Article

Hydrological Modelling Using Rainfall Simulator over Experimental Hillslope Plot

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Abstract: Hydrological processes are complex to compute on hilly areas when compared to the plain areas. Most of the hydrological model do not take into account the critical rainfall-runoff generation processes such as subsurface storm flow, saturation excess flow, overland flow, return flow and pipe storage. The simulations of the above processes in the soil matrix requires detailed hillslope hydrological modelling. In present study, a hillslope experimental plot is designed to study the runoff generation processes on the plot scale. The setup is designed keeping in view the natural hillslope conditions prevailing in the north western Himalayas, India where high intensity storm event occurs frequently. Using the experimental data and the developed conceptual model, the overland flow and the subsurface flow through macropore dominated area has been estimated/analyzed on the pixel basis. Over the experimental hillslope plot, a rainfall simulator was installed to generate the rainfall intensity in the range of 15 to 150 mm/hr which represented the dominating rainfall intensity range in the region. Soil moisture sensors were also installed at 100 mm and 300 mm depth at different locations of the plot to observe soil moisture variations. It was found that once the soil is saturated, it remains in the field capacity for next 24-36 hours. Such antecedent moisture conditions are most favorable for the generation of rapid stormflow from hillslopes. Dye infiltration test was also performed on the undisturbed soil column to observe the macropore fraction variability over the vegetated hillslopes. The surface runoff predicted using the developed hillslope hydrological model compared well with the observed surface runoff under high intensity rainfall conditions.

Keywords: hydrological processes; hillslope hydrological modeling; rainfall simulators; subsurface flow processes

1. Introduction

Rainfall simulators are the principal apparatus for the study of the infiltration, soil erosion and sediment transport as it can be used in the field as well as in the laboratory conditions for controlled rainfall generation. A rainfall simulator permits to generate the rainfall of known intensity in controlled manner. In country like India, which is mainly based on the agriculture and where the increasing population have pressure on the land and water resources, this type of field experiments are much useful in understanding the soil erosion problem. Also in India, experiments using rainfall simulators for observing runoff, soil erosion etc. are very less done. [1] constructed a wind tunnel and a rainfall simulator to study the effect of wind and rainfall characteristics on soil erosion. The simulator consisted of three pipes covering a 12 x 1.2 m section with sprinklers working with pressurized water. [2] used a rainfall simulator to compare runoff and sediment production under distinct rainfall intensities in a vineyard plantation in Spain. The simulator consisted of a sprinkler located at a height of 2.5 m with pressurized water for 30 min simulations on a 0.45 m diameter plot. Three different types of sprinklers were used for three rainfall intensities: < 40, between 45 and 70, and > 70 mm/h. It was observed that plot of small size ceases the information to be obtained. [3] obtained soil loss values in 10 plots with bare soil in the Coquimbo Region. Each experimental simulation lasted 20 min, system pressure was 100 000 Pa, and rainfall reached a mean intensity of

130 mm/h. [4] conducted laboratory experiments on an impermeable smooth plane surface with a movable sprinkling-type rainfall simulator to simulate a moving storm. The results indicate considerable differences in runoff volumes and peaks and in overland flow hydrograph shapes, for storms moving upstream and downstream at differing velocities. [5] used a simulator to obtain a modified erodibility index which could be used to predict annual erosion rates for forest roads. They used a rainfall simulator on 1.5 x 2.0 m plots, and carried out simulations for 30 min with an intensity of 100 mm h^{-1} and an estimated kinetic energy of 0.295 MJ ha^{-1} mm^{-1}, which is similar to the kinetic energy of high intensity rainfall. [6] designed a new rainfall simulator which is easy to operate and transport while maintaining the intensity, distribution and energy characteristics of the natural rainfall. Experiments was performed on plot size of 1.5m X 2m with the coefficient uniformity of 93%. A single 50WSQ nozzle has been used producing the kinetic energy of 25 J m^2 mm^{-1} which is 87% of natural rainfall and drop size of 18 mm diameter with an intensity of 70mm hr^{-1}. The usage of water was also less due to use of single nozzle. [7], developed a cost efficient rainfall simulator for urban hydrology studies. The study was done for urban water quality study, evaluation of built-up and runoff studies on different pavement and roof materials. The developed rainfall simulator simulates the rainfall events with raindrops of median diameter (D50) of 2.12 mm and kinetic energy (KE) of 22.53 J/mm.m^2, which represents 90.12% of KE of natural rainfall events. The designed rainfall simulator is able to simulate rainfall intensities from 40 mm/h to 182 mm/h with Christiansen coefficient of Uniformity (CUC), ranging from 68.3 to 82.2%. [8] designed two different rainfall simulators to obtain different rainfall intensities with drop sizes and energies similar to natural rainfall. One of the rainfall simulators was constructed using a full-cone jet nozzle and achieved variable rainfall intensities by means of a solenoid valve (RS1). Rainfall intensities ranging from 21 to 83 mm $h^{-1}$with coefficients of uniformity ranging from 80 to 92%. Drop diameters ranged from 0.5 to 2.8 mm with this simulator and Kinetic energy associated to the mean raindrop diameter calculated on the basis of the corresponding terminal velocity was 15.1 J m_2 mm_1. The second one (RS2) used three plane-jet nozzles to obtain variable rainfall intensities by varying the number of nozzles working simultaneously providing rainfall intensities between 20 and 59 mm h_1. Drop diameter ranged from 0.5 to 2 mm, approximately the range observed for natural rainfall in the area. Mean kinetic energy (calculated on the basis of mean drop size and the corresponding terminal velocity) was 10.1 J m_2 mm_1. The coefficient of uniformity ranged between 80-86%. It was observed that the design using plane jets (RS2) provided a more realistic drop size distribution and lower cost than that using solenoid valve (RS1). [9] designed a high accuracy rainfall simulator for runoff and soil erosion studies. The mean drop size was found to be 1.5mm and energy flux was 76% of the energy flux expected for natural rainfall of same intensity.

In this study, rainfall simulator was used to generate rainfall event of variable intensities. The experimental rainfall response was observed and hillslope hydrological model was developed.

