The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: Implications for surface and sub-surface hydrology

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SUMMARY

There is comparatively limited information in the humid tropics on the surface and sub-surface permeability of: (i) forests which have been impacted by multi-decades of human occupancy and (ii) forestation of land in various states of degradation. Even less is known about the dominant stormflow pathways for these respective scenarios. We sampled field saturated hydraulic conductivity, K^* at 23 sites at four depths (0 m, $n = 166$), (0.10 m, $n = 139$), 0.45–0.60 m, $n = 117$, (1.35–1.50 m, $n = 117$) under less disturbed forest (Forest), disturbed production forest of various local species (Degraded Forest) and tree-plantations (*Acacia auriculiformes*, 7–10 years old, *Tectona grandis*, ∼25–30 years old, *Casuarina equisetifolia*, 12 years old) in the Uttar Kannada district, Karnataka, India, in the Western Ghats. The sampling strategy was also undertaken across three physiographic blocks and under three main soil types. Subsequently the determined K^* were then linked with rainfall intensity–duration–frequency (IDF) characteristics to infer the dominant stormflow pathways.

The Degraded Forest shows an *order of magnitude decline* in K^* at the surface as result of human impacts at decadal to century time scales. The lowest surface permeability is associated with the Degraded Forests over the Laterite (*Eutric Nitosols* and *Acrisols*) and Red soils (*Eutric Nitosols*) and infiltration-excess overland flow, IOF probably occurs. Further there is a progressive decline in K^* with depth in these soils supporting Degraded Forests. The *A. auriculiformes* plantations over the Red and Lateritic soils are progressively restoring the near-surface K^*, but their K^* still remain *quite low* when compared to the less disturbed forest permeability. Consequently these plantations still retain the 'memory' from the previous degraded state. In contrast the permeability of the Black soils (*Vertisols*) are relatively insensitive to *T. grandis* plantations and this soil group has a very low K^*, irrespective of land cover, so that IOF likely prevails. Overall, the Laterites are the most variable in K^* when compared to the other soil groups. Thus when compared to other studies, IOF is probably more prevalent in this region. More especially so, when taking into account the marked reduction in surface K^* during the wet season when compared to dry season measurements. In addition, we have demonstrated the potential for the 'infiltration – trade-off' hypothesis to be realized in this landscape under certain conditions of land degradation and restoration. It is most relevant to the combination of degraded sites and *A. auriculiformes* plantations on Red or Laterite soils using the less disturbed forests as the baseline. The intensity of forest use and effects of monoculture plantations on soil ecology (relative to native, mixed forests) is likely to be the critical factor in affecting surface K^* over time. Predicted changes in the intensity of rain events in the future is likely to enhance overland flow on degraded sites on all soils and especially on Black soils, and restoration efforts by all stake-holders, preferably using native or non-invasive species, are needed to address this concern.

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1. Introduction

Over the last few decades, dramatic land use (LU) and land cover (LC) changes (defined and described in Drigo, 2004, 2006) have taken place in the humid tropics (Chang and Lau, 1993) which have resulted in rapid rates of deforestation. In response, Giambelluca (2002) remarked that hydrologists have traditionally focused on the hydrological impacts of forest conversion to cleared, actively used land, that is, at the respective extremes of this LC taxonomy (e.g. Bruijnzeel, 1990, 1996, 2004; Costa, 2004; Grip et al., 2004). The LC of the tropics is now becoming more fragmented and highly complex, and secondary forest is now emerging as the dominant forest type interspersed with remnants of old-growth forest and other intermediate LCs (Giambelluca, 2002; Drigo, 2004; Holscher et al., 2004; Cuo et al., 2008). These intermediate LCs include degraded, previously converted forest land now under various LUs as well as Degraded Forest (Lal, 1987; Scott et al., 2004; Safriel, 2007).

The storm runoff hydrology of these intermediate LCs from multi-decades of human occupancy, and 'forestation' (afforestation–reforestation, defined in Scott et al., 2004; Wiersum, 1984) of land in various states of degradation, have been much less studied across a range of soils and scales (Giambelluca, 2002; Bruijnzeel, 2004; Holscher et al., 2004; Scott et al., 2004; van Dijk et al., 2007; Ilstedt et al., 2007; Malmer et al., 2010). The need for such attention is emphasized when one considers that globally an increasing proportion of the population in the humid tropics are becoming dependent on these intermediate LCs for their livelihoods and ecosystem services because of decreasing availability and access to less disturbed (or old-growth) tropical forest (Drigo, 2004; Chazdon, 2008). For example within South and Southeast Asia, it was estimated that about 45% of the total land area has been affected by human-induced soil degradation (Eswaran et al., 2001; Scott et al., 2004). At the small scale ($\sim$1 km^2); Ziegler et al. (2004, 2007) presented a case study from northern Vietnam that demonstrates the surface hydrologic consequences of landscape fragmentation and a predictive frame-work for restoration scenarios.

Contrary to results from controlled, paired experimental research basins (Hewlett and Fortson, 1983; Andreassian, 2004; Bruijnzeel, 2004), there are an increasing number of reports from both degraded and converted tropical forests of the occurrence of Horton-type (infiltration-excess) overland flow IOF, across various scales of investigation (e.g. Pereira, 1989,1991; Sandstrom, 1995, 1996, 1998; Chandler and Walter, 1998; Zhou et al., 2001; Costa et al., 2003; Bruijnzeel, 2004; Ziegler et al., 2004; Chandler, 2006; de Moraes et al., 2006; Cuo et al., 2008;Chaves et al., 2008; Mehta et al., 2008; Zimmermann and Elsenbeer, 2008, 2009). The reason for this dichotomy is that most of the controlled experiments relate to the two-class land-cover taxonomy of Giambelluca (2002) where the various states of resilience of different soils to disturbance have remained high. Further the short duration of most controlled experiments has not captured the hydrological responses to *multi-decadal* degradation (Bruijnzeel, 1989, 2004; Sandstrom, 1998). Consequently the soils in the controlled experiments have retained comparatively high infiltration rates towards those of pre-disturbed conditions, and so LC change had a minimal effect on the *dominant* stormflow pathways (Chappell et al., 2007, e.g. sub-surface stormflow, SSF). In the context of the 'infiltration trade-off' hypothesis of Bruijnzeel (2004), the preceding description would be fit within the 'non-degraded scenario'.

The principal reason for enhanced IOF is a significant reduction in soil infiltrability (Hillel, 1980) and permeability due to various forms of disturbance at multi-decadal time scales (e.g. Scott et al., 2004). Strictly however *in situ* measurements made above a water table to represent saturated hydraulic conductivity, K_{sat} are known as field, saturated hydraulic conductivity, K^* because the latter can be as low as 0.5 K_{sat} (Bouwer, 1966; Talsma and Hallam, 1980; Talsma, 1987). Following Williams and Bonell (1988), K^* will be thus adopted in this work. Further K^* and 'permeability' will be used interchangeably for the same reasons as outlined in Zimmermann and Elsenbeer (2009).

A common cause for enhancing the occurrence of IOF is surface soil compaction arising from various trampling pressures such as intensive over-grazing, human pathways and roads (Ziegler et al., 2004; Hamza and Anderson, 2005; Cuo et al., 2008; Zimmermann and Elsenbeer, 2008, 2009). Moreover selected soils in the tropics are particularly vulnerable to significant changes in structure as a result of human disturbance (e.g. Gilmour, 1977; Schaak-Kirchener et al., 2007). Additional causes are the exposure of unprotected soils to high rainfall intensities which can result in raindrop compaction and sealing (Sandstrom, 1998; Grip et al., 2004; Scott et al., 2004).Thus the overall reduction in surface permeability (and thus infiltration) results in a change of the dominant stormflow pathways from SSF (supplemented by SOF) to IOF. It will also affect the vertical percolation (VP) flux in the uppermost soil layers. These circumstances are part of the 'degraded scenario' of the '*infiltration trade-off*' hypothesis (Bruijnzeel, 2004).

The fragmented LCs of the Karnataka State part of the Western Ghats in India are typical of those commonly found in the more highly elevated and densely populated parts of the humid tropics. Further in this area, a mix of State Government and community-based forestation programmes have been implemented for more than two decades within degraded forests and severely degraded, former forest-covered land (Pomeroy et al., 2003; Ramachandra et al., 2004). Consequently this area offered an opportunity to make a preliminary assessment of first, the impacts of long-term, land-forest degradation at multi-decadal to century time scales on both soil permeability and inferred runoff generation processes (Blanchart and Julka, 1997; Menon and Bawa, 1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al., 2010). A second objective is to evaluate the corresponding hydrological impacts of subsequent rehabilitation of this degraded land-forest through forestation. Further it is believed that this is the first study to present soil permeability data for Indian tropical forests.

The long time scales of disturbance in the Western Ghats forests are typical of the densely populated Asian region where similar hydrological studies have been undertaken (Chandler and Walter, 1998; Chandler, 2006; Zhou et al., 2001; Ziegler et al., 2004, 2007; Cuo et al., 2008). Elsewhere reports from similar work being undertaken in the Amazon basin and montane Ecuador are monitoring the hydrological impacts of comparatively recent disturbance of approximately 20–30 years (Tomasella and Hodnett, 1996; Elsenbeer et al., 1999; Godsey and Elsenbeer, 2002; Zimmermann et al., 2006; de Moraes et al., 2006; Chaves et al., 2008; Zimmermann and Elsenbeer, 2008, 2009; Germer et al., 2010). Consequently some of the results from that South American work will provide an interesting comparison with the present study.

