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Watershed approach for studying soil preferential flow: A case study

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ABSTRACT

Preferential flow (PF) is a generic term used for water flow paths through biopores, fractures and macro pores. Many studies and models were already established to describe the PF. In semi-arid regions, the connecting aboveground and below ground processes to investigate how soil redistribute rainfall and nutrient and their impact on subsurface flow, is a fairly overlooked phenomenon. In this era of fast changing climate, erratic rainfall and rain water management, soil constitution plays an important role. In semi-arid regions, watershed is the basic hydrologic unit which gives study of the soil preferential flow a holistic look. In this regard, a study was conducted in Hayath nagar micro-watershed, Hyderabad, during 2020-2021.results revealed that the micro-watershed mainly comprises of heterogeneous matrix flow and fingering at surface while at sub surface macropore flow with low and mixed interaction prevails. This suggested that subsurface soils were mainly responsible for spatial redistribution of flows and generating lateral flow than vertical flow. Thus, the watershed under study requires better management practice to harvest water and check runoff at the time of high intensity rainfall. The results and the methodology of the present study have relevance in studying the preferential flow of diverse watersheds.

Keywords: Preferential flow, macropores, watershed, Brilliant Blue dye.

INTRODUCTION

Semi-arid ecosystems are important ecological and economic hotspots that comprise over 40% (6B ha) of the world's total land surface (Hassan 2005). In general, a semi-arid landscape is characterized by shallow soils and large proportions of bare rock, both expected to influence infiltration and groundwater recharge processes considerably. The dynamic soil matrix generally precludes the use of the traditional, deterministic modelling approach to predict flow and transport at the field scale. Preferential flow is a generic term used for obvious flow paths like biopores, fractures and macropores whereby water movement through a porous medium follows favoured routes bypassing other parts of the medium (Luxmoore 1991). It was not until the late seventies that increasing agricultural and environmental concerns created a renewed interest in the subject (Beven and Germann 2013). Since then, numerous studies have been undertaken to describe, measure, and model preferential flow. Application of geographic information system (GIS) and image analysis helps reduce field work and traversing and establish relationship between landform and soil in the watershed and its sub-divisions. In the water shed study, the delineation of drainage pattern, its network characters, landforms, land use, soil, vegetation *etc*, the use of remote sensing techniques considerably increases the efficacy of work. The relationship between soil and physiography (landform) helps properly understand and interact with soil for their different uses. By integrating spatial data with other data, GIS adds value and creates useful information for decision-making by analysis and by creating new data. Different disciplines analyse and describe data based on different land-based units. In hydrology, the land unit is the watershed, which also may be referred to as a basin or catchment. Watershed hydrology is determined by the local climate, land use, and pathways of water flow. Preferential flow, a common form of soil water movement, is a concept of soil hydrology taken a new pace in recent years, as it influences solute transport (Toor *et al.* 2005; Makowski *et al.* 2020) which in turn directs groundwater pollution. Heeren*et al.* (2010) proposed that preferential flow is water (together with dissolved and suspended matter) which accounts for a small proportion of the total pore network but is larger than the micro-scale. This view added insight on preferential flow from the perspective of a spatial

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network scale comparison.Thus, preferential flow bypasses the porous soil matrix and moves through a certain path in the soil, which has spatial and temporal heterogeneity (Guo and Lin 2018; Demand *et al.* 2019).

