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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.

Key words: Hydraulic conductivity; green infrastructures; mixed grass cover; tree vicinity; vegetation density

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), 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; Woolhiseret 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 (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

Pongamiapinnata 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 *Pongamiapinnata* tree vicinity contains *Cyperus, Poaceae* and *Bauhuniapurpurea* 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 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, 2011), according to the unified soil classification system. Saturated hydraulic conductivity of the soil is found to be 2.4 ± 0.9 x 10^{-4} m/sec.

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 (Picard, 1982; Louis, 1990; Ghosh et al., 2003; Awanyoet al., 2011). Pongamiapinnata is selected based on its wide availability in natural slopes and plane grounds in sub-tropical regions (Karmee and Chanda, 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, 4m 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 x 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 sec, 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, 2013) 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 5 (b). The MDI consists of two chambers, i.e., upper and lower chambers, which are filled with water. Suction is controlled in the top chamber which is also known as bubble chamber. Lower chamber contains a sintered disk at the bottom, which would not allow water in free air due to its high air entry value. Air entry value is the suction above which air starts to enter the pore of soil. In MDI, the flow through sintered disk at the bottom of the lower chamber is controlled by the suction value adjusted in the upper chamber. This suction controlled flow through sintered disk is capable of eliminating the flow through macro pores such as cracks, whose air entry value is smaller than the suction of the MDI. The suction value in the infiltrometer can be adjusted between 0.5 cm and 6 cm, depending on soil type and density (Zhang, 1997a). MDI measures hydraulic conductivity in relatively shallow area, which is a major limitation of the MDI. Due to this fact, relatively large number of hydraulic conductivity measurements need to be performed in relatively small area for capturing spatial variation.

Axis-symmetric flow was ensured by firmly placing the MDI on the vegetated soil vertically and maintaining good contact between the sintered disk and soil. Accumulated air bubbles in the disk were removed frequently by placing the disk in boiled water. Removal of air bubbles assures accurate measurements of hydraulic conductivity. Hydraulic conductivity measurements were taken in the afternoon to account for the preferential flow in this study. This is because it was found from the study by Noguchi et al. (1997) that the diameter of fine root may decrease and become 40 % of its original diameter during noon, when radiant energy is maximum. During this period, preferential flow through soil-root interface is significant (Aubertin, 1971; Ghestem et al., 2011).

2.5 Field monitoring programme

The field monitoring programme for quantifying spatial and temporal variation of vegetation density and hydraulic conductivity in mixed grass cover in the vicinity of trees was conducted from 1st January, 2016 to 30th, June 2016. The tree vicinity was instrumented for six months at the locations shown in Fig. 3. It is clear that vegetation density and hydraulic conductivity are quite uncertain spatially (Warmink, 2007; Gui et al., 2000; Hazra et al., 2016). To quantify spatial uncertainty, vegetation density was quantified in the areas enclosed within grids (Fig. 3). Whereas, hydraulic conductivity was measured at 149 different points (refer to asterisk (*) in Fig. 3) once every month.

Atmospheric parameters such as wind speed, net radiation, air temperature, relative humidity and monthly rainfall were monitored by micro-climate monitoring system. Monthly rainfall depths during the monitoring period are shown in Fig. 6. It can be observed that the lowest rainfall depth of 5 mm occurred in the month of February and the highest value of 275 mm occurred in April. Rainfall depths in April, May and June are much higher than those in January, February and March. This clearly shows that the first three months of observation (i.e., January, February and March) correspond to the dry period, which implies the relatively lower availability of water content in vegetated soil. The three months period of April, May and June can be referred as the wet period, which implies the relatively higher available water content in vegetated soil. Temperature is found to vary between 9 ˚C and 36 ˚C during the monitoring period.

The duration (January, 2016 to June, 2016) of the testing was able to capture maximum and minimum values of meteorological parameters (air temperature, rainfall and relative humidity corresponding to region of study; Laskaret al., 2014) as well as vegetation cover growth (vegetation density of approximately 0 m^3/m^3 to 1 m^3/m^3). Hence, the selected field monitoring period is reasonable to understand the effects of variation in mixed vegetation cover on hydraulic conductivity.

Images were captured using drones in ambient light, over the entire tree vicinity in three successive days at the end of each month. Vegetation density of each small area as shown in Fig. 3 was determined by dividing the surface area of vegetation cover by total surface area considered. Surface area of vegetation cover was determined by means of image analysis using ImageJ (Rasband, 2012; public domain image processing program, which can quantify pixel value statistics and density of user-defined selections, i.e., vegetation cover on soil). Captured image was imported into the ImageJ and cropped to only account for the desired portion or size (see Fig. 3). The cropped image was converted into a binary image. Pixel values of vegetation cover in the binary image were then converted into surface area. This shows the area covered by mixed grass in the selected portion. Vegetation density (m^2/m^3) was calculated as the surface area covered by mixed grass in the selected portion divided by the total area of the selected portion. Grid size of the selected portion was considered as 1 m x 1 m for the present study. By definition, vegetation density will vary from 0 m^2/m^3 to 1 m^2/m^3, which is consistent with that found in the study by Warmik (2007).

A series of hydraulic conductivity experiments were performed at the designated locations (149 number as indicated with *; Fig. 3) in three successive days at the end of each month. After placing the MDI on vegetated soil, water is allowed to infiltrate at the preset suction. The suction was set at 0.5 cm as adopted in the study by Zhang (1997a). Initial condition is assumed as time zero condition. Water that infiltrates into vegetated soil through the disk is measured as a function of time. Cumulative depth of water infiltrating was plotted as a function of time. Three dimensional transient infiltration rate can be approximated using equation 1 (Zhang, 1997a, b).

$$I = c_1 t + c_2 \sqrt{t} \quad (1)$$

Where:

C_1, C_2 = fitting constants,

t= time.

The near saturated hydraulic conductivity (k or k_h corresponding to the suction applied on the disk (h)) defined by Zhang (1997a) is given by equation (2)

$$k \text{ or } k_h = \frac{c_1}{A} \quad (2)$$

where:

"A"= Parameter dependent on van Genuchten (vG) SWRC parameters suction applied on disk and radius of disk as represented by equation (3.1 and 3.2).

$$A = \frac{11.65(n^{0.1}-1)\exp[2.92(n-1.9)\alpha h]}{(\alpha r)^{0.91}} ; \quad \text{For } n > 1.9 \quad (3.1)$$

$$A = \frac{11.65(n^{0.1}-1)\exp[7.5(n-1.9)\alpha h]}{(\alpha r)^{0.91}} ; \quad \text{For } n < 1.9 \quad (3.2)$$

where:

n, α = the vG parameters of vegetated soil,

r = the disk radius,

h = the suction applied on the disk.