Following a description of the study area, the research questions will then be listed by drawing upon selected issues previously raised from global reviews (Bruijnzeel, 2004; Holscher et al., 2004; Scott et al., 2004; van Dijk et al., 2007; Ilstedt et al., 2007). A comparative overview of K^* across soil groups and land covers is then presented. Subsequently using a strategy similar to that undertaken elsewhere in the tropics and sub-tropics, field measurements of K^* are compared with various rainfall characteristics (IDF, intensity–duration–frequency) to infer *dominant stormflow pathways* (Chappell et al., 2007; and using the terminology of Chorley, 1978) under the more *extreme* rainfalls (Bonell et al.,

1983; Gilmour et al., 1987; Elsenbeer et al., 1999; Godsey and Elsenbeer, 2002; Zimmermann and Elsenbeer, 2009). Finally the implications for forest management, hydrologic restoration and likely changes in hydrologic response under climate change scenarios will be briefly examined.

2. The study area

2.1. The physical background

The study area is shown in Fig. 1. Apart from Uttara Kannada, part of the Shimoga and Dharwad Districts were incorporated in the field campaign, which gave a combined area of ~16,000 km².

The geology is highly complex with the most important formations being (i) the Archaean (Peninsular Gneiss), (ii) the Archaean to Lower Proterozoic (Dharwar schist) belt, (iii) the Upper Proterozoic (granite) and (iv) pockets of Paleocene to Recent laterite in the coastal hinterland (Geological Survey of India, 1981). Such geological formations results in an equally complex distribution of soil groups, soil orders and associated permeability (Shivaprasad et al., 1998).

The geomorphology reflects the complex geology by resulting in a sharp, contrasting topography. Within Uttar Kannada district, there are gentle undulating hills which rise steeply from a narrow coastal strip bordering the Arabian Sea to a plateau at an altitude of 500 m with occasional hills rising above 600–860 m. Using the landform classification of the National Bureau of Soil Survey and Land Use Planning, NBSSLUP (NBSSLUP, 1993), the study area can be thus broadly categorised into three distinct blocks that is, (i)

the Coastal Lands (ii) the mostly forested Sahyadrian interior corresponding to the Western Ghats proper (Malnad) and (iii) the Eastern Margin where the table land or plateau begins that merges with the Deccan plateau. Following the landscape groupings of Gunnell and Radhakrishna (2001), these blocks are termed respectively as Coastal, Mid-Ghat/Mid-lands and Up-Ghat.

Gunnell (1997) outlined the climatic features of the Western Ghats in some detail, which is distinctly monsoonal. The rainfall is dominated by the orographic uplift of moist, southwest monsoon airflow with the topographic barrier of the "Western Ghats-Central Sahyadri" during the months June–September (Pascal, 1982; Gadgil and Joshi, 1983; Singh, 1986; Katiyar, 1990). Spatially annual rainfalls are highly variable and range from 1150 mm to greater than 5000 mm over the highest topography. There is a distinct drying gradient on the eastern slopes and onwards towards the Deccan plateau.

The complex geology, geomorphology, climate of the Western Ghats is reflected in a corresponding diversity of vegetation and soils. The vegetation of the Western Ghats has been classified using criteria such as physiognomy, phenology and floristic composition (Pascal, 1982, 1984, 1986, 1988; Ramesh and Pascal, 1997; Ramesh and Swaminath, 1999). There are five major floristic types, namely evergreen and semi-evergreen forest (low, medium, high elevation) and deciduous forest (dry type, moist type); all of which are closely correlated with the temperature and rainfall regimes (Pascal, 1986). Following other tropical countries which contain very old landscapes and soils (e.g. Brazil, Oliveira et al., 1992, as highlighted by Elsenbeer et al. (1999) and de Moraes et al. (2006); Australia, Isbell, 2002; McKenzie et al., 2004, as adopted
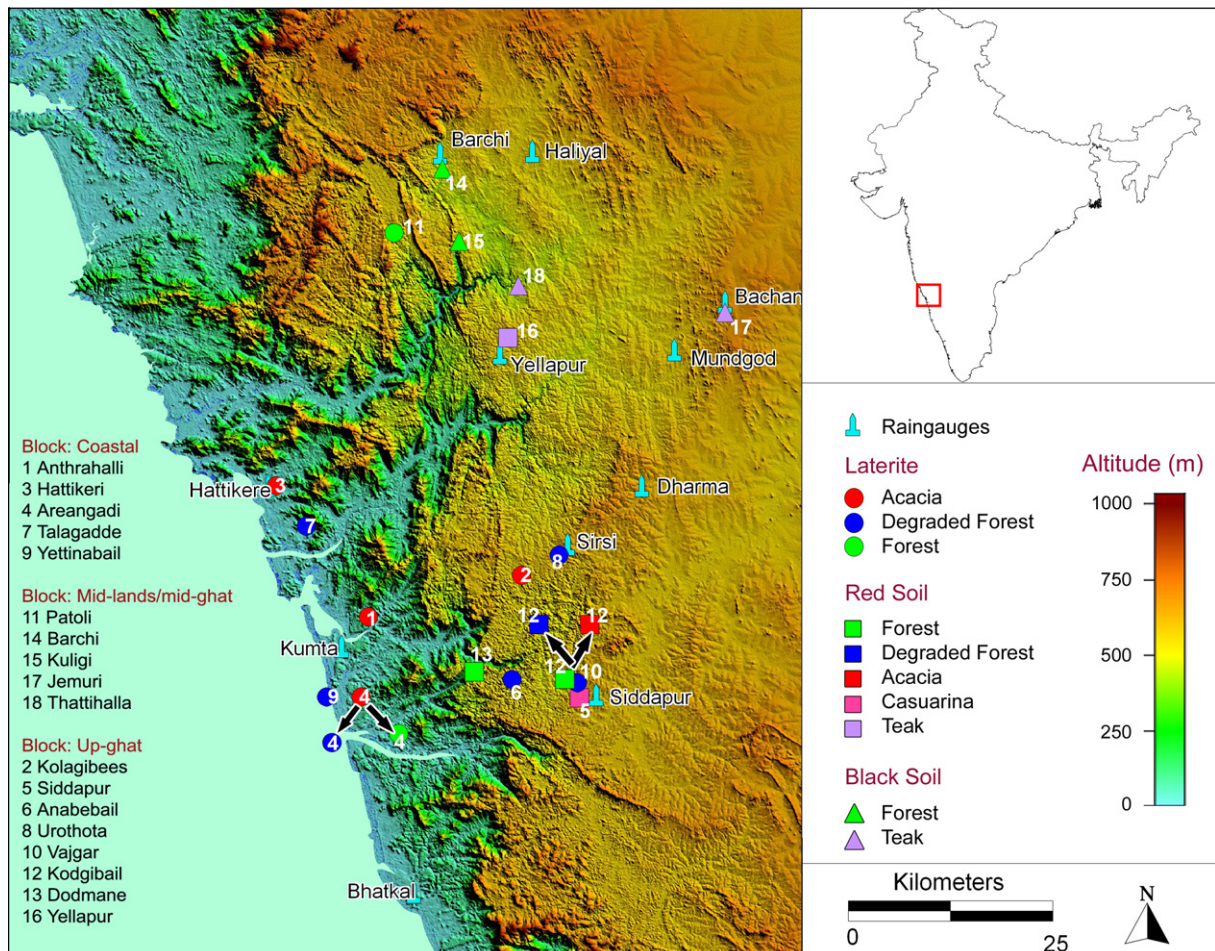

Fig. 1. The study area. Highlighted are (i) the three Blocks (Coastal, mid-Ghat, Up-Ghat), (ii) the soil-land cover sites and (iii) the network of continuous rainfall recorders.

by Bonell (2004) and Bonell et al. (1983)), India has its own soil classification of the NBSSLUP (1993) which we will use as the preferred identification of the soils (Fig. 1). Shivaprasad et al. (1998) mapped the soils at a coarse scale of 1:250,000 using the more traditional soil groups of the NBSSLUP (Table 4.8 in Shivaprasad et al., 1998). These writers noted that the dominant soil groups are the Black soils, Laterite soils and Red soils, or respectively Vertisols and a mixture of Alfisols and Ultisols for the USDA (Soil Survey Staff, 1975, 1999); and likewise for the FAO-UNESCO classification (FAO-UNESCO, 1974, 1988; FAO, 1998), Vertisols and a mixture *Eutric Nitosols* and *Acrisols*.

2.2. Placing the Western Ghats of India in the context of degraded land cover – runoff generation issues

As a result of degradation of forests over multi-decadal to century time scales, the land cover is complex (Blanchart and Julka, 1997; Menon and Bawa, 1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al., 2010). Patches of remnant forest, which are less disturbed and less used by people are at one end of the disturbance gradient and at the other end are a heterogeneous category of disturbed and heavily used forest which consist of open forest, grassland and savannah woodlands. Livestock grazing, fuel wood and fodder extraction, fire as well as extraction of leaf-manure and cropland are major land-uses in these highly disturbed or degraded sites which provide local communities with substantial "provisioning" ecosystem services (Millennium Ecosystem Assessment, 2005) and sustain many livelihoods (Lele, 1993; Rai, 2004). However the trade-offs of these provisioning services with respect to hydrologic functions and services (Elmqvist et al., 2010) is relatively unknown. Further within the humid tropics, Rai (1999) estimated that nearly 80% of forestation using both native and exotic species was taking place in India and the Karnataka State portion of the Western Ghats has taken a lead in such forest restoration. Many degraded patches of land cover have been reforested with *Tectona grandis* plantations, pre-1980 (from here on referred to as 'Teak'), exotic *Acacia auriculiformes* plantations, post-1980 ('Acacia') and more locally, *Casuarina equisetifolia* plantations, post-1980 ('Casuarina') (Pomeroy et al., 2003; Pontius and Pacheco, 2004; Ramachandra et al., 2004).

