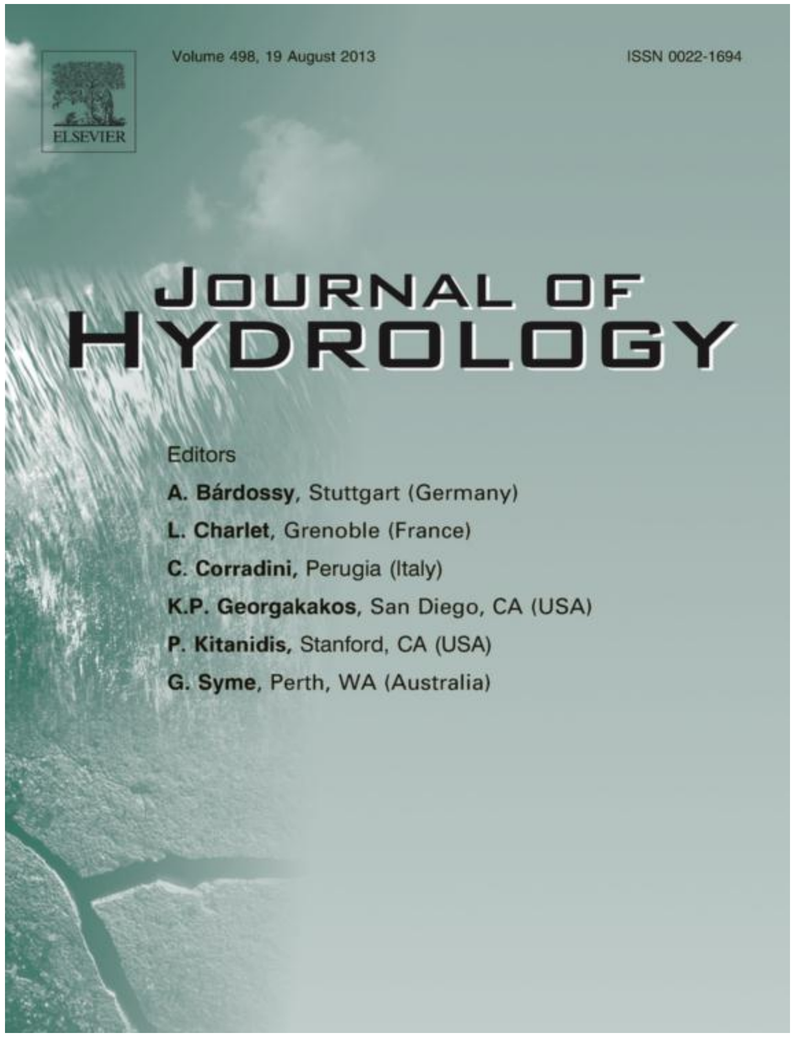
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The groundwater recharge response and hydrologic services of tropical humid forest ecosystems to use and reforestation: Support for the "infiltration-evapotranspiration trade-off hypothesis"

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SUMMARY

The hydrologic effects of forest use and reforestation of degraded lands in the humid tropics has implications for local and regional hydrologic services but such issues have been relatively less studied when compared to the impacts of forest conversion. In particular, the "*infiltration-evapotranspiration trade-off*" hypothesis which predicts a net gain or loss to baseflow and dry-season flow under both, forest degradation or reforestation depending on conditions has not been tested adequately. In the Western Ghats of India, we examined the hydrologic responses and groundwater recharge and hydrologic services linked with three ecosystems, (1) remnant tropical evergreen forest (NF), (2) heavily-used former evergreen forest which now has been converted to tree savanna, known as degraded forest(DF), and (3) exotic Acacia plantations (AC, *Acacia auriculiformis*) on degraded former forest land. Instrumented catchments ranging from 7 to 23 ha representing these three land-covers (3 NF, 4 AC and 4 DF, in total 11 basins), were established and maintained between 2003 and 2005 at three sites in two geomorphological zones, Coastal and Up-Ghat (Malnaad). Four larger (1–2 km^2) catchments downstream of the head-water catchments in the Malnaad with varying proportions of different land-cover and providing irrigation water for areca-nut and paddy rice were also measured for post-monsoon baseflow. Daily hydrological and climate data was available at all the sites. In addition, 36 min data was available at the Coastal site for 41 days as part of the opening phase of the summer monsoon, June–July 2005.

Low potential and actual evapotranspiration rates during the monsoon that are similar across all land-cover ensures that the main control on the extent of groundwater recharge during the south-west monsoon is the proportion of rainfall that is converted into quick flow rather than differences in evapotranspiration between the different land cover types. The Flow duration curves demonstrated a higher frequency and longer duration of low flows under NF when compared to the other more disturbed land covers in both the Coastal and Malnaad basins. Groundwater recharge estimated using water balance during the wet-season in the Coastal basins under NF, AC and DF was estimated to be 50%, 46% and 35% respectively and in the Malnaad it was 61%, 55% and 36% respectively. Soil Water Infiltration and Movement (SWIM) based recharge estimates also support the pattern (46% in NF; 39% in AC and 14% in DF). Furey–Gupta filter based estimates associated with the Coastal basins also suggest similar groundwater recharge values and trends across the respective land-covers: 69% in NF, 49% in AC, and 42% in DF. Soil water potential profiles using zero flux plane methods suggest that during the dry-season, natural forests depend on deep soil moisture and groundwater. Catchments with higher proportion of forest cover upstream were observed to sustain flow longer into the dry-season. These hydrologic responses provide some support towards the "*infiltration-evapotranspiration trade-off*" hypothesis in which differences in infiltration between land-cover rather than evapotranspiration determines the differences in groundwater recharge, low flows and dry-season flow. Groundwater recharge is the most temporally stable under natural forest, although substantial recharge occurs under all three ecosystems, which helps to

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sustain dry-season flow downstream in higher order streams that sustain local communities and agro-ecosystems. In addition to spatial scale effects, greater attention also needs to be given to the role of hydrogeology within the context of the above hypothesis and its implications for hydrologic services.

1. Introduction

Land use and land cover change profoundly transformed terrestrial hydrological budgets and processes (Vorosmarty and Sahagian, 2000; Stonestrom et al., 2009). Although the effects occur at multiple spatial scales from local (small basins) to global, the scale at which local communities and land-use managers are affected is of special concern as decision making on ecosystem services, especially hydrologic services is often at this scale (<10 km^2). In tropical landscapes where land-cover and land-use change have been rapid and complex, this issue is of particular interest (Turner et al., 1994). One of the important paradigms that was dominant for much of the 20th century in local scale terrestrial hydrology, and supported by observed and experimental data, is the relationship between accumulation of forest biomass and decrease in stream flow as a result of increased evapotranspiration, or vice versa, in the case of loss of forest cover (Bosch and Hewlett, 1982; Brown et al., 2005). However, based on emerging evidence to the contrary, especially from the tropics, Bruijnzeel (1989, 2004) proposed the "*infiltration-evapotranspiration trade-off hypothesis*". Part of this hypothesis states that under certain conditions of land-cover and land-use change in the seasonal tropics, a degraded forest's ability to allow sufficient infiltration may be impaired to such an extent that the effects on delayed flow or dry-season flow would be detrimental, even after accounting for gains from reduced evapotranspiration. Recent work in the Andes mountains of Columbia by Roa-García et al. (2011) put forward some of the first evidence in support of the *Infiltration- Evapotranspiration 'trade-off'* hypothesis based on a comparative basin study (0.6–1.7 km^2), albeit involving volcanic ash deposits i.e., Andisols, that are vastly different than the soils in the Western Ghats. Roa-García et al. (2011) noted in particular that their stream flow frequency–duration curves (FDCs) highlighted that the basin with highest forest cover (68%) showed the smallest reduction in flow during the dry season. Moreover the highest low flows were maintained during the dry season from this forest-dominated basin in contrast to a grassland dominated basin. In addition, soil moisture release curves undertaken in that study showed that the natural forests has a larger capacity to store and release soil moisture in comparison to the grassland. These writers thus concluded that the preceding two findings support the "*infiltration-evapotranspiration trade-off*" hypothesis for tropical environments (for) soils that are subject to compaction (such as highly grazed grasslands) have a reduced rainfall infiltration, which impairs the maintenance of baseflows." (Roa-García et al., 2011, p.11).