Modelling catchment hydrology, water quality and spatiotemporal characterization of hydrological flow paths resulting from complex subsurface heterogeneities (Lin 2006) is new challenge for hydrologists in recent past. Still, many contemporary models are based on conventional theories (such as Darcy's Law, the advection-dispersion equation, and conservation of mass), implying that water and solutes move within a slight deviation of an average (advective) velocity. Explicit mapping of all the heterogeneous sub-surface properties is practically an impossible task even in small research watersheds (McDonnell *et al.* 2007). The channel drainage network (topology) is also an essential hydrologic control in watersheds where landscape features adjacent to the stream are important sources of run-off (McGlynn *et al.* 2004; Buttle 2006) and at larger spatial scales, where in-stream transit times are significant. Spatial distribution of preferential flow path and its vertical connectivityenhances field characterization. Preferential solute transport simulation in soils convey better spatial and temporal variation prediction, which may help to tailor buffer design to site-specific conditions. Movement of water and solutes through heterogeneous media, typically soil, often encounter regions of enhanced flux,*i.e.* a small fraction of media (such as wormholes, root holes, cracks) leading to maximum flow through it, allowing much faster transport of contaminants, pesticides, nutrients, heavy metals, and pathogens. This creates significant consequences for ground-water quality in a watershed. The Watershed hydrological system consists of a soil matrix and a macropore domain, which interact depending on moisture contents and soil morphology (Van Schaik 2008). The macropore flow can result in subsurface flow, ranging from 13% contribution to total discharge for a large event of high-intensity rainfall or high discharge to 80% of total discharge for a small event with low intensity rainfall or low discharge (Van Schaik 2008).Based on this background information, this study was taken up to assess importance of watershed-based approach for studying soil preferential flow.

MATERIALS AND METHODS

Study area:

Hayathnagar micro-watershed is situated in Hayathnagar village, Rangareddy district of Telangana lying between 17^0 20' 18.00'' to 17^0 21' 8.94 N latitude and 78^0 35' 26.14'' to 78^0 36' 4.890'' E longitudes. The total area of the micro-watershed is 154 ha. The area has been divided into 3 units upper-reach, middle and lower-reach. The area under upper-reach is 54 ha, middle-reach is 60 ha and the lower-reach is about 40 ha.

Data source and watershed delineations:

Global Digital Elevation MAP (GDEM) of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) were downloaded from a free source Earth Explorer USGS website. It has a 30-metre resolution of image and in World Geodetic System (WGS84) projection. The ASTER GDEM comprises of Geo-referenced Tagged image file (GeoTIFF) format. ASTER was processed to delineate the watershed boundary. Arc Hydro is a set of tools that used to support geospatial and temporal data analyses especially related to soil and water assessment. According to Bryan and Curran (2004), ArcHydro does a good job at data management and ArcHydro is a better choice, when a large amount of data is required to be collected. A 10-metre interval contour line was also drawn based on elevation data extracted from ASTER-GDEM. ArcGIS10.3 software was used to delineate the micro-watershed. Based on this, the study areas was divided into upper, middle and lower reach to facilitate the flow analysis study in the micro-watershed.

Dye solution preparation and soil application:

A new hybrid methodology was developed to study preferential flow in the study area. It combines flow path study with the help of Brilliant Blue FCF solution with a concentration of 4 g/L (Flury and Flühler1994) and image analysis for the dye coverage. Since