Consequently the Western Ghats (Karnataka State) offers an opportunity to evaluate LC impacts on permeability at contrasting time scales namely the impacts on soil permeability of:

(i) forest land use and degradation,
(ii) forestation over previously degraded land, relative to less used native forest.

Both these land cover scenarios are in line with the storm runoff generation issues highlighted above.

3. Scientific objectives

Using the relatively less disturbed evergreen forest – semi-evergreen forest – moist deciduous forest (now referred to as 'Forest') at one end of the LC spectrum and heavily-used production forest land (including some grassland/Savannah-Woodlands) at the other (hereon referred to as 'Degraded Forest'), the following issues will be addressed:

i. To what extent is K^* altered due to long-term degradation of forests?
ii. To quantify any changes in permeability following forestation of landscapes in various states of degradation using plantations of Teak or Acacia?

iii. To what extent are the inferred dominant stormflow pathways comparable with other reports from elsewhere in the humid tropics?
iv. To quantify what is the likely effect of wet-season conditions on actual hydraulic conductivities in contrast to measurements made in the dry season that are the normal procedure for field measurements? What implications does this have for predicting hydrologic consequences of forest degradation?

4. Methods

4.1. Sampling design

4.1.1. Land covers and physiographic blocks
The sampling sites scattered across the ~16,000 km^2 area were selected based on the five principal land covers associated with land-forest management (Fig. 1). They included less disturbed, natural forest ('Forest'), disturbed production forest of various local species ('Degraded Forest') and tree-plantations (Acacia, Teak, Casuarina). The total number of K^* samples (n) for these respective LCs across all tested soil depths were Forest ($n = 205$), Degraded Forest ($n = 174$), Acacia ($n = 142$), Teak ($n = 53$) and Casuarina ($n = 18$). The sampling design also included the three principal soil groups (Black, Laterite, and Red) and the three physiographic blocks, namely the Coastal, the Mid-Ghat and the Up-Ghat (Fig. 1). These blocks are characterized by distinct topographic position and associated rainfall regimes (Gadgil et al., 1988).

In consultation with the Karnataka Forest Department, patches of distinct land-cover and land-use that were considered homogeneous were surveyed and selected using topographic maps and ground-surveys (Pomeroy et al., 2003; Karnataka Forest Department, 1997; Khanna, 1996). In addition, the soil types were identified initially using the mapping of Shivaprasad et al. (1998) and later confirmed from samples taken for laboratory analyses.

4.1.2. Total number of sites
Based on logistical constraints of access and the limitations of transporting equipment and large quantities of water over large distances for the permeability measurements, finally, a total of 23 sites were selected (Fig. 1). These included 7 in the Coastal, 5 in the Mid-Ghat and 11 in the Up-Ghat region.

4.1.3. Number of sites by land cover
When concerning LC, the sites included 5 Acacia plantations (varying from 7–10 years old), 7 Degraded Forests and 7 Forests, supplemented by, 3 Teak plantations (~25–30 years old) and 1 Casuarina plantation (12 years old) (Pomeroy et al., 2003). With the exceptions of the Teak and Casuarina, all other land covers are represented across the three physiographic blocks (Fig. 1). Two of the three Teak plantations are confined to the Mid-Ghat in association with the Black soils. The additional Teak plantation, as well as that of the Casuarina, is located over Red soils in the Up-Ghat region (Fig. 1). A sub-set of these sites (17 in all) covered replicate sites for Forest, Acacia and Degraded Forest on Red and Laterite soils. This procedure resulted in the respective replicates of 5 sites (Forest), 5 sites (Acacia) and 7 sites (Degraded Forest).

4.1.4. Number of sites by soil group
The three soil groups were not evenly spread across all three physiographic blocks. For example, the Black soils are concentrated in the Mid-Ghat (4 sites) and the Red soils (7 sites) are located in the Up-Ghat. The Laterite soil group (12 sites) is the only one which is represented across all three physiographic blocks.

4.1.5. Sampling strategy within each site or plot

At each site, the plot sizes for K^* sampling ranged from 10×10 m to 20×20 m depending on suitable ground for measurement and constraints such as density of vegetation, tree roots and rocks. Soil was sampled for K^* at points randomly selected within each plot up to 1.5 m at four depths: 0, 0.1, 0.45–0.60 and 1.20–1.50 m. The number of samples taken at each depth depended on the size of the land-cover patch as well as logistical considerations. But at least five samples were taken by depth and at some sites up to 18 points were measured for selected soil layers. When concerning the presentation of the results, the latter will be abbreviated here on using the lower depths, viz. 0.60 and 1.50 m. Table 1 summarizes the number of K^* samples across the four sampling depths for each soil group. Table 2 shows the corresponding sample sizes for the replicate sites for Forest, Acacia and Degraded Forest on Red and Laterite soils.

4.2. Determination of field, saturated hydraulic conductivity, K^*

For the surface and 0.1 m depth, the disc permeameter was used for the determination of soil hydraulic properties (Perroux and White, 1988; McKenzie et al., 2002). Close attention was given to problems with the method and data quality control linked with any individual tests (as outlined in detail by Perroux and White (1988) and McKenzie et al. (2002)). This particularly applied to the Black soils during tests undertaken during the dry season due to the appearance of soil cracks from the clay dominant texture. Any tests affected by short-circuiting, which counters the assumption of matrix flow theory, had to be rejected and replicated again (Wooding, 1968; Perroux and White, 1988; McKenzie et al., 2002).

For the deeper layers, the field logistics of water transport in difficult terrain restricted the determination of K^* to the 0.45–0.60 m and 1.20–1.50 m depths using an adaptation of the constant head well permeameter (CHWP) of Talsma and Hallam (1980) Reynolds et al. (1983, 1985), Philip (1985), Reynolds and Elrick (1987) and Mackenzie (2002). The use of the CHWP was restricted to the dry season to minimise errors from "smearing" of the auger hole walls (Mackenzie, 2002; Chappell and Lancaster, 2007).

The disc permeameter (or its predecessor, the Talsma infiltrometer ring, Talsma, 1969) and CHWP are now commonly used as part of inferring dominant stormflow pathways in the humid tropics (e.g. Elsenbeer and Vertessy, 2000). On the other hand, there has been extensive discussion on the inherent weaknesses and uncertainty in these methods for providing a true representation of K^* linked with the methodologies themselves and the fact they only measure at a point-scale (e.g. Talsma, 1987; Sherlock et al., 2000; Mackenzie, 2002; McKenzie et al., 2002; Chappell and Lancaster, 2007). From the hillslope scale upwards (Keller et al., 1986, 1988; Bazemore et al., 1994; Noguchi et al., 1997; Brooks et al., 2004; Uhlenbrook, 2006; Jourde et al., 2007) the order of magnitude of K^* can be much higher due to a greater incorporation of conductive macro-pores. The description by Putty (Putty and Prasad, 2000a,b; Putty, 2006) for a headwater, catchment study located south of the Study Area within the Dakshina–Kannada district of the Western Ghats emphasizes this point. Within the evergreen forest of that study, the conveyance of SSF was principally by pipes (ranging for a few mm to 1 m diameter) and the corresponding percolation rates (100–300 mm h^{-1}) were high.

Thus there are several issues which potentially affect the reliability of measured K^* (viz, scale effects, insufficient incorporation of macro-pores and pipes, a bias towards the soil matrix, and experimental errors even at the point-scale). Taking these into account, then the K^* data presented here might be better considered more as 'indicators' when inferring pathways of stormflow.

4.3. The temporal variability of the surface K^*

The surface K^* data were also based on measurements taken in the dry season. On the other hand, for some time there has been recognition that the surface K^* can exhibit both temporal as well as spatial variability (Topalidis and Curtis, 1982; Gish and Starr, 1983; Bonell and Williams, 1986; Elsenbeer et al., 1999; Chappell and Lancaster, 2007). Such temporal variability is particularly marked in the tropics where the kinetic energy of rainfall is high. This results in mechanically-based disruption of the surface soil structure over areas not protected by a low vegetation cover, i.e. compaction from raindrop impact (McIntyre, 1958a,b; Mott et al., 1979). In addition, physical–chemical changes can occur in soils of high clay content (e.g. the Black soils) due to swelling on contact with percolating rainwater. Mechanical disruption to surface soil aggregates also occurs where overland flow is frequent.

To check for such temporal variability of surface K^*, one set of spot estimates for both the dry season and the wet season respectively were taken at 15 sites. These sites were selected to include the range of soil types and land covers. The disc permeameter was placed over the same sampling points within each plot.

4.4. Rainfall intensity–duration–frequency analysis (IDF)

In the study area, Water Resources Development Organization of the Govt. of Karnataka is maintaining a rain gauge network, within which, there are 12 recording and about 90 of the non-recording type of rain gauges. In an earlier study carried out by Gadgil et al. (1988) these writers identified three zones in the study area using a disparity index (defined in Gadgil et al., 1988) and the monthly rainfall distribution as the principal indicators, viz, (i) the Coastal zone, (ii) Mid-Ghat zone and (iii) the Up-Ghat. However a key problem is the poor spatial representation of these zones by the limited number of rain recorders (Fig. 1) and the short duration of continuous records (ranging from 6 to 25 years). This led to pooling to form a larger regional data set. The rainfall intensity for each of the 15 min duration was then calculated up to 5hrs. Subsequently the values of annual maximum rainfall intensity (mm h^{-1}) were regressed against duration (15 min to 5 h). The Weibull plotting position procedure, as described by Sharma (1987) was then used to estimate the return periods.

