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Spatial and temporal variation of hydraulic conductivity and vegetation growth in green infrastructures using infiltrometer and visual technique

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ABSTRACT

Hydraulic conductivity of a vegetated soil (i.e., mixed grass cover) is an important parameter governing the hydrological performance of green infrastructure (GI). This paper focuses on GI with mixed grass cover in the presence of trees. Due to shading effects (interception of radiant energy) of tree canopy, mixed grass cover in the vicinity of trees may not receive direct photosynthetically active radiation (PAR). This can hinder the growth rates resulting in the low grass cover (i.e., in density). The hydraulic conductivity and the performance of GI can be further affected. Several field studies were conducted to investigate hydraulic conductivity in different types of vegetated covers. However, any variation in growth and hydraulic conductivity of mixed grass cover in the vicinity of trees was rarely investigated. The objective of this study is to quantify spatial and temporal variation of vegetation growth and hydraulic conductivity in a mixed grass cover in the vicinity of a tree. Field monitoring of a mixed grass cover in the vicinity of a tree in a GI was conducted for about six months. Hydraulic conductivity tests were carried out using mini disk infiltrometer (MDI) at 149 locations in a selected site once every month. Vegetation density was quantified using image analysis and the images were captured by a DJI Phantom drone. The growth of mixed grass cover around tree vicinity (within 5 m radial distance) was found to be more uniform during months characterized by high rainfall depth. Spatial heterogeneity in both vegetation density and hydraulic conductivity is found to be more significant during a dry period than wet period. Variation of hydraulic conductivity with respect to the change in vegetation density is found to be significant in a wet period than dry period. It is also found that hydraulic conductivity is higher at the portions where shredded leaves are present. The obtained dynamic spatio-temporal relationship of soil, vegetation and atmospheric parameters can support the design of green infrastructures and contribute to a better understanding of the maintenance practices.

1. Introduction

Hydraulic conductivity of a vegetated soil is an important parameter governing available water content in vadose zone (Nielsen et al., 1973; Bordoloi et al., 2015, Bordoloi et al., 2016, Vardhan et al., 2016), ground water table recharge (Gee and Hillel, 1988) and slope stability (Simon and Collison, 2002; Leung et al., 2015a). It is also important for understanding the hydrological performance of urban green infrastructures, which are widely adopted as sustainable drainage systems (SuDS) for management of surface water runoff (Dunne et al., 1991; Woolhiser et al., 1996; Berretta et al., 2014; Stovin et al., 2015). The hydraulic conductivity behavior can have an influence on the long-term performance of SuDS and maintenance practices.

The hydraulic conductivity of vegetated soil is affected by available water content and evapotranspiration induced suction in root zone (Fredlund and Xing, 1994; Fredlund et al., 1994). Available water content as well as evapotranspiration induced suction depends on the area of vegetated soil exposed to various atmospheric parameters, such as air temperature (Penman, 1948; Chahal, 1965), relative humidity (Delage et al., 1998; Cuisinier and Masrouri, 2005), rainfall (Eltahir, 1998; Knapp et al., 2002) and photosynthetically active radiation

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(PAR) (Ng et al., 2013). However, PAR may not intercept vegetated soil due to shading effect (Atwell et al., 1999). In such case, evapotranspiration induced suction in vegetated soil as well as vegetation growth may be relatively low (Garg et al., 2015a). This can further influence hydraulic conductivity (Gadi et al., 2016). Vegetation growth is commonly expressed by the term of vegetation density. Vegetation density (m^2/m^3) is defined as the projected area of vegetation per unit volume (Warmink, 2007).

$$\text{Vegetation density} = \frac{\sum A_v}{AL}$$

where:

A_v = Area covered by vegetation,

A = plot area,

L = Length of plot in flow direction.

Grass growth in grass lands is found to be responsive to atmospheric parameters such as rainfall and temperature (Whitford, 2002; Went, 1949; Peacock, 1976; Khan and Rizvi, 1994). Mixed grass lands, in which more than one type of species can be seen, occur widely (Walker and Noy-Meir, 1982; Bourlière et al., 1983; Scholes and Archer, 1997; Scholes and Walker, 2004). In the cases of mixed grass and the grass in the vicinity of trees, root systems overlap (Van Noordwijk and Purnomosidhi, 1995). Grass growth may become slow due to the overlap (Casper and Jackson, 1997). Grass cover changes on vegetated soil can influence the proportion of CO_2 in atmosphere, which is a key factor for global warming (Auerswald et al., 2009; Auerswald et al., 2012). However, previous studies rarely investigated the vegetation cover change (vegetation parameters such as vegetation density and shoot growth) explicitly.