The vG parameters n and α were adopted using the method prescribed by Carsel and Perish (1988). They were obtained with the help of measured soil water retention curve of bare soil. However, it must be noted in general, these parameters may not be the same for bare soil and vegetated soil (Leung et al., 2015b; Gadi et al., 2016). As the main focus of present study is to develop a working knowledge on hydraulic conductivity spatial variation at different locations in the tree vicinity, vG parameters of bare soil (i.e., poorly graded sand; Carsel and Perish, 1988) were adopted.

3. Results and discussions

3.1 Vegetation cover change during monitoring period

Figures 7 (a)-(f) show the overview of variation in surface area of the selected site during monitoring period. It can be observed that very small area of the selected site is covered with vegetation during the initial stage of monitoring period (Refer to image captured in January, 2016; Fig. 7(a)).Whereas, Fig. 7 (b) (28 February 2016) shows yellow shredded leaves with relatively minor vegetation growth. Shredding of leaves occurred during the month of February, which also marks the transition from a dry to a wet season (refer to Fig. 6). This phenomenon of shredding of leaves was also observed at similar times in the field study by Wright (1990). Fig. 7 (c) is the image captured on 31 March 2016, which shows greening and vegetation regrowth during March. Only *Cyperus and Poaceae* species were found in the tree vicinity till the end of March. Majority of the tree vicinity area is found to be densely covered by the end of April (Fig. 7 (d)). Growth of *Bauhinia purpurea* species also occurred during April. The vegetation species in the tree vicinity were observed to keep on growing during May and June, as shown in Fig. 7 (e) and Fig. 7 (f). This indicates that abundant growth of new vegetation species was experienced during wet period, while that was hardly present during dry period.

3.2 Measured vegetation density

Fig. 8 (a), (c), (e), (g), (i) and (k) illustrate the spatial variation of vegetation density range in the tree vicinity for six months. Contours were used for illustrating vegetation density. The range from the minimum to maximum values of vegetation density in contour was divided into seven intervals.

Vegetation density is found to vary between 0.001 m^2/m^3 and 1.000 m^2/m^3. Vegetation growth is found to be highly dissimilar on right and left side portions of tree stem. Vegetation density around tree vicinity is found to fluctuate much more significantly than away from tree stem. At the end of January and March, vegetation density variation with change in radial distance on the left side of tree stem is found to be more significant as compared to that on the right side (see Fig. 8 (a) and (e)). Unlike at the end of other months in dry period, difference in vegetation density ranges between left side and right side of tree stem is low at the end of February. This is due to the presence of shredded leaves at the end of February (see Fig. 8(c)). This implies that the vegetation growth around tree vicinity is not axi-symmetric, which is usually assumed in many of numerical studies (Fatahi et al., 2010; Garg and Ng 2015).

Unlike during dry period, significance of vegetation density variation with change in radial distance is found more on the right side of tree stem than that on the left side at the end of April, May and June (see Fig. 8 (g), (i) and (k)). However, vegetation densities on right and left sides of tree stem are found to be similar in smaller region of annuli during wet period. This shows that, spatial variation of vegetation density is more significant during dry period than wet period.

Vegetation density in the annuli at greater radial distances from tree stem is found to be higher as compared to that in the annuli nearer to the tree stem. This is observed during the entire monitoring period except in the month of February during which shredding of leaves occurred. This may be attributed to the presence of tree roots and tree shading at near distance from tree stem. Mixed grass root systems overlap tree roots, because of which roots growth may be slow (Casper and Jackson, 1997). At the end of February, vegetation density within around 2 m radial distance from tree stem is observed to be higher than that in between the radial distances of 1.7 m and 4.2 m. This is due to the presence of shredded leaves. Substantial increase (16 % - 498 %) in vegetation density over the entire tree vicinity at the end of April is found, as compared to that at the end of other months. However, any vegetation density variation trend is not found with respect to various rainfall depths during the observation period (see Fig. 6 and Fig. 8). This shows that, rainfall depth may not effect spatial variation of vegetation density significantly. Effect of season change on spatial variation of vegetation density is observed to dominate the effect of rainfall depth.

3.3 Spatial variation of measured hydraulic conductivity

Fig. 8 (b), (d), (f), (h), (j) and (l) illustrate the spatial variation of measured hydraulic conductivity range in the tree vicinity for six months. Difference between maximum and minimum measured hydraulic conductivities during six months was divided into seven ranges, which are shown in colour scale. Significance of hydraulic conductivity range variation with change in radial distance can be observed from the number of hydraulic conductivity ranges found in the tree vicinity. Unlike vegetation density, any trend of variation is not found in case of hydraulic conductivity with respect to the change in radial distance from tree stem. Fig.8 (b), (d) and (f) show hydraulic conductivity range for spatial variation at the end of January, February and March, respectively. At the end of January, February and March, measured hydraulic conductivities are found to be dissimilar on the right and left sides of stem. However, the dissimilarity in measured hydraulic conductivity between the right and left sides of tree stem is relatively lower during wet period. The observation is consistent with that of observed dissimilarity in vegetation density around tree stem. This indicates that during modeling of water flow around tree stem, it is important to consider the heterogeneity in it with respect to seasons.

Fig.8 (h), (j) and (l) show the spatial variation of hydraulic conductivity range at the end of April, May and June, respectively. At the end of April, May and June, hydraulic conductivities at similar radial distances on the left and right sides of tree stem are found to be the same. Unlike during dry period, significant variation of hydraulic conductivities with change in radial distance from tree stem was found during wet period.

3.4 Effect of vegetation density on hydraulic conductivity

In the right side of tree stem, hydraulic conductivity is found to vary between 1.43x 10^{-6} m/sec and 2.86 x 10^{-6}m/sec over majority area of the region in which vegetation density varies between 0.001 m^2/m^3 and 0.143 m^2/m^3at the end of January. However, over a minor region between 1 m and 2m radial distances from tree stem in right side, hydraulic conductivity is found between 0.01 x 10^{-6} m/sec to 1.43 x 10^{-6} m/sec. In this region, vegetation density is observed to be very low i.e., close to 0.001 m^2/m^3, which may be the reason for less hydraulic conductivity. Hydraulic conductivity is found to vary between 2.86 x 10^{-6}m/sec and 4.28 x 10^{-6} m/sec over the majority of the region in which vegetation density varies between 0.144 $m^2/m^3$and 0.714 m^2/m^3 at the end of January.

