Run-off generation from fields with different land use and land covers under extreme storm events

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Land use and land covers (LULC) are known to influence hydrological processes like infiltration and run-off generation from the watersheds. We report here the effects of some common LULC types on run-off generation in North East India. LULC were found to be closely related to soil macroporosity and the resulting infiltration and surface run-off generation capacities under varying high-intensity rainfall events. The MACRO 5.0 model was used to simulate water transport through soils in both macropore and micropore domains. The model simulations revealed that LULC significantly influenced the moisture content and water flow rate in both the domains. Undisturbed forest soils, having a high degree of macroporosity, showed higher preferential flow and low run-off. However, paddy fields exhibited very high surface run-off due to lower infiltration owing to hard pan formation at a shallow depth. Soils under *jhum* cultivation showed significant number of active macropores in the upper soil layer, whereas the macropore connectivity was apparently lost in the lower horizons. Less infiltration of rainwater was observed in the grasslands, where the surface-initiated macropores were blocked by eroded, fine soil particles. Under extreme storm events, rainfall characteristics primarily controlled the run-off generation processes as the intake capacity of the soil macropores was exceeded.

Keywords: Land use and land cover, run-off generation, infiltration, extreme storm events.

THE physical properties of soil depend on several factors like structure, texture, organic matter content, bulk density, activity of soil fauna, climate and land use and land covers (LULC). The dominance of macropores or micropores in the soil profile is closely associated with the existing LULC[1]. Soil macropores are known to affect several hydrological processes like infiltration, run-off generation, subsurface stormflow, flash floods, landslides and subsurface erosion[2–6]. Low capillary potential and high hydraulic conductivity enable the macropores as an effective medium for rapid water transport, which may be equivalent to overland flow rate[7]. The presence of highly active macropores in the soils of headwater catchments, often results in devastating flash floods in rivers. Therefore, it is important to understand the physical process of water infiltration and movement through soils for better formulation and evaluation of process-based rainfall–run-off models. In this context, the requirement of detailed and accurate soil data is well understood[1]. The information on soil macroporosity should help to better predict and explain the process of subsurface stormflow and its consequences[6,7].

Soil macropores are highly dynamic in nature and thus show wide spatial and temporal variations. The effect of tillage, pore continuity, LULC, rainfall intensity, antecedent moisture conditions and soil profile formations are closely related to macropore flow rate[1,6–11]. In macropore-dominated soils, where a large amount of infiltrated water by-passes the soil matrix, the concept of average hydraulic conductivity for a homogeneous soil mass cannot be applied[12]. In such cases Darcy's principle often fails to describe the infiltration process[13–16]. Therefore, a two-domain modelling concept, with Darcian flow in the soil matrix domain and kinematic wave flow in the macropore domain, was introduced[17].

Physical properties of soil, climate and soil fauna can also influence the macroporosity of the soil. Mere presence of a large number of macropores in the soil does not guarantee high subsurface run-off generation. The hydraulic effectiveness of soil macropores rather depends on pore size, pore structure, depth distribution, network and connectivity in both lateral and vertical directions, and their seasonal dynamics as well[5]. Macropore connectivity is an important parameter for rapid preferential transport of water and solutes. Vegetation and its root network are known to have a significant effect in creating new flow paths as well as in establishing the connectivity between the existing soil macropores to make them hydrologically active[5,18–20]. Therefore, a strong correlation between the vegetation density and preferential flow rate could be observed[21]. As vegetation dynamics is primarily influenced by the existing LULC, it is considered to be a critical parameter in both surface and subsurface run-off generation processes[1,22–26].