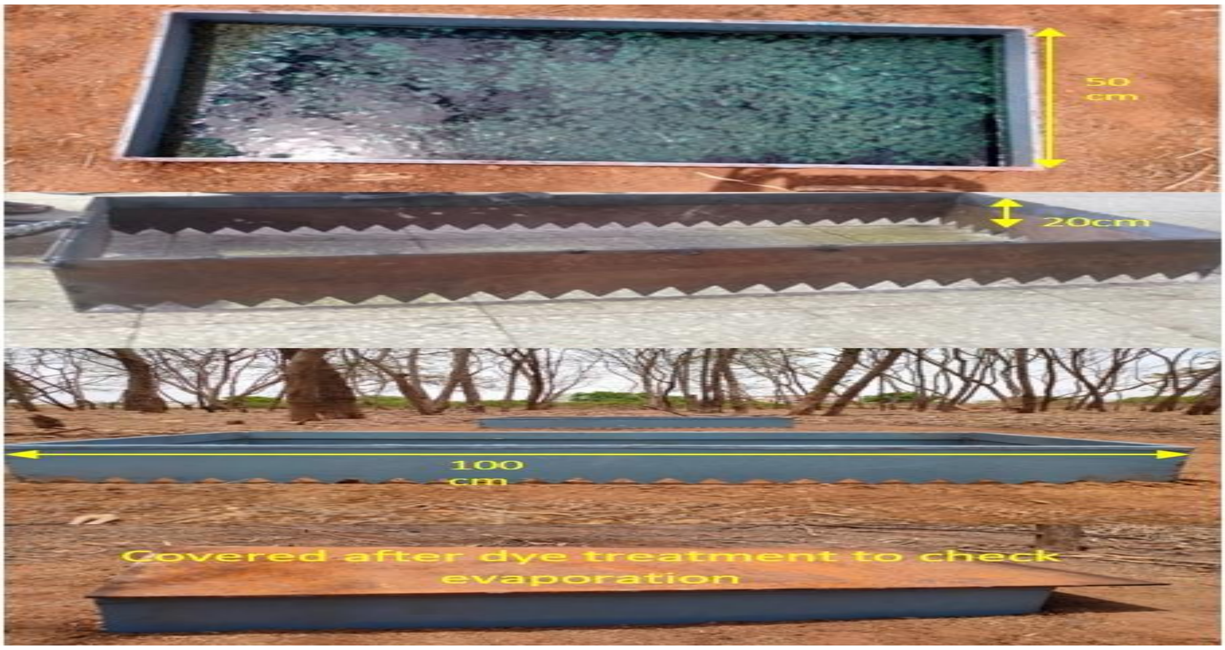


Figure 1: Iron frame fabricated for preferential flow study

the soil is sandy loam in the whole infiltration depth, adsorption and retardation of the dye were expected to be extremely low (Lipsius and Mooney 2006). The use of dye tracers is a common means to determine the distribution of preferential flow paths, and Brilliant Blue FCF is widely used (Hamed *et al.* 2015) coupled with image analysis. Tracer experiments were carried out in October-December 2020. At each site, two 1×1 m flat plotwas selected and an iron frame with a volume of 1.0×0.5 ×0.20 mwas embedded into the soil (Fig 1). The soil surface within 5 cm at the inner and outer sides of the iron wall was compacted to keep the dye from leaving the frame. Brilliant Blue FCF in water was applied manually at a concentration of 4 g/L with a backpack sprayer (Fig. 2). The application rate was determined by the infiltration capacity of the soil because ponding was to be prevented. The application took 1.2 hours. After 24 hours, a profile was dug beside the dye application area and the plot was excavated in five vertical profiles, each with a depth of 10 cm. The stained area was defined as the preferential flow path whereas the unstained area was considered the soil matrix.

Figure 2: Application of Dye- water with power sprayer

RESULTS AND DISCUSSION

Dye coverage in different land use:

Dye coverage experiment in this research highlights the preferential flow occurrence in the semi-arid environment at the present location. The dye coverage was almost 100 per cent in the upper 5-10 cm and then decreased rapidly with depth. Different physiographic area displayed different preferential flow properties. The results showed high dye coverage value (more than 50%) for soil depth of 0 to 10 cm which reduced to (< 30%) lower value for depth below 30 cm in all of the land-use types (Fig. 3), similar observations were also made earlier by Cheng*et.al.* (2011). The vertical distribution differed widely in the various land-use types. Plantation and cropped land had more preferential flow paths in the topsoil compared with forest land, and fallow land. At all the elevations the three land use systems showed different dye movement pattern among themselves.