Elsewhere for rainfall analysis in India, Kothyari et al., 1990 had used the intensity values obtained after fitting the Gumbel distribution in deriving the IDF equation. This approach is to some

Table 1
The sample sizes of K^* for each soil group.

| | Surface | Sample sizes by depth | | |
		0.1 m	0.60 m	1.5 m
Soil group				
Black	22	17	16	16
Laterite	57	47	45	45
Red	87	75	56	56

Table 2
The sample sizes of K^* for each soil group land cover (sub-set of replicate land covers, 17 sites).

| | Surface | Sample sizes by depth | | |
		0.1 m	0.60 m	1.5 m
Land cover				
Forest	46	46	39	38
Acacia	44	36	31	31
Degraded forest	55	45	37	37

extent acting as a representation of the Gumbel distribution itself; whereas, the method of Sharma (1987) avoids the preceding problem to derive the IDF. Moreover the rainfall characteristics and environmental circumstances in which the method of Sharma (1987) was developed, matches with the conditions of the current study area (the exception is the Coastal region). Hence it was decided to adopt the Sharma (1987) approach in developing the IDF characteristics.

4.5. Data analysis

The untransformed, point K^* measurements classified by soil group and land-cover will be presented using box plots. Box plots show a measure of central tendency (median) and a measure of dispersion (inter-quartile range), upper and lower quartiles and outliers. They are one of the most useful diagnostic graphical tools for comparing highly heterogeneous variables such as hydraulic conductivities across soil types or land-cover categories. When the untransformed point K^* data are used in the box plots, the dispersion reflects both within-plot and across site variability.

On the other hand, in view of the fact we are comparing widely separated sites across a very large study area, there is need for an alternative approach which shows inter-site variability across the landscape only and does not include intra-site variability as well. A first step was to calculate the geometric (or log-average) mean from the individual K^* data at a specific depth within each site. These plot – averaged geometric K^* means were taken as representative of each depth in the sites concerned. We will use strip charts (R version 2.9.1; http://www.r-project.org) to compare these plot averaged K^* across all soil types and land-cover categories. Stripcharts produce one dimensional scatter plots (or dot plots) of the given data and they are a good alternative to box plots when sample sizes (i.e. no. of sites) are small. Further 'jittering' (using R software above) has been applied to enable similar valued or coincident data points to be viewed clearly.

A statistical summary of the plot averaged K^* by soil group and land-cover will be presented. The 95% confidence intervals about the medians will be bounded by zero at the lower end.

The rain IDF characteristics will be superimposed on both the box plots and strip charts so that the dominant storm pathways can be inferred, i.e. under *extreme rainfalls*. The assumption will be for near-saturated, antecedent soil moisture conditions (typical of optimal conditions of wetness during the summer monsoon season) so that any vertically percolating rainwater (VP) will be controlled by vertical changes in K^* under a unit hydraulic gradient (in line with Darcy's law) (Gilmour et al., 1987).

The differences in seasonal K^* at the surface will be statistically examined using the nonparametric Mann–Whitney U Test which is suitable for comparing two populations consisting of small samples (Siegel, 1956, p. 116). Further the respective wet and dry season K^* data were lumped and compared also using box plots. These plots will illustrate any changes in the central tendency and the dispersion of K^* about the median.

5. Results

This section will compare the K^* data with the rainfall IDF.

5.1. Rainfall intensity–frequency–duration analysis (IDF)

Overall the IDF characteristics shown in Table 3 are in line with the earlier observations of Putty and co-workers (Putty et al., 2000; Putty and Prasad, 2000a,b). This is an environment of high daily totals but relatively weak, short-term intensities in comparison with other humid tropics rain stations, c.f. Bonell et al. (2004).

5.2. Field saturated hydraulic conductivity, K^*, for specific layers

In line with early work (e.g. Talsma, 1969; Rogowski, 1972; Nielson et al., 1973; Baker, 1978); the K^* data often have a logarithmic statistical distribution. In this study the pooled K^* data when transformed with a log10-transform produced a symmetrical distribution indicating that the underlying distribution is log-normally distributed. Elsewhere other researchers have applied different transformations for selected shallow, soil layers (e.g. Elsenbeer et al., 1992; Zimmermann et al., 2006; Zimmermann and Elsenbeer, 2008). The former two studies thus used root transformations of K^* data such as the fourth – root transformation as a better descriptor of this variable for the upper soil 0.1 m. layer whilst reverting to the log transformation below 0.1 m depth. Whereas Zimmermann and Elsenbeer (2008) used either the square root, or reciprocal of the square root, for data taken at 0.125 m and 0.20 m depths in the case of two of the eight land covers considered. Otherwise they found the logarithm transformation was the most appropriate.

For a comparison across soil types and LCs in the present study, emphasis is made on the medians (when concerning the box plots) and the log-average or geometric means (expressed in original standard units of mm h^{-1} following taking the antilog) rather than the arithmetic means for any graphical or statistical comparisons across soil type or land-cover. In view of the errors connected with the field methods, it is probably more realistic to place greater emphasis on the order of magnitude differences between K^* (mm h^{-1}) and the equivalent hourly rain intensities (for specified durations and return periods), rather than solely depend on absolute values, for inferring dominant stormflow pathways.

Table 3
The rainfall intensity–duration–frequency (IDF). Estimates using the method of Sharma (1987) of rainfall intensity (in mm h^{-1} equivalent)–duration and frequency (selected return periods are given) for the entire region.

Entire region with station names	Duration	Return periods							
		1 year	2 year	5 year	10 year	25 year	50 year	75 year	100 year
(12 raingauges) Kumta, Hattikeri, Bhatkal,Sirsi, Yellapur,	15 min	49.15	56.65	79.86	95.23	114.65	129.06	137.43	143.36
Joida, Siddapur, Barchi, Mundgod, Bachaniki, Dharma, Haliyal	30 min	38.00	43.52	60.59	71.89	86.17	96.76	102.92	107.28
	45 min	30.92	35.84	51.07	61.16	73.90	83.35	88.85	92.73
	1 h	25.83	29.80	42.08	50.21	60.48	68.10	72.52	75.66
	2 h	17.42	20.06	28.24	33.65	40.49	45.56	48.51	50.60
	3 h	14.37	16.39	22.63	26.77	31.99	35.87	38.12	39.72
	4 h	12.27	14.19	20.13	24.06	29.03	32.72	34.86	36.37
	5 h	10.81	12.41	17.35	20.62	24.76	27.82	29.61	30.87
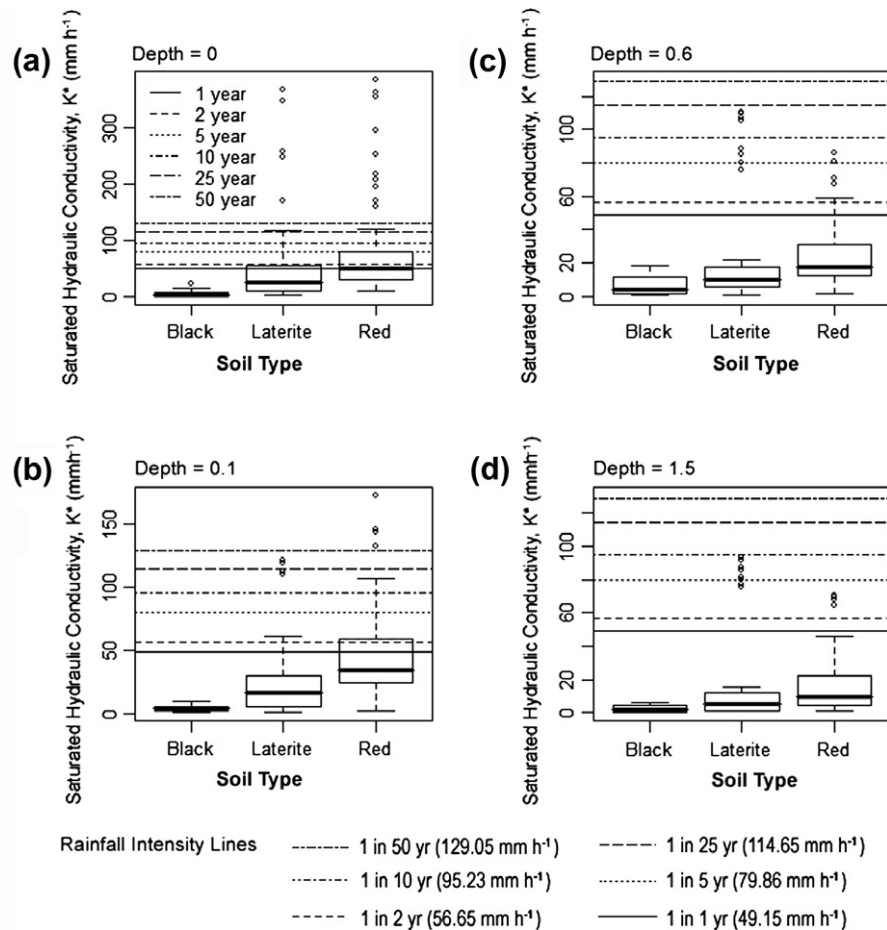
Fig. 2. The box plots of K^* by Soil Group (Type) for (a) surface (b) the 0.1 m depth (c) 0.6 m depth and (d) 1.5 m depth and the rainfall intensities (mm h^{-1}) for the 15 min duration for the selected return periods (1 in 1 year, 2 years, 5 years, 10 years, 25 years, and 50 years).

