

# An experimental and modelling investigation of macropore dominated subsurface stormflow in vegetated hillslopes of northeast India

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**Abstract** In northeast India, where the hillslopes are characterized by high degree of soil macroporosity and the area receives extreme rainfall events frequently during the monsoon season, rapid lateral preferential flow is the major source of storm runoff. Such rapid movement of storm water from the adjacent hilly areas either in the form of old or fresh water, often triggers soil erosion, landslides and flash floods in the rivers. However, due to lack of experimental data or reliable empirical models for these watersheds, very little seems to be known about infiltration behaviour, macropore connectivity, and subsurface flow pattern through soil macropores. Therefore, as a prerequisite to developing any rainfall-runoff model it is essential to characterize both surface and subsurface flow behaviour with good understanding of the critical hydrological processes prevailing in the region. The present investigation aims at characterizing the macropore flow for the region through *in situ* experiments and modelling.

**Key words** macropores; hillslope; hydrology; experiments; modelling; northeast India

## INTRODUCTION

Macropores, commonly referred to as the preferential pathways of soil, are known as one of the most significant parameters to control rapid subsurface water movement in hillslopes. Densely vegetated hillslopes with favourable subsoil formations are mainly suitable for subsurface stormflow generation under high intensity storm events (Emmett, 1970; Kirkby, 1978). The vegetated hillslope soils of Northeast India are characterized by highly interconnected macropores which are primarily responsible for generating rapid subsurface stormflow during high intensity storm events. This often leads to well-known water resources issues like flash floods, subsurface erosion, landslides, waterlogging, etc. Moreover, the preferential flow influences some of the long-term hydrological problems such as groundwater pollution.

Due to high rainfall characteristics of northeast India (Soja & Starkel, 2007), the soils of most of the watersheds of the region remain saturated throughout the rainy season. Though, saturated macropore flow is considered to be one of the most critical hydrological processes of these hilly watersheds, but with very little understanding of the physical aspects of subsurface stormflow it often becomes difficult to develop a realistic hydrological model for the area. The lack of experimental data about infiltration behaviour, macropore connectivity, and subsurface flow pattern through soil macropores, is one of the major constraints encountered by the hydrologists working in the watersheds of the region. So, there is a clear need to quantify soil macroporosity and the dominating flow paths within continuous soil macropores to elucidate the underlying flow mechanisms at the macropore scale. The present investigation uses a simple laboratory set-up to show and analyse experimentally the macropore flow patterns and their variability under different land-use practices. A simple plot-scale experimental investigation was used to develop a physical based model for predicting lateral subsurface stormflow from the vegetated hillslopes of the region.

## DESCRIPTION OF THE STUDY AREA

In general, the hillslopes of northeast India are reported to have deep, coarse loam or sandy loam soils (Vadivelu *et al.*, 2004). Subsurface geology indicates a two-layer soil formation, with a