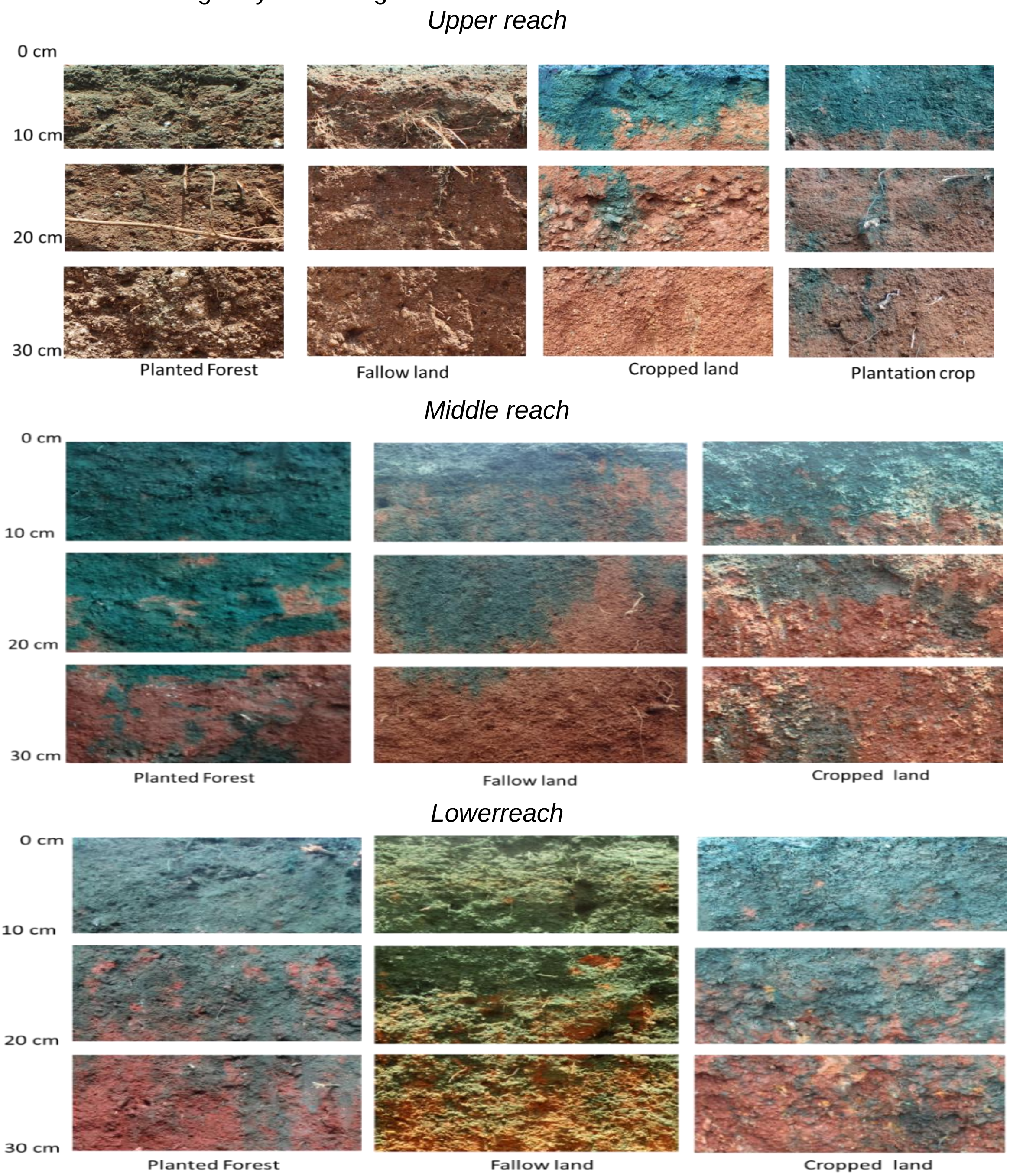


Figure 3: Typical soil profile under different elevation and land use (upto 30 cm)

At lower reach, the dye pattern of all land use system coverage at around 20cm of depth. The funnelling after this depth was more prominent in cropped land use system, one more dip in dye coverage wasobserved at around 30 to 33 cm of depth. This may be due to continuous rocky fragments at this depth (Chen *et al.,* 2018). This effect was less prominent in forest and fallow land, owing to weathering of rocks at higher rate in these land use systems. Forest soils also showed slight funnelling at this depth while in middle elevation zone, the dye pattern showed funnelling by 30 centimetres in all theland use systemstudied. Soil profile below 30 to 40 centimetres in all these systems was found to be very compact. Compaction mainly disrupts and destroys macropores in the soil. It might reduce the extent of preferential flow (Mossadeghi-Bjorklund, 2016) in the soil. Cropped land showedmuch more compaction at this depth than planted forest and fallow land.