2. Materials and Methods

Study area

The experimental hillslope site is located in the campus of Indian Institute of Remote Sensing, Dehradun, India at an elevation of 435 m above sea level. The size of the plot is 5m X 10m, average annual temperature is 27^0C and mean annual rainfall of 2000 mm. The onset of monsoon starts form June and continuous upto September. A detailed topographic survey has been done with a uniform grid of 0.05 m using total station. The study area have loamy sand on top surface which has been found out experimentally. The undisturbed soil samples were collected from the hillslope site from top layer (0-10cm) and bottom layer (10-30cm). Bulk density test and soil texture analysis was done in the laboratory. Table 1 shows the soil profile of the experimental plot. The hard rock layer has been observed at a depth of 0.5m below the ground surface. Such an establishment can be highly conductive for quick subsurface stormflow generation under saturated conditions. The experimental plot is covered with small shrubs throughout the year. The degree of vegetation depends on the climatic conditions. Fig shows the location of study area

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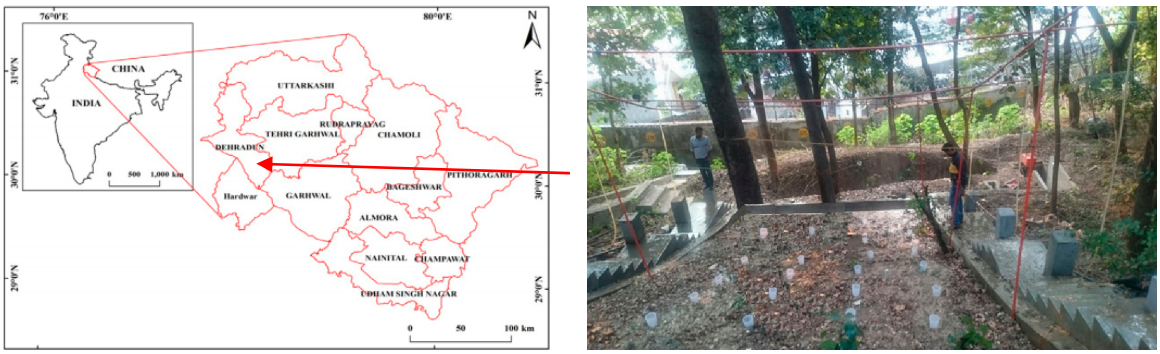

Fig.1: Location of the study area

Table 1: Soil profile of plot area

Soil Layer	Texture	% Sand	% Silt	% Clay	Bulk Density (g/cm^3)
Top Layer (0 -10 cm)	Loamy Sand	78.68	12.74	8.66	1.450
Bottom Layer (10 – 30cm)	Loam	49.12	43.44	7.44	1.527

Rainfall Simulator Design

The designed simulator is a continuous sprinkler system with under pressure water. The frame of the simulator is constructed from the 1.25 inches diameter steel pipe and is installed on the experimental plot size of 5m X 10m. The simulator frame consists of six legs made of steel pipe, three on each side. The legs are inserted into the ground upto a depth of 30 cm for the support purpose. Above the frame, four parallel pipes of 0.5 inch, with uniform spacing between them, each consisting of 2 nozzles and a pressure gauge are connected. The parallel pipes are connected with the water supply pipes from both sides.

Water supply consists of two big tanks each of 10,000 l capacity. The water from the big tank is supplied to a small tank of 400 l capacity through gravity. The small tank is connected to a pump which supplies the water to both the pipes which are connected to the parallel pipes. The nozzle system used on the simulator is Spraying Systems Fulljet 1/2HH 50WSQ nozzle. Two nozzles are placed at the top of the frame on each 0.5 inches pipe, almost 10 feet high from the ground surface. The nozzle is threaded directly into the 0.5 inches pipe. The selection of the nozzle is done based on literature review for having the effect of natural rainfall on the plot.

Experimental Setup

For conducting the rainfall experiments on the plot scale level experimental setup has been designed keeping in view the natural hillslope conditions which is dominant in the north western Himalayas. The main criteria for the design of experimental setup is as follows: (a) Setup should be portable and flexible and can be installed in hillslopes; (b) Setup should not be affected by dense vegetation; (c) should be able to produce varying intensities of rainfall; (d) should be cost effective.

Keeping the above conditions in mind, an overland flow generation system for varying rainfall intensities has been setup at the experimental site. It consists of a water tank at upstream to for supplying of water to the rainfall simulators. The rainfall simulators have been installed to generate the varying intensities of rainfall. The simulator is designed in such a way that it cover the whole area of the test plot and distributes the rainfall equally and uniformly over the whole test plot. To collect the runoff, a collecting channel with a gentle slope of 2% has been made with H flume at the outlet of channel. The runoff water will be collected in the water tank constructed at the downstream which is connected to Digital Water Level Recorder (DWLR). Small holes are made in the wall of the channel along the side of the plot to collect the subsurface flow. A pump is used to feed the water from the tank at upstream to the rainfall simulator pipes. For uniform sprinkling of water through nozzles of pipes, a proper pressure is maintained at each pressure gauge located at each top pipe. Schematic

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diagram of the experimental plot and digital elevation model of the experimental plot is shown in fig. 2

Drop Size Estimation

The drop size distribution of simulated rain was determined by using the flour pellet method described by Hudson (196S). A tray) of flour was exposed to simulated rainfall for a period of 2 seconds. The flour was then dried for 24 hours at room temperature (28–30 °C) and the pellets formed were passed through a series of sieves (4.75, 3.35, 2.36, 1.18 and 0.85 mm). The pellets were then dried for 24 hours at 105^0 C, weighted and measured. Drops smaller than 2mm diameter could not be produced while those larger than 6 mm could not be determined accurately by this method.