Extensive field studies were conducted to investigate hydraulic conductivity of vegetated soil (Gish and Jury, 1983; Noordwijk et al., 1991; Mitchell et al., 1995; Leung et al., 2015a). Few studies show that, increase in hydraulic conductivity with vegetation growth (i.e., root growth) occurs due to preferential flow through the channels formed around the live or dead roots (Noguchi et al., 1997; Newman et al., 2004). Whereas, some other studies show that, decrease in hydraulic conductivity with growth of vegetation occurs due to water repellency exhibited by roots (Aubertin, 1971). However, previous researchers rarely studied the hydraulic conductivity of mixed grass cover. In addition, the hydraulic conductivity of mixed grass cover in tree vicinity was rarely investigated. Furthermore, any understanding of the correlation of spatial and temporal variation of hydraulic conductivity with that of vegetation density in a mixed vegetated area with trees is rarely interpreted. The objective of this study is to investigate the spatial and temporal variation of hydraulic conductivity and vegetation density in a mixed grass cover in the tree vicinity. In addition, spatial variation of the hydraulic conductivity for six months was compared and interpreted with quantified spatial variation of vegetation density.

2. Materials and methods

2.1. Site description

Pongamia pinnata tree vicinity with mixed grass cover is located in front of a building called core-4, IITG (IIT Guwahati), as shown in Fig. 1. The *Pongamia pinnata* tree vicinity contains *Cyperus*, *Poaceae* and *Bauhunia purpurea* species on a flat ground. In this study, field monitoring was conducted on mixed grass cover in the tree vicinity. Field monitoring is designed to better understand the spatial and temporal variation of vegetation density and hydraulic conductivity.

2.2. Soil properties

Eight disturbed soil samples are collected from eight different locations i.e., four samples from right side of tree stem and the remaining samples from left side of tree stem for determining index properties. In these eight samples, four samples were collected within 2.5 m radial distance from tree stem and the remaining samples were collected from the space between 2.5 m and 5 m radial distances from tree stem. It was found that in situ dry densities of the eight samples varied between 1315 kg/m^3 and 1387 kg/m^3, with an average value of 1351 kg/m^3. The average in situ dry density was approximately equal to 78.3% of the maximum dry density. The average contents of gravel (particle size $D \geq 2$ mm), sand ($0.63 \text{ mm} \leq D \leq 2$ mm), silt and clay ($D \leq 0.63$ mm) were found to be 0%, 98.6% and 1.4%, respectively. Based on the measured particle size distribution, the soil covered with mixed vegetation in the tree vicinity is classified as poorly graded sand (SP; ASTM, 2010), according to the unified soil classification system. Saturated hydraulic conductivity of the soil is found to be $2.4 \pm 0.9 \times 10^{-4}$ m/s.

2.3. Overview of testing site containing mixed grass cover in the tree vicinity

Cyperus, *Poaceae* and *Bauhinia purpurea* were selected for the present study based on (i) the wide spread presence in sub-tropical regions (Santos et al., 1997; Cheng et al., 2002; Au et al., 1992) and (ii) the ability to tolerate drought, which is suitable for slope stabilization (Pickard, 1982; Louis, 1990; Ghosh et al., 2003; Awanyo et al., 2011). Pongamia pinnata is selected based on its wide availability in natural slopes and plane grounds in sub-tropical regions (Karmee and Chadha, 2005). It was identified as the resource of agroforestry and landscaping (Scott et al., 2008). Fig. 2 shows the overview of tree vicinity with the mixed grass cover. It can be seen that, tree vicinity is categorized into five concentric semicircles. This categorization of tree vicinity is aimed to quantify the spatial variability of vegetation density and hydraulic conductivity. Radii of these semicircles are 1 m, 2 m, 3 m, 4 m and 5 m, respectively. These radii are considered based on visual observation, within which vegetation density appears to be less variable. Groundwater table depth at the tree vicinity is 5.6 m. Groundwater depth data was collected from the WRIS India (Water resource information system (WRIS), India; http://www.india-wris.nrsc.gov.in/wris.html). Non-uniform distribution of vegetation density and shredded leaves can be observed over the tree vicinity.

2.4. Instrumentation on the vegetated soil in the tree vicinity

Typical layout showing locations (149 measurements), where vegetation density and hydraulic conductivity were quantified is shown in Fig. 3. The selected area of tree vicinity is categorized into small grids for quantifying spatial heterogeneity in hydraulic conductivity and vegetation growth. The selected grid size was determined based on the initial trial measurements of hydraulic conductivity and vegetation growth. Maximum area of grid size is 0.125 m × 0.125 m.

A commercially available drone (DJI Phantom; Themistocleous et al., 2015) which has a high-resolution camera onboard was used to capture images in the tree vicinity. Resolution of the camera installed underneath the airframe is 12 megapixels. The service ceiling of the aircraft is 6000 m above sea level. Photographs of the drone and its transmitter during field monitoring are individually shown in Fig. 4(a) and Fig. 4(b). Focal length, ISO speed and exposure time were maintained at 35 mm, ISO-640 and 1/8000 s, respectively. Images were captured from the angle of 90° to the ground at a height of 2 m. To avoid any observational errors, ambient light was ensured during image capture operations.

MDI (Decagon Devices, 2012) is used to measure hydraulic conductivity in the mixed grass cover. Measurement of hydraulic conductivity and the overview of the MDI are separately shown in Fig. 5(a) and (b). The MDI consists of two chambers, i.e., upper and lower chambers,