In formerly forested regions in the humid tropics, notably in the more densely populated regions of south and south–east Asia such as the Western Ghats of India, major land-cover changes have occurred at a century time scale. The latter have included permanent deforestation and conversion to a variety of agro-forestry and agro-ecosystems, regrowth as well as reforestation. Consequently there is a particular need for decision makers and policy makers to have information from hydrological studies that address the fundamental processes associated with such land cover changes. Over 100 million people depend on surface water sources in streams and rivers that emanate from the Western Ghats. Further this region is a major repository of carbon in its forests and soils (Seen et al., 2010) and is a global biodiversity hotspot (Das et al., 2006). In an era where various ecosystem services are being recognized and valued, it is essential for ecological economists, policy and decision makers to be aware of the synergies and trade-offs between various regulatory and provisioning services (Elmqvist et al., 2010). Thus an investigation of the hydrological effects of specific land-cover changes is a high priority (DeFries and Eshleman, 2004).

1.1. Relevant previous work in the study area

In previous work, we established that the soil hydraulic properties (notably field, saturated hydraulic conductivity (Bouwer, 1966)), K_{fs}, in the tropical, humid Western Ghats can be significantly altered from land-cover change up to a century time scale from forest conversion or degradation. The enhanced occurrence of infiltration-excess overland flow (*IOF*) was inferred (and thus reduced vertical percolation and groundwater recharge) when comparing selected rainfall intensity–duration–frequency with K_{fs} across both various land covers and soil types. Such changes are sufficient to allow the hill slope hydrology aspects of the infiltration-evapotranspiration trade-off hypothesis to be realized (Bonell et al., 2010).

Later work using experimental catchments also showed how land-cover change from native forest to heavily used forest and its subsequent reforestation have major effects on the rain-runoff process in the wet-season (Krishnaswamy et al., 2012). They showed the highest proportions of rain converted to runoff being associated with the degraded forests whereas the natural forests showed the lowest runoff yields. Using stream hydrograph separation, they also reported much higher quick flow volumes from degraded forest and reforested, former degraded land in the form of *Acacia auriculiformes* plantations when compared to the less disturbed natural forest. Furthermore, time series analysis showed much shorter rainfall-runoff time lags for the degraded forest and *Acacia auriculiformes* plantations when compared to natural forest. This characteristic of a faster rainfall-runoff responsiveness supports the notion of the frequent occurrence of *IOF* within the former two, more human-impacted land covers. Pertinent to the current work, the data in Krishnaswamy et al., 2012, clearly indicates that even assuming the maximum measured annual evapotranspiration (AET) for humid forests globally (~1500 mm, Kume et al., 2011), the estimated water available for recharge from natural forest catchments annually after accounting for both measured runoff and AET was 259 mm (rainfall of 2252 mm) and 978 mm (rainfall of 4016 mm). Thus we concluded from the earlier work that (i) a significant amount of rainfall was potentially available for recharge to groundwater and for downstream baseflow and dry-season flow, (ii) deeper subsurface water or groundwater of possible large capacity, had a significant role in the storm runoff generation process and (iii) the continuation of a secondary, longer rainfall-runoff time lag in the intensely, disturbed land covers indicated that there was a retention of 'memory' of the previous natural forest response.

In the current study, the more detailed aspects of the wet and dry season flows and the water balances of these same catchments were investigated in relation to modelled evapotranspiration, and thus the provision of various estimates of recharge to groundwater.

2. Objectives

We will attempt to test the "*infiltration-evapotranspiration trade-off*" hypothesis in the humid Western Ghats by quantifying the groundwater recharge and low flow characteristics components within 11 experimental basins in the Upghat (Malnaad) and Coastal regions across three land covers (Natural Forest, Degraded Forest, Acacia Plantations) within Uttara Kannada. In the absence of detailed process hydrology information, we will use several approaches to evaluate if there is a consistency in the interpretation of the results. The techniques used are as follows:

- The development of basin frequency–duration–curves (FDC).
- The use of basin water balances in the wet season.
- The application of the Furey–Gupta (2001) filter hydrograph model.
- An evaluation of soil water hydraulic potentials in the absence of rainfall and thus confined to dry season only in combination with the application of the zero flux plane (ZFP) method.
- Finally, a brief assessment of the scale issue and downstream dry-season river flow will be subsequently considered.

3. Study area

3.1. Landscape, soils, geology and hydrogeology

The locations of the 11 instrumented head-water catchments (listed in Table 1) are shown in Fig. 1. In the Malnaad these are located and nested within four larger catchments that supplied irrigation water to downstream areca nut plantations and rice-paddies. As indicated in Table 1, there are two groups of experimental basins which are located in two of the three distinct landforms identified in the classification of Gunnell and Radhakrishna (2001), *viz*, the Coastal plain and the hilly Upghat or Malnaad region (see also Fig. 1 in Bonell et al., 2010; Krishnaswamy et al., 2012). The geology is mainly Archaen-Proterozoic-Dharwad schist and granitic gneissic, meta-volcanic and some recent sediment in the coastal belt. Greywacke prevail from the Western slopes to the Malnaad (Geological Survey of India, 1981).

Many of the upper geological sequences of this region are lateralized due to their exposure to suitable climatic conditions over a prolonged period. Their thickness ranges from a few cm to as much as 60 m in depth (Geological Survey of India, 2006). Figure 16b in Bourgeon (1989) provided a simplified latitudinal cross-section of the geology and location of laterites (known as lateritic caps) from the coast through to the Malnaad (incorporating Siddapur and Sirsi, shown in Bonell et al., 2010). This cross – section is in proximity to the latitude where the study basins are located.

In the escarpment of the Ghats, the catchments in the Coastal zone are dominated by rocks of the Archean complex. The associated soils are dominated by 1:1 clays associated with iron and aluminium oxy hydroxides. We used the Indian soil classification system (NBSSLUP, 1993, Shivaprasad et al., 1998; Bonell et al., 2010) and these Coastal basin soils belong to the Laterite soil group. Under the FAO system these soils are mixture of Eutric Nitosols and Acrisols (FAO-UNESCO, 1974; FAO, 1998) and would be classified under the USDA system as Alfisols, Ultisols and Oxisols (Soil Survey Staff, 1975, 1999) (Table 1). A separate French survey of the Western Ghats undertaken by Bourgeon (1989) described the soils as being "Lithosols" and "Ferrallitic". A soil description of the evergreen forest within ~5 km of the Coastal basins is provided elsewhere (Table 1, Bourgeon, 1989 and reproduced in Krishnaswamy et al., 2012).