Hydraulic conductivity range variation trend with respect to the change in vegetation density at the end of February and March is similar to that at the end of January over majority area of the tree vicinity. Difference of 33% - 99 % occurred between hydraulic conductivities of soil with higher vegetation density and those with lower vegetation density during dry period. This may be due to the dissimilarity of preferential flow through the channels around the roots.

During dry period, for variation of vegetation density range between 0.144 $m^2/m^3$and 0.714 m^2/m^3, hydraulic conductivity varies from 2.86 x 10^{-6} m/sec to 4.28 x 10^{-6} m/sec. The variation is relatively smaller as compared to that during wet period (400% increase in the month of April). This may be due to the occurrence of relatively low rainfall depths during January, February and March. Low rainfall depth indicates less available water content in root zone (Walker and Rowntree, 1977). Suction in vegetated soil increases due to root water uptake by higher vegetation density (Garg et al., 2015a). As the suction in vegetated soil increases, flow through the soil decreases (Leung et al., 2015a). Hence, although higher preferential flow occurs at greater vegetation density, however this effect may be countered by the presence of higher suction in dry period. Furthermore, hydraulic conductivity is found to be 49 % - 100 % higher in the region (2 m radial distance from tree vicinity) covered with shredded leaves than that in other areas of the site without shredded leaves. This may be attributed to lowering of evapotranspiration induced suction due to the covering of surface with vegetation.

At the end of April, substantial increase (24 % - 149 %) in hydraulic conductivity can be found over the tree vicinity. This may be due to considerable increase in vegetation density during April. Unlike during dry period, hydraulic conductivity is found to increase by 24 % - 66 % with rise in vegetation density between 0.430 m^2/m^3 and 1.000 m^2/m^3 during wet period. Higher hydraulic conductivity is observed to be exhibited by soil vegetated with greater vegetation density during wet period. This may be due to higher rainfall depth values occurred during wet period. Higher rainfall depth implies greater available water content (Tohariet al., 2007). Suction induced in vegetated soil decreases with the increase in available water content (Garg et al., 2015b). Higher hydraulic conductivities occur at lower suction values (Ho et al., 2007).

An increase of 250 % - 400 % in hydraulic conductivity is found at the end of June, as compared to that in January. Results reported by Noordwijk et al.,(1991), Ghestemet al.,(2011) and Mitchell et al.,(1995) also showed that increase in hydraulic conductivity by up to 400 % is possible with increase in growth of roots in soil. This (i.e., increased hydraulic conductivity) is revealed to be attributed to preferential flow through the pore space around the roots (Nieber and Sidle, 2010). However, effect of spatial variation in vegetation growth was not demonstrated by previous studies. This study shows that hydraulic conductivity may increase or decrease with vegetation growth depending on atmospheric conditions.

In previous literature, any variability in hydraulic conductivity and its understanding with respect to grass growth in presence of tree vicinity is rarely understood. This is important for improving water balance estimations in green infrastructures. Results of the present study also expose the longevity of leaves and its effect on hydraulic conductivity, which is a key factor to devise drainage. This study has a great implication on analyzing the performance of green roof systems in urban regions, where there is high tendency of occurrence of trees in the vicinity of such systems. Such occurrence of tree vicinities is due to strategic plantation of trees in urban areas, which is adopted broadly for landscape (Smardon, 1988; Honjo and Takakura, 1990; Robitu et al., 2006). These hydraulic conductivity results help the numerical modelers to better understand the non-uniformity of vegetation density and hydraulic conductivity to simulate the ground water flow (i.e., ground water recharge estimation) accurately.

4. Conclusions

This study explored the interpretation of spatial variation of hydraulic conductivity and vegetation density of mixed grass cover in tree vicinity during drying and wetting periods. Vegetation density is found to increase from as low as 0.001 m^2/m^3 in the dry period (January) to 1.000 m^2/m^3 in the wet period (June). Whereas, hydraulic conductivity is found to change from 0.01 x 10^{-6} m/sec to 9.97 x 10^{-6} m/sec in the dry and wet periods, respectively.

Spatial variation of vegetation density is more significant during dry period as compared to wet period. Vegetation density in the annuli at greater radial distances from tree stem is found to be higher as compared to that in the annuli nearer to the tree stem. This may be attributed to competition due to presence of tree roots and tree shading near tree stem. Root growth of mixed grass cover is therefore slowed by this competition (Casper and Jackson, 1997). During dry period, with an increase in vegetation density from 0.144 m^2/m^3 to 0.714 m^2/m^3 (4.8 times), hydraulic conductivity was found to increase by 50 % (i.e., from 2.86 x 10^{-6} m/sec - 4.28 x 10^{-6} m/sec). However, during wetting period, the increase in hydraulic conductivity with respect to change in vegetation density (2.3 times; from 0.43

m^2/m^3 to 1 m^2/m^3) is much higher (i.e., 66%). This may be attributed to relatively high rainfall depth in wet period, which might have caused higher vegetation density and hence preferential flow. Substantial increase (24 % - 149 %) in hydraulic conductivity is found in the tree vicinity at the end of April. This may be due to considerable (16 % - 498 %) increase in vegetation density during April. Hydraulic conductivity in the vegetated soil covered with shredded leaves is found to be 49 % - 100 % higher than that in soil without the presence of shredded leaves. In addition, the presence of growth of new vegetation species during wet period could also contribute to significant rise in hydraulic conductivity in the month of April.

The obtained results can be useful to support the design of green infrastructures with similar characteristics to the studied one. Further, long term monitoring with consideration of more number of cycles of seasons, vegetation species and vegetation growth can be useful.

