Effect of scale on infiltration in a macropore-dominated hillslope

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Accurate measurement of infiltration for modelling flow and transport processes is critical in macropore-dominated hillslopes, where the flow patterns can change even within a short distance. To study the effect of scale, in situ experiments were conducted using both local and plot-scale measurements. Local-scale infiltration was measured using a double-ring infiltrometer, whereas plot-scale infiltration was estimated by conducting run-off experiments using a sheet flow generation system. The results indicate that the local-scale measurements were not reliable and produced irregular patterns of infiltration. The plot-scale measurements were fairly consistent and accurate in describing the infiltration process.

Keywords: Hillslope, infiltration, macropores, scale.

Infiltration is one of the critical processes of the hydrologic cycle as it controls the spatio-temporal partitioning of rainfall into surface and subsurface flow, and the subsequent movement in and between these two general components of the hydrologic cycle. Proper understanding of infiltration behaviour is essential for accurate modelling of the hydrological response of a watershed. Over the past few decades several infiltration models based on Darcy’s law have been proposed for estimating infiltration behaviour under different conditions. Though some of these models have been commonly used, their main limitation is that they are conceptually valid for water flow through the soil matrix only. When a significant amount of water flows through the preferential pathways (macropores) of soil bypassing the soil matrix, assumptions of homogeneity of the soil hydraulic properties over some representative cross-sectional area are no longer valid and thus the flow concept based on an average hydraulic gradient is expected to fail. A number of studies have reported that the results obtained from Darcy-type infiltration models failed to represent the irregular patterns of infiltration observed in macropore-dominated soils. The presence of macropores generally leads to heterogeneity of flow within the soil. The size of macropores as well as their connectivity, which may change within a few centimetres as well, influence the infiltration behaviour of the soil. Under such conditions, a combined experimental and modelling approach for predicting infiltration has been adopted by many researchers. However, performance of the physical-based infiltration models largely depends on the accuracy of the infiltration measured in the field. Parr and Bertrand classified infiltration measurement procedures as: (a) estimation of infiltration over a plot from run-off data obtained using rainfall simulators; (b) point measurement of infiltration using infiltrometers, and (c) estimation of infiltration from natural rainfall data. But the selection of a particular method is critical as the error involved in the estimation largely depends on the scale of measurement, and also the physical conditions of the site which influence infiltration rate. Haws et al. studied the spatial variability of infiltration and effect of measurement scale on steady-state infiltration rate on an agricultural landscape considering local-scale, hillslope-scale, and landscape-scale measurements. They reported a representative measurement area (RMA) above which the scale effect of infiltration was not evident, about 400 sq. cm. Infiltration measurement particularly on a hillslope is complex, as the lateral gravity component influences the soil wetting pattern considerably. Relatively little has been reported on the infiltration and redistribution of soil moisture on hillslopes. Negi emphasized the need of micro-scale (plot-level) and meso-scale studies in the Himalayan mountainous regions for better understanding of the hydrological processes. The present investigation aims at field measurement of infiltration on a macropore-dominated hillslope and also to compare the local-scale infiltration measurements with the plot-scale measurements.

The in situ experiments were conducted on a hillslope plot (Figure 1) located near Guwahati on the northern bank of Brahmaputra River (26°12’N lat., 91°42’E long, elevation 55 m asl). The plot has an average slope of 20% along the...
Table 1. Soil profile data of the experimental site

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Average bulk density (g/cubic cm)</th>
<th>Saturated hydraulic conductivity (Ks) (mm/h)</th>
<th>Average porosity</th>
<th>Average sand (%)</th>
<th>Average silt (%)</th>
<th>Average clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer (up to 40 cm)</td>
<td>1.139</td>
<td>62.48</td>
<td>0.57</td>
<td>69.55</td>
<td>18.03</td>
<td>12.42</td>
</tr>
<tr>
<td>Bottom layer (40–100 cm)</td>
<td>1.240</td>
<td>42.43</td>
<td>0.53</td>
<td>59.08</td>
<td>29.83</td>
<td>11.09</td>
</tr>
</tbody>
</table>

Figure 2. Infiltration measurement points in the plot.

