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RESEARCH ARTICLE

SIMULATION OF SOIL MOISTURE AND RUNOFF GENERATION UNDER DIFFERENT LANDUSE CLASSES IN THE BRAHMAPUTRA BASIN

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ABSTRACT

An understanding of the soil moisture variability is indispensable to characterize the relation between a region's hydrology, ecology and hydropedology. The objectives of the present study were: (a) to understand spatio-temporal variability of soil moisture content under different land covers in the humid tropical Brahmaputra basin and (b) to characterize the differences in spatial and temporal patterns of soil moisture content and surface and subsurface runoff generation patterns influenced by different classes of landuse and land cover by application of the SWAP agrohydrological model. An experimental study site located in Amingaon, Kamrup district of Assam, India was selected for monitoring of profile averaged soil moisture. Four plots composed of homogenous land covers of broadleaved deciduous forest, shrubs and bamboo were selected with soil moisture monitoring facility. Hydrometeorological data mainly daily rainfall, maximum temperature, minimum temperature, relative humidity, solar radiation, wind-speed were monitored for two years from January 2011 to December, 2012. The SWAP model was calibrated from profile probe measurements for May 2011 to October 2011. The model simulations revealed that land use and land covers significantly influenced the moisture contents, surface and subsurface runoff .Undisturbed forest soils, having high degree of macroporosity, showed higher preferential flow and low runoff. However, paddy fields exhibited very high surface runoff due to lower infiltration owing to hard pan formation at a shallow depth. The subsurface drainage and soil moisture storage was moderate in paddy. Soils under Jhum cultivation showed significant numbers of active macropore in the upper soil layer, whereas the macropore connectivity was apparently lost in the lower horizons. Therefore surface runoff was very high. The subsurface drainage as well as the soil moisure storage was higher in jhum. In case of grasslands the higher unsaturated hydraulic conductivity favoured more infiltration of water causing higher subsurface flow and soil moisture storage. Less infiltration of rain water was observed in grasslands, where the surface initiated macropores were blocked by eroded fine soil particles causing higher surface runoff. In case of bamboo, the subsurface drainage as well as the soil moisture storage was high indicating higher preferential flow in the lower soil layers. The broadleaved deciduous forest soil thus generated high magnitudes of surface runoff due to its clayey soil. The subsurface drainage was high but the soil moisture storage was moderate. In tea-garden, surface runoff rate from the tea garden was moderately high. The subsurface drainage and soil moisture was also moderately high in forest under Jhum due to lower saturated hydraulic conductivity. In case of bamboo, the subsurface drainage as well as the soil moisture storage was high indicating higher preferential flow in the lower soil layers. The broadleaved deciduous forest soil thus generated high magnitudes of surface runoff. The subsurface drainage was high but the soil moisture storage was moderate. In case of shrubs and alpine shrubs, due to well developed macropore network, more percolation of water resulted in lesser surface runoff. The subsurface drainage and soil moisture was also moderately high. In case of needleleaved evergreen forest, subsurface flow was less and soil moisture storage was moderate. In case of broadleaved evergreen forest subsurface flow was very high but soil moisture storage was less. In case of croplands and plantation, obstructed macropore connectivity resulted in higher runoff. In case, of plantation, the subsurface drainage was high but soil moisture storage was moderate. In case of cropland, subsurface drainage was moderate but soil moisture storage was high.

INTRODUCTION

Soil moisture is the most significant parameter which controls the partitioning of rainfall into runoff and infiltration and therefore has an important impact on the runoff response of a catchment (Aubert *et al*., 2003). Soil moisture is one of the most critical variable to estimate because of its interaction with factors such as vegetation, soil and topography. Spatial and temporal variability of soil moisture has been attributed to factors such as precipitation and climate (Famiglietti *et al*., 1998), land-cover/vegetation (Venkatesh *et al*., 2011). Accurate estimation of spatial and temporal variations of soil moisture is indispensable for proper representation of the process-based hydrological modeling. Scanlon and Albertson (2003) developed a simple water balance model with a representation of climate–soil–vegetation interactions and the dynamic behaviour of vegetation in controlling the spatio–temporal patterns of water balance variability. Attempts have also been made to evaluate the influence of land cover on soil moisture predictions using water balance models (Federer, 2002). Therefore, the present study was taken up with the objective of understanding the spatio-temporal variability of soil moisture content, surface and subsurface runoff under different land covers in the experimental study site located in Amingaon, Kamrup District of Assam, India. Four plots composed of homogenous land covers of broadleaved deciduous forest, shrubs and bamboo were selected with soil moisture monitoring profile sites. The selection criteria of these plots were that, they fell within a homogeneous climatic region and possessed similar soil type and geology but differed only in the nature of land cover classes. The major objectives of the present study are: (a) quantification of spatio-temporal variability of soil moisture under different land covers by calibrating the SWAP model using long-term

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field based soil moisture observations (b) simulation of soil moisture storage, generation of runoff and subsurface drainage under different land cover classes.

