phases. A similar relationship was developed to predict profile mean moisture from climatic variables and near-surface soil moisture, which may prove useful in studies utilizing estimates of surface soil moisture from satellite remote sensing.

Based on overall results of this study, it can be concluded that the selected watersheds can be considered as hydrological responsive units with respect to soil moisture soil moisture variability since no significant spatial and temporal variations across different land covers was evident. These results may also prove useful in developing more physically realistic representations of the vadoze zone component in catchment-scale hydrological models.

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References

Asano, Y., Uchida, T., Ohte, N., 2002. Residence times and flow paths of water in steep un-channeled catchments, Tanakami, Japan. Journal of Hydrology 261, 173–192.

Bell, K.R., Blanchard, R.J., Schmugge, T.J., Witczak, M.W., 1980. Analysis of surface moisture variations within large field sites. Water Resource Research 16 (4), 796–810.

Bhat, D.M., Murali, K.S., Ravindranath, N.H., 2002. Comparison of Field Performance of Two Exotic Species: Acacia Auriculiformis and Cassia Siamea in Hilly and High Rainfall Zone of Uttara Kannada District, Western Ghats, Southern India, Technical Report No. 93, Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.

Bourgeon, G., 1989. Explanatory Booklet on the Reconnaissance of Soil Map of Forest Area: Western Karnataka and Goa, Instiut Francia de Pondichery, Pondicherry.

Brocca, L., Morbidelli, R., Melone, F., Moramarco, T., 2007. Soil moisture spatial variability in experimental areas of central Italy. Journal of Hydrology 333, 356–373.

Calder, I.R., Hall, R.L., Adlard, P.G., 1992. Growth and Water Use of Forest Plantations. John Wiley & Sons, Chichester, England. 381p..

Crave, A., Gascuel-odux, C., 1997. The influence of topography on the time and space distribution of soil surface water content. Hydrological Process 11, 203–210.

Famiglietti, J.S., Rudnicji, J.W., Rodell, M., 1998. Variability in surface moisture content along a hillslope transect: Rattlesnake Hill, Texas. Journal of Hydrology 210, 259–281.

Fernandez-Galvez, J., Simmonds, L.P., Barahona, E., 2006. Estimating detailed soil water profile records from point measurement. European Journal of Soil Science 57, 708–718.

Freer, J., Mc Donnel, J.J., Beven, K.J., Peter, N.E., Burnd, D.A., Hooper, R.P., Aulenbach, B., Kendall, C., 2004. Role of bedrock topography on subsurface storm flow. Water Resources Research 38, 1269.

Fu, B., Chen, L., 2000. Agricultural landscape spatial pattern analysis in the semi-arid hill area of the Loess Plateau, China. Journal of Arid Environments 44 (3), 291–303.

Fu, B., Wang, J., Chen, L., Qiu, Y., 2003. The effect of land use on soil moisture variation in the Danangou catchment of the Loess Plateau, China. Catena 54, 197–213.

Gadgil, M., 1987a. Depleting renewable resources: a case study from Karnataka Western Ghats. Indian Journal of Agricultural Economics 42, 376–387.

Gadgil, M., 1987b. An Operational Research Programme for Integrated Development of Microcatchments in Uttara Kannada District: A Proposal, Technical Report No. 49, Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.

Hodnett, M.G., Bell, J.P., 1986. Soil moisture investigation of groundwater recharge through black cotton soils in Madhya Pradesh, India. Hydrological Sciences Journal 31 (3), 361–381.

Jackson, T.J., 1993. III Measuring surface soil moisture using passive microwave remote sensing. Hydrological Processes 7, 139–152.

Jha, C.S., Dutt, C.B.S., Bawa, K.S., 2000. Deforestation and land use changes in Western Ghats, India. Current Science 79 (2), 231–238.

Kallarackal, J., Somen, C.K., 2008. Water loss from tree plantations in the tropics. Current Science 94 (2), 201–210.

Kamath, S.U. (Ed.), 1985. Karnataka State Gazetteer: Uttara Kannada District. Gazetter of India. (Government of Karnataka: Bangalore).

Kim, S., Lee, H., Woo, C., Nam, Kim, J., 2007. Soil moisture monitoring on a steep hillside. Hydrological Processes 21 (21), 2910–2922.

Kroner, C., Jahr, T., 2005. Hydrological experiments around the superconducting gravimeter at moxa observatory. Journal of Geodynamics 41 (1–3), 268–275.

Lélé, Sharachchandra, Hegde, Gurupada T., 1997. Potential herblayer production and grazing effects in anthropogenic savannahs in the moist tropical forests of the Western Ghats of India. Tropical Grasslands 31(6), 574–587.

Lele, S., 1993, Degradation, Sustainability, or Transformation: A Case Study of Villagers' Use of Forest Lands in the Malnaad Region of Uttara Kannada District, India'', Ph.D. Thesis, Energy & Resources Group, University of California, Berkeley.

Lin, H.S., Kogelmann, W., Walker, C., Bruns, M.A., 2006. Soil moisture patterns in a forested catchment: a hydropedological perspective. Geoderma 131, 345–368.

Longobardi, A., 2008. Observing soil moisture temporal variability under fluctuating climatic conditions. Hydrology and Earth System Science 5, 935–969.

Mahmood, R., Hubbard, K.G., 2007. Relationship between soil moisture of near surface and multiple depths of the root zone under heterogeneous land uses and varying hydro climatic condition. Hydrological Processes 21, 3449–3462.

Mani, A., 1985. Agrarian Technology and Eco-degradation of Betta Forests in Salkani Village in North Kanara district, Karnataka, Technical Report No. 1, Centre for Ecological Sciences. Indian Institute of Science, Bangalore, India.