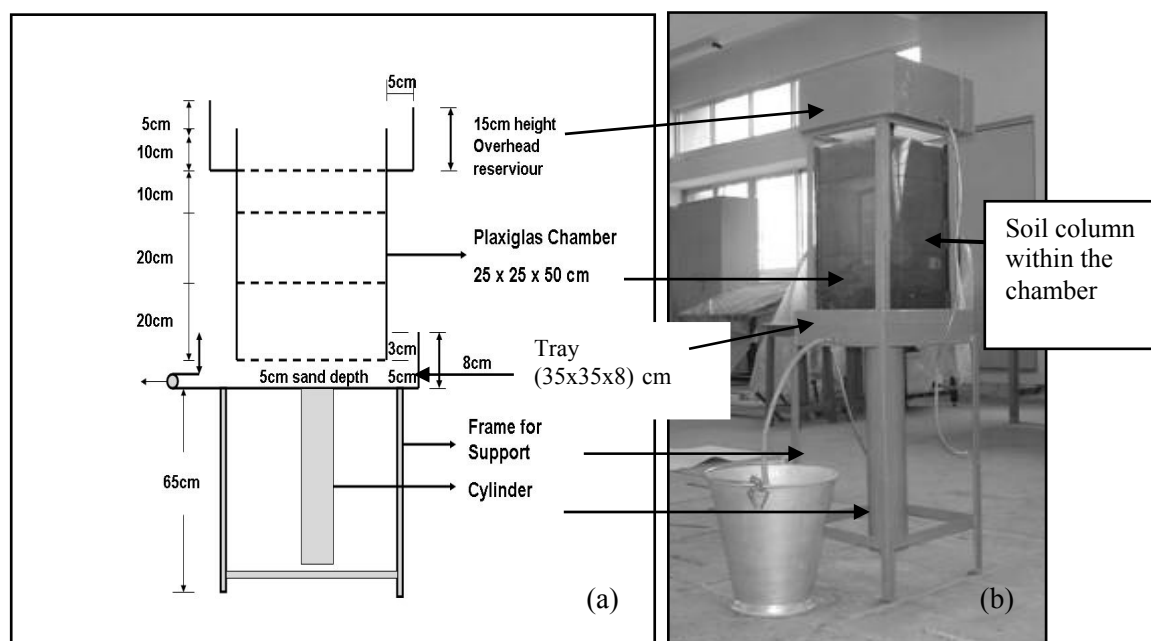
highly permeable coarse soil layer overlain a fine textured soil. An impermeable layer is found at about one meter depth from the land surface (Sarkar *et al.*, 2008). The natural vegetation of the hillslopes consists mainly of close-growing grasses and shrubs (*Cynadon dactylon*, *Saccharum spontaneum*, *Mimosa pudica*, *Ageratum conyzoides*, *Ageratum haustonianum*, *Lantana camara*, *Mikania micrantha*, *Parthenium hysterophorus*, etc.). Though the rooting depth of these plants extends up to one metre, root density is very high, which can significantly influence the macropore connectivity, as was evident within 50 cm depth below the ground surface. The native plant varieties of the dense evergreen forests of the region consist mainly of timber species, such as: Haldi (*Adina cordifolia*), Sundi (*Acer niveum*), Toon (*Cedrella toona*), Jarul (*Lagrostomia flosregina*), Bonsum (*Phoebe* spp.), and Muli bamboos (*Melocanna bambusoides*). Mixed forests are composed of plants such as: teak (*Tectona grandis*), Khen (*Melanorhoa usitata*), Semul (*Bombax malabaricum*), Pareng (*Alnus nepalensis*), and pine (*Pinus khasya*). The climate of the region may be divided into four primary seasons, namely, winter (December–February), pre-monsoon (March–April), monsoon (May–September), and retreating monsoon (October–November). The average annual rainfall of the area is about 1611.9 mm (Singh *et al.*, 2004).

### SOIL MACROPORES AND THEIR VARIABILITY

In forested hilly watersheds the spatial and temporal variation of the active macropore flow network primarily governs both surface and subsurface runoff generation processes. To quantify the effects of different management practices on soil macroporosity, sampling of soils was done from different locations of northeast India having distinct local land-use features. In order to understand the variability of macropore flow networks and their connectivity, infiltration experiments were conducted with colour dye tracer for undisturbed soil columns collected from various sites of the region, such as undisturbed forested hillslopes, paddy fields in the flood plains, Jhum cultivated abandoned forested hillslopes, and agricultural lands under Jhum.