Study area

The Brahmaputra basin lies in the north eastern part of India which abounds in diverse land cover classes. The landscapes are mainly dominated by vegetated hillslopes and floodplains of the rivers. The area receives very high amount of rainfall, which is largely concentrated in the monsoon season. Due to frequent occurrence of high intensity storm events, both the processes of rapid surface and subsurface runoff are evident in this region. The region falls in the Indo-Malayan biodiversity hotspot which comprises some of the rarest vegetation species on earth. Twelve major landcover classes were selected for the present study and detailed soil textural and structural properties of six replicate profiles under each landcover classes were analysed shown in Table 1.

The average areas of these selected plots are (300 sq m) These plots lie between 91˚41′E to 91˚42"E and 26˚11"N to 26˚12"N. The climate of the region may be divided into four principal seasons, namely, winter (December - February), pre-monsoon (March – April), monsoon (May –September), and retreating monsoon (October – November). The majority of rainfall in the study area (about 71 %) takes place during the period of May – August and the average annual precipitation for the region is 1717.7 mm. The maximum mean monthly rainfall is 353.6 mm, which occurs in July; with mean minimum monthly rainfall is 5.1 mm, which occurs in the month of December. The Intensity-Frequency-Duration curves of Guwahati) depict that for durations 15-60 minutes, high intensity storm events ranging from 150 -250 mm/hr are quite common in the study area during monsoons. An automatic weather station is established close to the shrub plot in the study area to monitor the hydro meteorological data mainly daily rainfall, maximum temperature, minimum temperature, relative humidity, wind-speed and solar radiation for two years from Jan 2011 to December, 2012.

Table 1. Soil Properties of the landcover plots

Profile-No	Depth (cm)	Colour	Texture			Bulk density (g/cm^3)	Organic content (%)	Ksat (cm/day)* Upper soil layer
			Sand	Silt	Clay			
Forest	0-30	10YR 5/6 M	66	18	16	1.28	2.1	24.33
	30-67	10YR 5/8 M	64.25	12.5	23.25	1.34	1.6	
	67-95	7.5 YR 6/8 M	63	14	23	1.33	1.7	
	95-195	7.5 YR 6/8 M	77.25	8.70	14.05	1.33	1.5	
Bamboo	0-22	5 YR 3/3 M	48	12	40	1.48	1.1	32.29
	22-54	5 YR 3/ 4 M	26.62	14.38	59	1.30	0.6	
	54-90	2.5 YR 3/6 M	36.23	13.77	50	1.40	0.3	
	90-120	2.5 YR 3/6 M	46.57	19.43	34	1.54	0.2	
Shrub	0-15	10 YR 4/3 M	52.5	29.3	18.2	1.42	1.8	19.27
	15-40	5YR 5/8 M	61.0	25.6	13.4	1.59	0.4	
	40-60	5 YR 5/8 M	71.5	21.3	7.3	1.55	0.6	
	60-75	5YR 5/8 M	69.5	22.0	8.5	1.55	0.6	