Performance evaluation of Rainfall Simulator

Rainfall delivered by sprinklers and its uniformity was checked by Christiansen's uniformity coefficient which is given as:

$$CU = 100(1-(\sum |x - \bar{x}|/\bar{x}n)) \quad (1)$$

Where, n = no. of samples; x = rainfall (mm) at specific point; $\bar{x}$ = mean of x values

Sprinklers were simulated for the rainfall intensity of 100mm/hr. The experiment was performed for 30 minutes. The rainfall was collected in the 36 containers placed on the plot at uniform grid having spacing of 1 m apart from each other. Volume of each container is 600ml. Fig. 3 shows the observation of coefficient of uniformity on the plot.

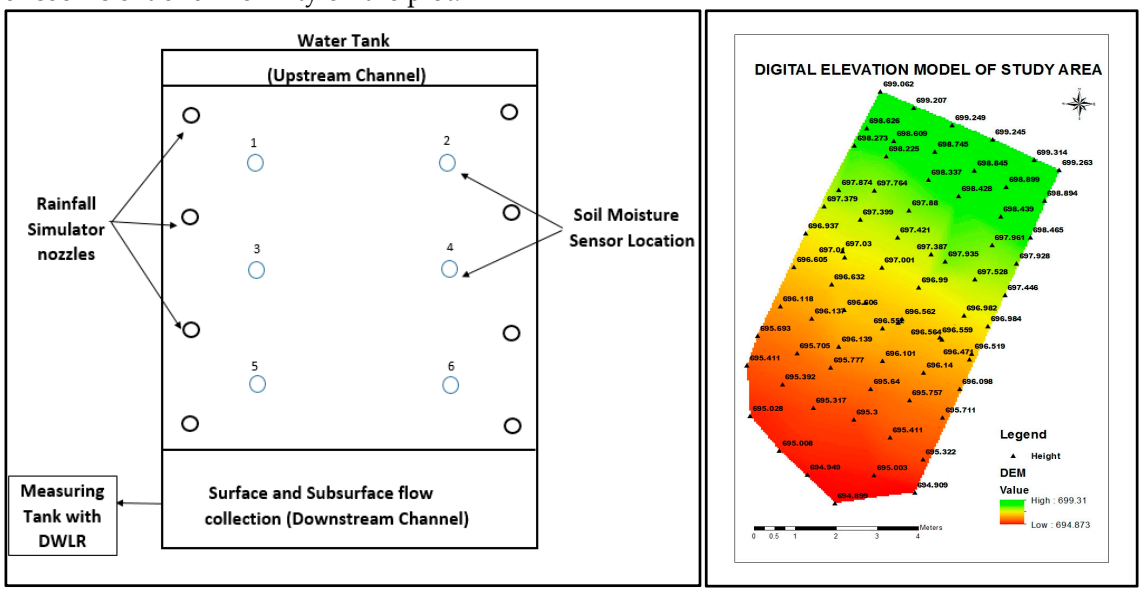

Fig.2: Schematic diagram of the experimental setup and digital elevation model (DEM) of plot

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Fig.3: Rainfall experiment for calculation of Coefficient of Uniformity

Kinetic Energy

The empirical equation given by Wischmeier and Smith (1958) for the kinetic energy of the raindrop is given as

$$e = 11.897 + 8.73 \log 10\ I \quad (2)$$

$$E = \sum_{i=0}^{n} e * P \quad (3)$$

Where, e is the kinetic energy (J m^{-2} mm); I is the rainfall intensity (mm/hr); P is the rainfall amount (mm); E is the kinetic energy (J m^{-2}); n is the number of rainfall periods.

Raindrop Velocity

Raindrop velocity is based on the raindrop diameter which is found out by modified Newton's equation

$$v = (17.20 - 0.84d) * (d) * 0.5 \quad (4)$$

Where, d is diameter of the raindrop

The relation between drop velocity and drop size when compared with its terminal velocity given by Lows and Parson [10] is given in table below

Table 1: Comparison of Measured velocity and Terminal velocity wrt to drop diameter

Drop Diameter (mm)	Terminal Velocity (m/s)	Velocity (m/s) measured by [10]
1	4	3.3
1.5	5.3	4
2	6.5	5
2.5	7.2	5.7
3	8	6.2
3.5	8.5	6
more	<= 9	-

Runoff and Subsurface flow collection

The runoff from the experimental plot flows through the channel constructed at the downslope of the plot and gets collected in a tank. The collecting channel has gentle slope of 2% with an H flume at outlet. The collection tank is equipped with a digital water level recorder (DWLR) which records the water level at an interval of five minutes. A solar panel is attached to DWLR for charging its battery. For collection of subsurface flow, small holes are provided in the collecting channel along the side of

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the plot at downslope side. A portable rain gauge has also been used to measure the intensity of the rainfall from simulator.

Hydrological Modeling

This part describes the hydrological model for the hillslope areas. The study area is conceptually divided into four hydrologically similarity classes (HSC) namely vegetated hillslope, agricultural field, settlement area and bare soil. . This model is based on the physical processes on the hillslopes, where top most layers deals with the rainfall events. If the soil is saturated, retention excess flow will occur for vegetated hillslope area and the agriculture field which will directly added to the channel flow and if the soil of the above two classes is not saturated then water will infiltrate into soil and enter the macropores area causing the occurrence of macropore dominated processes like subsurface flow, return flow, through flow and pipe storage. From macropore storage, water will enter in the root zone storage from where it will be a part of return flow or through flow depending on the condition. The water from return flow will directly add-up to channel flow and the water from the through flow will be added to subsurface flow processes. The hydrological processes on the other two classes i.e. settlement area and the bare soil is based on the Hortonian Infiltration. If the rainfall intensity is less than the infiltration capacity of the soil, then the water will added to the subsurface flow while for the reverse case, infiltration excess flow will occur which will contribute to the channel flow. Total subsurface flow will be calculated by adding the through flow and the flow from Hortonian infiltration and the total channel flow will be estimated by adding return flow, retention excess overland flow and infiltration excess overland flow. Fig.4 shows the conceptual flow chart of hydrological processes and their interdependence in the hilly watershed.