### EXPERIMENTAL SET-UP

Undisturbed soil columns (25 cm × 25 cm × 50 cm) from various locations were carved from a pedestal of soil block and then a rectangular chamber made of 6 mm thick Plexiglas sheet was inserted from the top of the soil column by careful trimming of the excess soil around the sides of the column. It is true that while collecting the undisturbed soil samples, the area around the edges are bound to be disturbed. However, considering that the size of the macropores is very small, the large dimension of soil column should provide reasonably correct information about macropore size, density, active flow network, and depth wise distribution. This information can be very useful for developing hydrological models. The samples were taken to the laboratory to conduct the infiltration experiments. The laboratory experimental set-up consists of a soil infiltrometer chamber, a square overhead water reservoir, a square tray mounted on the stand, a hollow cylinder, and an outlet for excess water flow (Fig. 1). The Plexiglas chamber, which was used for collecting the soil samples, was used as an infiltrometer chamber. The chamber containing the soil column was placed over the tray and the overhead tank was fitted above the soil column by means of screws for holding different parts tightly. A profile probe soil moisture meter of one meter length was inserted through the middle of the soil column up to the bottom of the hollow cylinder for monitoring the volumetric moisture content of soil. Before starting the experiment the soil column was saturated. Then it was left for 4–5 hours for gravity drainage of water until the soil moisture content attained its field capacity. Once the soil attained such wet antecedent conditions, dye infiltration experiments were conducted. The Brilliant Blue FCF as a dye tracer is popularly used as it is considered as one of the best available to date for visualizing flow paths in soil (Flury *et al.*, 1994). In the present study, Brilliant Blue R<sub>250</sub> (C.I. 42660) dye was applied at the rate of 4 g/L which was sufficient for clear visibility of the stained flow paths in heterogeneous soil mass. Infiltration experiments were conducted with dye solution for each wet soil samples by



**Fig. 1** Laboratory set up for conducting dye infiltration experiments.

maintaining a ponding depth of 2 cm in the overhead tank. After 3 hours supply of dye solution was stopped and the soil was left for 4–5 hours for allowing proper distribution of dye. Then the overhead tank and the Plexiglas chamber were removed and the soil column was sliced horizontally at every 1 cm intervals from the top to analyse the dye distribution patterns. Each cross-sectional slice was circumvented by a 1 cm wide square frame, which was marked with proper scaling on each side to fix the same four corners of each layer. Serial images of each horizontal slice were taken using a digital SLR camera (Canon EOS 400D, 10 Mega Pixels resolution) for further digital image analysis of the dye patterns. For accurate measurement of stained areas, the images were colour corrected, digitally rectified, and scaled to a resolution of one square millimetre per pixel.

## RESULTS

The analysis of the resulting dye patterns using digital image processing techniques clearly showed the effects of different management practices on the macroporosity of the soil. The horizontal and vertical dye patterns for each soil column were analysed following the digital image processing techniques outlined by Weiler (2001). Figure 2 illustrates the image analysis procedure of horizontal dye patterns and Fig. 3 shows the digitally processed dye patterns at various depths for the vegetated undisturbed natural hillslope soil column. The horizontal dye patterns gives an indication of flow area, depth of dye penetration, type of flow, and the spatial distribution of the soil macropores on a horizontal surface. Whereas vertical dye patterns shows the depth wise distribution of dye coverage in terms of volume density, size distribution of macropores, total number of macropores and maximum or minimum size of macropores present in the soil profile. These parameters were used to identify the size of active macropores, their depth wise distribution, connectivity, and the resulting active macropore flow processes. Figure 4 shows the depth wise dye coverage distribution and Fig. 5 depicts the depth distribution of number of stained path widths (SPW) for different soil columns. For undisturbed forested hillslope soils active macropores were clearly visible up to the entire depth of the soil column. In conventional paddy field soils no active macropore was evident due to formation of hard pan in the puddled top soil layer. The Jhum cultivation significantly disturbed the natural soil macroporosity. After

