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Lateral flow assessment in laterite terrain under simulated rainfall conditions

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ABSTRACT

The subsurface flow of water in laterite terrain can play a vital role in regulating the groundwater. The state of Kerala experiences an average annual rainfall of about 3000 mm. Conversely, it experiences severe dry spells during the post–monsoon season leading to an unusual decline in the groundwater levels resulting in water scarcity. The study highlights the analysis of lateral flow in a laterite terrain and its variation with varying soil profile depths. The possible contribution of lateral flow in groundwater recharge has been analyzed and emphasized in the study. The experiment was carried out in Tavanur, a village located in the Malappuram district of Kerala. Lateral movement of water was assessed through a soil profile under simulated rainfall conditions. It was done by using the conventional gravimetric method of moisture measurement. A trench of dimensions (6 m × 0.5 m × 2 m) was installed to monitor the lateral movement of water. Moisture measurements were carried out for three soil profile depths of 0–40 cm, 40–80 cm, and 80–120 cm over a period of 12 hrs. Simulation of rainfall was carried out throughout a week for 12 hrs continuously in a day using a butterfly sprinkler. The study revealed that the lateral flow in the site accounted for 28.3% of the total simulated rainfall. It was inferred from the study that a major portion of applied water was lost in the form of rapid lateral flow even when there was no considerable surface runoff. Thus, the study signified the adoption of effective interventions for rainwater harvesting and its conservation in laterite terrain irrespective of abundant annual rainfall for effective groundwater replenishment.

1. INTRODUCTION

Kerala state, located in the south–western part of India, is known in earth science literature as the '*type locality*' of 'laterite', a name first coined by Francis Buchanan in 1800 at the Angadipuram of Malappuram district of the state Kerala (Krishnan *et al.,* 1996; Chandran *et al.,* 2005). Subsurface flow plays a very important role in governing the hydrological response, especially in humid areas (Anderson *et al.,* 2009). The lateral flow of water can play an extremely vital role towards groundwater recharge in the areas with underlying crystalline rock aquifers and laterite soils (Bonsor *et al.,* 2014). Malappuram, the north–western district of Kerala is covered up to 85%, by the crystalline and laterite aquifers. The laterite acts as the potential aquifer for the area due to its high porosity and permeability. Given this high porosity, subsurface runoff is quite prevalent causing the loss of stored water. Thus, it minimizes the deep percolation of water and results in inadequate groundwater recharge. Furthermore, hydraulic conductivity of these soils varies in the range of 10^{-4} to 10^{-5} cm s^{-1} which describes its high permeability resulting in quick drain off from unconfined aquifers. The present study focuses on assessing lateral flow and its rate of flow in the vadose zone under simulated rainfall conditions. It was done specifically from three soil profile depths of 0–40 cm, 40–80 cm, and 80–120 cm. The lateral flow was induced through simulated rainfall at an intensity to imitate a moderate rainfall in the site.

2. MATERIALS AND METHODS

Description of Study Area

The study was carried out in the KCAET campus, Tavanur, Malappuram district, of Kerala, India (Fig. 1). It is situated at latitude and longitude of 10°51'18”N and 75° 59'11”E, respectively at an altitude of 12 m above mean sea level. The terrain is lateritic in nature with a gentle slope and sandy loam soil type. The average annual rainfall received by the area lies in between 2600 mm to 3322.4 mm. The variation of average temperature in the study area ranges

Fig. 1. The study area

between a maximum of 31^{0}C to a minimum of 26^{0}C. The area is rich in vegetation with deep and dense rooted flora.

Experimental Details

Site selection: The site was selected subject to the following criterions:

- Terrain with a gentle slope
- Minimal through fall
- Availability of pumping facilities (inclusive of irrigation source and electricity supply)
- Needful transportation

Determination of Soil Physical Properties

Soil physical properties such as dry density, specific gravity, porosity, voids ratio, and soil texture were determined for the experimental site.

Installation of the Experimental Setup for Lateral Flow Monitoring

The experiment for lateral flow monitoring was carried out in the post–monsoon season of the year. The area under consideration was 78 m^2 with a general slope of 5%. The site was first well protected by a vegetative barrier as an enclosure, to prevent trespassing, livestock, and wild animals straying. A trench of length 6 m, width 0.6 m, and depth 1.8 m was dug at the downslope of the site with at most care as to prevent any major soil disturbance in the site as shown in Fig. 2.

A tin sheet having a thickness of 14 gauge (1.628 mm) and a length of 5 m was, tilted towards the depth of the trench, was inserted on the monitoring face of the trench at a depth of 1.2 m from the soil surface as shown in Plate 1.