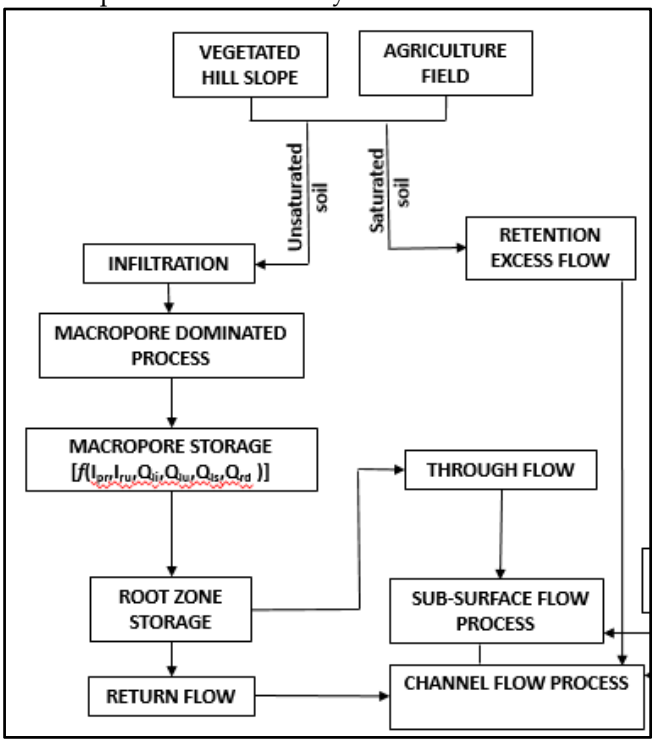

Fig.4 : Conceptual flow chart of Hillslope Hydrological Model

Mathematical modeling

The mechanism of infiltration in hilly water shed is mainly controlled by macropores. Macropores initiates the subsurface stormflow by saturating the surroundind soil matrix. The water stored in macropores after the infiltration as given in Altera report1649-Swap 32 (2008)

$$S^t - S^{t_0} = \int_{t0}^{t} (\boldsymbol{Ipr} + \boldsymbol{Iru} + \boldsymbol{qli} - \boldsymbol{qlu} - \boldsymbol{qls}) \qquad (5)$$

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Where:

$$qli = \int_{z,if,bot}^{z,if,top} \boldsymbol{qli}\,; \qquad qlu = \int_{z,uns,bot}^{z,=0} \boldsymbol{qlu}\,; \qquad qls = \int_{z,prof,bot}^{z,uns,bot} \boldsymbol{qls}$$

Where the +ve terms are for infiltration into soil matrix and –ve terms are for exfiltration from soil matrix. Depths *z,if,top, z,if,bot, z,uns,bot and z,prof,bot* (cm) refer to top and bottom of interflow zone, and bottom of unsaturated zone and soil profile, respectively and

1. Storage of water in the main bypass domain of macropore $\mathbf{S_{mb}}$ (cm);
2. infiltration of water into macropores at soil surface, by precipitation, irrigation and snowmelt water falling directly into macropores $\mathbf{I_{pr}}$ and by overland flow (runoff) into the macropores $\mathbf{I_{ru}}$ (cm d^{-1});
3. Lateral infiltration into the unsaturated soil matrix $\mathbf{q_{lu}}$ (cm d^{-1});
4. Lateral exfiltration out of the saturated soil matrix $\mathbf{q_{ls}}$ (cm d^{-1});
5. Lateral exfiltration out of the saturated soil matrix by interflow out of a zone with perched groundwater $\mathbf{q_{li}}$ (cm d^{-1});

The rate I_{pr} of precipitation, irrigation and snowmelt water routed directly into the macropores at the soil surface at a given precipitation/irrigation/snowmelt intensity P (cm d^{-1}) is calculated as:

$$I_{pr} = Amp*P \qquad (6)$$

Where, Amp (cm^2 cm^{-2}) is the horizontal macropore area fraction at the soil surface which equals Vmp_o, (cm^3 cm^{-3}) the total macropore volume fraction at soil surface.

Ponding occurs when the total of precipitation, irrigation, snow melt runoff and inundation intensity exceeds soil matrix infiltration capacity and subsequently overland flow occurs. Infiltration rate I_{ru} due to overland flow or surface runoff is numerically given as:

$$I_{ru} = h_o/\Upsilon_{Iru} \qquad (7)$$

Where, h_o is the pressure head at the soil surface which is equal to the ponding height in cm and Υ_{Iru} is the resistance of macropore inflow at soil surface.

Lateral infiltration of macropore water into the unsaturated soil matrix (q^*_{lu}) takes place strictly over the depth where stored macropore water is in contact with the unsaturated matrix. Absorption is the dominant mechanism at low soil moisture contents. It will be negligible under wet conditions even when there is a large pressure head gradient and for this condition Darcy flow will be dominant. Darcy flow is very small under dry conditions because of very low hydraulic conductivities.

Using one dimensional flow equation combined with Darcy's equation, Shakya (1995) computed the lateral infiltration as

$$q^*_{lu} = S_r / 2t^{-1/2} \qquad (8)$$

Where, S_r is the sorptivity, which is computed by using Young's estimation formula (Jain et al., 2013)

$$S_r = 6.3\,(\theta-\theta_r)^{0.5}\,K_{sat}{}^{0.25} \qquad (9)$$

Where, θ is the moisture content at the present time, θ_r is the residual moisture content i.e. moisture content at wilting point.

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Lateral exfiltration out of saturated soil matrix water into the macropores (q^*_{ls}), only concerns static macropores below the groundwater table, since in the present concept in saturated condition the soil is assumed swollen to its maximum volume. The lateral exfiltration rate per unit of depth $q^*_{ls,}$(cm cm^{-1} d^{-1}) in case of water filled macropores ($h_{mp} > 0$) is described by Darcy flow:

$$q^*_{ls,} = f_{shp} * 8* K_{sat} * (h_{mp}-h_{mt})/ (d^2_{pol}) \quad (10)$$

Parameter *f*shp is a shape factor to account for the uncertainties in the theoretical description of lateral infiltration by Darcy flow originating from uncertainties in the exact shape of the soil matrix polygons. Theoretically, the value of *f*shp lies between 1 and 2. Infiltration occurs if $h_{mp} > h_{mt}$ and exfiltration if $h_{mp} < h_{mt}$.