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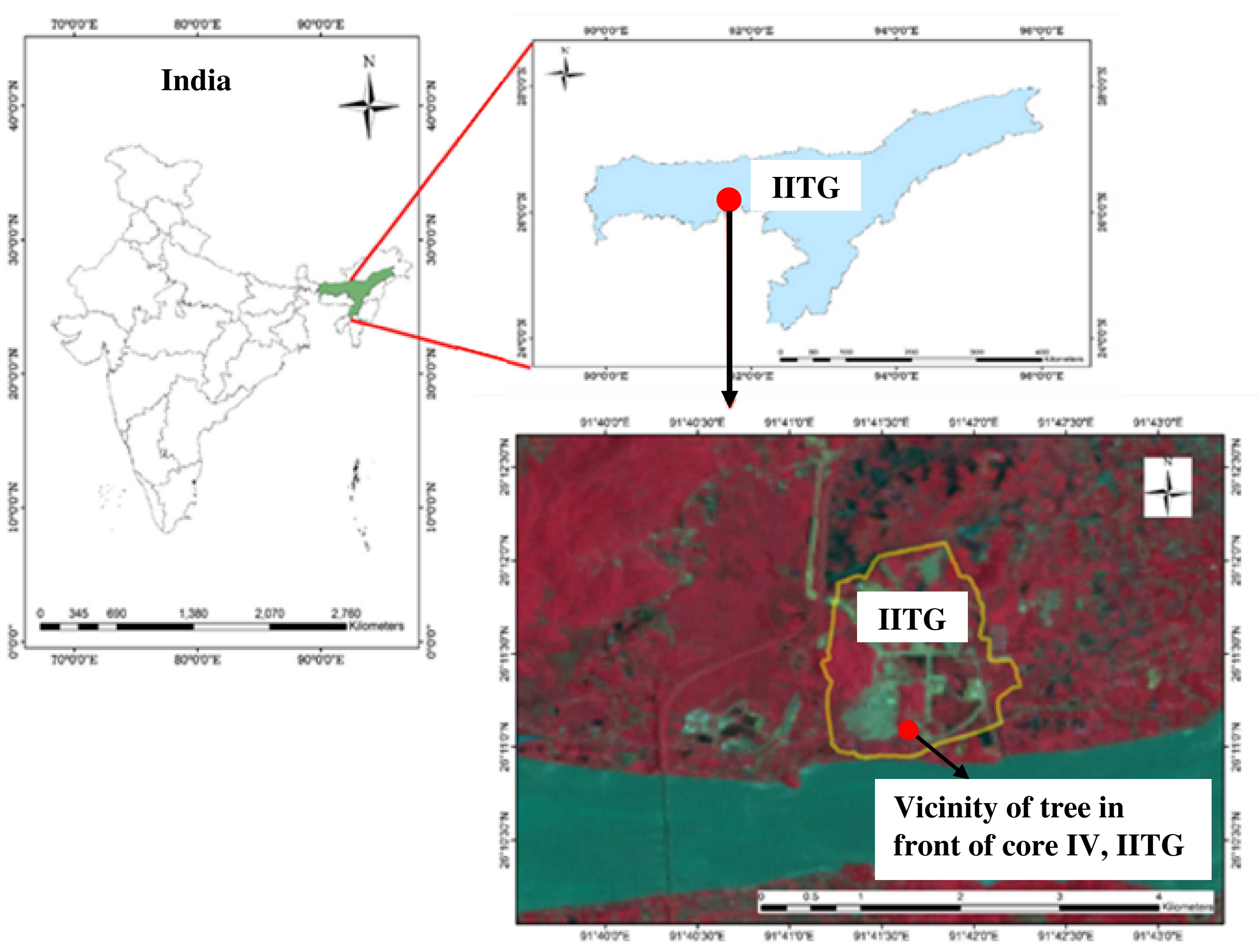


Fig. 1. Map of India showing the location of field testing site (core IV, IITG campus, Guwahati, Assam)

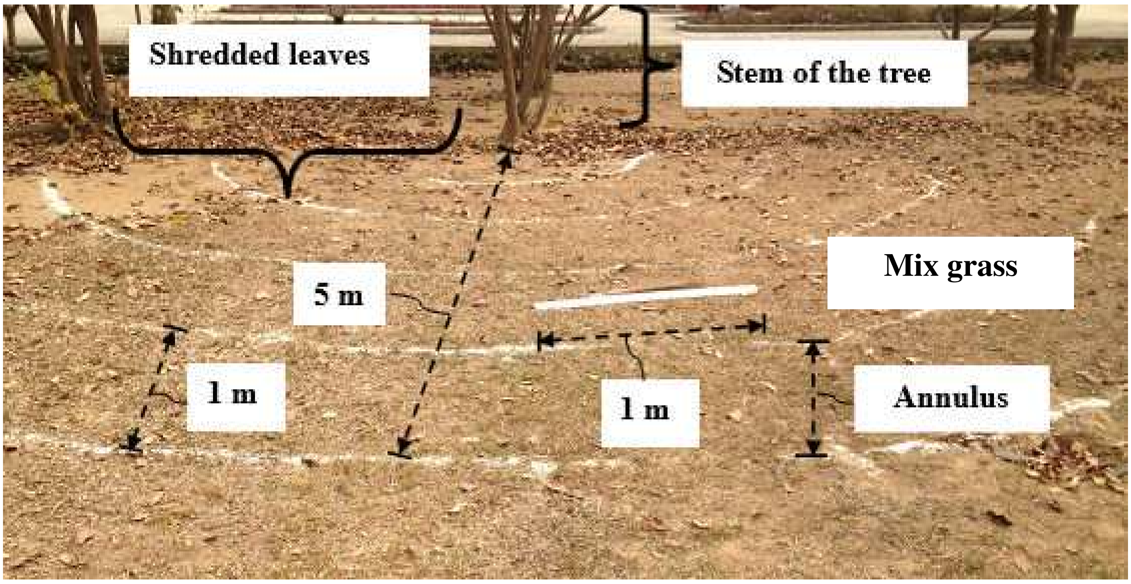


Fig. 2. Over view of test site (*Pongamia pinnata* tree vicinity with mix vegetation (grass))