The catchments in the Malnaad are on the back slopes of the Western Ghats, deeply dissected, and the geology is dominated by Greywackes. The associated soils have similar clay minerals as above. They are classified as Red and Laterite (Shivaprasad et al., 1998), with similar equivalent classifications of FAO to those soils of the Coastal basins. When concerning the USDA, they are a mixture of Alfisols, Inceptisols and Oxisols (Shivaprasad et al., 1998; Table 1).

The soils in both the Coastal and Malnaad basins are deeply weathered similar to the description of Putty and Prasad (2000a).

Table 1
The physical characteristics of the experimental basins in the Up-ghat (Malnaad) and Coastal regions. Land-cover types include natural forest (NF), acacia (AC) and degraded forest (DF).

Basin	Site	Land cover	Area (ha)	Land cover code	Average elevation (m)	Average slope (deg)	Mean annual rainfall (1988–1997) (mm)	Soil type as per Indian Soil Classification and USDA *Soil Survey Staff* (1999)[a]; NBSSLUP (Shivaprasad et al., 1998)
Coastal basins								
1	Areangadi	Natural Forest	23	NF1	255.03	17.16	3672	Laterite, Clayey, kaolinitic, *Ultisol (Ustic Kandihumults)*
2	Areangadi	Degraded Forest	7	DF1	52.71	10.38	3793	Laterite, Clayey, kaolinitic,*Ultisol (Ustic Kandihumults)*
3	Areangadi	Acacia	7	AC1	112.25	15.23	3793	Laterite, Clayey-skeletal, kaolinitic, *Ultisol (Petroferric Haplustults)*
Malnaad (UP-GHAT)								
4	Vajgar	Natural Forest	9	NF1	618.09	7.51	2750	Red, Fine, kaolinitic, *Alfisol(Kandic Paleustalfs)*
5	Vajgar	Degraded Forest	10	DF1	587.27	7.07	2750	Laterite, Fine, kaolinitic, *Alfisol(Kandic Paleustalfs*
6	Kodigibail	Natural Forest	6	NF1	540.14	7.56	2750	Red, Clayey-skeletal, kaolinitic, *Inceptisol(Ustoxic Dystropepts)*
7	Kodigibail	Degraded Forest1	9	DF1	522.16	4.76	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol(Ustoxic Dystropepts)*
8	Kodigibail	Degraded Forest2	45	DF2	536.50	5.10	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol(Ustoxic Dystropepts)*
9	Kodigibail	Acacia1	7	AC1	538.00	5.51	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol, (Ustoxic Dystropepts)*
10	Kodigibail	Acacia3[b]	6	AC3	544.83	4.34	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol, (Ustoxic Dystropepts)*
11	Kodigibail	Acacia2	23	AC2	544.10	3.36	2948	Red, Clayey-skeletal, kaolinitic, *Oxisol(Ustoxic Dystropepts)*

[a] NBSSLUP – National Bureau of Soil Survey and Land Use Planning.
[b] Acacia3 is nested within Acacia2.

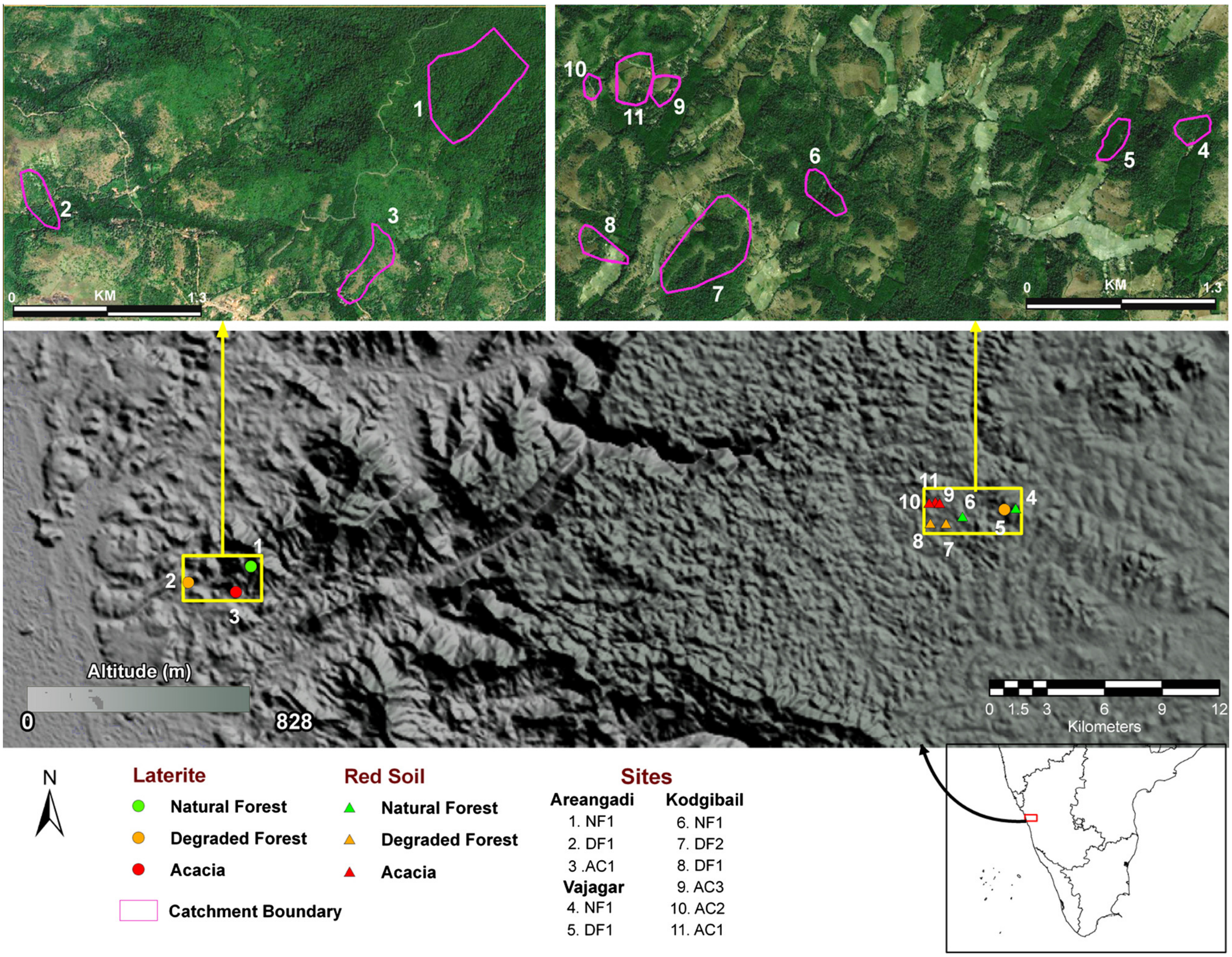

Fig. 1. The location, soil types and land covers of the research basins in the Western Ghats, Uttara Kannada District of Karnataka State.