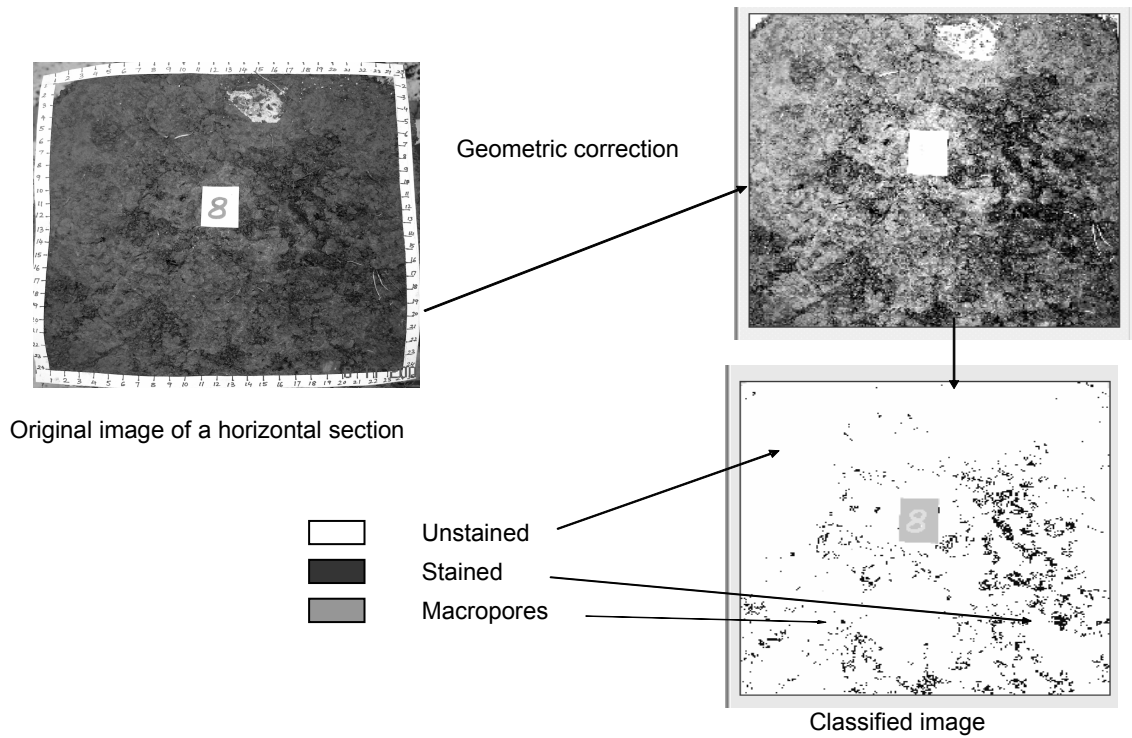


Fig. 2 Image analysis procedure of horizontal dye patterns.

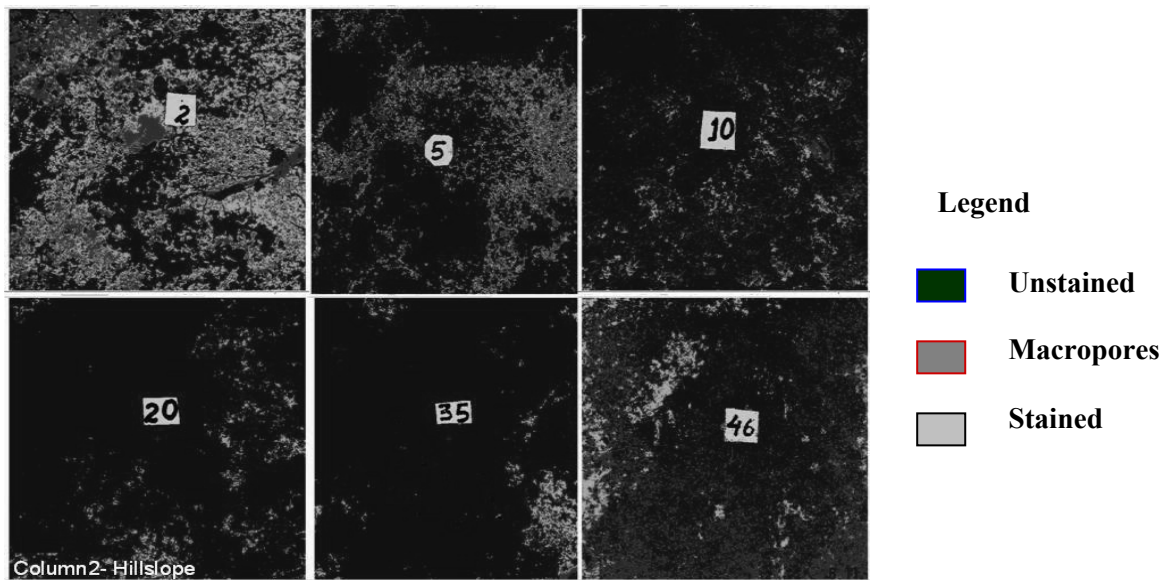


Fig. 3 Digitally processed images of undisturbed hillslope soil at different depths.