Lateral exfiltration out of the saturated matrix as interflow (q^*_{li}) is a special case of exfiltration of soil water from the saturated zone into the macropores and is described as

$$q^*_{li=} - (f_{shp} * 8* K_{sat} * (h_{mp}-h_{mt})/ (d^2_{pol})) \quad (11)$$

If $h_{mp} > h_{mt}$, infiltration into the saturated matrix in the perched groundwater zone occurs. Here perched groundwater is defined as the subsurface water that forms a saturated horizon within porous media at an elevation higher than the local or regional groundwater table, d_{pol} is the effective diameter of soil polygon which is nothing but the macropore diameter and is given by

$$d_{pol} = d_{p,min} + (d_{p,max} - d_{p,min})*(1-M) \quad (12)$$

Where, $d_{p,min}$ and $d_{p,max}$ are the minimum and maximum diameter of the macropores, M is the relative macropore density which is the ratio of the static macropore volume to the static macropore volume at surface.

Retention excess flow occurs if the soil is already saturated. Main factor affecting this flow is the availability of soil moisture content. Retention excess flow can be calculated as

$$Q_{re} = P – I \quad (13)$$

Where, P is the rainfall intensity in mm/hr and I is the infiltration capacity in mm/hr

Return flow (Saturation Overland Flow) occurs where the soil is completely saturated and no additional water will be accepted into it. This type of flow is most common near the toe of the slopes where the accumulated water from the entire hillslopes is enormous in volume. This is a time dependent condition i.e. the longer the rainfall occurs, the more water will be in the soil layers hence greater area will be subjected to saturation. This flow returns to the land surface after flowing short distance in upper soil horizon. Return flow per unit length at the hillslope can be calculated using the following equation:

$$Q_{return} = H_o V_{lat} (L-L_s) \quad (14)$$

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Where, Q_{return} is the return flow (mm/day), H_o is the saturated thickness normal at the hillslope outlet expressed as function of total thickness (mm/mm). V_{lat} is the velocity of the flow at the outlet (mm/day) which can be defined as

$$V_{lat} = K_s \sin(\alpha) \quad (15)$$

Where, α is the hillslope angle.

Through flow is the downslope flow of water occurring physically within soil surface under unsaturated condition. Through flow can maintain both low flows (baseflow) in rivers by low subsurface drainage and also contribute to high peak flows (stormflow) through its role in generating saturation excess overland flow. In this study, through flow is calculated as the difference between the root zone storage and the return flow.

$$\text{Through flow} = S_{rz} - \text{Return flow} \quad (16)$$

Where, P is the rainfall intensity and S_{rz} is the root zone storage.

The above process will occur in the areas having vegetated hillslopes and agriculture land. For the areas covered with settlement and the bare soil, two scenarios occurs. First, when rainfall intensity is lesser than infiltration capacity. In this case, the water directly infiltrates into the soil and contributes to the subsurface flow. In second case i.e. when rainfall intensity is higher than infiltration capacity, infiltration excess overland flow occurs. This flow is also known as Hortonian flow and occurs mainly in irrigated areas, urban areas and generally during the storms with very high intensity of rainfall. The infiltration excess overland flow is calculated by Horton's equation which is given as

$$f_p = f_c + (f_0 + f_c)\, e^{-kt} \quad (17)$$

Where, f_p = the infiltration capacity (depth/time) at some time t, k = constant depends on soil characteristics and vegetative cover, f_c = a final or equilibrium capacity, f_0 = the initial infiltration capacity.

3. Results

3.1 Rainfall Simulator Characteristics

3.1.1 Uniformity

8 nozzles (1/2HH50WSQ) are used mounted on the 4 pipes on the frame over the plot. Rainfall experiments were performed with duration of 30 minutes for three times to produce uniformity between 76 – 82%. This uniformity is quite satisfactory on the plot of bigger size. Simulators with multiple nozzles have less uniformity although they have capability of producing higher intensities of rainfall. The uniformity coefficient will less for the lower intensity of the rainfall as the spread angle of the water distribution will be less for lower intensities.

3.2 Hydrological Response of Hillslope plot

3.2.1 Soil Macropores Characteristics

In order to quantify the macropore structures in the hillslopes, an undisturbed soil column has been obtained from the study site. The soil column has circular dimension having diameter of 53 cm which has been made using a steel ring of the same diameter and depth of 30 cm. The initial wet conditions of the soil columns has been obtained by continuously supplying the water for 1 hour with a constant ponding depth of 3 cm. Then the soil column was left for 2-3 hours to attain field capacity. The dye test was done after the soil has attained the field capacity. Here, blue ink which is used in fountain

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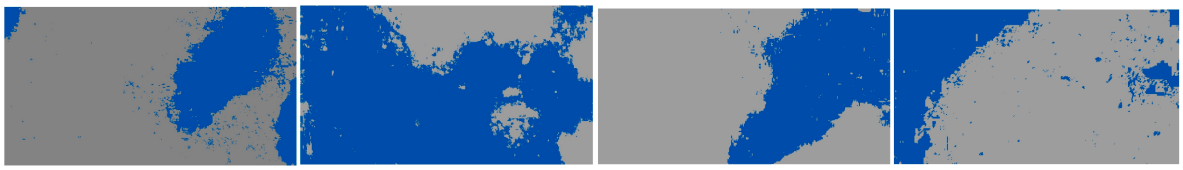
pen is used as dye tracer. The dye was applied for 1 hour with a constant ponding depth of 3 cm. Then the soil column was left for 3 hours for proper spreading of dye. Then the steel ring was removed and the column was divided horizontally at 2 cm intervals by using sharp knife and chopper. Serial images of the slices were taken using a digital camera for image analysis. After every image analysis, a classification report has been made to find the percentage coverage area of the dye in the soil slices. The image analysis of soil provided the useful detail of the depth of the dye penetration. The dye penetration was visible upto the last sliced part of the soil. This indicates that the continuous macropores are present in the soil throughout the depth. This type of macropore connectivity is possible in the soils with densely vegetated roots. Fig. 5 shows the subset images of the classified images