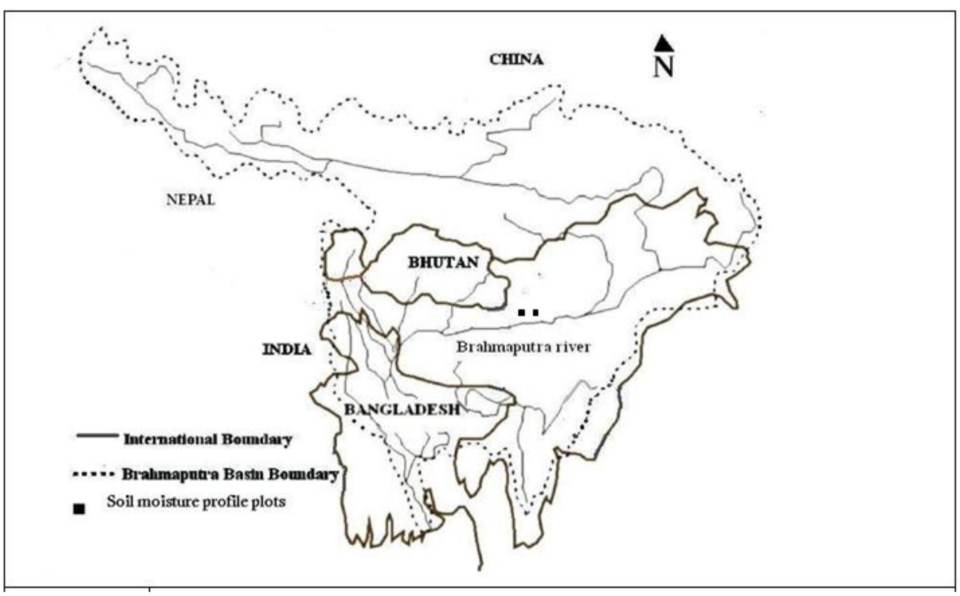

Fig. 1. Study area showing the soil moisture profile plots

Experimental plots

The experimental area selected for the study (Figure 1) are situated in Amingaon, Kamrup District of Assam, India. This study considers four plots, under broadleaved deciduous forest, bamboo and shrub.

Soil moisture measurements

To measure the spatio-temporal variation of soil moisture in the subsurface zone, Delta-T soil moisture profile probe was used for monitoring the soil moisture conditions of the soil moisture plots. The HH2 type moisture meter is a versatile unit for use with Delta–T moisture devices. The instrument is especially designed for quick measurements in field. It can give instantly the soil moisture data in volume basis (cm^3/cm^3) or millivolt (mV) and can store up to 1100 readings with multiple user defined soil types. The accuracy of the instrument is ± 3%. The instrument is calibrated for the three land-cover types. In the present investigations, soil moisture contents at 100, 200, 300, 400, and 1,000 mm from the ground surface were monitored at three different vegetative classes' viz., broadleaved deciduous forest, shrub and bamboo and under six profile sections.

METHODOLOGY

The Soil Water Atmosphere Plant (SWAP) agrohydrological model has been adapted as an ecohydrological in this study, to simulate vertical flow of water near the soil surface under transient conditions. The model includes crop growth, solute transport and heat flow. The variably saturated water flow in the soil matrix is based on the Richard's equation, including terms for root water uptake and macropore exchange:

$$\frac{d\Theta}{dt} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(1+\frac{dh}{dz}\right)\right]}{\partial z} - Sa\,(h) - Sm(h)$$

where Θ is soil moisture content (-), t is time (T), h is soil water pressure head (L), C(h) is the differential soil moisture capacity (L^{-1}), K(h) is the hydraulic conductivity (LT^{-1}), *z* is the vertical coordinate, positive upward (L), S_a is the sink term for the root water uptake (T^{-1}) and S_m is the macropore exchange term. The top-boundary conditions are determined by precipitation, irrigation and evapotranspiration. Potential evapotranspiration is calculated with the Penman-Monteith equation using daily meteorological data: total radiation, maximum and minimum temperature, humidity and wind speed and daily rainfall depth (mm). The bottom boundary conditions in SWAP include pressure head, soil water flux, free drainage and seepage face. The applied SWAP version has a detailed concept for modeling macropore flow through cracks and/or bio-pores which has been parameterized from dye-tracer experiments. For a more detailed description Kroes *et al*. (2008) may be referred.

Model Calibration Using Field Data

The SWAP model was applied using a daily time step .As stated earlier, observed depth-wise soil moisture content data at daily time step was available from May 2011 to December 2012. Data from May 2011 to October 2011 was used for calibrating the model. At each sampling point, depth-averaged soil moisture measurements were integrated over the 1.0 m depth using the following equation:

$$\Theta\, i = \frac{1}{\sum D_i}\left(\sum D_i \;*\; \sum \Theta_i\right)$$

where θ_i is the soil moisture content of profiles at layer i and depth D_i taken at each of the profiles. Field data of depth wise soil particle size distribution, textural and structural properties, pH, organic carbon content, etc. were analysed using standard procedures. Using the data of particle size distribution, organic carbon content, and degree of compaction, soil bulk density was determined from the Soil Water Characteristics Model developed by the Agricultural Research Services of United States Department of Agriculture (USDA). Soil retention curves were derived from the soil moisture data taken at 100 mm interval in the soil profiles to define the soil water versus hydraulic potential at each soil layer as shown in Fig. 2.