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Table 1. Description of the study areas under different land use and land covers (LULC) types

LULC no.	Geographic location	Elevation (m amsl)	LULC type
1	Balipara, Sonitpur, Assam Lat.: 26°49′32″N Long.: 92°43′0″E	50–70	Paddy field
2	Mathurapura Tea Estate, Sonari, Sibsagar, Assam Lat.: 26°58′14″N Long.: 94°54′11″E	110	Tea garden
3	Kalachand, North Cachar Hills, Assam Lat.: 25°19′0″N Long.: 93°13′0″E	250	Grassland
4	Disai Valley, Mariani, Jorhat, Assam Lat.: 26°35′57″N Long.: 94°20′53″E	180–250	Forest under *jhum* cultivation
5	Silonijan, Karbi Anglong, Assam Lat.: 26°18′0″N Long.: 93°47′30″E	180–250	Forest with bamboo plantation
6	Buramayang, Morigaon, Assam Lat.: 26°14′42″N Long.: 92°47′0″E	120	Moderately dense forest
7	Malita, Mirza, Kamrup, Assam Lat.: 26°5′12″N Long.: 91°32′51″E	250–350	Sparse forest
8	Disai Valley Reserve Forest, Mariani, Jorhat, Assam Lat.: 26°35′32″N Long.: 94°21′11″E	250–450	Mixed forest

The objective of the present study is to study the effect of LULC on active soil macroporosity and the subsequent run-off response in subtropical hilly areas under varying high-intensity storm events. The data of soil macroporosity and existing LULC were collected for different locations of North East (NE) India. The surface and subsurface water flow in soils under these LULC types were simulated using the MACRO-5.0 model[27]. The model has been calibrated and used widely for simulating solute and water transport processes in macroporous soils with good accuracy[28–31]. The simulation results under different high-intensity rainfall events were analysed to compare the run-off generation potential of different soils under varying LULC types and macropore structures.

Study area

North East India has diverse LULC types. The landscapes are mainly dominated by vegetated hillslopes and floodplains of rivers. In general, the area receives very high amount of rainfall, which is largely concentrated during monsoon season. Due to frequent occurrence of high-intensity storm events, both the processes of rapid surface and subsurface run-off are evident in this region. To represent the diverse LULC types of the area, eight different locations having distinct LULC features were selected (Table 1). Detailed soil textural and structural properties of these locations were collected[32].

The MACRO-5.0 model

MACRO is a one-dimensional model that considers non-steady flow of water and solutes in the soil. The model uses a two-domain concept with different porosities for the micropore and macropore domains. It considers a first-order equation for the interaction between the two domains. There are provisions of defining different values of hydraulic conductivity, flow rate, degree of saturation, solute concentration and solute flux density for both the domains. Simulations can be done for the complete water balance, including precipitation, evapotranspiration, root water uptake, seepage and drainage. The model can be used to simulate the processes either in one (micropore) or two domains (both micropore and macropore). It can also be used to compute the surface and subsurface flow generation capacity of a given soil defined by its microporosity and macroporosity. The model has in-built tools for a quick statistical and/or graphical comparison of the simulation results with the measured data.

Model parameterization using field data

Field data of depth-wise soil particle size distribution, textural and structural properties, pH, organic carbon content, etc. were collected from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP)[32], Nagpur for the selected locations. Useful information

Table 2. Basic soil data for the sites under different LULC types

LULC types	Soil depth (cm)	Dominating soil textural class	Average bulk density (g/cm^3)	Average saturated profile permeability (cm/day)	Soil structure	Macropore structure
Paddy field (LULC 1)	100	Clay loam	1.51	6.90	Medium blocky	Top layer macropores destroyed by puddling
Tea garden (LULC 2)	100	Sandy clay loam	1.57	8.60	Medium blocky	Deep root-induced macropores
Grassland (LULC 3)	100	Silty clay	1.27	15.97	Medium granular to blocky	Shallow macropores with surface sealing
Forest under *jhum* cultivation (LULC 4)	100	Clay loam	1.54	8.20	Medium blocky	Discontinued lower horizon macropores
Forest with bamboo plantation (LULC 5)	100	Clay	1.46	10.25	Coarse to medium blocky	Moderately active network
Moderately dense forest (LULC 6)	48	Clay loam	1.54	7.28	Fine to medium blocky	Macropore network is not well connected
Sparse forest (LULC 7)	70	Sandy loam	1.58	19.82	Medium granular	Active network
Mixed forest (LULC 8)	73	Sandy loam	1.49	62.36	Medium granular to blocky	Highly active network