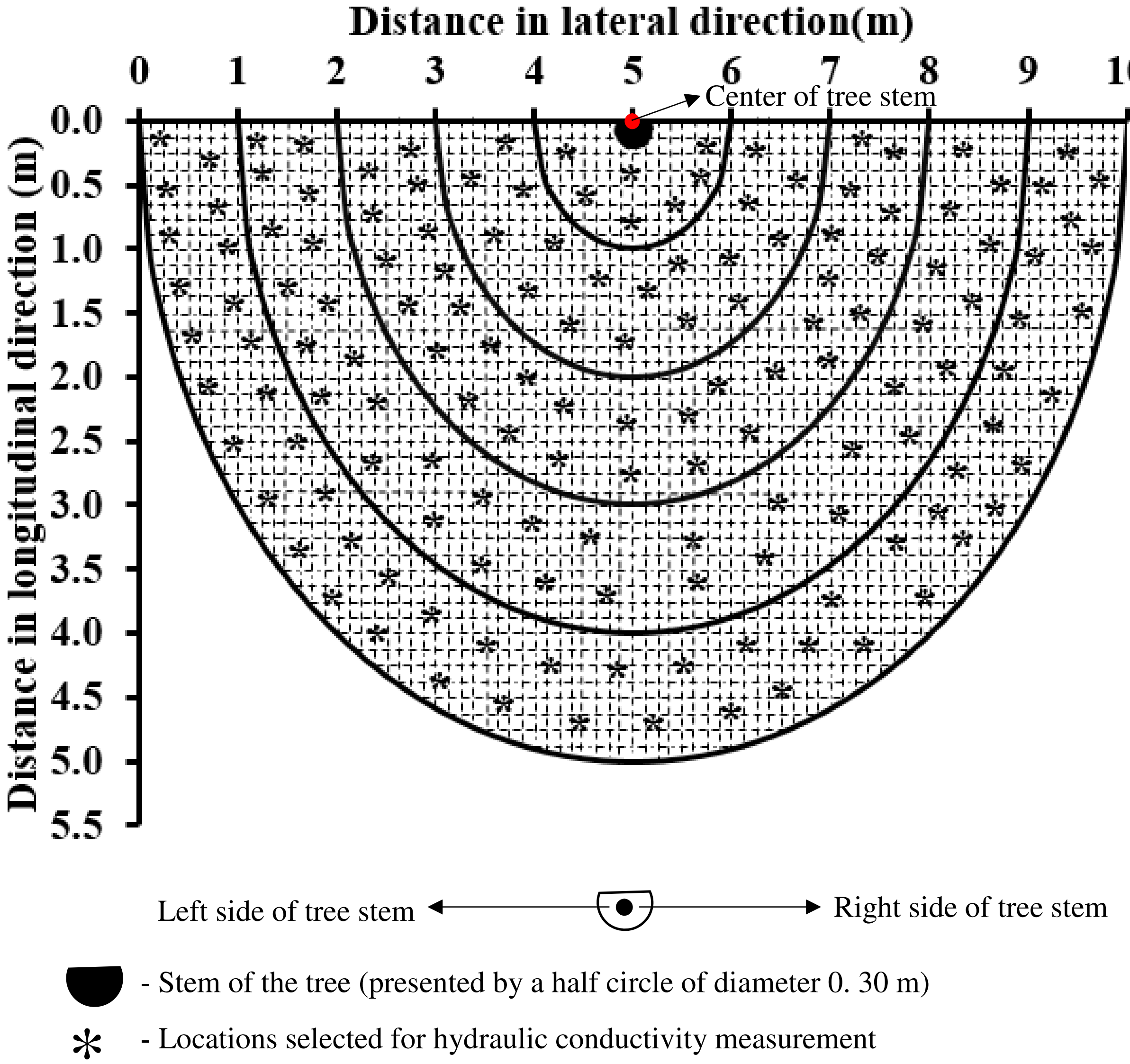
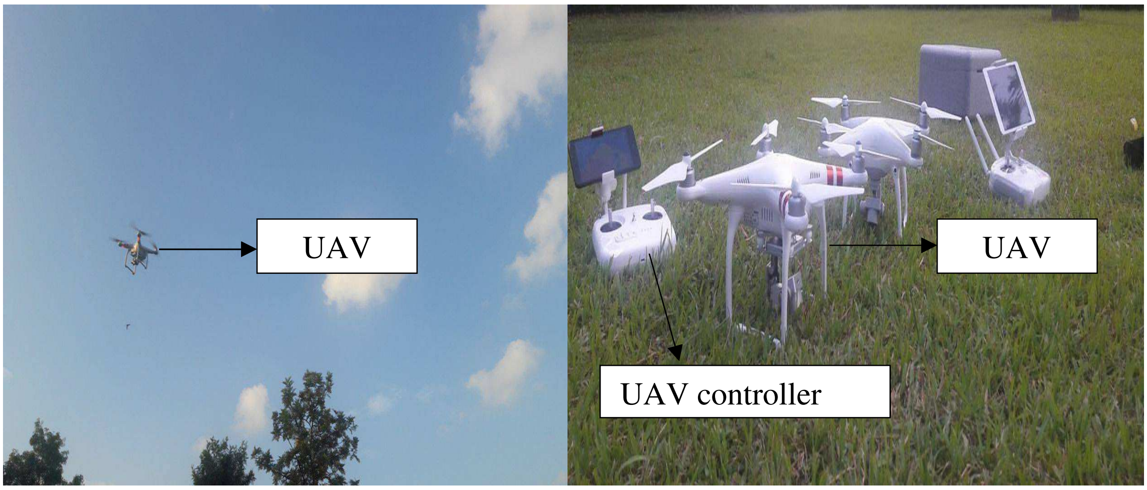
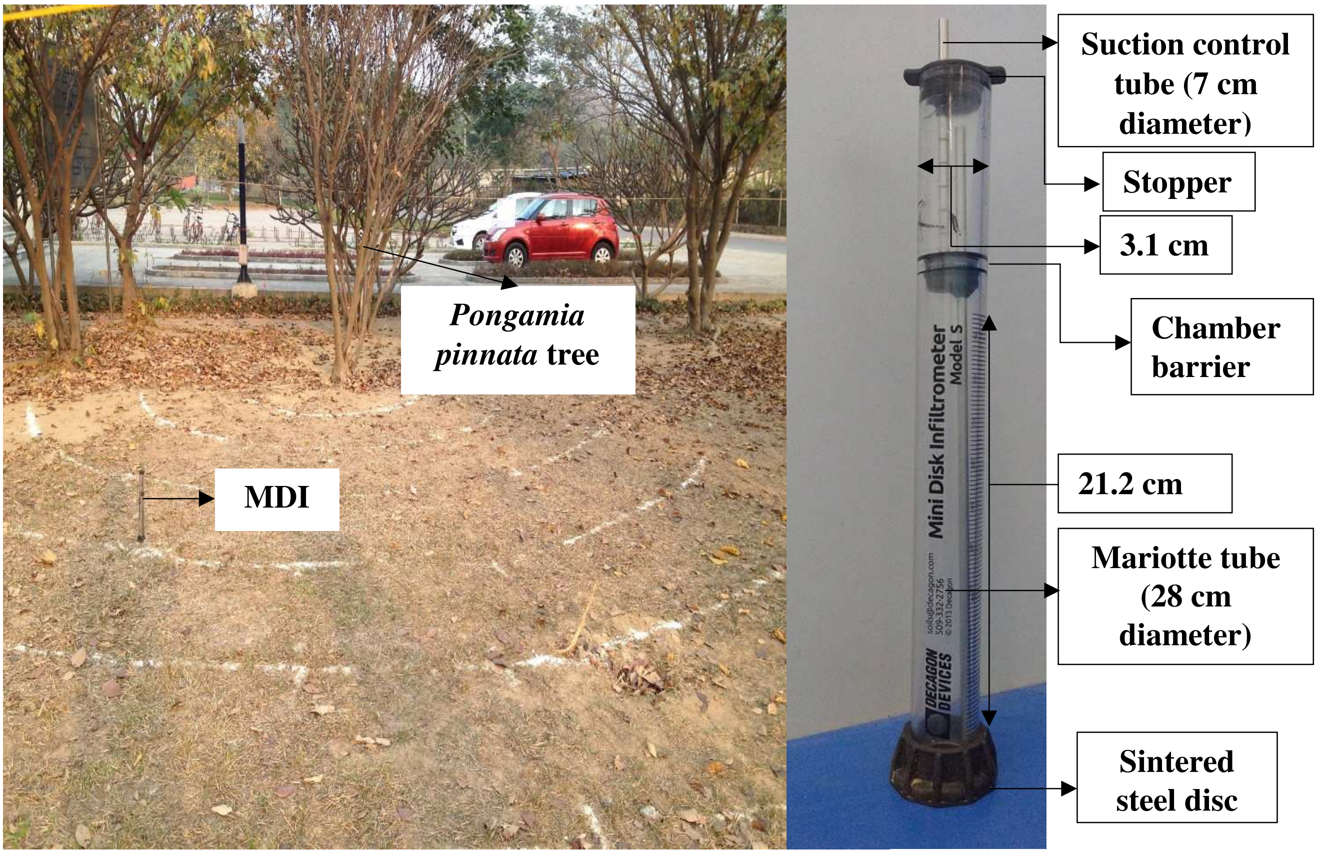