Model calibration results

The SWAP model calibration result is shown in Fig. 3. The model predicts the soil moisture variation adequately for the calibration period. The Nash Sutcliffe efficiency for broadleaved deciduous forest (BDF), bamboo and shrub are 0.9, 0.75 and 0.80 respectively. It can be seen that forest simulation performs better than bamboo and shrub. It could be due to higher bulk density of the upper soil surface in bamboo and shrub compared to forest. The retention curve in bamboo and shrub reports higher suction potential compared to forest indicating higher losses due to evapotranspiration.

RESULTS AND DISCUSSION

The model being calibrated is used to understand the soil moisture variability, subsurface drainage and surface runoff for all the land-use classes for two water years 2011 and 2012 as shown in Table 3. The year 2011 with annual rainfall rainfall of 1470 mm, was a normal year with few rainfall events in the month of August and September. However, the year 2012 with a annual rainfall of 2120 mm was a wet year with many significant rainfall events scattered over May to October. The rates of surface runoff were explained with the structural, textural as well as the hydraulic properties of soil.

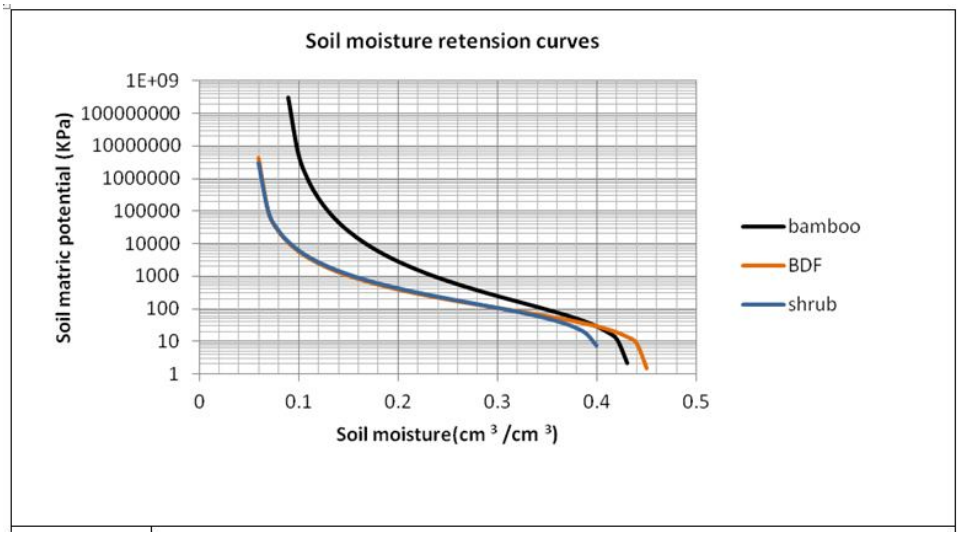

Fig. 2. Soil moisture retention curves for SWAP calibration

In paddy fields, due to a hard pan layer at a shallow depth from the ground, deep percolation of the infiltrated water is prevented. Therefore, the water flow was confined in the upper soil layer only. The hard pan layer of the paddy fields has lower hydraulic conductivity and repeated puddling activity also destroys most of the soil macropores. Consequently, resulting in high surface runoff rate from the paddy field. Similar studies have been reported in literature

(Mishra *et al*., 2008). The subsurface drainage and soil moisture storage is moderate in paddy.

