Use of digital topographic data in predicting potential soil infiltration patterns

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Abstract

Infiltration of water into the soil is a function of soil properties as well as land-use land-cover conditions. Mapping soil infiltration variability is crucial for better inputs to physics-based rainfall-runoff simulations. However, a substantial time and effort is spent in mapping the spatial variability especially for large catchments. Spatial patterns representing the potential soil infiltration variability can be used to guide the interpolation of field based point infiltration data. These patterns can be obtained from digital elevation models and field-mapped stream hydrographic data. Channel head locations are controlled by the upstream catchment area, the topographic slope, and the permeability of surface cover. Drainage extracted from digital elevation models is usually based on channel initiation thresholds that combine upstream catchment area and slope in different proportions, without, of course, considering the permeability of surface cover. The differences in drainage patterns mapped in the field and extracted from the elevation models must, therefore, yield signatures of potential surface permeability variations. With this underlying premise, field based and DEM based drainage networks were compared using GIS tools to yield potential spatial variability of surface permeability. This was compared with the interpolated pattern of field based soil infiltration patterns in a hard rock catchment in southern India. Good correlation was found between the two patterns, confirming the usefulness of the spatial patterns obtained from digital topographic data in guiding the interpolation of field based soil infiltration data.

Keywords: DEM, GIS, infiltration, drainage pattern

Introduction

Infiltration is the transfer of surface water into the soil. Infiltrated water can move downwards as gravity drainage or percolation to recharge the groundwater. It may move laterally within soil macropores to be drained quickly back to nearby streams, it may be taken up by vegetation and transpired back to the atmosphere, or it may evaporate back to the atmosphere through soil surface. Soil infiltration is spatially and temporally variable *(William and Bonnel, 1988; Jetten et al, 1993)*. Spatial variability of infiltration is due to spatial variability of soil properties (texture, structure, organic matter), landuse, and topographic position. Temporal variability is mainly due to changes in antecedent soil moisture with time.

Capturing the spatial variability of soil infiltration is crucial for many hydrological applications e.g. the determination of runoff generating areas especially in semi-arid regions where infiltration excess runoff development (Hortonian flow) is a dominant process. These patterns are also indicative of the potential groundwater recharge zones if several other factors such as lateral redistributions through interflow, evapotranspiration etc. are considered.

Spatial variability of infiltration is usually captured by in-situ point measurements using soil Infiltrometer tests at selected locations in a catchment *(Berndtson and Larson 1987)*. This is a time consuming task since a dense network of observations points is needed to reproduce patterns close to the true variability, especially if the catchment is large. It would be quite helpful if a spatially variable pattern, representing potential infiltration variability, derived from a different source, is employed as a proxy to guide the interpolation of sparse in-situ infiltration measurements.

In this study, we present such a proxy spatial pattern derived from digital topographic data that can be used to guide the interpolation of in-situ point infiltration measurements obtained from soil Infiltrometer tests.

Study Area

The study was conducted in the Maheshwaram catchment (figure 1), situated about 35 km south of Hyderabad city in India. The catchment, with an outlet in the North-East, has an area of 53 km^2 and extends from longitude 78˚24'30"E to 78˚29'00"E and latitude 17˚06'20"N to 17˚11'00"N.