In the absence of any deep drilling in the basins, however no detailed soil descriptions down to bed rock exist. Exposures in hills and stream banks do suggest that soils extend well beyond 2 m in depth. Further no detailed mapping of soil pipe occurrence (Putty and Prasad, 2000a,b) was undertaken, although we have observed soil pipes in the forested catchments in the region and there was evidence of vertical macro-pore flow in soil exposures and an example is shown in Fig. 2 of Krishnaswamy et al., 2012.

The main aquifers in the study area are the weathered and fractured zones of metavolcanics, metasedimentaries, granites and gneisses, laterites, along with the alluvial patches found along the major stream courses. Significantly there is no primary porosity in the hard rocks. It is the secondary structures like joints, fissures and faults present in these formations up to ~185 m below ground level (mbgl) which act as a fractured rock aquifer (e.g., Cook, 2003) with an effective porosity of 1.0 – 3.0% and contain groundwater. The transmissivity of aquifer material are in the general range from 2.09 to 24.41 $m^2\ day^{-1}$ (CGWB, 2008). At depths $\leqslant$30 mbgl unconfined, groundwater dominates but there is a tendency towards a more confined status at greater depths due to the complexity of the geological formations and associated fracture zones. Spot surveys undertaken in May (pre-monsoon) and November (post-monsoon) 2006 and using a network of 30 of the national hydrograph stations, showed that pre-monsoon water levels between 5 and 10 mbgl were typical over large parts of Uttara Kannada. In the post-monsoon, the prevailing depths within the Coastal and Malnaad areas were respectively 2–5 and 5–10 mbgl (CGWB, 2008).

3.2. Climate

The climate is classified under Koppen as 'tropical wet and dry'. Rainfall is monsoonal and unimodal (June to September). The annual rainfall varies from 3979 mm in the Coastal zone to 3275 mm in the Malnaad (1950–2000 mm average, derived from Hijmans et al., 2005). Long-term annual reference Potential evapotranspiration (PET) is 1482 mm for the Coastal basins and 1527 mm in the Malnaad basins (Hijmans et al., 2005).

On a monthly basis, and pertinent to this paper, there is marked reduction in PET following the onset of the monsoon in June until its termination from October onwards (Hijmans et al., 2005) and shown in Fig. 2. This 'dip' in PET is due to persistent high humidity and cloudiness with frequent rainfall (Bourgeon, 1989; Hijmans et al., 2005). Of high relevance to the current work, there have been no studies undertaken in the Western Ghats that have made direct measurements of actual evapotranspiration (AET) using micrometeorological methods. Consequently AET estimates will be derived from modelling.

The dry season lasts from 5 to 6 months and so during this time PET > rainfall. The annual mean temperature ranges from 26.4 °C in the Coastal plains and slopes, to 24.5 °C in the Malnaad (Hijmans et al., 2005). Annual average relative humidity is ~72.3% in the

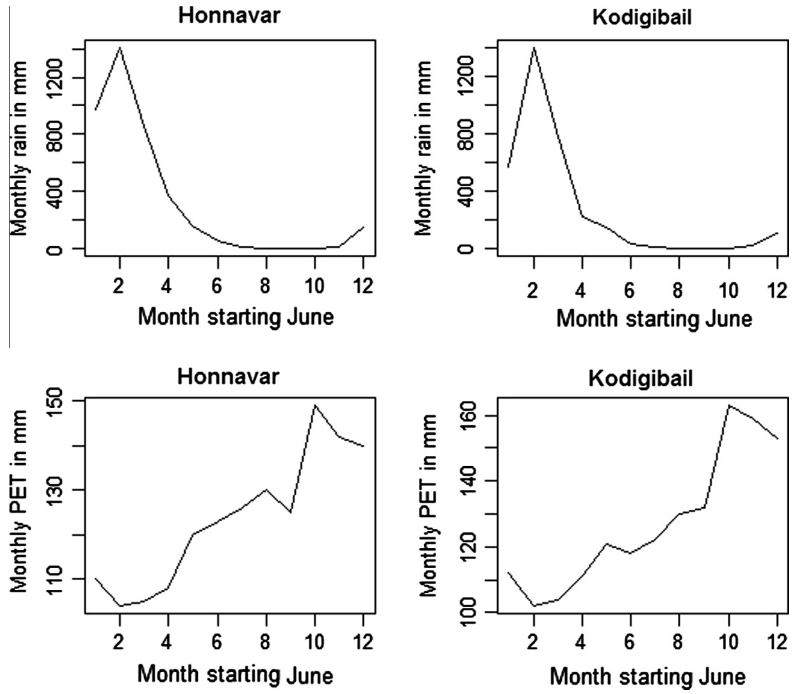

Fig. 2. Time series of rainfall and Potential evapotranspiration, PET for the Coastal and Malnaad (Up-Ghat) sites (after Hijmans et al., 2005).

Coastal basins and 70% on the Malnaad slopes (1960–1990, New et al., 1999).

Maximum rainfall intensities for a duration of 15 min across the study area range from 50 mm h^{-1} (1 in 1 year) to 130 mm h^{-1} (1 in 50 year) (Bonell et al., 2010). Overall these short-term rainfall intensities are comparatively low by global standards for the humid tropics (Bonell et al., 2004). On the other hand, the long duration of rain events (often over several days) ensures very high precipitation totals (Putty and Prasad, 2000a,b) and the latter was also shown in Krishnaswamy et al. (2012).

3.3. Vegetation and land-cover/land-use

The natural and modified vegetation of the study area is highly diverse in response to the equally complex geology, geomorphology and climate of the Western Ghats. Based on criteria such as physiognomy, phenology and floristic composition, the vegetation of the study area is classified principally as evergreen and semi-evergreen which are two of the five major floristic types identified within several detailed studies of the region (Pascal, 1982, 1984, 1986, 1988; Ramesh and Pascal, 1997; Ramesh and Swaminath, 1999). Within the framework of a highly fragmented land cover and land use system (Blanchart and Julka, 1997; Menon and Bawa, 1998; Pomeroy et al., 2003; Pontius and Pacheco, 2004; Seen et al., 2010), there are typically three principal stable patterns of land use and management, *viz*:

- Less disturbed, dense forest (referred to also as *Natural Forest, NF, or Forest)* which has resulted from a limited extraction regime, and is commonly associated with Reserve Forest patches.
- Dominantly tree savannas (*Degraded Forest, DF, or Degraded*) that result from intense harvest of fuel wood, leaf and litter manure and grass, as well as intermittent fires (Rai, 2004; Priya et al., 2007). These tree savannas were previously occupied by mostly evergreen and semi-evergreen forest prior to severe disturbance over decadal to century time scales. The specie composition, tree density and basal area of this land cover however can be highly variable between first-order basins (see Table 1).
- Exotic *Acacia auriculiformes* plantations planted since 1980 (*Acacia, AC*) that are part of the 'forestation' programme of the Karnataka Forest Department (Rai, 1999). Typically these plantations have replaced grazing land, or highly degraded forest land, some of which have become barren land. The initial survival of the AC plantings has been ensured through fencing and guarding. The ages of AC plantations in the study basins ranged from to 7 to 12 years at the time of the hydrological data collection (Krishnaswamy et al., 2012). Historically, people would have used and occupied the more accessible sites, which are currently under "degraded" forests or are under "restoration" through establishment of tree plantations.