abandonment of Jhum cultivated land the natural vegetation starts to grow again. The top soil layer regains its natural macroporosity to some extent, but the lower soil layers take a very long time to regain their macroporosity. Similar results have also been reported by Ziegler *et al.* (2004).

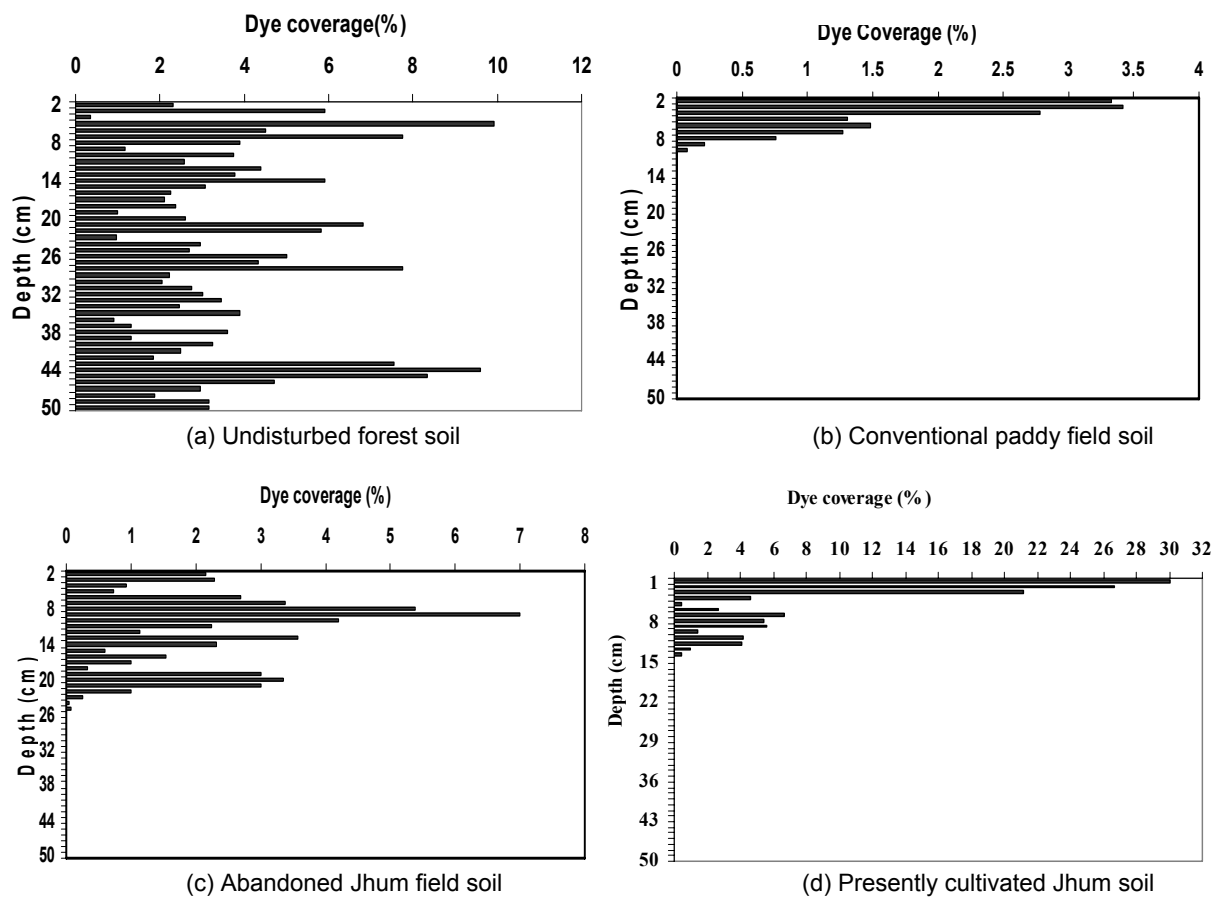


Fig. 4 Depth wise dye coverage distribution of soil columns of various sites.