(a) 4 cm (b) 12 cm (c) 18 cm (d) 22 cm

Fig.5: Subset digitally processed Image of soil sample of hillslope at different depths

Lateral Subsurface flow observation

The channel constructed at the downslope of the hillslope plot for collecting runoff has been provided with the holes on the side of the plot to collect the subsurface flow. The experiment for subsurface flow observation has been carried out in sparse and dense vegetation condition. From the experiment it was evident that the subsurface flow in the sparse condition was very less and had negligible contribution to the surface flow. While in the dense vegetation condition, due to increase of macropores in the plot, the subsurface flow plays an active part in the channel flow. Although the subsurface flow stars late in the dense condition, it last for a longer time even after the rainfall experiment has stopped. Fig. 6 shows the observed subsurface flow recorded during the experiment at an interval of 5 seconds. Each observation for each time step has been recorded after an interval of 10 seconds.

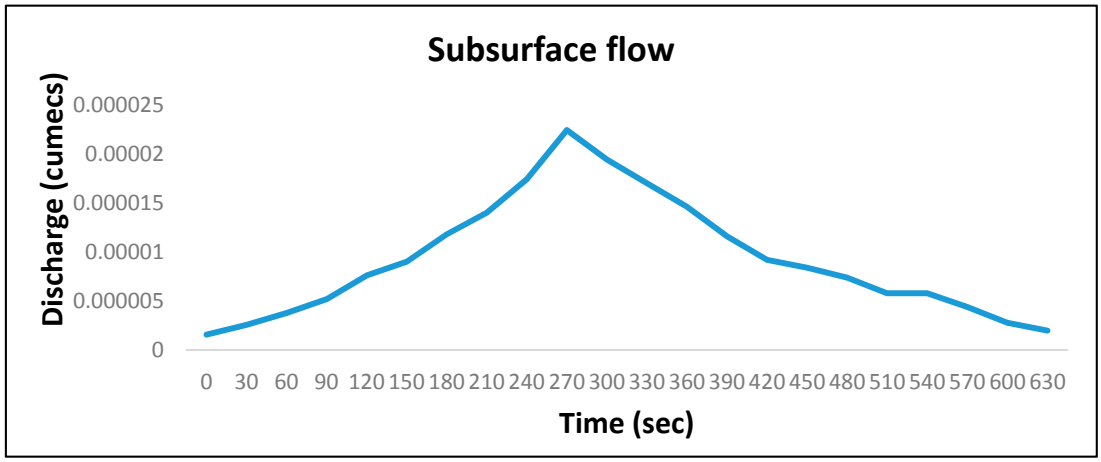


Fig. 6: Subsurface flow for a dense vegetation condition

Subsurface soil moisture measurement

To measure the spatial and temporal soil moisture at the subsurface, soil moisture sensors were installed at a depth of 10cm and 30cm at six different locations on hillslope plot. Measurements were taken just after experiments conducted for 30 minutes. The soil moisture gives reading in centibars / Kilopascals. The pressure plate test was done to convert the soil moisture readings from centibars to

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volumetric water content and to define the relationship between soil water content and soil water tension. Soil moisture measurement was also continued for extended period after the rainfall experiments for 36 hours. It was found that soil remains in the wet condition for a long time after single rainfall experiment which is shown in the fig 7 (a-b). It is important because from initial monsoon rainfall, the top layer of the soil is expected to be wet and to be remained in field capacity for a long time. Hence, the succeeding rainfall event can cause the rapid subsurface stormflow from hillslopes.

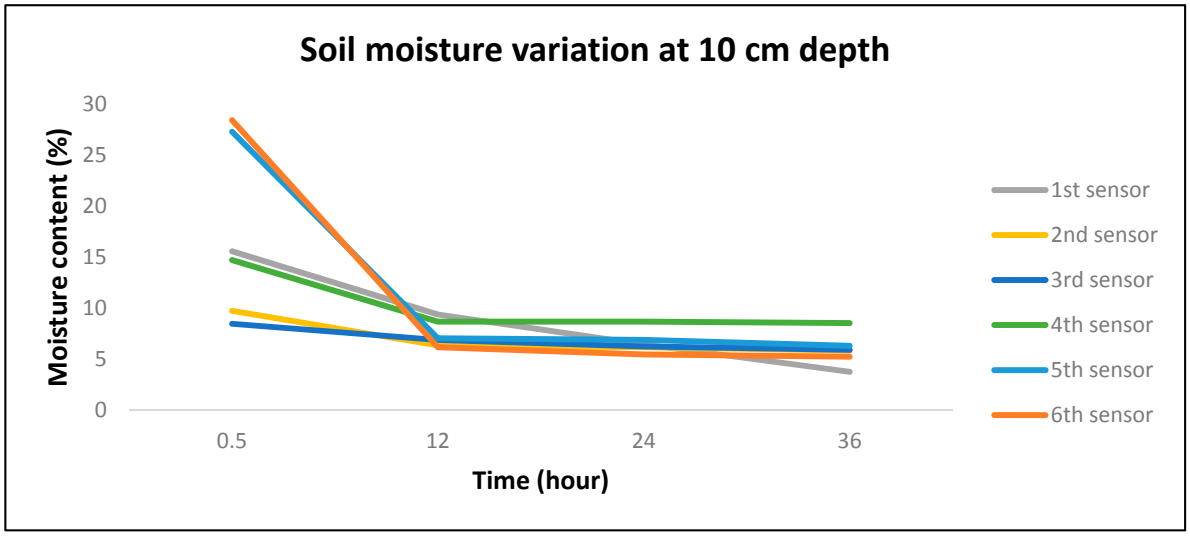

Fig.7 (a): Temporal Soil moisture at 10cm depth for soil moisture sensor at different locations