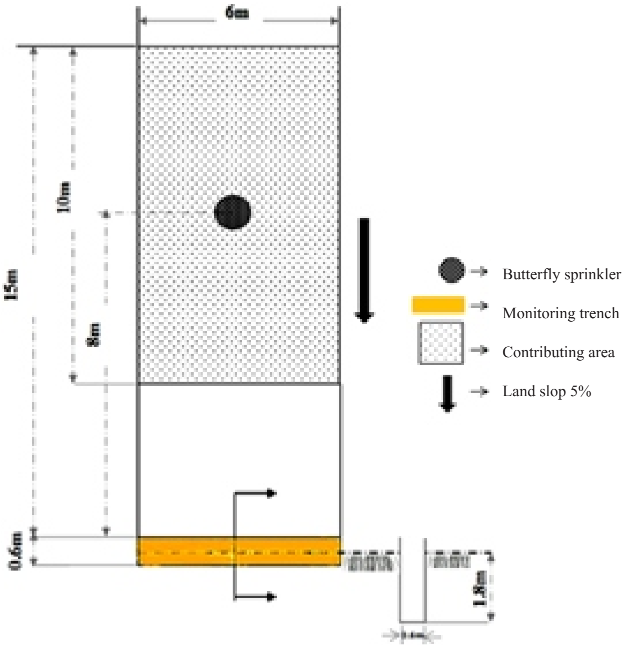

Fig. 2. Plan view of the experimental setup

Plate 1. Installation of experimental setup

A water collecting can was kept at the collecting phase of the trench at the end of the inserted tin sheet. The trench was covered with a tarpaulin sheet to prevent the direct fall of irrigation water into the trench. Motor, pipelines, and ancillary connections to fix the sprinkler system were installed in the field to derive water from a nearby pond. A disc–type filter was provided in between to prevent the clogging of sprinklers. The sprinkler was connected through lateral to the mainline. A pressure gauge was also installed in the line to measure the pressure. A butterfly sprinkler was operated at a pressure of 1 kg cm^{-2} using an induction motor of 1.02 HP power. The sprinkler was erected at the center of the experimental site to ensure uniform wetting of the area. A spray diameter of 10 m was obtained and a uniformity coefficient of 90.90% was achieved in the study site. The height of the lateral was adjusted keeping no tradeoff between uniform wetting of the site and no direct fall into the trench.

The experiment was carried out to determine the precise lateral flow rate of water in the site. The sprinkler was erected at the center of the experimental site at a distance of 8 m from the downslope trench. Continuous irrigation was carried out for twelve hours a day at an operating pressure of 1 kg cm^{-2}. The discharge obtained from the sprinkler at this operating pressure was 660 lph

(0.84 cm hr^{-1}). A variation in the application rate of sprinklers due to the clogging of the disc filters was subsequently confronted by cleaning the disc filters after every two hours of irrigation. Soil samples for the gravimetric analysis were collected in steel cans after every 2 h interval. The soil samples in the can were carefully placed in the oven for 24 hrs at 105^0C. The experiment was carried out for seven days in succession. The experiment provided an insight into the changing flow pattern of water in soil matrix throughout a day and its effect on the lateral flow rate.

Quantification of Lateral Flow

The present study has considered the variation in volumetric water content as the base to quantify the lateral flow of water through the soil matrix. Thus, the volume of water entering a unit width of soil column may be determined as:

Volume of water present in the soil column at time t_1) – (Volume of water present in soil column at time t_2.

Therefore, $V_1 - V_2 (L_1 \times W_1 \times H_1 \times \theta_1) - (L_2 \times W_2 \times H_2 \times \theta_2)$.

Where, L = Length of the soil column, W = Width of the soil column, H = Height / Depth of the soil column, θ = Volumetric soil water content.

For, the same soil column volume of water entered in time ($t_1 - t_2$).

$$V = L \times W \times H \times (\theta_2 - \theta_1)$$

Subsequently, let Q be the discharge rate of subsurface flow through a cross–sectional area of A, then pore velocity can be determined as:

$$v = \frac{Q}{A * Porosity}$$

In the present study quantification of lateral flow has been done for a unit width of the soil column.

3. RESULTS AND DISCUSSION

Soil Physical Properties

The soil physical properties of the site depicted an increase in the bulk density with increasing depth as shown in Table 1. Thus, soil compaction with increasing soil depth was observed in the experimental site. Subsequently, increasing specific gravity was noted with the increase in soil depth representing finer soil layer at a depth of 80–120 cm as compared to the first two soil horizons. The soil layer at a depth of 0–40 cm had the highest porosity as compared to the other two depths. This was due to the presence of rich organic matter and coconut tree roots along with grass present in the site.