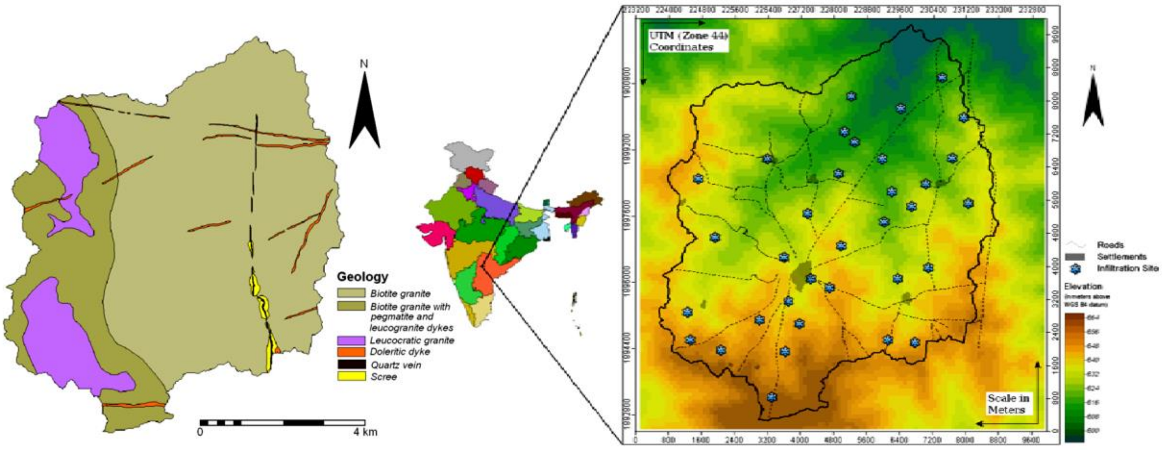

Figure 1: Maheshwaram Catchment – Location, Topography, Geology

The catchment slopes gently from south to north with a topographic relief of 90 meters (590 to 680 meters above mean sea level). The average surface gradient is 1.79 degrees. The topography is undulating with sub-dendritic type of drainage, marked by a number of gullies draining into local streams with eroded banks. The area is characterized by a distinct rainy season from June to September, when more than 80% of the annual rainfall is received from the South West Monsoon.

The catchment area is underlain by Achaean granites, characteristically weathered to form small hills with boulder strewn outcrops. These granites are intruded by quartz veins and dolerite dykes and are characterized by abundant horizontal and sub-horizontal fractures.

Methods

Derivation of potential soil infiltration spatial patterns is based on the premise that differences in the surveyed and simulated catchment drainage network is representative of soil permeability anomalies. Fluvial drainage network, that converges sediment and water to the catchment outlet, develops in response to the flow concentration, surface gradient, and soil permeability. Flow concentration depends on the topographic position; increasing along the downstream direction. Flow concentration leads to an increase in surface runoff thereby increasing the shear stress available for eroding a new channel. Surface gradient also tends to increase the shear stress at the base of the flow. Soil permeability, however, tends to control surface runoff by controlling infiltration. Therefore, permeable soils suppress runoff generation and reduce the depth of overland flow, causing less shear stress and suppression of channel initiation.

While extracting drainage network from digital elevation models, the channel initiation thresholds consider flow concentration (upslope area) and surface gradient (slope), but do not consider the soil permeability. On the other hand, the surveyed drainage network has evolved in response to all the above factors. Thus, the difference in the two networks must yield spatial signatures of soil permeability anomalies.

Surveyed drainage network was vectorised from topographic map (56 K/8) and cross checked using high resolution satellite imagery in Google earth coupled with field checks. SRTM digital elevation model (30 meter spatial resolution) was used to extract the drainage network using a slope-area product threshold *(Montgomery and Dietrich, 1988)*:

$$\mathbf{A \times S^2}$$

Where,

A is upslope contributing area

S is local surface gradient

Spatially variable drainage density grids were prepared using the surveyed and extracted drainage networks. Initially, the two networks were used to derive the length of overland flow based on the downstream distance to the nearest channel segment. The length of overland flow grids were filtered to yield grids of spatially variable drainage density. The grids were filtered based on the procedure of *tucker et al (2001)*. The method uses identification of the spatial autocorrelation structure of the two overland flow distance grids and estimating the autocorrelation distance. This distance was then used to derive the kernel size used to filter the overland flow grids.

The two drainage density grids were then used to derive a normalized difference grid, by dividing the arithmetic difference of the grids by the arithmetic sum of the grids. The normalized difference grid is a potential soil infiltration variability map. This was used as a guiding pattern (external drift) in the geostatistical interpolation of the sparse infiltration measurements.

A double ring Infiltrometer was used to measure soil infiltration capacity at 34 locations. The rings were pierced into the soil down to the depth of 5 cm, without tilt or undue disturbance of the soil column and with constant annular space between the rings in all directions. The water column height within both rings was maintained at 5 cm throughout the duration of the experiment. Infiltration in the inner ring was recorded using a stop watch at 1 minute interval for the first 5 minutes; every 2 minute from 5 to 12 minutes; every 5 minute from 15 to 30 minutes, every 10 minute from 30 to 60 minutes, then every 20 minute from 60 to 80 minutes. All infiltration tests were conducted for at least 60 minutes duration. The infiltration test was conducted till stabilized infiltration rate was achieved.