Merz, B., Plate, E.J., 1997. An analysis of the effect of spatial variability of soil and soil moisture on runoff. Water Resources Research 33, 2909–2922.

Mishra, B.K., Hegde, M.S., Subramanian, D.K., Prasad, S.N., 1985. Studies in Village Ecosystems of North Kanara District of Karnataka, Technical Report No. 12, Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.

Montgomery, D.R., Dietrich, W.E., Torres, R., Anderson, S.P., Loague, K., 1997. Piezometric response of a small catchment. Water Resources Research 33, 91–110.

Moore, I.D., Burch, G.J., Mackenzie, D.H., 1988. Topographic effects on the distribution of surface soil water and the location of ephemeral gullies. Transactions of the American Society of Agriculture Engineering 31, 1098–1107.

Nadkarni, M.V., Pasha, S.A., Prabhakar, L.S., 1989. The Political Economy of Forest Use and Management. Sage Publications, New Delhi.

Nandagiri, L., Kovoor, G.M., 2006. Performance evaluation o reference evapotrasnpiration equations across a range of indian climates. Journal of Irrigation and Drainage Engineering, ASCE 132 (3), 238–249.

Pascal, J.P., 1986. Explanatory Booklet on the Forest Map of South India, Travaux de la Section Scientifique et Technique, Hors Série No. 18, French Institute, Pondicherry.

Pellenq, J., Kalma, J., Boulet, G., Wooldrudge, S., Kerr, Y., Chehbouni, A., 2003. A disaggregation scheme for soil moisture based on topography and soil depth. Journal of Hydrology 275, 112–127.

Prasad, S.N., Hegde, H.G., 1986. Community forest for the degraded, high rainfall tracts of peninsular India. International Tree Crops Journal 4, 57–67.

Prasad, S.N., Hegde, M.S., Gadgil, M., Hegde, K.M., 1985. An experiment in eco-development in Uttara Kannada district of Karnataka. South Asian Anthropologist 6 (1), 73–83.

Priya, D., Arjun, M., Pratjeesj, C.M., Carrigues, J.P., Puryavaud, J.P., Roessingh, Krista, 2007. Forest degradation in Western Ghats biodiversity hotspot, Resources collection, livelihood concerns and sustainability. Current Science 93 (11), 1573–1578.

Qiu, Y., Fu, B., Wang, J., Chen, L., 2001. Soil moisture variation in relation to topography and land use in a hillslope catchment of the loess plateau, China. Journal of Hydrology 240, 243–263.

Qiu, Y., Fu, B., Wang, J., Chen, L., 2003. Spatiotemporal prediction of soil moisture content using multiple-linear regression in a small catchment of the Loess Plateau, China. Catena 54, 173–195.

Rai, N.D., 2004. The Socio-economic and Ecological Impact of Garcinia gumm-gutta Fruit Harvest in the Western Ghats, India. Forest Products, Livelihoods and Conservation. Case Studies of Non-Timber Forest Product Systems. Volume 1-Asia. Edited by Koen Kusters and Brian Belcher. CIFOR, pp. 23:42.

Reddy, A.N.Y., Sarmah, D., Pande, P., Narvekar, G.B., Gouda, B. S., Yekanthappa, K., 1986. Integrated Approach for Eco-development of Uttara Kannada District, Office of the Conservator of Forests, Canara Circle, Karnataka Forest Department, Dharwad, Mimeo.

Rodriguez-Iturbe, I., 2000. Eco-hydrology: a hydrologic perspective of climate-soil-vegetation dynamics. Water Resources Research 36, 3–9.

Teuling, A.J., Uijlenhoet, R., Hupet, F., Van Loon, E.E., Troch, P.A., 2006. Estimating spatial mean root zone moisture from point scale observations. Hydrology Earth System Science 10, 755–767.

Uchida, T., Kosugi, K., Mizuyama, T., 2002. Effect of pipeflow and bedrock groundwater on runoff generation at a speed headwater catchment Ashiu, Central Japan. Water Resources Research 38 (7), 1119. doi:10.1029/2001WR000261.

Van Genuchtern, M.Th, 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.

Vandana, S., Bondhopadhdyay, J., 1983. Eucalyptus – a disastrous tree for India. Ecologist 13, 184–187.

Venkatesh, B., Lakshman Nandagiri, Purandara, B.K., Reddy, V.B., 2010. Variability of soil hydrologic characteristics under different land covers a case study from Sahayadri mountains, India. In: Proceedings of National Seminar on Sustainable Water Resources Management'', Organised by NITK, Surathkal, India, 7–9 Jan 2010.

Vischel, T., Pegram, G.G.S., Sinclair, S., Wagner, W., Bartsch, A., 2008. Comparison of soil moisture fields estimated by catchment modeling and remote sensing: a case study in South Africa. Hydrology Earth System Science 12, 751–767.

Western, A.W., Bloschl, G., 1999. On spatial scaling of soil moisture. Journal of Hydrology 217, 203–224.

Western, A.W., Grayson, R.B., Bloschl, G., Willgoose, G.R., McMohan, T.A., 1999. Observed spatial organization of soil moisture and its relation to terrain indices. Water Resources Research 35 (3), 797–810.

Wilson, D.J., Western, A.W., Grayson, R.B., 2005. A terrain and data based method for generating the spatial distribution of soil moisture. Advances in Water Resources 28, 43–54.

Zhou, G.Y., Morris, J.D., Yan, J.H., Yu, Z.Y., Peng, S.L., 2001. Hydrological impacts of reafforestation with eucalyptus and indigenous species: a case study in Southern China. Forest Ecology and Management 167 (1–3), 209–222.