Fig. 3. Categorization of testing site into small zones for vegetation density quantification and hydraulic conductivity measurement



(a) (b)

Fig. 4. Photogrammetric view of (a) UAV (ARLab, IIT Guwahati) in air during field monitoring; and (b) UAV and its controller in the study area



(a) (b)

Fig. 5 (a) Measurement of hydraulic conductivity in the tree vicinity; and (b) Over view of MDI

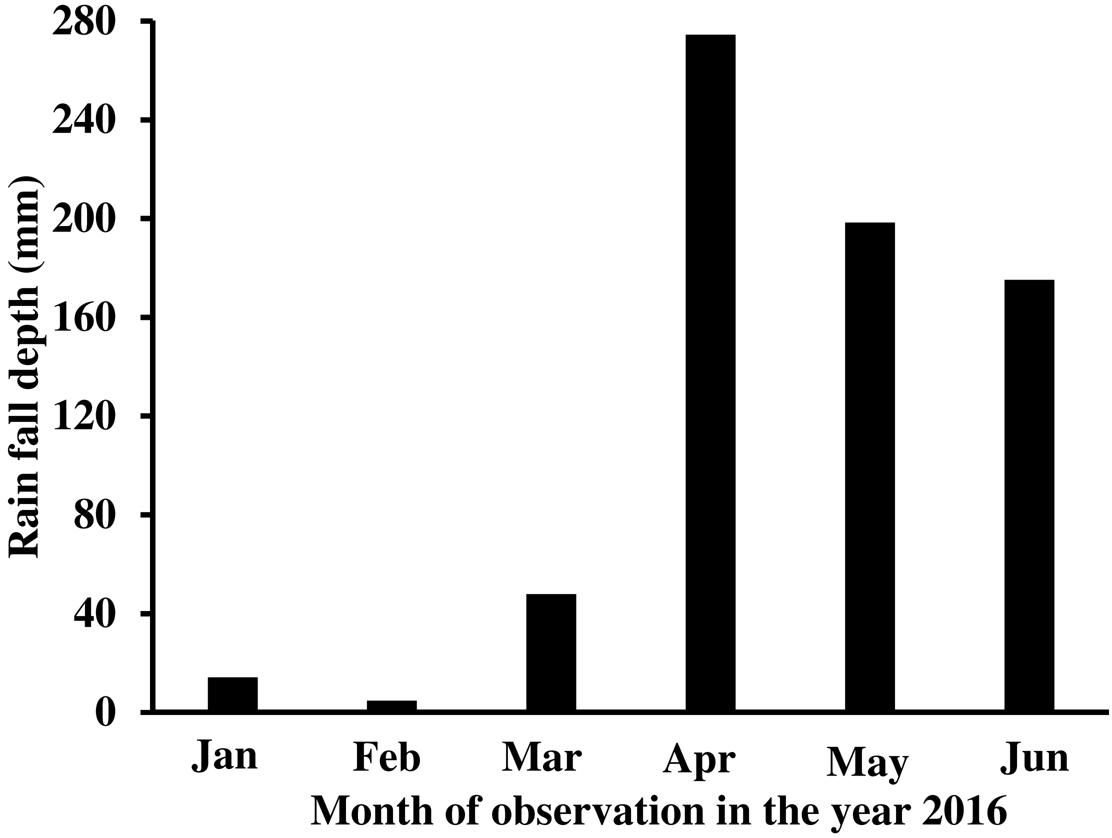


Fig. 6. Monthly rainfall depth in the study area over the monitored six months

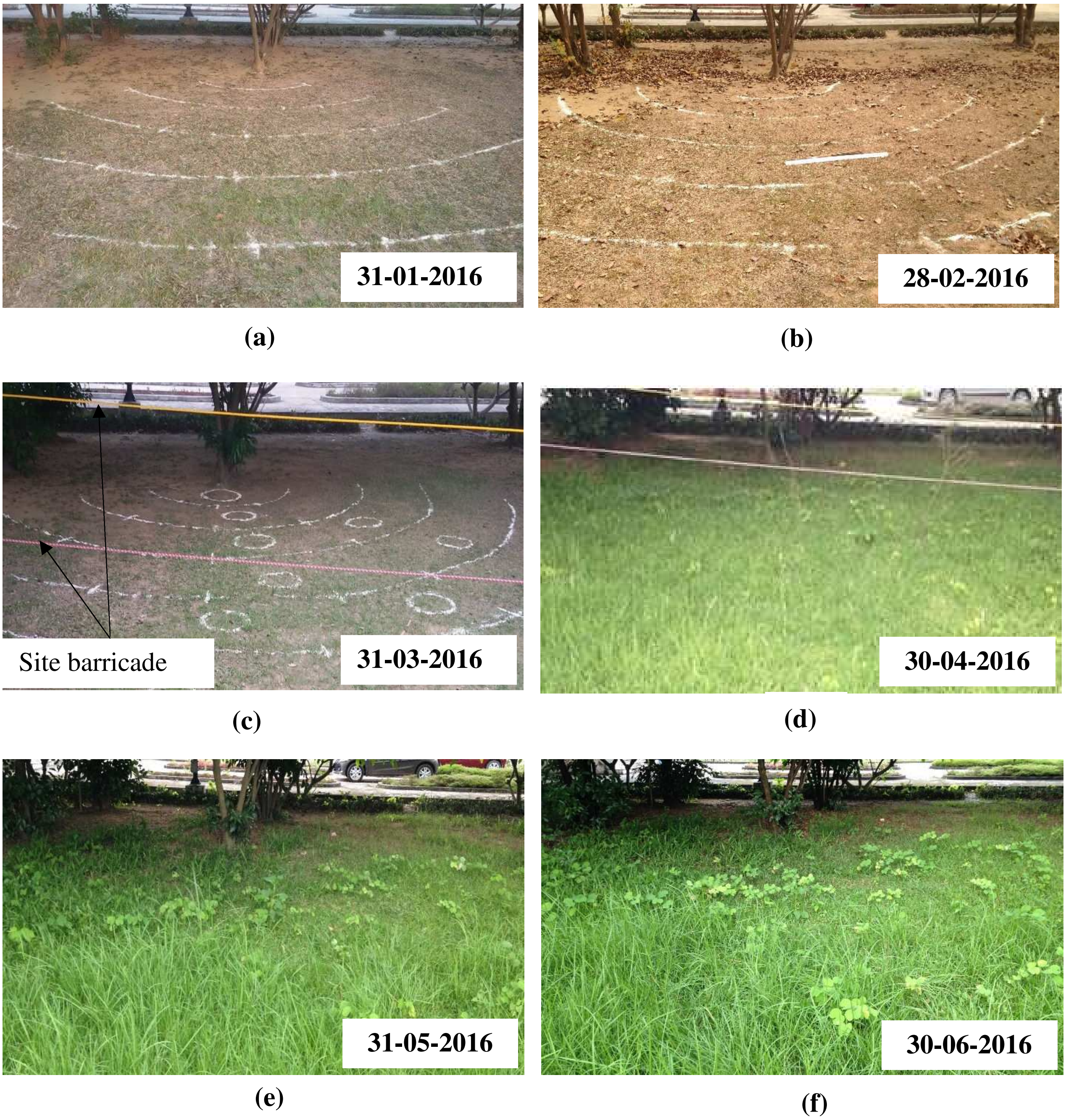
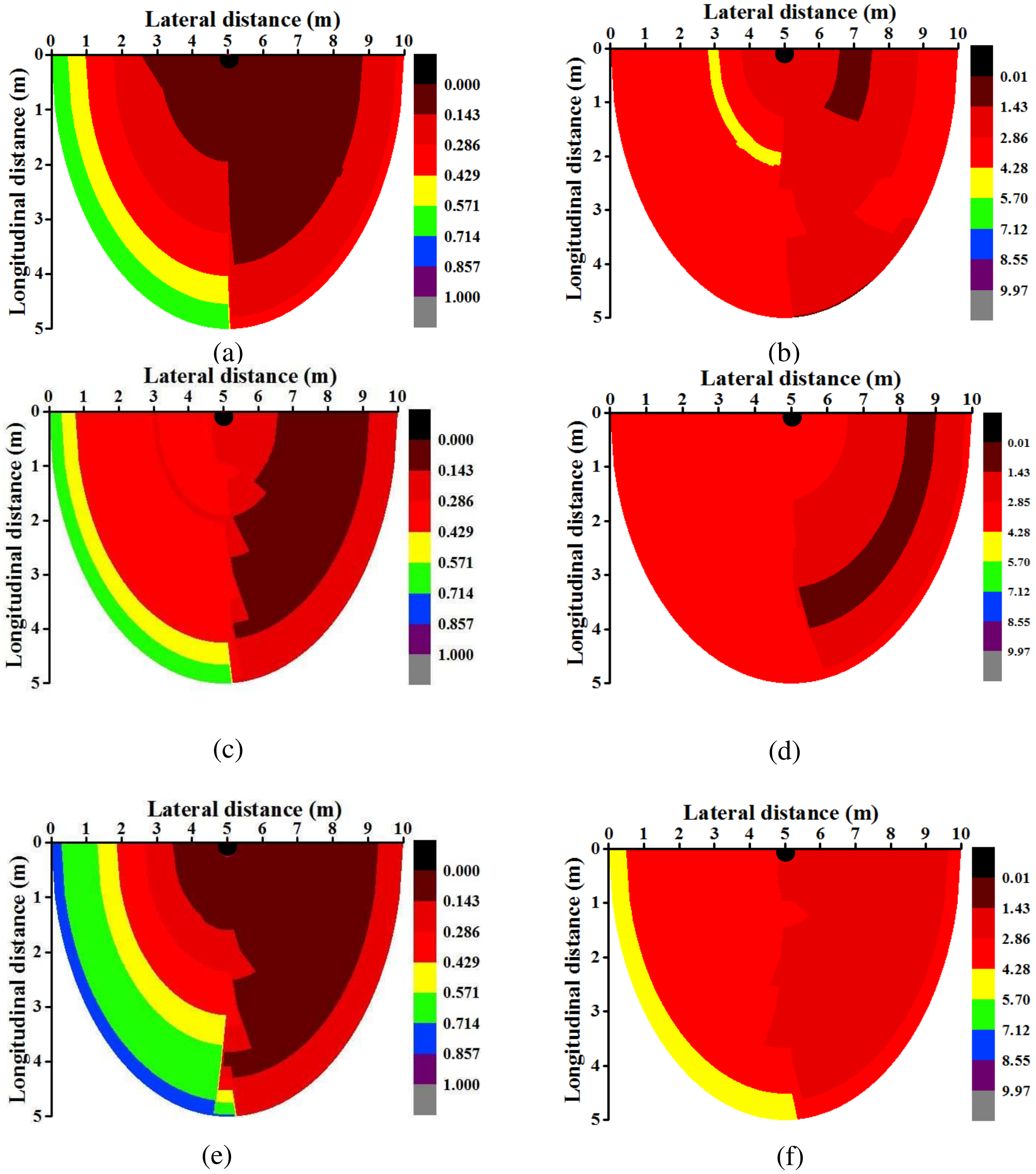
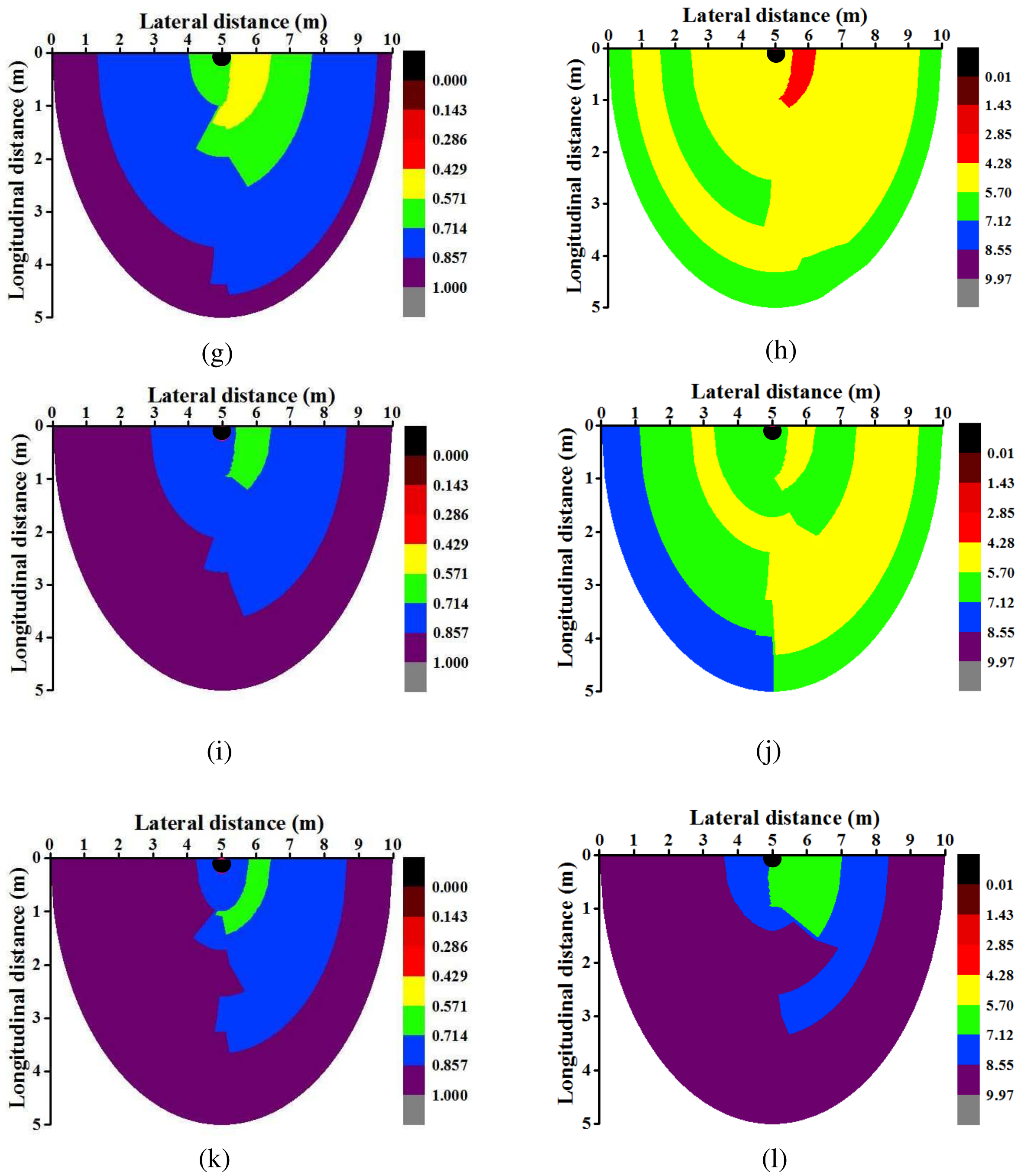