Detailed description of the dominant vegetation types in the experimental basins are given elsewhere (Krishnaswamy et al., 2012). It should be noted that the Acacia plantations are not wholly monoculture but do incorporate a few other species. One of the Acacia basins (Kodigibail, *Acacia 3* in Table 1) is nested within another (i.e. *Acacia 2*) and the latter basin also includes some agriculture.

In the Malnaad the head-water basins are nested within more heterogeneous catchments that supply water to local communities and provide irrigation water to areca nut plantations, home gardens, orchards and rice paddies.

3.4. Tree root depths

Krishnaswamy et al. (2012) summarised knowledge of tree root patterns in the study area. Roots extend well beyond 2 m depth under the Natural Forest. For the young Acacia plantations most roots were located at <1.5 m depth and are known to be more densely concentrated between 0.3 and 1.0 m (Kallarackal and Somen, 2008). Depth of roots under the Degraded Forest were more varying, but mostly <0.6 m, depth due to the more extensive low herbaceous cover (dominated by grass species) in between the surviving trees.

3.5. The experimental basins

Krishnaswamy et al. (2012) provided details of the experimental basins. In summary, the complex mosaic of land use in the study area resulted in most basins having small areas (⩽10 ha) to ensure as close as possible 'homogeneity' in land cover for each basin. Moreover the sub-soil field, saturated hydraulic conductivity, K_{fs} down to 1.5 m depth is comparatively permeable (in excess of 10 mm h^{-1}) when compared to other reports elsewhere in similar soil groups (Bonell et al., 2010; Krishnaswamy et al., 2012). This combination of a marked concentration of rainfall in few months, small basin areas, comparatively permeable sub-soils and a fissured hydrogeology results in most of the study basins having intermittent flow regimes (i.e., no perennial flow). Streamflow terminates after the end of the monsoon at different times within each basin and will be later considered in this paper and the recharge during the monsoon at smaller scales aggregates and contributes to baseflow in higher order perennial streams.

4. Methods

4.1. Rainfall-runoff

Stream discharge in each of the 11 catchments (Table 1) was measured using either weirs or stage-velocity-discharge methods. In addition all catchments in the Coastal zone (Areangadi, Table 1) were instrumented with staff gauge, mechanical water-level recorders and a self-recording rain gauge. As these three basins were spatially close together, the same data from the one self-recording rain gauge was used. In the Malnaad group, rainfall and runoff data were collected daily supported by additional manual measurements of stream stage taken up to four times a day.

In summary, daily rainfall and stream discharge data for the years 2003, 2004 and 2005 are available for the Kodigibail and Vajagar catchments in the Upghat (Malnaad), and for 2004–2005 for the three Coastal basins (Table 4). In addition for part of the summer monsoon of 2005 (16 June–26 July, i.e., a total of 41 days), 36 min (0.6 h) data was available for rainfall-runoff for selected storms in the three Coastal catchments. Such information enabled us to monitor temporal changes in the rainfall-runoff response following the onset of the monsoon until maximum basin wetness was attained.

As indicated in Fig. 1, some of the small and relatively homogeneous catchments in the Malnaad sites were nested within larger basins (1.0–2.5 km^2) with different proportions of forest cover (as shown in Table 2). Downstream, these larger basins were instrumented with V-notches from December 14, 2004. Such steps will enable an assessment of the dry season flows at these larger scales.

Table 2
Summary of the downstream basins in terms of area and land-cover. These basins are located downstream of the more homogeneous head-water basins and typically have mixed land-cover.

Catchment	Total area (km^2)	Percent of area (%)		
		Forest	Acacia	Others
Golikai	1.05	27.2	5.2	67.6
Kodigibail[a]	2.42	26.5	6.6	66.9
Nirmundagi	1.64	15.3	7.4	77.3
Vajgar[b]	1.06	62.4	1.1	36.5

[a] the Kodgibail basins listed in Table 1 as basins 9 to 11 and shown in Fig. 1 are nested within this basin.
[b] The Vajgar sub-basins (4 and 5) in Table 1 are nested within this basin.

4.2. Potential evapotranspiration

Reference potential evapotranspiration (PET) was estimated at both the Coastal and Malnaad sites using available daily weather data. Data for more variables were available from an Indian Meteorological Department station close to the Coastal site so PET was calculated using the Penman–Monteith equation following the FAO approach (Allen et al., 1998, http://www.fao.org/). For the Malnaad sites where available weather data was more limited, the much simple empirical equation of Turc (1961) was adopted. In this context, an earlier comparative study of up to twenty different PET methods was undertaken by Jensen et al. (1990). Their work compared estimated PET against carefully selected lysimeter data from eleven stations across a range of climates. Jensen et al. (1990) noted that the Turc method compared very favourably with combination methods at their humid lysimeter locations. More pertinent, the Turc method was ranked second only to the Penman–Monteith method when only the humid locations were considered in that study (Jensen et al., 1990). Elsewhere another comparative study of reference ET methods by Yoder et al. (2005) came to similar conclusions.

4.2.1. Data inputs

More specific details on the data inputs, as part of using the above methods are now provided. In the absence of a meteorological station on site for the Coastal basins, we followed the FAO manual (Allen et al., 1998), which recommended that data from nearest meteorological station be used. Daily climate data (temperature, wind speed and relative humidity) were obtained from the Honnavar station of the Indian Meteorological Department (IMD) which is located about 10 km from the catchments. The variables solar radiation and maximum sunshine hours were not available from this station. Thus the use of a global formula which only requires latitude –longitude as the input for each specific catchment was adopted for this purpose (Allen et al., 1998, http://www.fao.org/). PET will be then plotted over the wet season and the initial stages of the post-monsoon season (May –December 2005, incl.).

Table 3
The Furey–Gupta Filter coefficients for the three land-cover types in the Coastal catchments.

Type	Recession constant	$C1_{mean}$, sd	C2	$C3_{mean}$, sd	$\frac{C3}{C1}$ median, IQR	Q_B	Q_F
D, delay = 1 time unit (36 min)							
Forest	0.98	0.0067, 0.019	0.69	0.31, 0.019	329, 1910	0.95	0.05
Acacia	0.91	0.1, 0.134	0.47	0.43, 0.109	6.88, 18.01	0.76	0.24
Degraded	0.89	0.21, 0.263	0.35	0.45, 0.197	4.22, 15.83	0.55	0.45

Note: C1 is the overland flow coefficient; C2 is the evapotranspiration and basin storage coefficient; and C3 is the ground-water recharge coefficient; C3/C1 indicates the fraction of precipitation that becomes recharge and is the ratio of ground-water recharge to the overland coefficient; sd is the standard deviation of C1 and C3; IQR stands for inter-quartile range; Q_B is the proportion of total flow Q estimated as baseflow and Q_F is the proportion of total flow Q estimated as Quickflow.

Table 4
The basin water balances for the wet seasons 2004 and 2005.