5.3. A comparison of the distribution of the untransformed, point K^* data using box plots with the strip charts including geometric mean K^*

Box plots are presented by soil groups (Fig. 2a–d) and land cover (Fig. 4a–d). These are adjoined with the respective strip charts (Fig. 3a–d and Fig. 5a–d). Also included are the average rainfall intensities (in mm h^{-1} equivalent) for 15 min duration over the study area by different return periods from one (1) year upwards. These provide a diagnostic for inferring the dominant storm runoff pathways under the most intense rainfalls.

5.3.1. Soil groups

The rank order of median K^* persists at all depths (Fig. 2a–d, Table 4). Thus the Red soils are the most permeable and the medians retain the same order of magnitude of K^* down to 1.5 m. depth. In contrast the Black soils have persistently the lowest K^* throughout the soil profile, irrespective of land cover, or when concerning both intra-site and inter-site variability (Fig. 2a–d and Fig. 3a–d, Table 4).

The Laterite and Red soil groups also show considerable dispersion in the box plots and is a feature which persists at all depths (Fig. 2a–d). On the other hand, it is the Laterites which are more variable across the landscape as shown in Fig. 3 and elsewhere by the corresponding 95% confidence intervals in Table 4. The box plots offer an explanation for such variability. The lower quartiles in Fig. 2a–d for the Laterite are almost on parity as those shown for the Black soils and in line with the lower bound of zero in the K^* data (Table 4). Further many of the geometric mean K^*

points in Fig. 3a–d are not too dissimilar between the Laterite and Black soils. The complex geology and topography of the study area and the corresponding, complex genesis of this Laterite group maybe a causal factor for such variability.

5.3.2. Land cover

Fig. 2a has already shown that the Black soils are impermeable and thus there are no marked impacts of land cover on surface K^*.

For the LCs with adequate sampling replicates (incorporating the Laterite and Red soils), as expected the median surface K^* (Fig. 4a, Table 5) is the lowest for the Degraded Forest and the highest for the Forest. This aspect is also clearly evident across sites, as shown in Fig. 5a. In addition the Acacia plantations enhance surface K^* so that the box plot median (Fig. 4a) occupies an intermediate position in rank order between the Forest and the Degraded Forest. At the 0.1 m depth (Fig. 4b), the main change is that the median K^* in the Forest has markedly reduced (Table 5) which is also evident by the inter-site comparison of K^* geometric means (Fig. 5a and b).

At the lower depths (0.6 m and 1.5 m) (Fig. 4c and d, Table 5) whilst the rank order of median K^* remains the same as for the more shallow depths, the differences between the Acacia and Forest are much less. In addition there is greater dispersion in K^* for the both the Acacia and Forest in contrast to the Degraded Forest. Fig. 5c and d also highlights the wide range of site geometric means under Acacia and Forest supported by the larger 95% confidence intervals, as shown in Table 5. This pattern maybe in part a reflec-
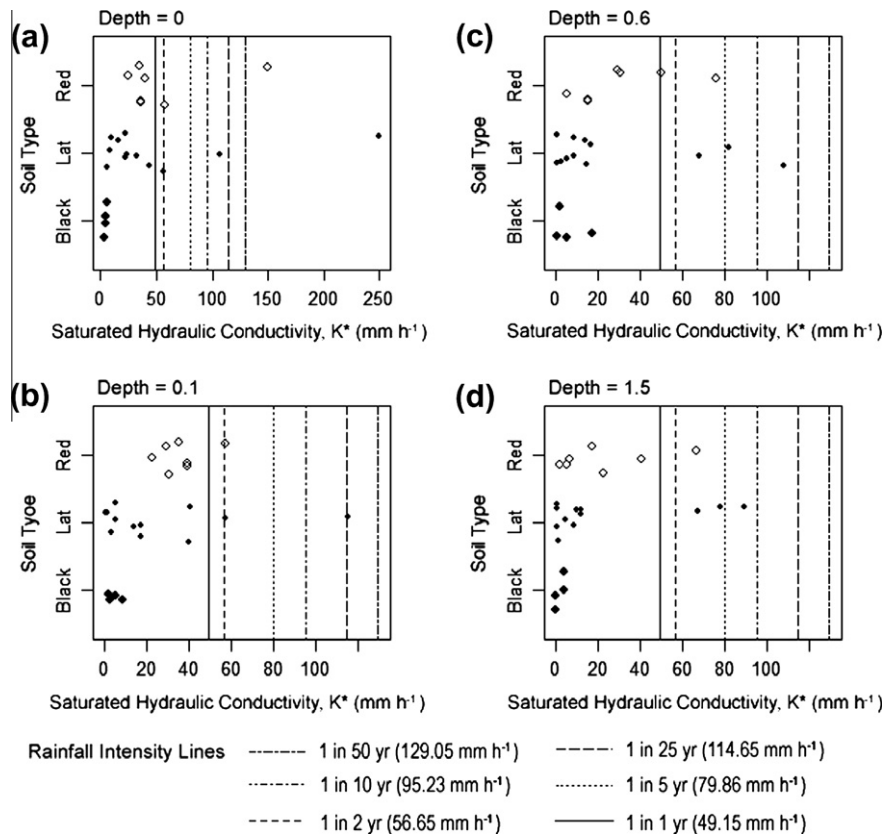
Fig. 3. Strip charts of the geometric mean K^* by Soil Group (Type) for (a) surface (b) the 0.1 m depth (c) 0.6 m depth and (d) 1.5 m depth and the rainfall intensities (mm h^{-1}) for the 15 min duration for the selected return periods (1 in 1 year, 2 years, 5 years, 10 years, 25 years, and 50 years). The soil types are Black, Laterite (Lat) and Red. Jittering has been used to enable similar valued or coincident data points to be viewed clearly.

tion of the variability in permeability of the Red, and even more so, the Laterite soils underlying the Forest and Acacia plantations.

Using the Degraded Forest as benchmark, the Acacia plantations over the Laterite and Red soils are increasing K^* in the surficial horizons ($\leqslant 0.1$ m depth). These shallow depths are more directly affected by the incorporation of soil organic matter and a reduction in human use and disturbance. Nonetheless the Degraded Forest and Acacia plantations have the same order of magnitude in surface K^*, c.f. the Forest (Table 5), and is linked with the land-use history (as described above). This trend supports the 'degraded scenario' of the 'infiltration trade-off' hypothesis.

In summary, the rank of median K^* is Forest > Acacia plantations > Degraded Forest for the upper soil layers ($\leqslant 0.1$ m depth). At 0.6 m and below, the above trends in the median K^* for each LC surprisingly remains the same (Table 5). The causes for the persistence of higher permeability beneath the Acacia when compared to the Degraded Forest however are inconclusive.

Two of the Teak plantations are associated with the Black soils (incorporated in Fig. 2 only and Table 4) where a low median value of K^* (and associated geometric mean K^*) persists across all depths. This indicates these plantations have no appreciable impact on K^* over the Black soils, c.f. Acacia.

5.3.3. Inferred dominant stormflow pathways
5.3.3.1. *Soil groups.* It is evident from both Fig. 2a and Fig. 3a for the Black soils that the IDF characteristics far exceed the entire range of K^* at the surface and infiltration-excess overland flow dominates. Further the IDF characteristics continue to far exceed all K^* (Fig. 2b–d, Fig. 3b–d, Table 4), at lower depths for this soil group as well. Thus vertical percolation is limited.

Whilst most IDF characteristics are above the medians for the Red and Laterite soils in Fig. 2a (the 1 in 1 year is the exception for the Red soil group), there are still many K^* data which still exceed the 1 in 5 year return period in the upper quartiles. The site geometric means (Fig. 3a) however, suggest such comments are only confined to two Laterite sites and one Red. Most site geometric mean K^* are below the 1 in 1 year return period. Consequently for these two soils groups either IOF or infiltration occurs, and more so IOF, when site rather than individual K^* data are considered. Such options occur in the Laterite and Red soils because of their inherent, high variability in K^*. Consequently IOF probably dominates in particular where the lower quartile of K^* in the box plot (Fig. 2a) or the site geometric means for the Laterite (Fig. 3a) are on parity with the Black soils. At the other extreme, the highest measured site K^* in the survey (geometric mean $K^* \sim 250$ mm h^{-1}) occurs also in the Laterite group and thus favours VP (Fig. 3a).

At 0.1 m depth (Fig. 2b), all medians for the Red and Laterite soils are exceeded by the IDF characteristics. Likewise only one Red site and two Laterite sites (Fig. 3b) are above the 1 in 1 year return period. These data indicate that for the Red and Laterite soils where infiltration prevails, a subsequent impedance to VP is possible at 0.1 m. depth and thus SSF (and SOF and RF) may develop. On the other hand taking into account the range of K^* at the surface (discussed above), overall the runoff generation process in these soil groups is complex. Three dominant pathways (IOF, SSF and associated SOF + RF, VP) are all possible depending on the point K^* measured or the corresponding site geometric mean of K^*.