Quantification of Lateral Flow

Table: 1
Soil physical properties in the experimental site

S.No.	Physical properties	Site 1		
		0–40 cm	40–80 cm	80–120 cm
1.	Initial soil moisture content (% GWC)	18%	15%	17%
2.	Dry density (g cm^{-3})	1.16	1.54	1.56
3.	Specific gravity	2.41	2.51	2.64
4.	Porosity	0.52	0.39	0.40
5.	Voids ratio	1.08	0.63	0.67
6.	Soil texture	Sandy loam	Sandy loam	Loamy fine sand

The experiment was carried out for 12 hrs a day from 6:00 am to 6:00 pm for seven consecutive days. The total water application rate of the butterfly sprinkler was 660 lph / 0.66 m^3 hr^{-1}. The total area under consideration was 78 m^2. Thus, the depth of water applied through the sprinkler in the site was 0.00846 m hr^{-1}.

Thus, depth of water applied throughout the *in–situ* experimentation for 12 hrs was given as:

d = 0.00846 * 12 = 0.10152 m / 12hrs or m day^{-1} (as per experimental hours).

Volume of water through the contributing area of 60 m^2 will be:

$V_c = d * 60 = 6.0912\ m^3 day^{-1}$

Thus the total volume of water through the contributing area for seven days will be given by:

$V = V_c * 7 = 42.6384\ m^3 = 42638$ litres

A total discharge of 1131.41 litres, 2576.85 litres, and 8415.57 litres was obtained from soil profile depths of 0–40 cm, 40–80 cm, and 80–120 cm, respectively for a period of seven days. This accounts for a total of 12123.84 litres as subsurface flow / lateral flow discharge in seven days of the experiment (Table 2). Thus, the calculated lateral flow from a soil profile depth of 2 m in the experimental site accounted for 28.43% of the simulated rainfall. The daily discharge and lateral flow velocity (Table 2) showed a dynamic variation in the lateral flow discharge through the three soil profile depths. This may be attributed to the diurnal evapotranspiration occurring in the first two soil depths and the capillary movement of water at third depth in the site. The diurnal variation of surface albedo is not symmetrical about mid–day and the variation is exponential (Guan *et al.,* 2009). There is a nonlinear dependency between soil moisture and soil thermal diffusivity which was observed. The thermal diffusivity will first increase with soil moisture, then decreases after reaching its maximum, (Roxy *et al.,* 2010). This phenomenon was also noticed and justified in the present study through the daily gravimetric soil moisture content analysis as shown in Fig. 3. On the first day of the experiment, all the three soil profile depths on the trench face reproduced a varying pattern in soil moisture increase and depreciation. Moisture content increased till 10:00 am and then started to dip till 4:00 pm at the soil profile depth of 0–40 cm. At depth of 40–80 cm, moisture content increased till 10:00 am, and successively experienced alternate raise and dips till the end of the experimental hours.

Nearly, the same pattern of moisture content variation was experienced at soil profile depth of 80–120 cm. With the advancement of the experiment, each day's pattern of soil moisture content variation became more dynamic in all three soil profile depths.

Visible macropores on the trench face can be a potential indicator of preferential flow pathways in the site (Beven and Germann, 2013). This phenomenon can be attributed to the sudden upsurge of moisture content observed at depths of 80–120 cm on 10th and 11th February, 2019. A negative discharge represented the draining of water from a specific soil depth.

4. CONCLUSIONS

The field experiment carried out at the site was a preliminary probe to examine, understand and establish the phenomenon of interflow in laterite soils and its dynamicity. The following conclusions can be drawn from the study:

Table: 2
Variation in lateral flow discharge and its rate in different soil profile depths

Date	Depth (cm)	Average lateral flow discharge $(l\ m^{-2}h^{-1})$
5/02/2019	0–40	7.15
	40–80	9.06
	80–120	8.21
6/02/2019	0–40	16.54
	40–80	15.22
	80–120	18.87
7/02/2019	0–40	10.29
	40–80	6.12
	80–120	16.66
8/02/2019	0–40	7.38
	40–80	28.90
	80–120	9.53
9/02/2019	0–40	12.39
	40–80	14.09
	80–120	21.84
10/02/2019	0–40	8.22
	40–80	8.08
	80–120	23.06
11/02/2019	0–40	15.13
	40–80	4.62
	80–120	12.48