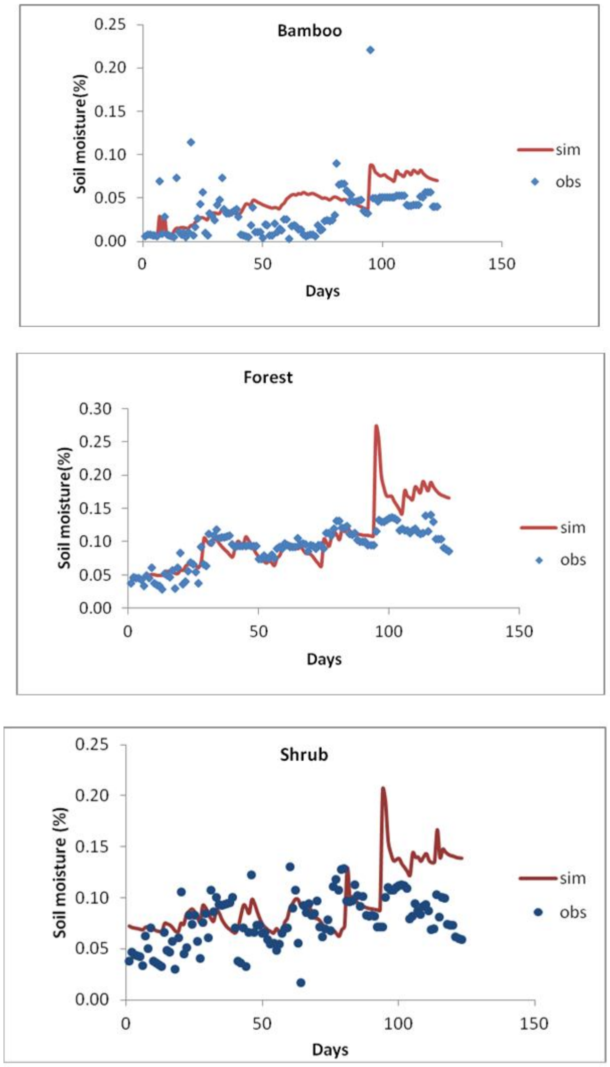

Fig. 3. Calibration of SWAP soil moisture with observed profile probe measurements*Days from 1May-31 October, 2011

Soil under tea-garden, has macropore connectivity only in the surface therefore, the infiltration rate through the soil macropores is low in the deeper zones. Consequently, the surface runoff rate from the tea garden is moderately high. The subsurface drainage and soil moisture is also moderately high. The collected soil data indicated that the textural class of the grassland soil was silty clay, which had lower infiltration rates. The soil was eroded in patches and the eroded fine particles (silt) might seal the surface initiated soil macropores. This might largely affect the soil infiltrability. The shallow rooting depths of the grasses are also responsible for lesser depths of water penetration in soil.

As a result, lower infiltration rate and higher surface runoff rate are evident from the grassland soil. In case of grasslands the higher unsaturated hydraulic conductivity favours more infiltration of water causing higher subsurface flow and soil moisture storage. Due to shifting cultivation the naturally developed macropore network in soil gets disturbed. After the land is abandoned, the topsoil slowly regains its macroporosity as the forest vegetation starts to grow back. But, it usually takes a very long time to establish the macropore connectivity between the upper and lower soil layers. In Jhum cultivated land a discontinuity between the upper and lower horizon macropores are often reported (Shougrakpam *et al*, 2010).Therefore, in forest under Jhum due to lower saturated hydraulic conductivity, increase surface runoff is very high. The subsurface drainage as well as the soil moisure storage is higher in jhum. Due to typical rooting characteristics of bamboo, the macropore network connectivity of forest with bamboo is high. Due to higher soil suction in the upper layer, hydraulic conductivity of bamboo is high resulting in lower runoff rates. In case of bamboo, the subsurface drainage as well as the soil moisture storage is high indicating higher preferential flow in the lower soil layers. In the broadleaved deciduous forest soil, the hydraulic conductivity through the of the clay loam soil profile is low. Consequently, the depths of water penetration and infiltration rates were less. The broadleaved deciduous forest soil thus generated high magnitudes of surface runoff. The subsurface drainage is high but the soil moisture storage is moderate. In case of shrubs and alpine shrubs, due to well developed macropore network, more percolation of water resulted in lesser surface runoff. The subsurface drainage and soil moisture is also moderately high.

In case of Broadleaved evergreen forest and needleleaved forest, highly active macroporosity of undisturbed soils were due to the presence of well developed root network and activity of soil fauna like earthworm, moles, ants, and rodents.