At 0.6 m and 1.5 m all IDF characteristics exceed the median K^* for the Red soils (Fig. 2c and d) and the site geometric means (except one, Fig. 5c, d) despite retaining a moderate permeability at
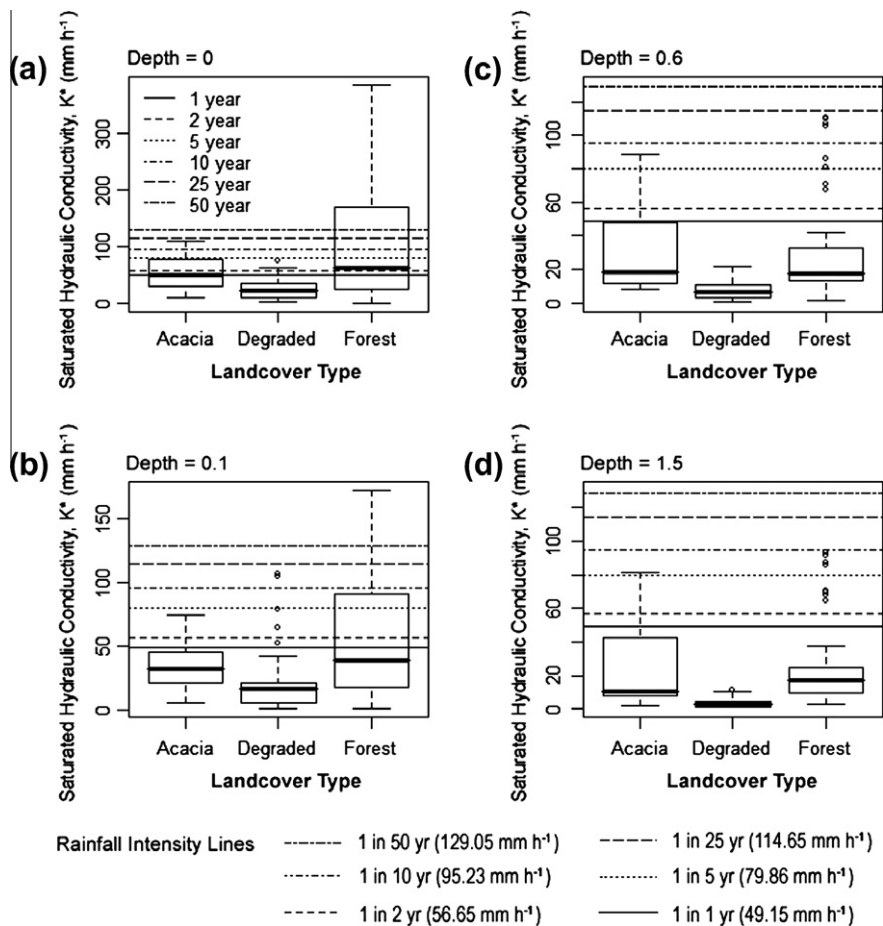
Fig. 4. The box plots of K^* by Land Cover (LC) with sampling replicates only (i.e., excluding the LCs over the Black soils and the Casuarina Plantation) for (a) surface (b) the 0.1 m depth (c) 0.6 m depth and (d) 1.5 m depth and the rainfall intensities (mm h^{-1}) for the 15 min duration for the selected return periods.

depth. By contrast some K^*, as represented in the upper quartiles for the Laterite and Red soils, remain above the 1 in 1 year or 2 year IDF. Thus in these circumstances VP is indicated except for the more extreme rainfalls.

5.3.3.2. Land cover. The IDF characteristics (Fig. 4a) exceed the surface K^* medians for both the Degraded Forest and Acacia (but only marginally so for the latter). The exceptions are the very highest K^*, as represented by the upper quartiles of the Acacia. The latter are reflected by two sites where the respective geometric mean K^* are being intersected by the 1 in 2 year return period line in Fig. 5a. Overall these circumstances suggest that IOF probably remains prevalent despite some recovery in surface permeability associated with forestation. The exceptions are at the mentioned two sites above, where infiltration is now indicated for the more frequent rainfalls in response to the small to moderate amelioration of surface K^* by the Acacia. Not surprisingly infiltration is inferred in the Forest where the median K^* exceeds the more frequent extreme rain events (up to 1 in 2 years return period), but not for events from 1 in 5 years upwards and so IOF is thus possible (Fig. 4a). By contrast Fig. 5a suggests IOF probably occurs at 2 sites (geometric mean $K^* < 1$ in 1 year return period of rainfall) whereas infiltration prevails even for return periods greater than 50 years at another 2 sites. On the other hand, at 0.1 m. depth the IDF characteristics exceed the median K^*, and also some of the geometric means of K^* for the Forest (Fig. 4b, Fig. 5b). Consequently SSF (and SOF with RF) is suggested.

At the lower depths (0.6 m and 1.5 m) (Fig. 4c and d) some K^* in the upper quartiles of the Acacia and Forest exceed the lower return periods of 1 in 1 year (and 2 year) and thus could facilitate VP. Likewise 2 sites each for these respective LCs have geometric mean K^* at or above the 1 in 2 year return period. For the most part, however, K^* are impeding to vertical water fluxes at these depths when compared to the IDF characteristics.

5.3.3.3. Summary. In summary the overall picture is one of prevalent IOF over the Black soils during extreme rainfalls, irrespective of land cover. At the highest end of the permeability spectrum, IOF or SSF (and SOF and RF) may develop within some of the Red soils. Nonetheless the large variability in K^* within the Red soils, and even more so in the Laterites (especially across the landscape), leads to up to three dominant pathways (IOF, SSF and associated SOF + RF, VP) all being possible depending on the individual point K^* or site geometric mean of K^* and the rain IDF.

For both the Degraded Forest and Acacia, IOF remains prevalent. A re-direction from IOF to infiltration in two of the Acacia sites however was inferred in response to enhanced K^* linked with that LC. Thus a movement towards the dominant stormflow pathway identified with the Forest, that is, SSF (with SOF and RF) seems to be an emerging scenario at the above Acacia sites. Paradoxically, Fig. 5a suggests that IOF could occur at two of the Forest Sites.

5.3.4. The temporal variability of the surface K^*

Table 6 presents a comparison of one set of spot estimates for both the dry season and the wet season respectively.
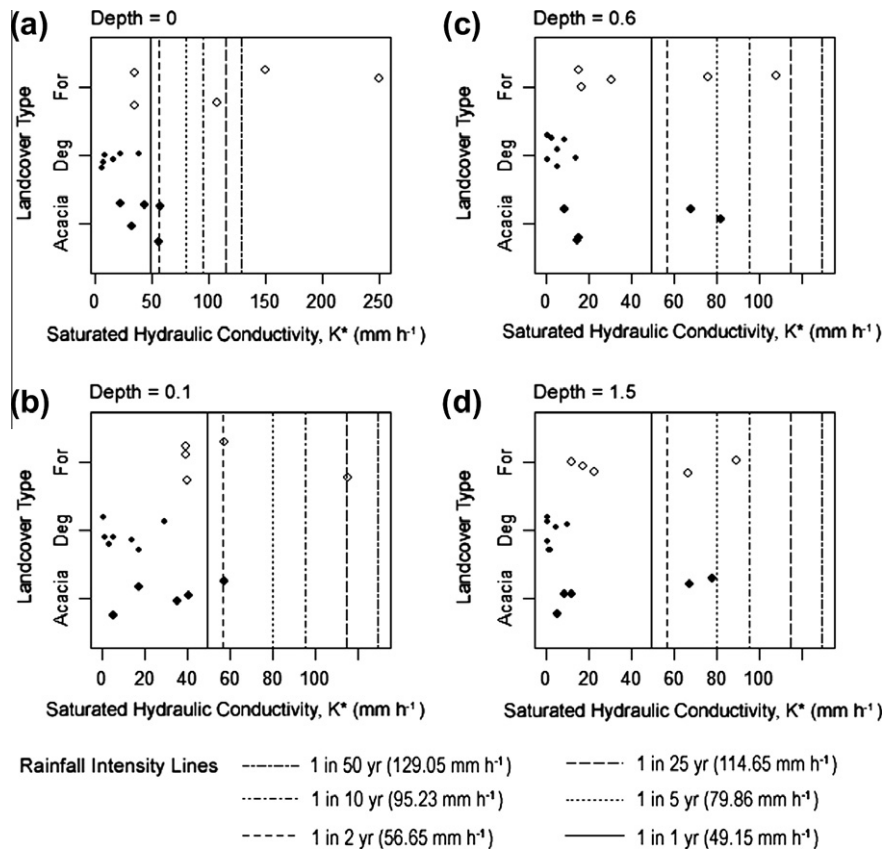
Fig. 5. Strip charts of the geometric mean K^* by Land-cover for (a) surface (b) the 0.1 m depth (c) 0.6 m depth and (d) 1.5 m depth and the rainfall intensities (mm h^{-1}) for the 15 min duration for the selected return periods (1 in 1 year, 2 years, 5 years, 10 years, 25 years, and 50 years). The land-cover types are Acacia plantations (Acacia), Degraded Forest (Deg) and less disturbed, Natural Forest (For). Jittering has been used to enable similar valued or coincident data points to be viewed clearly.

Table 4
Comparisons of plot averaged (geometric) hydraulic conductivities, K^* between soil groups at different depths. The medians (in bold) and corresponding 95% confidence intervals about medians, constrained to zero on lower bound are shown. The number of sites is shown as n.

Depth	Black, $n = 4$	Laterite, $n = 12$	Red, $n = 7$
0	**4.7**, 3.66–5.71	**22.7**, 5.41–39.97	**35.5**, 27.76–43.24
0.1	**4.2**, 0.57–7.80	**15.9**, 0–32.17	**35.6**, 30.03–41.25
0.6	**3.7**, 0–11.79	**11.5**, 0–28.84	**29.3**, 14.38–44.22
1.5	**2.3**, 0–5.21	**9.3**, 0–26.79	**17.4**, 1.99–32.73

Table 5
Comparisons of plot averaged (geometric) hydraulic conductivities, K^* between land-covers at different depths. The medians (in bold) and corresponding 95% confidence intervals about the medians, constrained to zero on lower bound are shown.