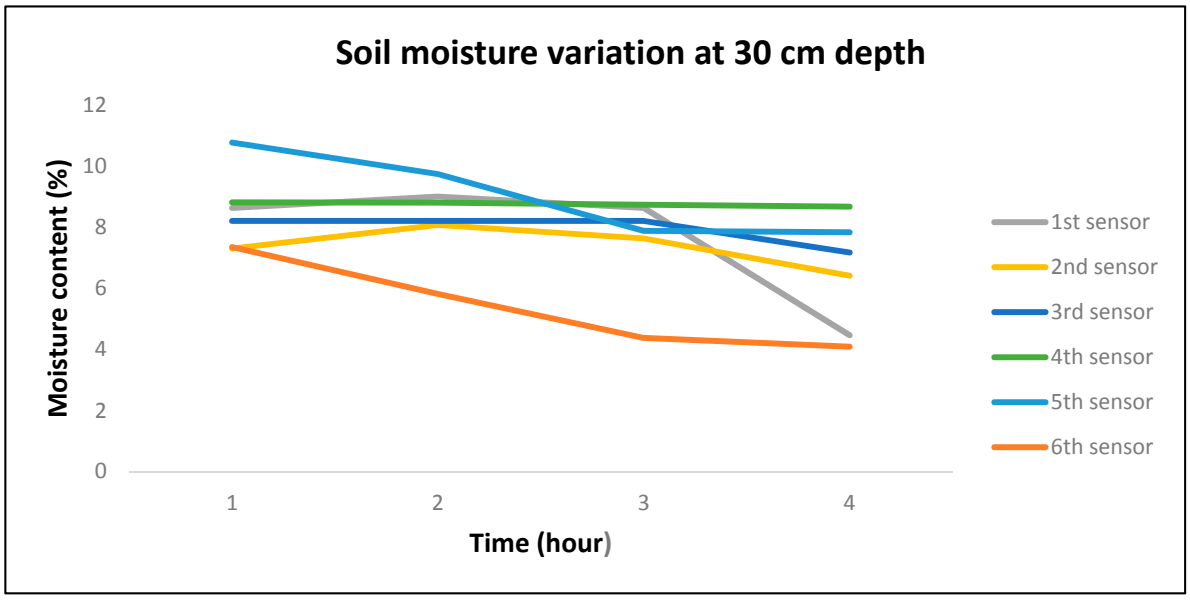

Fig.7 (b): Temporal Soil moisture at 10cm depth for soil moisture sensor at different locations

Runoff Hydrograph

The water collected in the collecting channel flows to the tank constructed at downslope of the hillslope plot. The water in the tank is measured at every 5 minutes interval using the DWLR.

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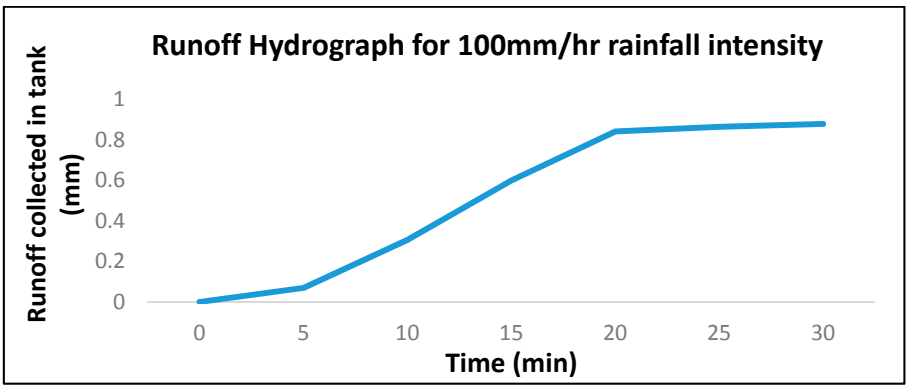

Fig.8: Runoff hydrograph for rainfall intensity of 100mm/hr for 30 minutes

Hydrological Modeling Results

The developed conceptual hydrological model is applied to plot scale in this study. Flow chart for conceptual model is shown in fig.4. The rainfall was having a constant rainfall intensity of 100mm/hr. for the first hour and there was no rain from simulator. Observation were taken for different parameters for the next six hours. The observations from the simulations concluded that components of macropore storage i.e. lateral infiltration into unsaturated matrix (q_{lu}), lateral exfiltration out of saturated soil matrix (q_{ls}), and lateral exfiltration out of soil matrix as interflow (q_{li}) has changed with time. As the rainfall starts, water enters into the macropore by directly falling into it or through overland flow (runoff). The infiltrated water first enters the main bypass (MB) domain and the internal catchment (IC) domain. The macropores in the MB domain are well connected throughout the depth of the soil while IC domain ends at different depths with no connection between them. After the rainfall initiation, the soil gets saturated and it gets swollen up. As the rainfall continues, the water starts building up the pressure on the saturated macropores because of which water already present in the macropores starts moving laterally into the groundwater (q_{ls}). After the rainfall, the $\mathbf{q_{ls}}$ component starts decreasing with decrease in water pressure on the macropores. On contrary, $\mathbf{q_{lu}}$ increases with time as water moves laterally to the unsaturated zone from the macropore domain. It occurs where the stored macropore water is in contact with unsaturated soil matrix. The lateral infiltration occurs due to absorption of macropore water because of capillary force. As the soil gets saturated, the water starts flowing out of it into the macropores which is termed as $\mathbf{q_{li}}$. This is the special case of exfiltration.