Table 3. Simulated soil water balance component for selected land covers

	Landcovers	Rainfall (mm)	Surface runoff (mm)	Subsurface drainage (mm)	Soil moisture (%)
	Paddy		100.3	103.9	31.2
	Tea		96.0	193.5	35.3
	BDF		111.9	206.8	33.7
	Shrub		55.8	186.6	37.8
	Plantation		123.5	193.6	34.4
	Bamboo		36.3	197.3	38.3
	BEF	1470	107.3	224.4	32.0
	NEF		138.9	83.3	33.8
	Grassland		146.8	207.7	36.1
	Jhum		204.8	171.8	38.5
	Alpine-shrub		53.9	142.6	41.9
2011	Croplnd		237.0	148.8	38.0
	Paddy		233.1	294.8	27.3
	Tea		271.7	446.0	26.0
	BDF		271.7	479.4	13.2
	Shrub		110.5	450.9	16.2
	Plantation	2120	245.2	451.9	17.4
	Bamboo		174.8	431.1	26.4
	BEF		126.2	563.8	12.9
	NEF		260.6	137.4	1.2
	Grassland		255.3	508.1	21.1
	Jhum		409.0	417.8	30.2
	Alpine-shrub		268.5	353.3	21.1
2012	Croplnd		465.7	370.6	29.0

The sandy loam soil was also conducive to rapid water movement through the soil matrix. Therefore, soils under these two land covers showed very high infiltration rates and low surface runoff compared to broadleaved deciduous forest. In case of needle leaved evergreen forest, subsurface flow is less and soil moisture storage is moderate. In case of broadleaved evergreen forest subsurface flow is very high but soil moisture storage is less. In case of croplands and plantation, human agronomic interventions related to depletion of macropore connectivity and hence only resulted in higher runoff. In case, of plantation, the subsurface drainage is high but soil moisture storage is moderate. In case of cropland, subsurface drainage is moderate but soil moisture storage is high.

Conclusions

The objectives of the present study were: (a) to understand spatio-temporal variability of soil moisture content under different land covers in the humid tropical Brahmaputra basin and (b) to characterize the differences in spatial and temporal patterns of soil moisture content and surface and subsurface runoff generation patterns influenced by different classes of landuse and land cover by application of the SWAP agrohydrological model. An experimental study site located in Amingaon, Kamrup district of Assam, India was selected for monitoring of profile averaged soil moisture. The calibration. The model predicts the soil moisture variation adequately for the calibration period. The Nash Sutcliffe efficiency for broadleaved deciduous forest, bamboo and shrub are 0.9, 0.75 and 0.80 respectively. It can be seen that forest simulation performs better than bamboo and shrub. It could be due to higher bulk density of the upper soil surface in bamboo and shrub compared to forest. Undisturbed forest soils, having high degree of macroporosity, showed higher preferential flow and low runoff. However, paddy fields exhibited very high surface runoff due to lower infiltration owing to hard pan formation at a shallow depth. The subsurface drainage and soil moisture storage is moderate in paddy. Soils under Jhum cultivation showed significant numbers of active macropore in the upper soil layer, whereas the macropore connectivity was apparently lost in the lower horizons. Therefore surface runoff is very high. The subsurface drainage as well as the soil moisure storage is higher in jhum.

In case of grasslands the higher unsaturated hydraulic conductivity favours more infiltration of water causing higher subsurface flow and soil moisture storage. Less infiltration of rain water was observed in grasslands, where the surface initiated macropores were blocked by eroded fine soil particles causing higher surface runoff. In case of bamboo, the subsurface drainage as well as the soil moisture storage is high indicating higher preferential flow in the lower soil layers. The broadleaved deciduous forest soil thus generated high magnitudes of surface runoff due to its clayey soil. The subsurface drainage is also high but the soil moisture storage is moderate. In tea-garden, surface runoff rate from the tea garden is moderately high. The subsurface drainage and soil moisture is also moderately high. In forest under Jhum, due to lower saturated hydraulic conductivity. In case of bamboo, the subsurface drainage as well as the soil moisture storage is high indicating higher preferential flow in the lower soil layers. The broadleaved deciduous forest soil thus generated high magnitudes of surface runoff. The subsurface drainage is high but the soil moisture storage is moderate. In case of shrubs and alpine shrubs, due to well developed macropore network, more percolation of water resulted in lesser surface runoff. The subsurface drainage and soil moisture is also moderately high. In case of needleleaved evergreen forest, subsurface flow is less and soil moisture storage is moderate. In case of broadleaved evergreen forest subsurface flow is very high but soil moisture storage is less. In case of croplands and plantation, of macropore connectivity and hence only resulted in higher runoff. In case, of plantation, the subsurface drainage is high but soil moisture storage is moderate. In case of cropland, subsurface drainage is moderate but soil moisture storage is high.

This study is a pioneering attempt to apply the SWAP model to generate soil water balance components for such a ewide variety of landuse asnd landcover classes underscoring the significance of preferential flow processes as well as ecohydrological parameters to adequately simulate the water-balance processes.

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