Depth	Degraded forest $n = 7$	Acacia $n = 5$	Forest $n = 5$
0	**15.9**, 7.34–24.42	**43.9**, 26.82–61.04	**107.1**, 26.45–187.78
0.1	**5.6**, 0–13.42	**35.6**, 19.49–51.79	**40.4**, 27.76–52.98
0.6	**5.6**, 2.49–8.61	**15.9**, 0–53.17	**30.9**, 0–72.58
1.5	**1.9**, 0.35–3.49	**11.9**, 0–53.54	**22.7**, 0–57.59

In spite of the very small sample sizes taken, most sites in Table 6 (dry season) indicate log mean K^* in the same order of magnitude as those used in the main data set (Figs. 2 to 5, Tables 4 and 5) which were also based on dry season measurements. During the wet season, a decline in log mean K^* by *an order of magnitude* is evident especially at many of the sites with Laterite soils. For the remaining soil groups, there is mostly a reduction in the absolute values of K^*. A consequence of this reduction is *to increase the potential frequency of occurrence of IOF much more than was suggested* during the discussion of the larger data set.

The non parametric Mann–Whitney U Test was used for comparing the K^* (as presented in Table 6). After aggregating the K^* from individual sites into two groups (soil and land cover), the non parametric Mann–Whitney U Test was used to test for differences in measured permeability between seasons. The amalgamation of sites by soil group and land cover also has the advantage of increasing the sample sizes. The exception was the Casuarina Plantation (site 5) which could only be considered separately because it is the only site.

If a significance level of $p = 0.05$ (two-tailed test) is adopted then the Black and Laterite soils show differences between seasons at the $p < 0.01$ level. Further the Red soils are also prone to this phenomena ($p = 0.04$), even though the associated K^* values (Table 6) suggest that these soils maybe more resilient to seasonal disruption of the soil structure.

When the LC is considered, the Casuarina plantation ($p = 0.25$) and the Forest ($p = 0.20$) show no statistically significant differences. For the Forest one might expect this result due to the greater protective effect of the organic litter layer over the forest floor. All other LC's are significantly different ($p < 0.05$) between seasons.

When lumping all the data together by season, the box plot in Fig. 6 highlights the lowering in K^* between the dry and wet season measurements. The average reduction in K^* is 61% when compared to the dry season test values, and the corresponding non parametric Mann–Whitney U Tests confirm this reduction (p-value = 0.02 for the paired test and p-value = 0.0235 for the lumped test).

Table 6
A comparison of the surface hydraulic conductivity between dry and wet season measurements at selected sites.

| Site number	Sation name	Soil type	Land cover	Dry season			Wet season		
				Number of samples	K^* mm h^{-1}		Number of samples	K^* mm h^{-1}	
					Log mean	Range		Log mean	Range
14	Barchi	Black	OGF	4	6.64	4.75–13.93	4	3.43	2.30–5.78
17	Jenmuri	Black	T	3	11.19	7.80–13.93	4	1.90	1.00–2.92
15	Kuligi	Black	OGF	4	3.64	2.20–5.50	4	1.79	0.90–5.56
18	Thattihalla	Black	T	4	9.71	7.06–22.80	4	2.03	0.72–3.38
6	Anabebail	Lateritic	DF	4	13.92	5.70–72.20	4	2.5	1.31–3.57
11	Patoli	Lateritic	OGF	4	299.26	256.00–367.30	4	25.08	14.30–30.90
1	Anthrahalli	Lateritic	AcP	4	33.75	23.70–48.30	4	11.66	3.84–25.68
2	Kolagibees	Lateritic	AcP	4	67.15	55.50–88.81	5	26.38	15.60–40.90
7	Talagadde	Lateritic	DF	4	7.10	3.60–14.50	6	5.03	1.12–12.14
3	Hattikeri	Lateritic	AcP	4	85.43	64.40–104.70	5	46.18	27.50–104.70
8	Urothota	Lateritic	DF	4	21.64	12.70–34.23	5	2.81	0.85–6.140
9	Yettinabail	Lateritic	DF	4	13.10	9.90–17.15	5	9.04	6.98–11.11
5	Siddapur	Red	CP	4	30.57	21.40–53.75	4	15.35	8.96–30.65
13	Dodmane	Red	OGF	4	34.71	25.76–39.90	5	13.44	1.75–61.93
16	Yellapur	Red	T	4	44.91	24.70–84.70	5	21.89	5.51–49.6

OGF old-growth forest (i.e., less disturbed natural forest).
DF degraded forest.
AcP acacia plantation.
CP casuarina plantation.
T teak plantation.
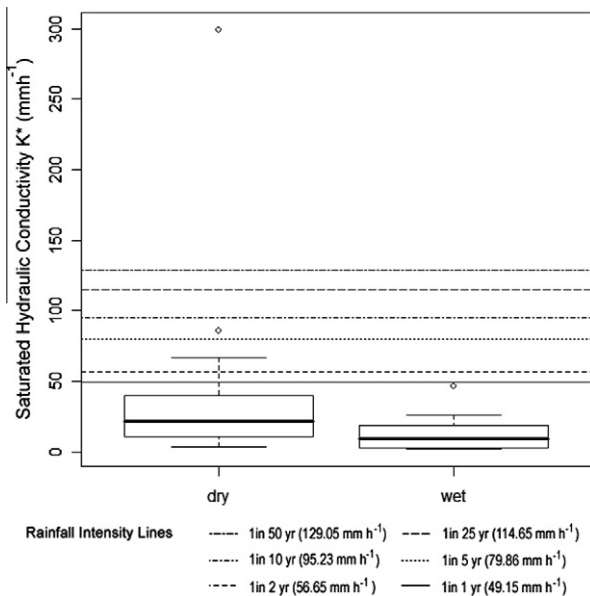
Fig. 6. The box plots of K^* sampled at the surface at 15 sites for (i) the dry and (ii) the wet seasons respectively.

6. Discussion

To ensure that a proper comparison with other published materials, a more detailed overview will be made.

Using the Forest cover over the Laterites (*Eutric Nitosols* and *Acrisols*) and Red soils (*Eutric Nitosols*) as a baseline, the Degraded Forest shows an *order of magnitude decline* in K^* at the surface as result of human impacts at decadal to century time scales. The profile of K^* with depth however for this combined data set does not show a progressive increase and then subsequent decrease within the subsoil permeability for the Degraded Forest. This feature contrasts with other reports elsewhere for converted forest to pasture) where surface compaction has led to the highest K^* being measured in the subsoil (Tomasella and Hodnett, 1996; Zimmermann and Elsenbeer, 2008. Rather, Table 5 for the Degraded Forest shows a

gradual decrease in K^* with depth similar to that reported in Rondonia, Brazil by Elsenbeer et al. (1999) and elsewhere in Malaysia (Ziegler et al., 2006). Closer inspection of the individual site data however, did detect that a minority of the K^*-depth profiles did show similar characteristics as reported in the above South American studies.

This gradual decrease in K^* with depth also makes it difficult to be conclusive at what depth human pressure impacts on permeability terminate. In contrast a decline in permeability up to about 0.20 m depth (from cattle grazing) was noted in some of the South American studies and elsewhere (Godsey and Elsenbeer, 2002; Zimmermann et al., 2006; Hamza and Anderson, 2005). The inclusion of two soils groups in which the Laterite soils in particular have been shown to have a high variability in K^*, adds a further complication. Such aggregation of soils groups may also account for the much lower subsoil K^* below the Degraded Forest when compared with the Forest.

The Acacia plantations over the Laterite and Red soils show an increase in K^* at the surface only. Such increases are in line with several other findings (Gilmour et al., 1987; Bruijnzeel, 2004; Holscher et al., 2004; Scott et al., 2004; Zimmermann et al., 2006; Ilstedt et al., 2007). But in agreement with Gilmour et al. (1987), the recovery time required for these Acacia plantations to even approach the "background" permeability of the Forests is still likely to take several decades. Further the preceding "background" in permeability may never be achieved because of the different soil ecology under monoculture plantations compared to less disturbed, old-growth forest (Rossi and Blanchart, 2005; Ashwini and Sridhar, 2008).

The above progressive recovery or lack of recovery of K^* at the Acacia sites could be linked to, and constrained by, changes in soil organic matter and the ability of associated fauna to restore macropores and thus soil hydraulic properties (Lal, 1988; Giertz et al., 2005; Chazdon, 2008). In the Western Ghats the quantity and quality of leaf-litter deposition, fine root biomass, as well as composition and abundance of soil macro-fauna are all a function of forest type, climate and the disturbance regime (Ashwini and Sridhar, 2008; Rossi and Blanchart, 2005; Sundarapandian and Swamy, 1996, 1999; Blanchart and Julka, 1997). For example the biomass of Pill millipedes *Arthrosphaera* was found to be sensitive to soil organic matter compared to other soil properties (Ashwini and

Sridhar, 2008; Kadamannaya and Sridhar, 2009). In addition soil macro-fauna (earthworms and millipedes) are most abundant in less disturbed, old-growth forest when compared to pastures and *A. auriculiformes* plantations (Rossi and Blanchart, 2005). The latter is an argument for forestation using native species, but there are enormous silvicultural challenges to achieve that objective (Rai, 1999; Lamb et al., 2005). We therefore suggest that that it is the intensity of forest use and effects of monoculture plantations on soil ecology that is the critical factor. For example human activities in the Degraded Forest may have reduced soil fauna. Further these activities indirectly may have reduced macro-porosity and hydraulic conductivity over time when compared to less-used and disturbed native forests.