Results and Discussion

The overland flow distance map for the surveyed and simulated channel networks is shown in Figure 2. Brown colours represent higher overland flow distance values to the nearest channel since they are farthest from any channel segment. Green colours represent low overland flow distance values and these sites are in proximity to the channel segments. It is clear from the maps that the overland flow distance map derived from surveyed drainage network possesses a big zone of high overland flow distance values in the eastern part of the catchment. However, the pattern of overland flow distance derived from simulated channel network reveals no such pattern.

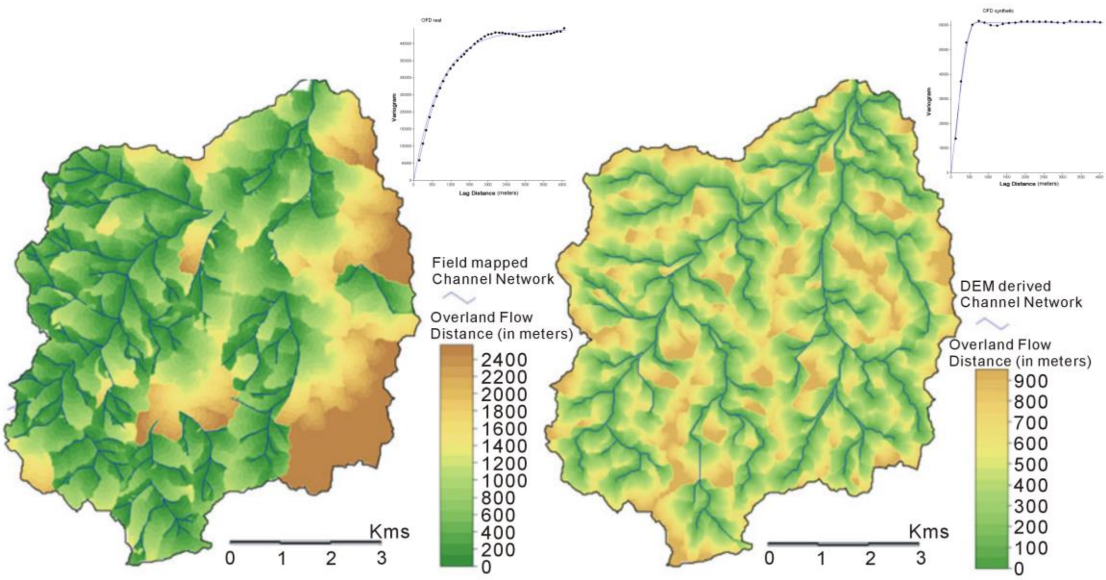

Figure 2: Length of overland flow obtained from field mapped drainage network (left) and DEM-extracted drainage network (right). The corresponding variogram showing the spatial autocorrelation structure is also shown.

The flow accumulation and local surface gradient are favourable for channelization in the eastern part of the catchment, as visible in the DEM derived channel network. But, on the ground, this zone is non-channelized. This suggests the presence of an anomaly in soil permeability in this zone of the catchment. This anomaly is an outcome of the geological features and weathering profile in this zone. Several dolerite dikes and quartz veins traverse this zone (figure 1). During the emplacement of dikes and veins, the ambient granitic rocks are fractured at the contacts due to thermal expansion and subsequent contraction as the dikes and veins undergo gradual cooling. Hence, the contact zones are profusely jointed and deeply weathered as compared to the surrounding area. Moreover, the quartz veins undergo weathering to produce coarse scree deposits around the vein. The scree deposits have developed highly permeable soils, which facilitate excessive infiltration of rainwater, thereby, suppressing runoff production and the process of channel initiation, leading to the local absence of surface drainage.

In this catchment, the autocorrelation distance for the overland flow distance maps derived from field mapped or surveyed channel network and the DEM derived channel network were found to be 600 & 500 meters respectively. These values were used to define the kernel dimension for filtering overland flow grids to obtain drainage density grids (figure 3).