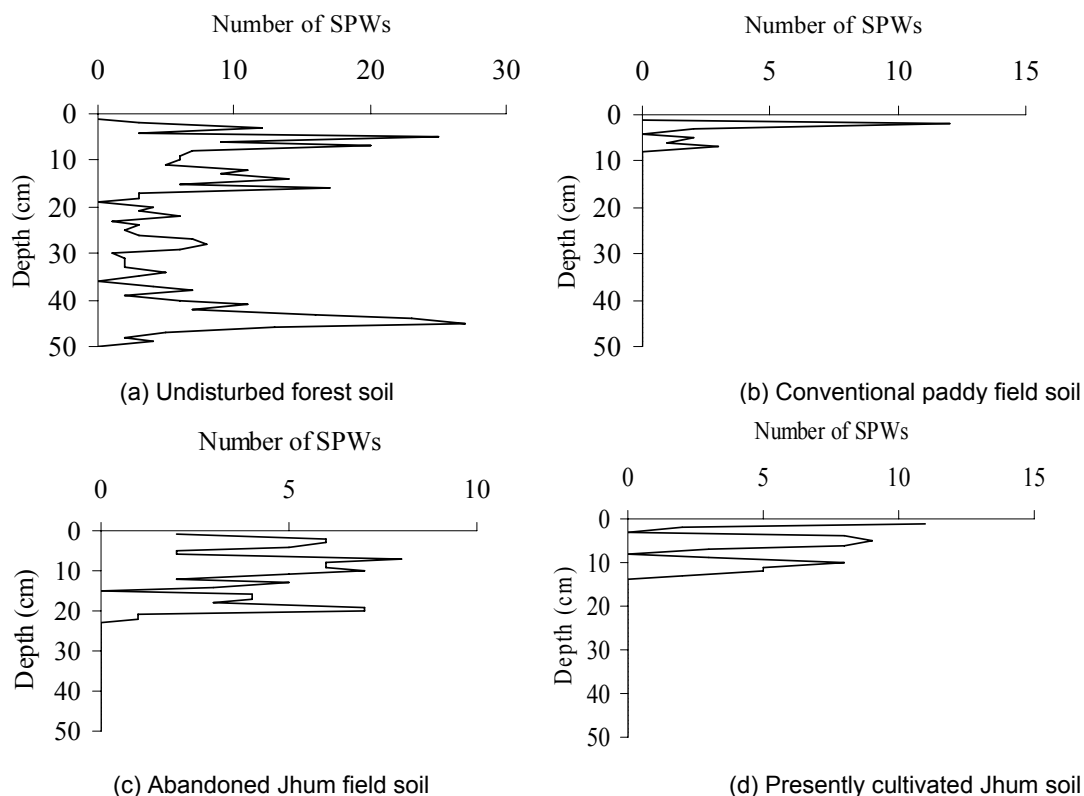


Fig. 5 Depth-wise distribution of number of SPWs under different soil conditions.

## MACROPORE FLOW AND ITS MODELLING

In order to understand the macropore flow behaviour *in situ* experiments were conducted on a vegetated hillslope plot of 18 m × 6 m size in the Brahmaputra River basin. The plot had clear evidence of well connected macropore network in its subsoil. The geographic location of the site is 26°12'N latitude and 91°42'E longitude with an elevation of about 55 m above mean sea level. A total station survey was conducted with a uniform grid spacing of 0.25 m to get the micro-topography data of the plot. The average surface slope was about 20%. For developing the subsurface flow model about 15 runoff experiments were conducted with a sheet flow generation system. The detailed description of the experimental set-up and site is given in Sarkar *et al.* (2008). The plot was instrumented with a profile probe soil moisture meter and 25 piezometers installed along five transects of the plot to keep track of subsurface moisture conditions and temporary water table build-up above the impermeable layer (Fig. 6).