Significantly forestation with Teak plantations over the Black soils (Vertisols) has *no major impact* on K^* (geometric mean $K^* \leqslant 5$ mm h^{-1} for all LCs and all depths). The collection of leaf litter and regular burning during the dry season further prevents the incorporation of organic matter in the Teak plantations. On the basis of the above discussion, such activities will also reduce the influence of soil macro-fauna and macropore development on K^* and thus minimise surface infiltrability (Hillel, 1980). It is the inherent soil properties (physical and chemical) of the Black soils that dominate K^* rather than LC. The overall picture given for this soil group is then one of consistent low permeability which is in line with other remarks for Vertisols elsewhere (Costa, 1938 cited in Bruijnzeel, 2004). By contrast when concerning the Kandiudults (an Acrisol) of Zimmermann et al. (2006), they established a significant increase in surface infiltrability within a Teak plantation (which was similar to other LCs namely capoeira and banana) when compared to pasture.

When concerning inferred dominant stormflow pathways by soil type, IOF prevails over the Black soils due to this soil group being at the lowest part of the permeability spectrum. Further IOF is indicated for many of the IDF characteristics when concerning selected Laterite and Red soils, despite the latter being at the most permeable part of the K^* spectrum. Overall however, the dominant stormflow pathways are complex in both the Red, and even more so, the Laterite soils as a result of the broad distribution of K^*. All storm flow pathways (IOF, SOF, RF, SSF and VP) are possible depending on the IDF. With regard to the Laterites, this is in response to some K^* being close to those of the Black soils and others to the Red soil group, and it is therefore a very spatially varied and complex soil group.

When concerning land cover, IOF is even possible in some of the Forests over the Laterites and for selected Red soils. Otherwise SSF (in combination with SOF and RF) is suggested which is typical of 'Acrisol-type' soils from other work in humid tropical forests (Elsenbeer and Vertessy, 2000; Elsenbeer, 2001; Bonell, 2004; Chappell et al., 2007). By comparison, the reduction in surface K^* within the Degraded Forest is analogous with an 'apparent' upward translation to the surface of the subsoil impeding layer of the Forest (Bonell, 1993; Ziegler et al., 2004; Zimmermann and Elsenbeer, 2008). The result in an increase in the occurrence of IOF within this degraded land cover under extreme rainfalls. These circumstances support findings from other studies in South America and Asia (Chandler and Walter, 1998; Zhou et al., 2001; Costa et al., 2003; Ziegler et al., 2004; Chandler, 2006; de Moraes et al., 2006; Cuo et al., 2008; Chaves et al., 2008; Mehta et al., 2008; Zimmermann and Elsenbeer, 2008, 2009). On the other hand for selected rainfall IDF, the SSF (and SOF + RF) pathway identified with the Forest remains still feasible in the Degraded Forest as well. Thus for the latter LC, the runoff generation process can be complex. Such findings emphasize the point that IOF does not automatically occur as a result of long-term human impacts on surface K^*. This issue was highlighted in the studies of Godsey and Elsenbeer (2002) and Zimmermann et al. (2006) where the Ferrasols and *Acrisols* (FAO, 1998)

remained sufficiently resilient to disturbance to retain SSF, supplemented by increases in SOF, as the dominant pathway.

The inferred occurrence of IOF within the Acacia plantations over the degraded Laterite and Red soils means that the surface K^* still retains a 'memory' of the previous LC in line with work in China by Zhou et al. (2001). In the longer term, however, it is these soil groups-plantation combination which potentially could moderately change the dominant stormflow pathway from IOF towards SSF (supplemented by SOF) in response to the recovery of surface infiltrability. The strip charts indicated that such re-direction of stormflow might be already occurring at two sites. Such changes are in line with the additional stormflow pathways suggested elsewhere from forestation (e.g. SOF, SSF, RF; Godsey and Elsenbeer, 2002). In contrast the inherent, low permeability at all depths within the Black soils (Vertisols) results in IOF being the dominant stormflow pathway, irrespective of land cover or forestation using Teak.

The above interpretations are *based on dry season measurements* when there is a tendency for surface K^* to be a higher order of magnitude at many soil sites in contrast to measurements taken in the wet season. Consequently there is a likelihood of IOF being *more frequent* in occurrence than suggested across all soils and LC's during the wet season.

The fact that IOF is prevalent over the region however is a surprising result taking into account that short-term rainfall intensities are not exceptional by humid tropics standards (Bonell et al., 2004). Such low rain intensities are offset however by the comparatively low K^* across the region when placed in the global context (c.f. Elsenbeer, 2001; Bonell, 2004; Chappell et al., 2007). These circumstances favour the occurrence of IOF, in particular, at many of the disturbed LCs in line with the conclusions of Putty (Putty and Prasad, 2000a,b; Putty, 2006), and elsewhere in a disturbed, headwater basin in Benin (Giertz and Diekkruger, 2003).

Supplementary to addressing the questions of this investigation, some comments on the relevance of the '*infiltration – trade-off*' hypothesis of Bruijnzeel (2004) as well as linkages with climate change are included.

The changes in surface K^* within the Acacia plantations over the Red and Laterite soils indicate the early stages of a movement away from a 'degraded scenario' (dominated by IOF) towards higher infiltration and potentially more recharge to deep groundwater (i.e. the 'non-degraded scenario'). With the Red soils being more inherently permeable, such observations may apply less because of their "good condition" status (Bruijnzeel, 2004). Moreover, the lower surface K^* associated with the Degraded Forests supports the 'degraded scenario' of the '*infiltration – trade-off*' hypothesis. By contrast the '*infiltration-trade-off*' hypothesis is not appropriate to the Black soils due to the persistence of very low permeability across all depths and LCs. Further from a forest – water management perspective, Teak does not really improve recharge to groundwater by VP within the Vertisols.

Earlier Lal et al. (2001) highlighted the predicted increase in rainfall and rainfall intensities in the Western Ghats under existing climate change scenarios. Subsequently the application of a high resolution model by Rajendran and Kitoh (2008), projects a substantial and spatially heterogeneous increase in heavy rainfall events over most parts of India including parts of the Western Ghats by the end of the 21st Century. Taking into account such predicted increases in rainfall and rainfall intensities, and our observations of the reduction in soil hydraulic conductivities under wet-conditions, there could be potentially a further major shift in dominant stormflow pathways. These would be from SSF and deep percolation towards a greater occurrence of overland flow in the future. Such increases in overland flow will enhance associated soil erosion in the Degraded Forests and over vulnerable soils such as the Black Soil, as indicated by our study. Restoration of these highly

vulnerable soils and land covers, preferably using native or non-invasive species, for sustaining hydrologic functions and associated services, and with the participation of local stake-holders, should be a high priority in the next few decades.

7. Conclusions

i. The lowest surface permeability over the Laterite (*Eutric Nitosols* and *Acrisols*) and Red soils (*Eutric Nitosols*) is associated with the Degraded Forests. These characteristics lend support to the notion of a loss of macro-porosity due to enhanced compaction and a reduction in soil fauna from multi-decadal disturbance, as reported elsewhere in the humid tropics. Further when combining the permeability data for all Degraded Forests over Laterite and Red soils, there is a progressive decline in K^* down the soil profiles. There is no gradual increase and then decrease of K^* with depth resulting from long-term human pressure at the surface in contrast to reports from selected other studies.

ii. Following forestation (~10 years) of degraded land using exotic *A. auriculiformes* plantations over the Red and Laterite soils, a *small* increase in the surface permeability was detected. But the surface K^* within these plantations still remain low when compared to most of the less disturbed, natural Forest. Thus the Acacia Plantations still retain a "memory" from the previous degraded state linked with long-term, human occupancy as found in other studies. Such circumstances are accentuated by a slow recovery of the soil fauna population linked with available organic matter in these production forests. Significantly forestation with *T. grandis* plantations (Teak) over the Black soils (Vertisols) has *minimal impact on* soil permeability. The collection of leaf litter and regular burning during the dry season within these Teak plantations further prevents the incorporation of organic matter to influence surface infiltrability.

iii. The Red soil sites have the most consistently high K^* and the Black soils the lowest. Thus when concerning intra-site variability in permeability for both the Red and Laterite soils, all dominant storm flow pathways (IOF, SSF with SOF and VP) can probably occur depending on the rainfall IDF characteristics under consideration. However, the greatest inter-site variability in permeability is shown by the Laterite soil group and thus the runoff generation process is more likely to be the most complex. Laterite soils therefore merit further investigation in terms of soil physical and chemical properties, mineralogy and soil evolutionary characteristics. The low permeability of the Black soils favours IOF.

iv. The less disturbed, natural Forest has a dominant stormflow pathway typical of 'Acrisol-type' soils (SSF supplemented by SOF) but IOF still remains possible. The Degraded Forests and Acacia plantations over the Laterite and Red soils are also probably dominated by IOF. But there are already indications of a change in the dominant stormflow pathway in some of the Acacia plantations from IOF towards SSF (with SOF) in response to a detected recovery of surface permeability. With the Black soils (Vertisols) being located at the lowest end of the K^* spectrum, IOF dominates across all land covers connected with this soil type including forestation by Teak plantations. Thus IOF is prevalent over the region and is a surprising finding taking into account that short-term rainfall intensities are not exceptional by humid tropics standards. Such low rain intensities are offset however by the comparatively low K^* across the region when placed in the global context. Thus continued human-impact pressures

leading to continued forest degradation (e.g. from trampling, reduction in soil fauna, litter and soil organic matter) will only enhance the occurrence of IOF in the future.

v. The above interpretations are *based on dry season measurements* when there is a tendency for surface K^* to have a higher order of magnitude at many soil sites in contrast to spot measurements taken in the wet season. Consequently there is a likelihood of IOF being *more frequent* in occurrence across all soils and LC's during the wet season than suggested when using dry season data.

vi. We have demonstrated the potential for the 'infiltration – trade off' hypothesis' to be realized in this landscape under certain conditions of land degradation and restoration and this needs to be tested with catchment hydrology data.

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