Period (Month/Year)	Land cover	P	Q	AET	Recharge – (% P)	Date in which the stream discharge stopped
Kodigibail water balance summary						
06/2004 to 09/2004	Forest	2514	541	352	1621 (64.5)	06-10-2004
	Acacia	2514	728	369	1417 (56.4)	13-09-2004
	Degraded	2514	1028	364	1122 (44.6)	06-10-2004
06/2005 to 09/2005	Forest	3392	1056	367	1969 (58.0)	24-08-2005
	Acacia	3392	1186	364	1842 (54.3)	24-09-2005
	Degraded	3392	2096	373	923 (27.2)	25-09-2005
Coastal basins water balance summary						
06/2004 to 08/2004	Forest	2842	1132	284	1426 (50.2)	Continues
	Acacia	2842	1148	282	1412 (49.7)	27-08-2004
	Degraded	2842	1468	268	1106 (38.9)	26-08-2004
06/2005 to 08/2005	Forest	2976	1226	288	1462 (49.1)	Continues
	Acacia	2976	1476	273	1227 (41.2)	22-08-2005
	Degraded	2976	1750	276	950 (31.9)	25-09-2005

Notes: (i) All values in mm and (ii) wet season = June to September 2004 and 2005.
Notes: (i) All values in mm and (ii) wet season = 2004 and 2005: June to August.

In the Malnaad, there was no IMD station data available. A meteorological observatory was established close to the Acacia basins (AC1 and AC2) in the study area at Kodigibail. The observatory was equipped with self-recording and ordinary rain gauges to measure rainfall. Air temperatures (maximum and minimum) and wet and dry bulb temperatures were also measured. The measurements were initiated from October 2004 onwards. Due to the non-availability of radiation and wind speed data, daily records of air temperature and relative humidity were used to compute potential evapotranspiration using the Turc method as recommended for sub-humid climates of India (Venkatesh et al., 2011; Nandagiri and Kovoor, 2006).

4.3. Actual evapotranspiration and daily water balance

When taking the appropriate reference PET (i.e., FAO or Turc methods), actual evapotranspiration (AET) in the wet-season was then estimated based on the following criteria:

- An initial condition is that AET can at most equal reference PET (Chiew and McMahon, 1991; Limbrick, 2002).
- The reference PET that we have used as an upper bound for daily AET for forest in subsequent water balance calculations are twice that are reported on a daily basis when compared with reports from a west Africa tropical forest study (Ledger, 1975). The latter had a similar rainfall regime to the Western Ghats with very high annual rainfall which is also concentrated in 4 months and then followed by a marked dry season (Ledger, 1975). Such lower AET values in the wet season also align with the noted wet season 'dip' in PET.

Thus the reference PET values on an annual basis used here are more generous and close to or above the highest values recorded for AET of tropical humid forests anywhere (Kume et al., 2011). They are assumed to be appropriate as the upper bound of actual evapotranspiration for the forest in the wet season. This is especially true for the wet-season when soil water is not limiting but energy is (Fig. 2). Differences in maximum AET between land-covers would be suppressed as they all would be constrained by available energy and not soil moisture and thus their AET would all be less than or equal to PET.

- Based on the water balance equation, AET would be smaller than the difference between rainfall (P) – streamflow (Q) because there is also a groundwater recharge component, viz:

$$P - Q = \text{AET} \pm \text{Gw(i.e., Gw recharge)} \tag{1}$$

- For the conditions if $P - Q > \text{PET}$ then AET = PET, and if $P - Q < \text{PET}$ then AET = $P - Q$. Basically, this means that groundwater recharge would only occur when AET demands of the vegetation are met and when there is a surplus over and above AET.
- During days when it is not raining but streamflow occurs, then it is assumed that the partitioning of soil moisture in the unsaturated zone is between contributions to AET and Q. Thus water will drain from soil to sustain streamflow only when the soil is sufficiently wet to meet AET demands and contribute to streamflow. Consequently, we assumed that AET was equal to PET under these conditions (Oishi et al., 2010; Palmroth et al., 2010). This assumption is supported by Venkatesh et al. (2011; Fig. 2) who showed that the matric potentials were close to saturation during the wet season with ample supplies of "free water" for sustaining AET at PET levels.

Following the estimation of AET (as outline above), groundwater recharge is calculated using the water balance Eq. (2):

$$\text{Groundwater recharge} = \text{Rainfall } (P) - \text{Streamflow}(Q) - \text{AET} \tag{2}$$

where, Rainfall and Streamflow are known over daily time steps for both Coastal and Malnaad basins.

4.4. Soil moisture and soil water hydraulic potential

Soil moisture was sampled twice per month for gravimetric soil moisture during the water year (May 2004–April 2005) within the Coastal basins. These were taken at depths from 0.15 m to 1.5 m at 0.15 m intervals using a soil auger at three sampling points located in the upper/mid/lower reaches of each land-cover basin. Subsequently the mean values of the soil moisture parameters (highlighted below) were derived from these three points.

The gravimetric soil moisture values were converted to volumetric moisture based on field sampling of bulk density at the same depths .The available moisture content at different depths (0–0.15 m, 0.15–0.30 m, ... 1.35–1.50 m) was calculated by finding the difference of volumetric moisture content between two consecutive months. Such differences were then converted to volume of available moisture by multiplying the moisture content value by the depth of soil column (0.15 m). Total volume of available moisture content for a given month is calculated by adding the volume of moisture at each of the depth ranges, that is, (0–0.15 m) + (0.15–0.30 m) + (0.30–0.45 m) + ... + (1.35–1.50 m). These were then summed up to estimate monthly volumes of available moisture content. The latter calculations provide inputs to the zero flux plane estimates (see below).

Furthermore in the absence of soil water pressure transducers, we used the pressure plate data on cores taken from these soils at the same depths to estimate the soil water hydraulic potential (using the soil surface as the reference position, see below) corresponding to the volumetric moisture contents.

4.5. Analytical methods

4.5.1. Water yields

The rainfall and discharge data were used to estimate annual water yields which were plotted against basin area and land-cover.

4.5.2. Flow duration curves

Flow duration curves, FDC (Vogel and Fennessey, 1994, 1995) were plotted using the daily discharge time-series data in depth units (mm day^{-1}). Essentially these have the magnitude of flow on a log scale on the y axis and the percentage of total number of days in which that flow was equalled or exceeded on the x axis. The FDC are extremely useful in comparing the distribution and magnitude of flows especially low and dry-season flow across sites and land-cover types (Smakhtin, 2001; Roa-García et al., 2011). The FDCs were computed and plotted using the FDC function in the HydroTSR package in R statistical package. These FDCs were computed and plotted on a comparative basis with some land-cover sustaining low flows when others did not have any flow and so are plotted on a log scale after removing zero flows.

4.5.3. The Furey–Gupta (F–G) filter analyses

The filter analysis of Furey and Gupta (2001) was applied to the continuous rainfall–runoff data of 41 days (16 June–25 July 2005) in the Coastal basins.