main sloping direction, with little micro-topographic variations. The hillslopes of the region are reported to have deep, coarse loam soils, classified under the hyperthermic family of Aquic udifluvents. Soil textural analyses (Table 1) of samples collected from the plot at different depths indicated a two-layer soil formation with a highly permeable coarse soil layer overlain by fine textured soil. In the subsurface up to almost 1 m depth, an intense macropore network, mainly induced by plant roots, was clearly evident. The plot was densely covered by its natural vegetation consisting of close-growing grasses and shrubs (Cynodon dactylon, Saccharum spontaneum, Mimosa pudica, Ageratum conyzoides, Ageratum haustorianum, Lantana camara, Mikania micrantha and Parthenium hysterophorus).

Infiltration measurements were carried out on a vegetated hillslope plot of 18 m x 6 m dimension. Local-scale measurements were made using a double-ring infiltrometer having an inner cylinder diameter of 30 cm. During measurement the two cylinders were inserted concentrically and water level was maintained in both the cylinders while infiltration measurement was carried out in the inner cylinder. This gives a measurement area of about 700 sq. cm for each set of measurements. Infiltration was measured at ten locations of the plot (Figure 2) under dry as well as wet antecedent conditions. The plot-scale measurement of infiltration was carried out by conducting run-off plot experiments using a sheet flow generation system. It consists of an upper channel at the upstream end of the slope and a lower channel at the downstream end. A centrifugal pump was used to feed water in the upper channel. Once the upper channel gets filled, water starts to spill from it and spreads over the entire plot in the form of sheet flow. Two side-plates were used to guide the overland water to the lower channel where it was collected, measured and discharged. Using the inflow and outflow hydrographs, spatially averaged infiltration rate over the plot was computed. The sheet flow generation system was preferred over rainfall simulators as it was more suitable in simulating a wide range of high-intensity (about 400 mm/h) storm events, often considered to be critical in macropore dominated hillslopes.

The double-ring infiltrometer tests were carried out in locations 1–5 under dry soil conditions with sparse vegetation and in locations 6–10 under wet soil conditions with dense vegetation. Infiltration tests under dry soil conditions showed no particular trends or patterns (Figure 3 a). Even after more than 1.5 h after the start of the experiment, the infiltration rate did not reach a steady-state condition under dry soil conditions. These behaviours are quite similar for infiltration in a preferential flow-dominated soil. The average infiltration rate varied within a wide range, i.e. 18–256 mm/h. However, under wet soil conditions the infiltration rate tends to reach a near steady-state condition about 1 h after the start of the test (Figure 3 b). The near steady-state infiltration rate varied in the range 42–130 mm/h (Table 2). This can be explained from the fact that under dry conditions soil suction pressure was high and as the water infiltrated downwards, it passed through different active networks of soil macropores which resulted in irregular patterns of infiltration. However, under wet conditions soil suction was less and all the macropores were primed for water flow. Therefore, a near steady-state infiltration condition was attained after sometime. However, from the wide range of infiltration rates in both cases, it is clear that even within a small plot the effect of local scale dominated. Infiltration rate in the upslope locations was higher than the downslope locations because of higher lateral gravity component in the upslope points.

The run-off plot experiment results (Table 3) indicate that the spatially averaged steady preferential infiltration
Table 2. Results of double-ring infiltrometer tests

<table>
<thead>
<tr>
<th>Location</th>
<th>Antecedent moisture condition</th>
<th>Degree of vegetation</th>
<th>Range of infiltration rate (mm/h)</th>
<th>Mean (mm/h)</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–5</td>
<td>Dry</td>
<td>Sparse</td>
<td>18–256</td>
<td>156</td>
<td>49</td>
</tr>
<tr>
<td>6–10</td>
<td>Wet</td>
<td>Dense</td>
<td>42–130</td>
<td>78</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 3. Results of plot run-off experiments