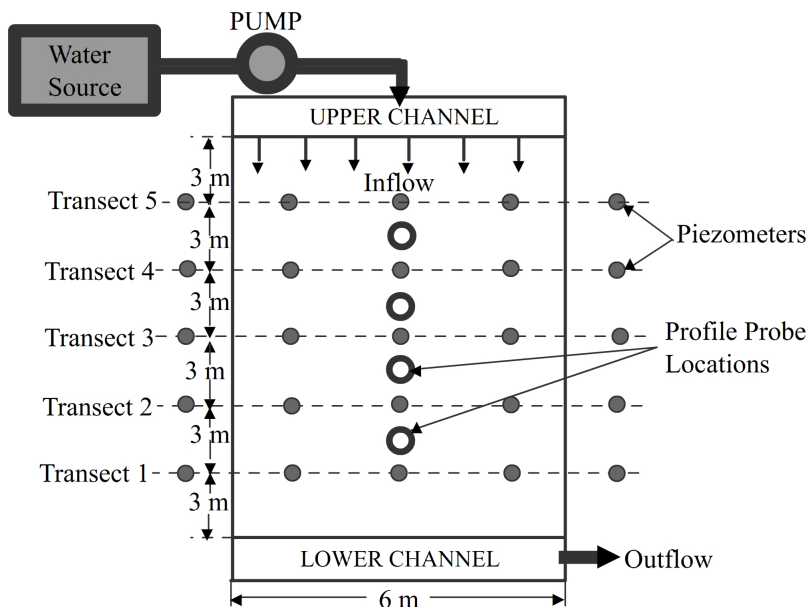


Fig. 6 Schematic diagram of the experimental set-up.

The modelling concept considers that the soil mantle consists of soil matrix and a population of lateral macropores. Total subsurface stormflow is due to saturated Darcian flow through the soil matrix and kinematic preferential flow through the macropores. The hydraulically effective soil macropores, which gets connectivity throughout the entire length of the slope, are assumed to be distributed in different layers of the soil profile. These lateral macropores are considered as circular pipes of small uniform diameter. Due to high preferential infiltration during extreme rainfall events a temporary water table is formed over the impermeable layer and starts contributing to lateral subsurface stormflow. Apart from the saturated matrix flow, the lateral macropores present below the temporary water table actively contributes to quick interflow mechanism from the hillslope. These macropores are termed “hydrologically active macropores”. The amount of water which seeps into the macropores is assumed to be discharged laterally with very high velocity without much interaction with the surrounding soil matrix (Anderson *et al.*, 2008). Thus, the temporary water table build-up and its recession are controlled by recharge as well as the number and diameter of hydrologically active macropores present within the saturated soil strata. The approximate possible numbers of macropores present in the soil layer, their depth wise distribution, and sizes can be obtained from the dye tracing experiments conducted with undisturbed soil samples.

Following the concept of Fan & Bras (1998) the basic equation of macropore dominated hillslope subsurface flow can be written as:

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = f(x,t)w - q(x,t) \tag{1}$$

$$Q = -k_s \frac{S}{\varepsilon} \frac{\partial z}{\partial x} \tag{2}$$

where  $f(x,t)$  is the rate of recharge to the saturated layer (m/h);  $Q$  is the subsurface discharge rate through soil matrix (m<sup>3</sup>/h);  $q(x,t)$  is the total discharge rate through the soil macropores per unit length of the hillslope (m<sup>2</sup>/h);  $w$  is the width of the hillslope (m);  $\varepsilon$  is the drainable porosity,  $S$  is the soil moisture storage;  $k_s$  is the saturated hydraulic conductivity of the soil matrix (m/h); and  $z$  is the bedrock elevation above a datum. Combining equations (1) and (2) yields a quasi-linear wave equation which can be solved numerically using a finite difference method considering Warming-Beam upwind scheme (Niyogi *et al.*, 2005).