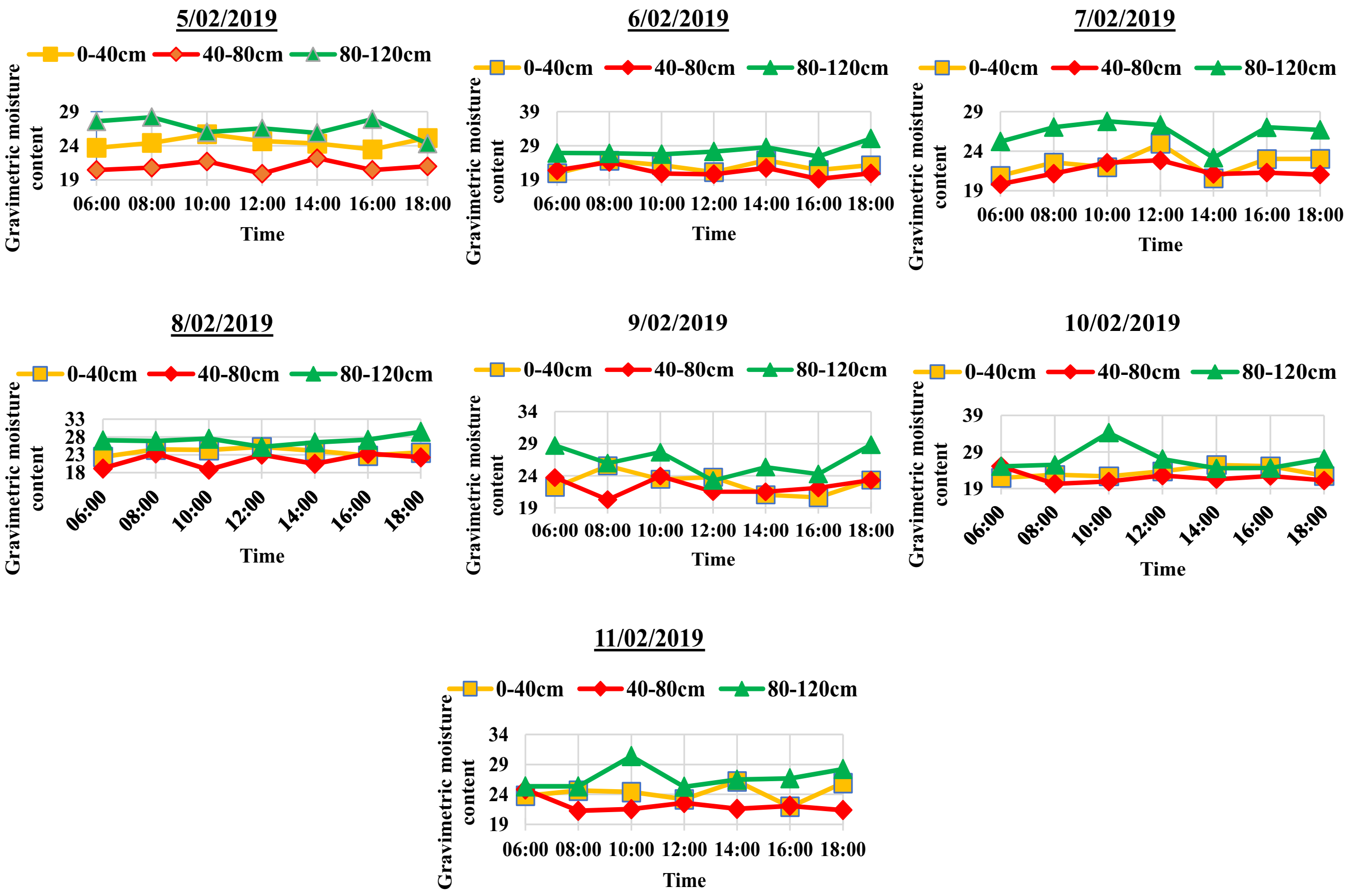

Fig. 3. Variation of gravimetric moisture content with time from 5/02/2019 to 11/02/2019

1. The physical properties of the soil show considerable variation even for small geographical separations and with respect to minor profile depth variations in laterite terrains.
2. It was seen that the most important physical property of the soil which governs the lateral flow is bulk density, effective porosity, and soil texture.
3. The study suggests that though the infiltration capacity of the lateritic soil is very high, a major portion of the infiltrated water moves laterally without reaching the water table. To augment groundwater recharge, more preferential flow in the vertical direction has to be enhanced through the presence of deep–rooted vegetation. Else mechanical barriers to check the lateral flow and to divert that in the downward direction are required.
4. The study also provides useful input for large–scale interflow assessments in laterite soil. It will be useful in suggesting suitable interventions for soil water conservation and groundwater replenishment. The present study highlights the need for a much in–depth study including mineralogy and bedrock characteristics in laterite terrain to better understand the soil water movement and its effect on regional hydrology.

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