The same simulations were carried out for rainfall intensities of 50mm/hr and 25mm/hr which is shown in fig.9 (a-c)

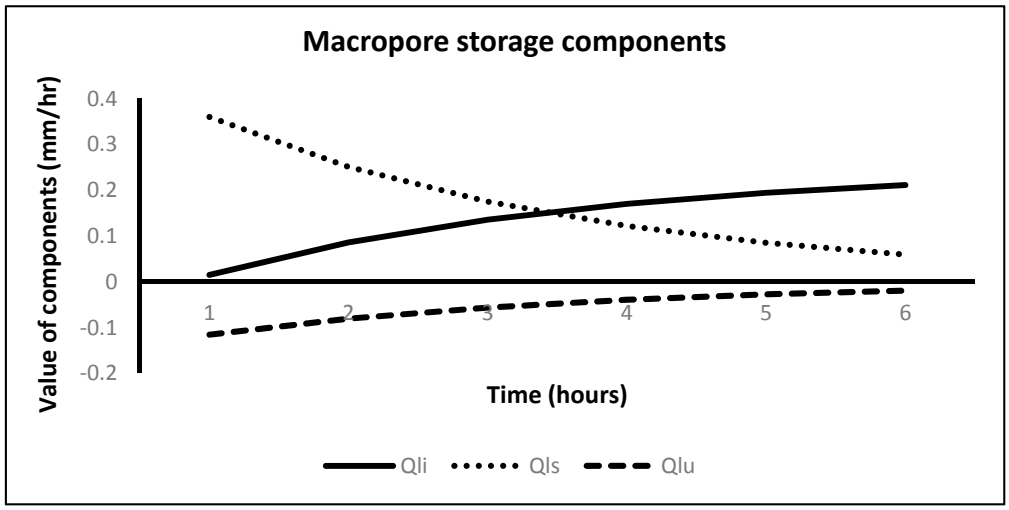

Fig. 9(a): Change in macropore storage w.r.t. time for 100 mm/hr rainfall intensity

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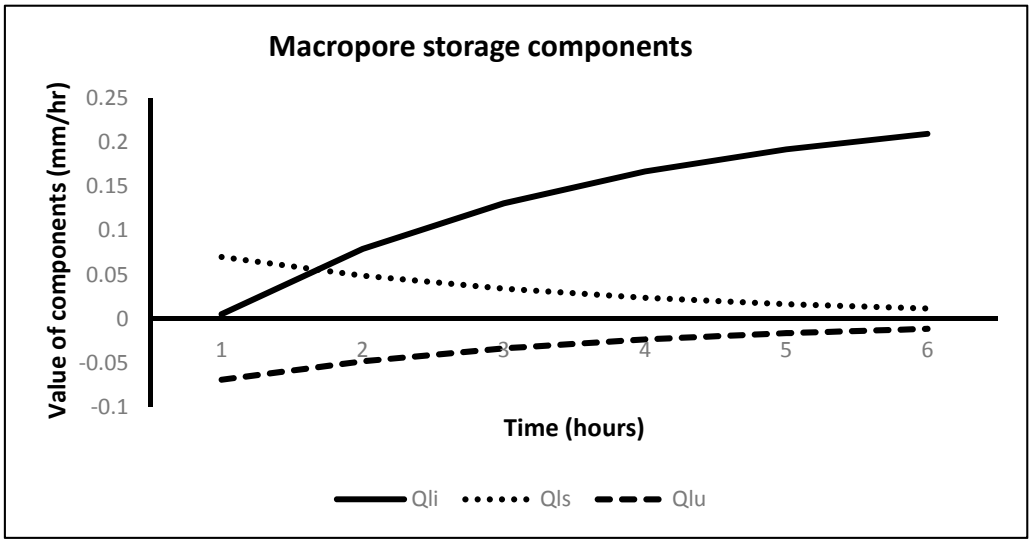

Fig. 9(b): Change in macropore storage w.r.t. time for 50 mm/hr rainfall intensity

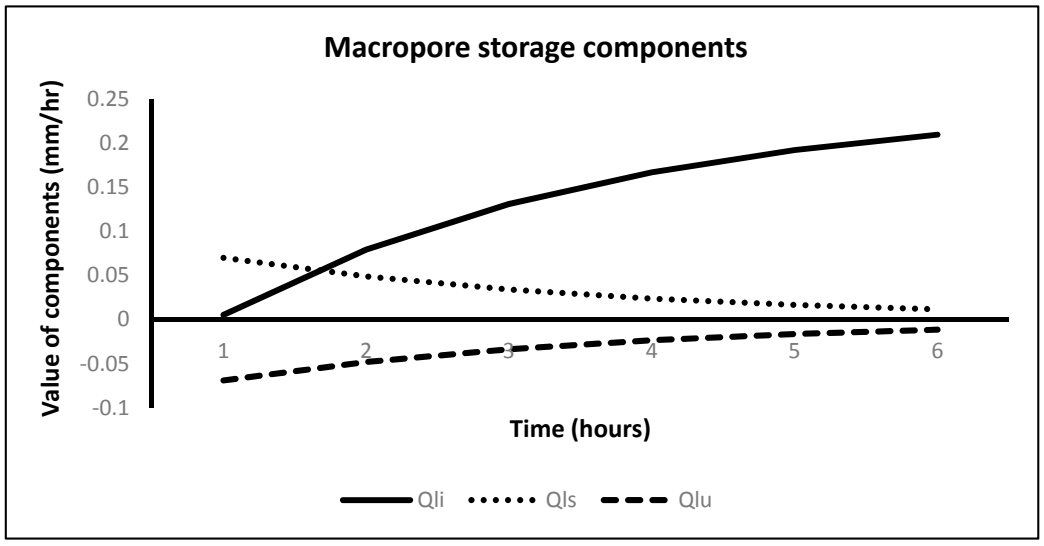

Fig. 9(c): Change in macropore storage w.r.t. time for 25 mm/hr rainfall intensity

Rainfall experiments were performed for different intensities and field observations were calculated for outflow discharge and simulated discharge was also computed using conceptual hydrological model. The comparison of the observed and simulated data was done using the statistical parameter known as Performance Index (PI) [11] as shown in table 2

Where, O = observed value, P = predicted value, and n = total number of data observations.

$$\text{Performance Index (PI)} = \frac{\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}}{\sum_{i=1}^{n}|O_i|}$$

The lower the PI, the better is the prediction.

Table 2: Comparison of Observed vs. Simulated discharge for different rainfall intensities

S.No.	Rainfall Intensity (mm/hr)	Observed Discharge (m^3/sec)	Simulated Discharge (m^3/sec)	Performance Index (PI)
1	140	0.00084	0.00087	0.035
2	100	0.00073	0.00078	0.068
3	50	0.00044	0.0	1
4	25	0.00026	0.0	1

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