The model was successfully used to simulate the observed temporal variations of water table build-up and recession in the experimental plot under various recharge conditions. All the experiments showed the common trend of increasing the number of hydraulically effective and hydrologically active macropores in soil with increasing rate of recharge. The field observations clearly showed very fast build-up and recession of the saturated zone above the impermeable layer, indicating the occurrence of rapid subsurface stormflow in the hillslope. In most of the cases within 2–3 hours from the cessation of recharge, major portion of subsurface runoff had occurred. With a very slow matrix flow rate such quick response is not possible and thus it is clear that the lateral preferential flow dominated the storm hydrograph. This typical runoff pattern seems to be captured properly in the model simulations. The peaks of both matrix and macropore flow hydrographs occurred immediately after the cessation of recharge. All the experiments clearly showed that matrix flow was almost negligible compared to the amount and rate of lateral preferential flow. Preferential flow contributed more than 99% of prompt interflow occurring immediately after the storm events and with the increasing rate of recharge, contribution of macropore flow also increased as a polynomial function (Fig. 7). Analysis of the computed subsurface flow hydrographs clearly showed that the peak rate of macropore flow has a good linear correlation with recharge. However, the peak matrix flow rate has a power relationship with recharge with comparatively poor correlation. This may be due to the significant domination of preferential flow over matrix flow prevailing in the hillslope.

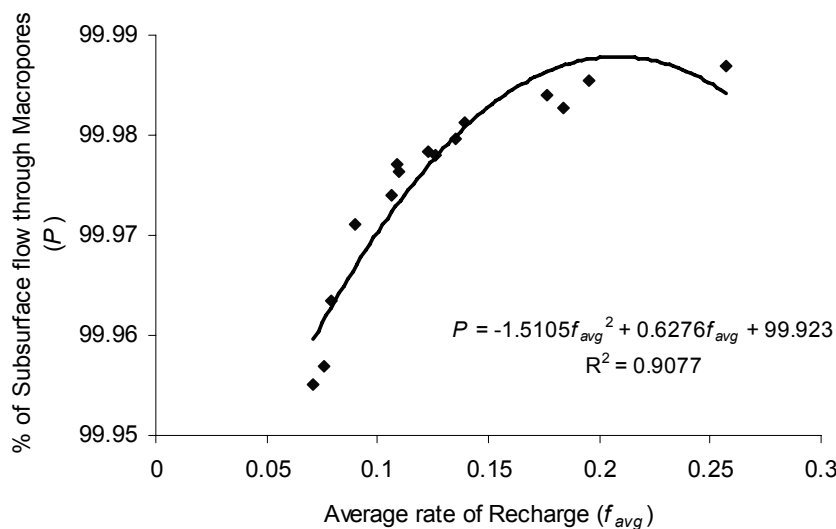


Fig. 7 Contribution of rapid preferential flow in subsurface flow hydrograph.

## CONCLUSIONS

The present investigation provides an insight to the dominating hydrological processes and their extremes in the hillslopes of Northeast India by coupling mathematical modelling with field investigation. The simple laboratory experimental set up provided valuable information about the macropore size, numbers, density, depth wise distribution, connectivity, and active flow network. Such information obtained from laboratory experiments were successfully used for modelling subsurface stormflow in a vegetated hillslope plot of the region. The model captured the rapid temporal variations of temporary water table build-up and recession above the impermeable layer. Apart from this, it was clearly evident that the hydraulically effective or hydrologically active lateral macroporosity, and peak rates of matrix and macropore flow are primarily controlled by the rate of recharge. Overall experimental procedure explained in this study can be very useful for developing physical based hydrological models for preferential flow dominated hillslopes where very limited information on qualitative or quantitative aspects of macropore flow is available.

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