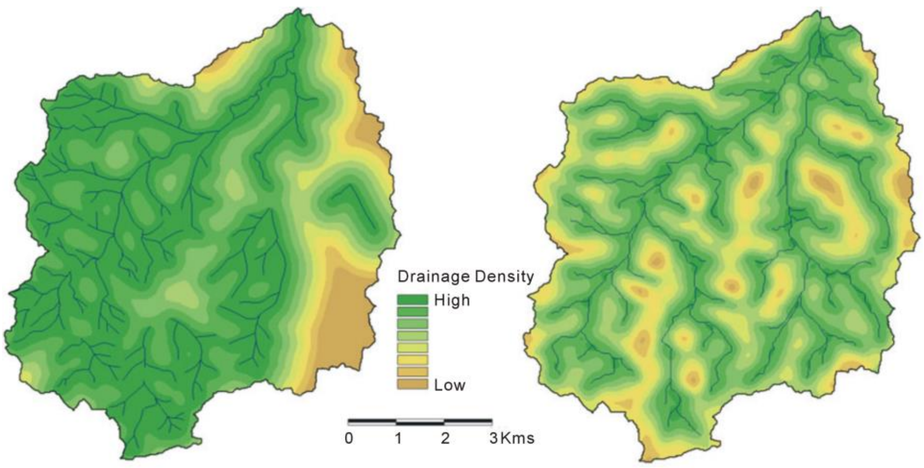

Figure 3: Drainage Density maps derived from field-mapped drainage network (left), and DEM-extracted drainage network (right).

As discussed in the methodology, the drainage density grids were used to derive the normalized difference grid (figure 4b), which represents the potential soil permeability variations in the catchment. This grid was compared to the spatial variability of soil infiltration variability obtained from Infiltrometer tests in the field. The infiltration capacity values obtained from field observations were interpolated using the geostatistical interpolation method of ordinary kriging implemented in many GIS software. The spatial variability of infiltration capacity is shown in figure 4a.

A visual comparison of the interpolated field-measured infiltration pattern and the normalized difference map shows broad similarity; however, visual map comparison is a subjective analysis, and the result of a visual map comparison contains bias of the person performing the comparison. An objective measure of map similarity or dissimilarity is a fuzzy set comparison method that simulates the human judgment very closely. This technique yields an overall figure for similarity, the Fuzzy Kappa *(Visser & de Nijs 2006)*, which is a numerical value aggregated from the detailed spatial results of fuzzy comparison between the two maps. The Fuzzy Kappa or K-fuzzy in short, is the expected percentage of agreement between two maps corrected for the fraction of agreement statistically expected from randomly relocating all cells in both maps. A fuzzy kappa value of 0.7 has been obtained for the two maps indicating a strong similarity between the two patterns indicating the usefulness of the potential soil permeability anomalies in characterizing the spatial variability of infiltration.

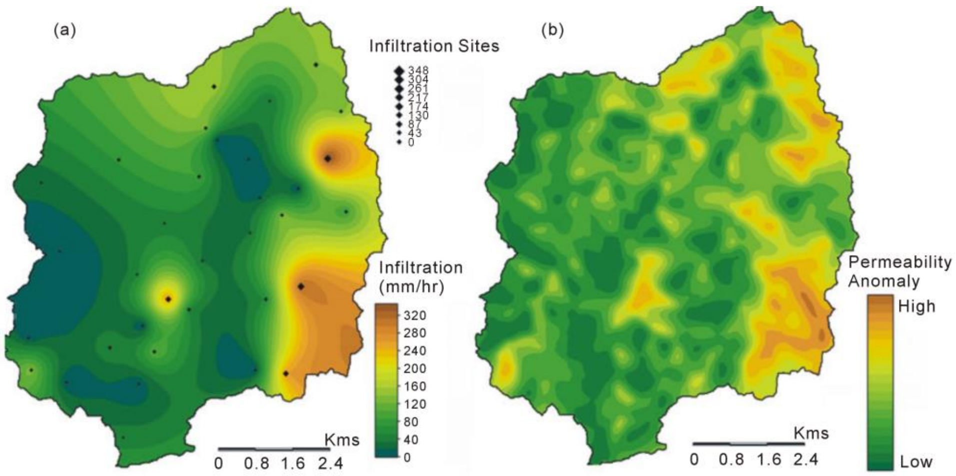

Figure 4: (a) Soil infiltration capacity map obtained by geostatistical interpolation of field measured infiltration values; (b) Normalised difference map indicating potential soil permeability anomaly pattern in the catchment.