The method is derived from a basic physical equation for a hill; a simple representation of stream flow; and by partitioning precipitation into overland flow, evapotranspiration, and groundwater recharge, where recharge is time lagged (Furey and Gupta, 2001). Thus, it is a physically-based digital filter that uses time-series of rainfall and streamflow to estimate the recession constant and three diagnostic basin coefficients: C_1 is the proportion coefficient of rainfall that becomes overland-flow, C_2 is the coefficient corresponding to evapotranspiration, and C_3 is the coefficient corresponding to groundwater recharge. These coefficients are constrained to conserve mass such that $C_1 + C_2 + C_3 = 1$. An input to the filter analysis is the estimation of D (see Eq. (11) in Furey and Gupta, 2001) which is the assumed delay time in time-steps between infiltration and ground-water recharge. The small size of the catchments and the high groundwater levels during the monsoon in Uttar Kannada (Central Groundwater Board, 2008) justifies the choice of smaller values of the delay factor, D. Such reasoning for the selection of small values of D is also in agreement with Furey and Gupta (2001). In our case, we assumed 0.6 h for the final reporting, the smallest time-step although we did a sensitivity analysis using varied values of D from 0.6 to 24 h for each of the land-covers and found that the patterns in relative comparisons of estimates of% quick-flow and baseflow between land-cover at different assumed values of D remained consistent throughout. In theory, D could be a function of land-use and land-cover, but hydro-geology is likely to play a major role, and given the spatial proximity of the catchments, we expect the values to be similar. The filter (equation 22 in Furey and Gupta, 2001) also gives the recession constant, 1- for (t/T) in $Q_t = Q_0\, e^{-t/T}$, where Q_t is discharge at time t and Q_0 is discharge at time zero.

The above filter of Furey and Gupta (2001) is based on four assumptions which these writers critically evaluated. Such an evaluation will now be placed in the context of the present work. The assumptions are namely: (a) the routing of water from hillside to stream gauge is near-instantaneous and will progressively degrade with increasing basin scale. In that context, the small scale of the Coastal basins may prove an advantage; (b) the ratio of C_3/C_1 is assumed to be constant in time and so does not allow for temporal variability in soil moisture and rainfall rate. Furey and Gupta (2001) noted that the estimates for C_1 are highly sensitive to error in the estimation of precipitation, and this error increases with increasing basin scale. As with assumption a), the small basin areas in the current work should reduce the error in precipitation measurement and thus the error in C_1. Moreover following the wetting up phase at the beginning of the summer monsoon, soil moisture in the study basins is close to maximum conditions of wetness, (as shown by Venkatesh et al., 2011); (c) the delay time, D between precipitation and groundwater recharge is constant. This assumption, however, can only be an approximation due to the variable depth to groundwater table. Further the lack of knowledge on the hydrogeology and the possibility of varying pathways and sources of deeper groundwater contributions (not just from the water table *per se*) to runoff from the underlying fractured rock (discussed in Krishnaswamy et al., 2012), could potentially affect D and thus the C_3 estimates across the basins; d) groundwater recharge is proportional to precipitation in a "damped" form.

Furey and Gupta (2001) concluded that the method is best applied at 'long' time scales for the more reliable estimates of baseflow or delayed flow (linked with C_3) and small basins. Preliminary analyses of the daily rainfall-runoff records over the wet season linked with the Malnaad basins showed that at the daily time resolution, in conjunction with the small size of these basins, the F-G method proved insufficient to capture all aspects of the flashy hydrograph responses. Thus the assumptions of this approach were not met and the recession constants, C_1, C_2 and C_3 could not be reliably estimated. We thus confined the application of the F-G method to the Coastal basins where rainfall-runoff time series were available at the 0.6 h time resolution.

4.6. Estimating groundwater recharge in wet-season using the Furey–Gupta coefficient, C_2

The Furey–Gupta filter analysis as applied to 0.6 hourly data for the monsoon of 2005 (41 days) yielded the coefficient C_2 which can be considered *as scaling coefficient* to compare and estimate evapotranspiration (and some temporary storage) across land-cover types. Following the short period of "transient wetting up" at the opening of the monsoon (16–25 June 2005, Krishnaswamy et al., 2012), the magnitude of transient storage is likely to stabilise so that AET will dominate C_2 for most of the 41 day record. We assume that the ratio of the C_2 coefficient values for any two land-covers will approximate the ratio of actual evapotranspiration of these land-covers during the period of the time-series data i.e.,

$$\frac{\text{C2 Acacia}}{\text{C2 Forest}} = \frac{\text{AET Acacia}}{\text{AET Forest}} \tag{3}$$

$$\frac{\text{C2 Degraded}}{\text{C2 Forest}} = \frac{\text{AET Degraded}}{\text{AET Forest}} \tag{4}$$

The use of these approximations (i.e. Eqs. (3) and (4)) requires that we have some independent reference AET for the Forest on which the relative scaling can be applied to obtain corresponding AET estimates for the Acacia and Degraded Forest. The AET are then applied to the water balance Eq. (2)) along with the respective total P and total Q for each basin, over the 41 days period, to estimate groundwater recharge for each land cover.

The independent estimate of AET for the Forest was taken from the water balance ET estimates of Ledger (1975) based on a study in Sierra Leone where very high rainfalls (7 year mean, 5795 mm) are concentrated in 3 months of the year (7 year mean rainfall, July – September, 4523 mm) (Bruijnzeel, per comm). As discussed (under Methods), such a rainfall total and its seasonal distribution are climatically similar to the present study sites as well as the Western Ghats (as described by Gunnell, 1997). When compared with most lowland forest ET estimates, the annual ET was found however to be low and only 1011 mm for a 7 year record (Ledger, 1975). As Roberts et al. (2004) noted elsewhere a typical annual estimate of ~1400 mm (Bruijnzeel, 1990) for AET is close the net radiation equivalent of evaporation (1500–1550 mm; Calder, 1999) for the drainage basin experiments.

The average daily ET over the wettest 3 months (July – September, total ET, 139 mm) was low at 1.5 mm d^{-1} (Ledger, 1975) *and it is this figure that will be used as the reference AET for Forest in equations 3 and 4).* It should be noted that use of this reference AET estimate acts as a scaling factor and is restricted to the Coastal basins which are very close to each other so that climate differences are negligible. The C_2 coefficient of the Furey–Gupta filter analysis is a surrogate estimate of differences in land cover characteristics (e.g., species composition, crown cover) on AET.

4.7. The SWIM model for estimating the water balance

We applied the CSIRO SWIMv2 (Soil Water Infiltration and Movement) model (Verburg, 1996; www.clw.csiro.au/products/swim/) SWIM v2.0 over a water year April 2004–May 2005 for the Coastal basins.

SWIM is based on a numerical solution of the Richards' equation and the advection–dispersion equation. Of relevance to this study, SWIM can be used to simulate runoff, infiltration, redistribution, plant uptake and transpiration, soil evaporation and deep drainage (Verburg, 1996). However the model deals only with a *one-dimensional profile* and assumes that there is one hydraulic conductivity function (based on data from Bonell et al., 2010) for each soil horizon so that macropore flow can only be accounted for in a limited way. Moreover previous work (Bonell et al., 2010; Krishnaswamy et al., 2012) has reported the existence of 2-Dimensional flow (i.e., sub-surface storm flow) within the soil profile during storms so the assumption of 1-Dimensional flow will break down at such times during the wet season. Nonetheless, its application will provide some useful insights into the impacts of land cover on evapotranspiration as well as runoff and groundwater recharge which can then be compared with the results for other methods.

The outputs of SWIM will also be compared with the daily water balances of the Malnaad and Coastal basins.