Fig. 7. Vegetation cover at the end of six different months: (a) 31 January 2016 (b) 28 February 2016 (c) 31 March 2016 (d) 30 April 2016 (e) 31 May 2016 (f) 30 June 2016


Lateral distance (m)
Longitudinal distance (m)
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5
0.000
0.143
0.286
0.429
0.571
0.714
0.857
1.000
(a)
0.01
1.43
2.86
4.28
5.70
7.12
8.55
9.97
(b)
0.000
0.143
0.286
0.429
0.571
0.714
0.857
1.000
(c)
0.01
1.43
2.85
4.28
5.70
7.12
8.55
9.97
(d)
0.000
0.143
0.286
0.429
0.571
0.714
0.857
1.000
(e)
0.01
1.43
2.86
4.28
5.70
7.12
8.55
9.97
(f)



Colour scale of Fig. (a), (c), (e), (g), (i), (k) indicates vegetation density (m^2/m^3)

Colour scale of Fig. (b), (d), (f), (h), (j), (l) indicates hydraulic conductivity (10^{-6} m/sec)

■ - Stem of the tree

Fig. 8. Spatial variation of vegetation density and hydraulic conductivity ranges at the end of: (a) & (b) January 2016; (c) & (d) February 2016; (e) & (f) March 2016; (g) & (h) April 2016; (i) & (j) May 2016; (k) & (l) June 2016