Fallow land both in middle and lower reach showeduniform infiltration more than forest and cropped land as the number of fine roots were found to be more in fallow land. Zwartendijk (2017) also found similartrend infallow lands. Cropped land was having more finer roots but the macropore channels were disturbed leading to bottleneck pattern of dye movement in the land use. Excessive lateral flow was observed just beneath the surface, even though macropores were present below this depth. Zwartendijk (2017) found that most of the infiltrated water stays in the top 30 centimetres of soil or it results in shallow lateral flow due to clay layers just below it letting very little water to percolate. Planted forest in the whole micro-watershed was more than 40 years old while plantation crop was 30 years old. Several studies showed thatthe predominant flow paths could remain stable for decades. These findings accord well with theresults reportedby Hagedorn and Bundt (2002). Though plantation crop was younger compared to a forest, the root system of the plantation crop was very well developed. This may be the reason for much more developed preferential flow pathways in this land use (Colloff*et al.*, 2010). In all the land use of upper reach funnelling starts at lesser depth, 10 to 20 centimetres as compared to middle reach, 30 to 40 centimetres and lower reach, 30 to 40 centimetres (Fig. 4). The dye pattern clearly showed that each land-use system has its own pattern of dye movement on a vertical scale. These patterns were observed to be much more distinct at upper elevation, stepping down till lower elevation for all the land-use systems.

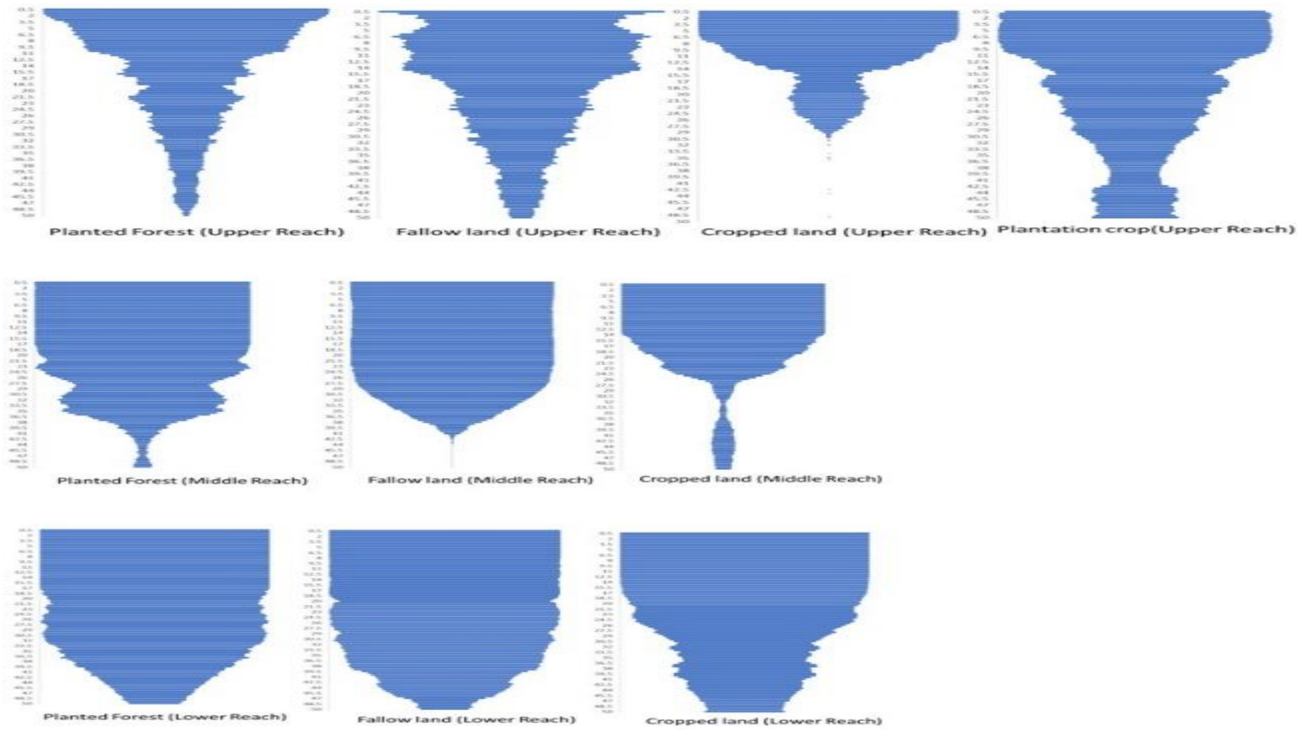
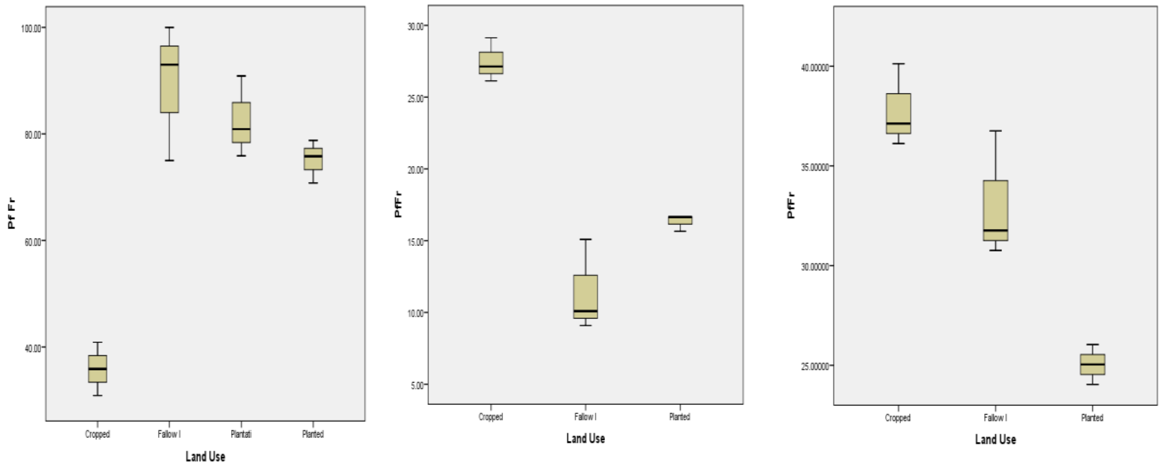