Table 3. Initial volumetric moisture content values for different LULC types

LULC type	Initial volumetric moisture content (%)
Paddy field (LULC 1)	10
Tea garden (LULC 2)	10
Grassland (LULC 3)	16
Forest under *jhum* cultivation (LULC 4)	10
Forest with bamboo plantation (LULC 5)	15
Moderately dense forest (LULC 6)	10
Sparse forest (LULC 7)	12
Mixed forest (LULC 8)	03

about the soil structures was also collected from the selected sites. 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 the United States Department of Agriculture (USDA). Table 2 enumerates some important soil parameters collected from the study area. User-defined soil physical properties were used to define the initially dry soil moisture condition and the lower boundary condition was defined by the pressure potential. A bare soil with water flow only was considered for the simulations under different conditions. The objective was to study the infiltration and run-off generation characteristics of initially dry soils under prolonged high-intensity rainfall events. Depending upon the existing soil properties under different LULC types, the dry antecedent volumetric water content of the soils was initialized by the model (Table 3). Soil physical parameters like saturated, boundary and residual water contents, van Genuchten's *N*, saturated hydraulic conductivity, boundary hydraulic conductivity, effective diffusion path length and van Genuchten's alpha were computed using the in-built pedotransfer function of the MACRO-5.0 model.

Site-specific data like rainfall, minimum and maximum temperatures and potential evapotranspiration for July were obtained from the website www.indiawaterportal.org. The average climatic data for July (Table 4) were computed from the weather data of 12 years (1991–2002). These data were required as input parameters to the MACRO-5.0 model.

Model simulation results

The model was simulated with rainfall intensities 100, 150, 200 and 250 mm/h for each type of LULC. The simulation results showed that the soil micropore and macropore moisture contents were not affected significantly by the rainfall intensities for a particular LULC type (Table 5). Under different rainfall intensities the variations in the maximum micropore and macropore moisture contents were within 1% and 0.35% respectively, for any given LULC type. Soil macropore moisture contents were less due to low capillary potential of the larger diameter pores[5]. The maximum depths of water penetration were found to be affected by LULC and rainfall intensity. In general, higher rainfall intensities caused

Table 4. Meteorological data for July based on 12-year average (1991–2002)

LULC type	Location (district)	Minimum temperature (°C)	Maximum temperature (°C)	Potential evapotranspiration (mm/day)
Paddy field (LULC 1)	Sonitpur	24.76	31.691	5.55
Tea garden (LULC 2)	Sibsagar	23.47	30.362	5.31
Grassland (LULC 3)	North Cachar Hills	22.73	28.96	5.07
Forest under *jhum* cultivation (LULC 4)	Jorhat	23.87	30.70	5.44
Forest with bamboo plantation (LULC 5)	Karbi Anglong	21.79	28.15	5.11
Moderately dense forest (LULC 6)	Morigaon	21.68	27.23	5.06
Sparse forest (LULC 7)	Kamrup	22.44	28.58	5.09
Mixed forest (LULC 8)	Jorhat	23.87	30.70	5.44

Source: www.indiawaterportal.org

Table 5. Range of maximum values of micropore and macropore moisture content, depth of water penetration, and infiltration rate under varying simulated rainfall intensities (100–250 mm/h) for different LULC types