<table>
<thead>
<tr>
<th>Degree of vegetation</th>
<th>Antecedent moisture condition</th>
<th>Range of simulated rainfall (mm/h)</th>
<th>Range of steady infiltration rate (mm/h)</th>
<th>Mean (mm/h)</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparse</td>
<td>Dry</td>
<td>59–361</td>
<td>33–139</td>
<td>62</td>
<td>45</td>
</tr>
<tr>
<td>Dense</td>
<td>Wet</td>
<td>87–310</td>
<td>83–245</td>
<td>135</td>
<td>36</td>
</tr>
</tbody>
</table>

Figure 3. Double ring infiltrometer test for dry (a) and wet (b) soil conditions.

rate \( f_i \) was a function of simulated rainfall intensity \( I \) (Table 4) under both physical conditions of the plot. Steady-state infiltration conditions were also attained much earlier (about 15 min) than the double-ring infiltrometer tests (Figure 4). The results indicate lower average steady infiltration rate values for sparse vegetation condition and higher values for dense vegetation. This is in agreement with the fact that under dense vegetation, higher root density would enhance the macropore connectivity and thus result in higher infiltration rate. It can also be observed that the run-off plot experiments under wet conditions produced higher infiltration rates than under drier conditions. This emphasizes the fact that in macro pore-dominated hillslopes, preferential pathways of infiltration play a more significant role in determining the infiltration behaviour rather than soil suction pressure. As in this case, the wet conditions also represent dense vegetation, the resulting high root density providing significant soil macropore connectivity to have a pronounced effect on preferential infiltration rate. Under dry conditions, in spite of higher soil suction, the average infiltration rate was much lower due to lesser root density for sparse vegetation, which provides less macropore connectivity in the subsoil. However, double-ring infiltrometer tests under dry conditions produced higher average infiltration rate (156 mm/h) and under wet conditions produced much lower average infiltration rate (78 mm/h). These can be attributed to the local-scale effect of measurement and thus do not represent macropore connectivity prevailing within the entire plot. Therefore, such point measurements are not reliable to interpret actual infiltration behaviour at the hillslope scale.

It is also worth noting that Hawks et al.\(^{21}\) reported an RMA of 400 sq. cm, above which the scale effect on infiltration measurement was not significant. However, in the present investigation even with a measurement area of about 700 sq. cm, the local-scale effect was clearly evident in double-ring infiltrometer results. Infiltrations measured from run-off plots were clearly more accurate and realistic as they represent infiltration rate spatially averaged over a larger area and thus consider the soil continuum behaviour by taking into account macropore connectivity within the soil. Further, the saturated hydraulic conductivity (Table 1) for water movement through the soil matrix only, as computed from soil textural data\(^{30}\), was much lower than the spatially averaged steady preferential infiltration rate computed from run-off plot experiments. This clearly indicates the high variability of infiltration rate due to the presence of macropores in the soil.
The experiments clearly indicate that local-scale infiltration measurements on macropore-dominated hillslopes using double-ring infiltrometers lead to grossly erroneous results, even with a measurement area of about 700 sq. cm. Such infiltrometer tests either over- or underestimate the infiltration rate and thus are not reliable for use in hydrological modelling. Whereas infiltration behaviour obtained from plot-scale run-off experiments was fairly consistent and could be interpreted easily with the existing physical conditions of the plot. Therefore, in macropore-dominated hillslopes where infiltration patterns largely depend on the existing soil macropore network and its connectivity, the plot-scale infiltration measurements are more reliable than local-scale measurements.

Structural attributes of lantana-invaded forest plots in Achanakmar–Amarkantak Biosphere Reserve, Central India

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Vegetation of lantana-invaded forest plots in the Achanakmar–Amarkantak Biosphere Reserve has been analysed. Only 20 out of the 126 plots examined were found infested with lantana (Lantana camara L.). These plots were divided into low lantana density and high lantana density groups. Ordination using Principal Component Analysis on the structural attributes of the vegetation separated the plots into low altitude and high altitude groups, but did not separate lower lantana density plots from higher lantana density plots. ANOVA also indicated no significant differences in the community-level structural attributes between lower and higher lantana density plots. Nevertheless, species-level differences were evident. Some species were more abundant and showed better regeneration potential in lower lantana density plots, while others did so in higher lantana density plots. However, time-series observations on permanent plots and experimental studies on competitive and allelopathic interactions in natural field plots are warranted for

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