Using the strong correlation between the two patterns, and the fact that potential permeability anomaly pattern is obtained with relative ease, the latter can be used to guide the interpolation of field infiltration measurements by employing a specialized interpolation technique known as Kriging with external drift (KED) *(Wackernagel, 2003; Chiles & Delfiner, 1999)*. In KED, the value of a variable at unknown locations is derived by considering the spatial structure (variogram) of the variable, as well as the spatial structure of a proxy variable that is known to have good spatial correspondence with the variable being interpolated. Here, we use the potential permeability anomaly pattern (normalised difference grid) as a proxy pattern to guide the interpolation of field infiltration measurements. The result is a map of soil infiltration variability (figure 5b) that is controlled by the actual field based values but that contains much more spatial variability than was available with simple geostatistical interpolation (ordinary kriging) of field infiltration measurements.

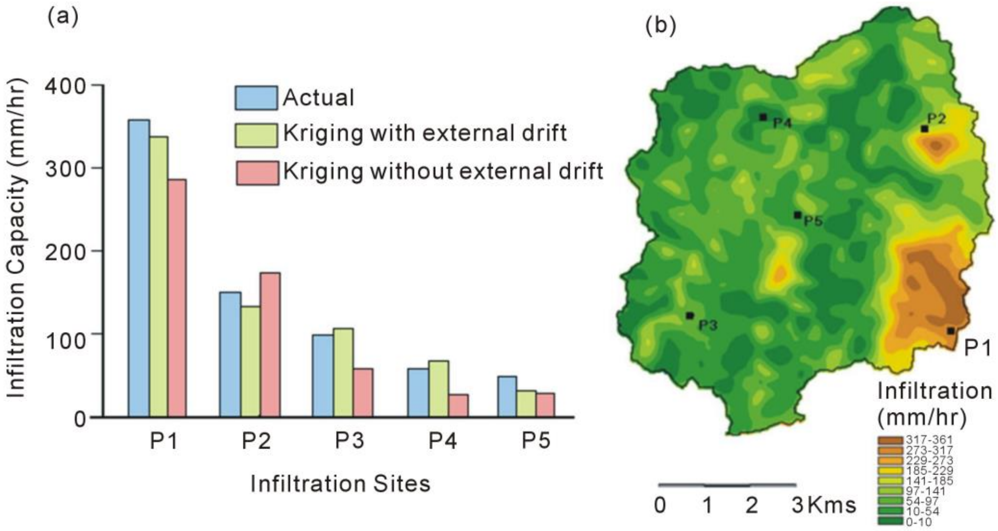

Figure 5: (a) Comparison of the actual field infiltration value, the value predicted by ordinary kriging interpolation, and the value predicted by KED using permeability anomaly map as external forcing; (b) Spatial variability of infiltration obtained using KED.

Cross validation was performed at five new locations (figure 5a) to check the accuracy of infiltration values obtained by ordinary kriging (Kriging without external drift) and KED methods. From the results, it is clear that infiltration values at the validation points are reproduced more closely to the true infiltration value when potential permeability pattern is used as an external forcing in the interpolation.

Conclusions

This study presents an efficient method for mapping spatially variable infiltration using digital topographic data, at catchment/regional scales in arid/semiarid hard rock terrain. In small first order catchments used for dedicated hydrological research, acquiring infiltration patterns using high density of field observations is quite meaningful, but in larger catchments at regional scales, and for operational use, this may prove a costly and time consuming affair. At these scales, a practical approach for infiltration variability mapping is to use a proxy pattern obtained by utilizing the differences in the structure of the field-mapped drainage and the DEM-derived drainage. This proxy pattern of potential soil permeability can be used as external drift or forcing in the geostatistical interpolation of field-measured infiltrations values at selected locations. The only field data required in using this approach is the infiltration measurements at a few points in the catchment. Thus, this approach is intended to be used in conjunction with some infiltration measurements. The technique is not intended to replace in situ measurements; rather it intends to reduce the number of infiltration measurements that have to be made to faithfully reproduce the spatial variability of infiltration patterns in a catchment.

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