	Maximum values under rainfall intensities 100, 150, 200 and 250 mm/h					
	Moisture content (%)		Depth of water penetration (cm)		Infiltration rate (mm/h)	
LULC type	Micropore	Macropore	Micropore	Macropore	Micropore	Macropore
Paddy field (LULC 1)	37.0 ± 1	3.0 ± 0.01	29.0 ± 1	20.5 ± 0.5	38.0 ± 1	55.0 ± 1
Tea garden (LULC 2)	35.5 ± 0.5	3.55 ± 0.05	45.0 ± 5	38.0 ± 1	55.0 ± 13	90.0 ± 1
Grassland (LULC 3)	47.5 ± 0.5	2.75 ± 0.05	21.0 ± 1	16.5 ± 1.5	25.5 ± 0.5	32.0 ± 1
Forest under *jhum* cultivation (LULC 4)	37.5 ± 0.5	5.5 ± 0.01	45.0 ± 5	35.0 ± 5	57.5 ± 22.5	115.5 ± 44.5
Forest with bamboo plantation (LULC 5)	42.5 ± 0.5	4.0 ± 0.01	45.0 ± 5	33.5 ± 1.5	25.5 ± 7.5	84.0 ± 9
Moderately dense forest (LULC 6)	37.5 ± 0.5	3.55 ± 0.05	31.5 ± 0.5	19.0 ± 1	27.5 ± 0.5	47.0 ± 1
Sparse forest (LULC 7)	35.5 ± 0.5	5.25 ± 0.25	57.5 ± 2.5	36.0 ± 4	52.5 ± 17.5	117.0 ± 27
Mixed forest (LULC 8)	35.5 ± 0.5	5.15 ± 0.35	52.5 ± 2.5	34.5 ± 5.5	70.0 ± 20	110.0 ± 15

deeper penetration of water front. In paddy field (LULC 1), grassland (LULC 3) and moderately dense forest (LULC 6) soils, the depths of water penetration were comparatively less both in the micropore and macropore domains. However, in tea garden (LULC 2), forest under *jhum* cultivation (LULC 4), forest with bamboo plantation (LULC 5), sparse forest (LULC 7) and mixed forest (LULC 8) soils, relatively higher depths of penetration of rainfall water was evident. Particularly in LULC 7 and LULC 8 soils, the depths of water penetration were found to be very high (Table 5).

Water infiltration rates through soil micropores and macropores were also studied through model simulations (Table 5). In general, the infiltration rates through the soil macropores were higher due to their higher conductance. Infiltration rates through soil micropores and macropores were low in soils under paddy field, grassland and moderately dense forest. It was also observed that the infiltration rates under these LULC types were less affected by the variations in rainfall intensity. Peak infiltration rates through soil micropores were 39, 26 and 28 mm/h under LULC 1, LULC 3 and LULC 6 respectively. Similarly, peak infiltration rates through soil macropores were 56, 33 and 48 mm/h for LULC 1, LULC 3 and LULC 6 respectively. In tea garden (LULC 2) soil, peak infiltration rate through micropores increased from 42 to 68 mm/h with increasing rainfall intensity, whereas peak macropore infiltration rate was 91 mm/h. The effect of *jhum* cultivation on soil infiltration rate was also evident from the results. Peak infiltration rate through macropores in forest under *jhum* cultivation (LULC 4) increased from 93 to 160 mm/h as rainfall intensity increased from 100 to 250 mm/h. The peak infiltration rate through micropores reduced from 80 to 35 mm/h with increase in rainfall intensity from 100 to 250 mm/h. The soil of forest with bamboo plantation (LULC 5) showed moderately low peak infiltration rate (33 mm/h) in micropore domain and medium peak infiltration rate through the macropores (93 mm/h). It was also observed that the peak macropore infiltration rate increased from 75 to 93 mm/h with the increase in rainfall intensity. In sparse forest (LULC 7) soil, peak infiltration rate through micropores reduced from 70 to 35 mm/h with increasing intensity of rainfall. Peak flow rate in macropore domain was above 90 mm/h for all the rainfall intensities. In mixed forest (LULC 8) soil as rainfall intensity increased from 100 to 150 mm/h, peak infiltration rate through the micropore increased from 50 to 90 mm/h, but at the rainfall intensity of 200 mm/h the rate was reduced to 60 mm/h and remained constant at the higher intensity of 250 mm/h. At