Figure 4: Funnel graph of the dye movement down the profile under different elevation of micro-watershed



Upper Middle Lower

First from left: Cropped land, fallow land, plantation, planted forest - (upper reach); cropped land, fallow land, planted forest – (middle reach); cropped land, fallow land, planted forest – (lower reach)

Figure 5: Preferential flow fractionunder different elevation and land use.

Wilcoxon signed-rank test-Significance at 0.05 level and box plot graph (fig. 5) was drawnwith the hypothesis that there is no change in preferential flow parameters with elevation and land use. Based on this study, the hypothesis was rejected with significance at upper reach by 0.002** middle reach by 0.008** and at lower reach by 0.008**.

Table 1: Correlation of dye coverage with Depth, elevation and land use

Units	Coefficients	Standard Error	t Stat	P-value
Intercept	562.32	14.73	38.18	0.00
Depth	-0.69	0.01	-59.84	0.00
Elevation	-1.019	0.03	-34.98	0.00
Land Use	-0.549	0.31	-1.77	0.048

Correlation of dye coverage with elevation, depth and land use was studied using 1101 samples (Table 1) showed that 81% of the variance of the dependent variable being studied is explained by the variance of the independent variable. Depth and land use are highly significant with $p< 0.001$ whereas land use was significant at $p<0.05$. Based on preferential flow fraction parameters compared under different elevations, the preferential flow advantage of forest land is more evident than that of fallow land. In upper reach of watershed, surface soil mostly has heterogeneous matrix flow and fingering while subsurface was observed to have more macropores with low interaction. Thus, the surface soil shows flow instability due to coarse texture and water repellence while subsurface is poorly permeable soil. Middle and lower reach was heterogeneous matrix flow and fingering as major flow type in the surface while macropores with mixed interaction in the subsurface of the soil profile. While taking watershed as unit to study preferential flow, we found that different land uses and elevations playan important role in deciding the type of preferentialflow which may lead to better management practices of respective soils for better water and crop productivity.

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