Table 6. Peak surface run-off rates under different rainfall intensities

LULC type	Peak surface run-off rate (mm/h) at rainfall intensity (mm/h)			
	100	150	200	250
Paddy field (LULC 1)	62	112	162	212
Tea garden (LULC 2)	17	57	118	168
Grassland (LULC 3)	68	118	168	218
Forest under *jhum* cultivation (LULC 4)	56	106	156	206
Forest with bamboo plantation (LULC 5)	67	121	170	223
Moderately dense forest (LULC 6)	51	101	151	201
Sparse forest (LULC 7)	12	63	112	163
Mixed forest (LULC 8)	0	21	71	121

100 mm/h rainfall intensity, peak macropore flow rate was found to be 95 mm/h. It increased to about 125 mm/h at rainfall intensity of 150 mm/h and then remained constant at higher rainfall intensities. Clearly, in LULC 4, LULC 5, LULC 7 and LULC 8, the macropore and micropore infiltration rates were found to be highly erratic. This may be attributed to the irregular geometry of soil structures and complex processes of macropore flow initiation and interaction in and between the two domains[33].

Infiltration is the key process which determines the quantity of rainfall that occurs as surface run-off. The surface run-off generated from the soils under different LULC types was due to the combined effect of soil micropore and macropore infiltration rates under varying rainfall intensities. The magnitude of the peak surface run-off generated increased with the increase in rainfall intensity for most of the LULC types (Table 6). Very high surface run-off was evident in paddy field, grassland and moderately dense forest. In tea garden, sparse forest and mixed forest run-off generation was comparatively lower. In forest under *jhum* cultivation and forest with bamboo plantation, the run-off generation was less at lower rainfall intensities. As rainfall intensity increased, the intensity of surface run-off also increased. It was also observed that for mixed forest soil no surface run-off was evident at 100 mm/h rainfall intensity. Even at 150 mm/h rainfall intensity, the peak surface run-off rate was only 21 mm/h (Table 6).

Discussion of results

In paddy field (LULC 1) soil, a hard pan layer is usually formed at a shallow depth from the ground surface due to puddling operation. Such a hard pan layer prevented deep percolation of the infiltrated water. 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, the infiltration rates through both soil micropores and macropores were found to be less. This also resulted in high surface run-off rate from the paddy field. It is worth mentioning here that in the present study the routing of surface run-off has not been considered. Therefore, the effects of surface topography and land forming (e.g. bunds) on surface run-off have not been evaluated. The infiltration excess flow has been taken as surface run-off rate. However, in bunded paddy fields threshold behaviour of run-off generation is evident. No run-off is produced in response of rainfall till the infiltration excess water stored in the basin reaches the bund height. After that, the run-off rate is almost equivalent to rainfall intensity. Similar hydrological response of paddy fields is well reported in the literature[34].

Soil under tea garden (LULC 2) had deep and well-developed root network, which enhanced the macropore connectivity. Therefore, the infiltration rate through the soil macropores was high. The peak infiltration capacity of the macropores was about 90 mm/h. The infiltration rate through the micropores increased with increasing rainfall intensity as the intake capacity of the macropores was exceeded and a higher infiltration head was developed. Consequently, the surface run-off rate from the tea garden was moderately low.

The collected soil data indicated that the textural class of the grassland soil (LULC 3) was silty clay, which had lower infiltration rate. The soil was eroded in patches and the eroded fine particles (silt) might seal the surface-initiated soil macropores[35,36]. This might have largely affected the macropore connectivity in the soil profile. The shallow rooting depths of the grasses were also responsible for lesser depths of water penetration in the soil. As a result, lower infiltration rate and higher surface run-off rate were evident from the grassland soil.

Due to shifting cultivation, the naturally developed macropore network in the 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 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 is often reported[1]. Therefore, in forest under *jhum* cultivation (LULC 4), the infiltrated water took about 45 min to reach the lower soil

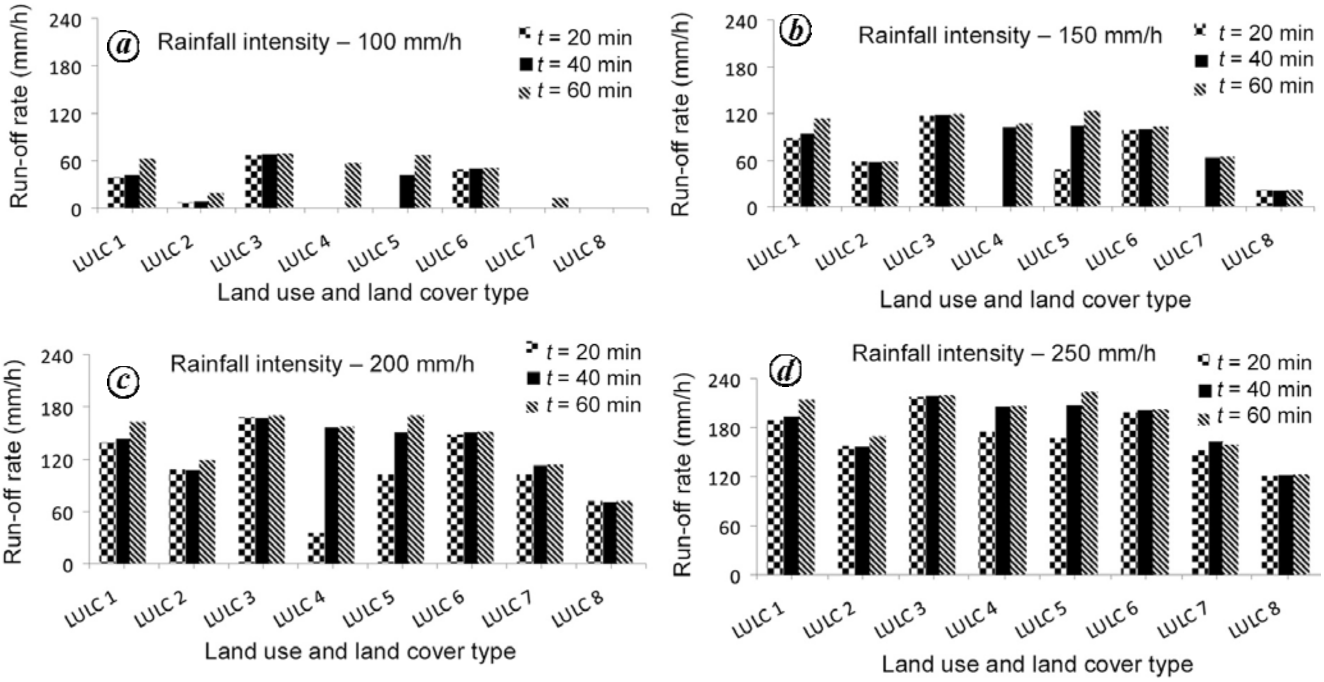

Figure 1 *a–d*. Ordinates of surface run-off hydrographs under different rainfall intensities for different land use and land cover types.

layer and thereafter the infiltration rate reduced drastically to increase surface run-off. Consequently, a time lag between the start of rainfall event and high surface run-off generation was evident.

Due to typical rooting characteristics of bamboo plantation, the macropore network connectivity of forest with bamboo plantation (LULC 5) was moderate. Similar to the shifting cultivation, human interferences affected the macropore structure of the soil. Therefore, at lower rainfall intensities run-off generation was less and at higher intensities surface run-off rates increased.

In the moderately dense forest (LULC 6) soil, a well-developed soil macropore network was not present and also the hydraulic conductivity through the micropores of the clay loam soil profile was low. Consequently, the depths of water penetration and infiltration rates were less. The moderately dense forest soil thus generated high magnitudes of surface run-off.

In both sparse forest (LULC 7) and mixed forest (LULC 8) lands, macropore flow was more prominent to result in higher infiltration rate and very low surface run-off. Highly active macroporosity of undisturbed forest soils was due to the presence of well-developed root network and activity of soil fauna like earthworms, moles, ants and rodents[1,5,37–40]. The sandy loam soil was also conducive to rapid water movement through the soil micropores. Therefore, soils under these two LULC types showed very high infiltration rate and low surface run-off. It can also be noted that the run-off rates from the soil under LULC 8 were minimum and even at a rainfall intensity of 100 mm/h, no surface run-off was generated. This clearly indicates high infiltration characteristics of undisturbed forest soils.

A comparison between the ordinates of run-off hydrographs generated from the soils with different LULC types under varying rainfall intensities is presented in Figure 1. It depicts the surface run-off generation patterns from the sites under study at time steps of 20, 40 and 60 min. In general, the rate of surface run-off increased with increasing rainfall intensity. In certain cases (LULC 4, LULC 5, LULC 7 and LULC 8), distinct threshold behaviour of run-off generation was evident. In forest under *jhum* cultivation (LULC 4), at 100 mm/h rainfall intensity no surface run-off was generated for 40 min since the start of rainfall. At 150 mm/h intensity, this time lag was 20 min. In forest with bamboo plantation (LULC 5), surface run-off was not evident for the initial 20 min under rainfall intensity of 100 mm/h. In both sparse forest (LULC 7) and mixed forest (LULC 8), higher rainfall thresholds were required for run-off generation. In LULC 7 under rainfall intensities of 100 and 150 mm/h, surface run-off was not generated for 40 and 20 min respectively. In LULC 8, no surface run-off was generated at 100 mm/h rainfall intensity. These results clearly indicate that a rainfall threshold is required before the initiation of surface run-off. However, under different LULC and soil types, the threshold value may vary widely. Similar threshold mechanisms of subsurface run-off generation are also well reported in the literature[41,42]. However, at higher rainfall intensities, as the infiltration capacity of soils was exceeded, the run-off generation process was mainly controlled by the rate of precipitation. It was also observed that after the cessation of rainfall, the macropores were drained fast due to their low capillary potential. But, in the micropore domain slow downward propagation of wetting front continued for about 2 h after the end of the storm events.

Conclusions

The infiltration and run-off generation processes were found to be affected significantly by the existing LULC types. The water infiltration rates through soil macropores and micropores together control the surface run-off response. The overall process of infiltration, macropore flow initiation and interaction between the two flow domains is complex. As the macropore infiltration rate is much higher than that of the micropores, run-off rate is more closely related to the preferential flow conditions of the soil. Water can flow into a macropore only when its entry pressure is exceeded. Therefore, different numbers and networks of soil macropores may be active under different rainfall intensities[7]. Thus, resulting infiltration rates and run-off responses were also controlled by the rainfall intensity. LULC play a significant role in developing the preferential flow features of a given soil and thereby affect the run-off generated from the soil. The model simulations showed that the run-off generation under different storm intensities is a highly threshold-driven process. In paddy field, grassland and moderately dense forest run-off generation was high due to low preferential infiltration rate. Lands which were affected by human interventions like shifting cultivation or bamboo plantation, showed their effect on run-off generation. Undisturbed forest soils produced very less surface run-off due to the presence of a high degree of active macroporosity in the soil. A higher rainfall threshold was required to obtain surface run-off from these soils. However, at very high rainfall intensities the infiltration capacities of the soils are exceeded and the run-off rate is primarily controlled by rainfall intensity.

The results presented in this study broadly reflect the run-off generation characteristics of soils under different LULC types. The field data presented here are spatially averaged over large areas under distinct LULC types. However, due to local variations in soil physical properties, especially at smaller spatial scales, the run-off responses may vary.

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