4.8. The zero flux plane method

The zero-flux plane (ZFP) method provides a point estimate of plant-water use and drainage to deeper layers (e.g., Cooper, 1980; Wellings and Bell, 1980; Kirsch, 1993; reviewed in Khalil et al., 2003). The method involves estimating a depth profile of total hydraulic potential of soil moisture and then the identification of a "zero flux plane" which separates the zones of upward and downward movement of water in a thoroughly wetted soil with evaporation and drainage occurring simultaneously. The ZFP separates upward movement of soil water to evapotranspiration from downward drainage towards the deeper soil and water table in the one-dimensional plane. Moreover the method is based on the premise that soil water recharge plus continued downward drainage under gravity is equal to changes in soil-moisture storage below the ZFP and that plant-water use above this zone is similarly estimated. In such circumstances, it is assumed that root extraction of soil moisture for AET below the ZFP is negligible, i.e. there is only drainage below the ZFP (Cooper, 1980). On the basis of the description of tree rooting patterns above, clearly the latter assumption of the ZFP method will not always be met. This notion applies especially once uptake for AET demands of freely available and shallow soil water has been completed in the early stages of the dry season (Venkatesh et al., 2011). Subsequently deeper root extraction is then more favoured especially when concerning the deeper-rooted, natural forest. In such circumstances the ZFP method would potentially over-estimate soil water drainage below the zero flux plane, and conversely under-estimate AET. The review of Khalil et al. (2003) suggested that in similar circumstances elsewhere errors in ZFP estimates were not considered large. But the latter rests on the premise that water is readily available most of the time in the upper soil layers.

As with SWIM above, the existence of 2-dimensional lateral flow during the monsoon (Bonell et al., 2010; Krishnaswamy et al., 2012), will cause a breakdown in the assumptions of the ZFP method. In addition the water table has to be deeper than the ZFP and the occurrence of perched water tables also during the wet season is another problem (Venkatesh et al., 2011; Krishnaswamy et al., 2012). Thus the application of the method is *restricted to the dry season only when no rainfall was recorded*. The method requires data on the soil matric potential (Ψ) with depth (z) to locate the ZFP as well as soil–water content to measure changes in storage. We used periodic (once a month) measurements of gravimetric soil moisture at various depths up to 2 m from the end of the wet-season in November 2005 through the dry-season until April 2006. As earlier indicated, these gravimetric data were then converted into volumetric soil moisture using bulk-density measured at the sites. Subsequently the matric potentials were obtained from the pressure plate data on soil cores taken at the same depths as the gravimetric moisture data. The total hydraulic potential (Φ) (i.e., total soil water potential) was then calculated at each depth, where $\Phi = \Psi - z$, and taking the surface as the reference datum ($z = 0$). Finally the total hydraulic potential – depth relation was then plotted to identify whether a ZFP exists and if so, evapotranspiration and recharge can be estimated for each land-cover using Eq. (1) in Khalil et al. (2003).

$$E = R + \int_0^{z_0(t_1)} \theta(t_1)dz - \int_0^{z_0(t_2)} \theta(t_2)dz + \frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)} [\theta(t_1) + \theta(t_2)]dz \quad (5)$$

where E is the Evaporation over the time period t_1 to t_2; R the Rainfall over the same period; t the time; z the depth measured positively downward; Z the Depth at which drainage is calculated; θ the Volumetric Moisture Content and $z_0(t)$ the ZFP depth at time t.

5. Results

5.1. Summary of the meteorological data

The annual rainfall for the Coastal site during the hydrologic year (June 2005–May 2006) was 3879 mm. The average rainfall for the hydrologic years 2004 and 2005 during the wet season (June–August) was 2751 mm and for the early the dry season period (September–December), the average was 386 mm. The average relative humidity for the hydrologic year 2005–2006 was 76.8% and average for the wet and dry seasons, as defined above (for the years 2004 and 2005) were 89% and 72.2% respectively. The PET estimated for the hydrologic year 2005–06 was 1479 mm (FAO, Penman–Monteith). The average wet season (June–August) PET for the years 2004 and 2005 was 309 mm (low for reasons stated earlier) and for the early dry season period(September–December), the PET (FAO, Penman–Monteith method) for the same years was 579 mm. The mean daily temperature for the year 2005–06 was 27.4 °C and the maximum and minimum daily temperature recorded was 37.5 °C and 15.9 °C respectively.

The Malnaad recorded an annual rainfall of 2724 mm during the 2004–2005 hydrologic year. The average rainfall during the wet season (June–September) and early part of the dry season (October–December) in 2004 was 2514 and 79 mm respectively and in 2005, 3392 and 140 mm respectively. The average daily relative humidity for the period 2005–2006 was 88.1%, and wet and dry season average for the years 2005 and 2006 were 93% and 89% respectively. The average of annual PET using the Turc method, for the hydrologic years 2004–2005 and 2005–2006 was 1560 mm. The wet season average PET for the years 2004, 2005 and 2006 was 401 mm and early dry season period (October–December) average was 412 mm. The mean daily temperature for 2004–05 was 24.8 °C, and the maximum and minimum daily temperatures were 40 °C and 11 °C, respectively.

For both the Coastal and Malnaad, it is important to note that these PET estimates for the wet season on a daily basis are more *than double* the daily AET cited by Ledger (1975) that will be used later in the F-G analysis. This supports the assumption that estimated PET used in the study is *well above* forest AET in the wet-season. The annual PET estimated for the sites are 1479–1560 mm, just above or close to the maximum measured ET of tropical rain forests (as reviewed in Kume et al., 2011). Thus we are confident of using our reference PET as the upper bound of actual forest ET in general and especially in the wet-season.

5.2. Basin area and flow

Fig. 3 shows the annual water yield as a percentage of annual rainfall for the three years 2003–2005, incl. It is evident that the basin area is not a major factor influencing the water yield. On the other hand over the same period, the impact of land cover is as much stronger driver as shown in Fig. 4.

5.3. Flow duration curves

As shown in Fig. 5, overall at both the Coastal and Malnaad (Kodigibail, Vajagar) sites, the NF sustains a higher proportion of low flows (depth units) and the most sustained and longer flowing is NF, Coastal (see also Table 4). These low flows also occupy a large proportion of total Q, consistent with observations of Roa-García et al. (2011). Flows below 20 mm day^{-1} in the Coastal, 40 mm day^{-1} in Kodigibail and 80 mm day^{-1}at Vajagar are largely confined to the forest and thus are the approximate thresholds for departure of the forest from the other land-covers. However in the Malnaad sites, NF does not necessarily maintain the lowest flow in mm and neither is it the longest flowing after the monsoon in a consistent manner (Fig. 5 and Table 4).

In the Coastal area flows below 0.5 mm day^{-1} are non-existent in the non-natural forest land-covers (AC, DF) sites) whereas the forest sustains flows as low as 0.01 mm day^{-1}. Most of the stream discharge is associated with storm events in AC and DF coupled with the more flashy nature of the hydrograph responses and the very low Q in between storms (as reported in Krishnaswamy et al., 2012). In combination, the latter results in a FDC biased towards the ⩽20% of flow spectrum.

Moreover despite differences in soil type at Vajagar, the trends between NF and DF are the same as described above. On the other hand when concerning the DF basin, the flows are sustained longer within this Vajagar basin when compared to this same land cover at Kodigibail and the Coastal site. These results indicate then the importance of differences in soil hydraulic properties (e.g., K_{fs}, Bonell et al., 2010) between soil groups as well as basin size but with land-cover playing the dominant role. Overall, the FDC and the duration of flow beyond the monsoon suggests that the Coastal site is most representative of the *infiltration-evapotranspiration trade-off* hypothesis.

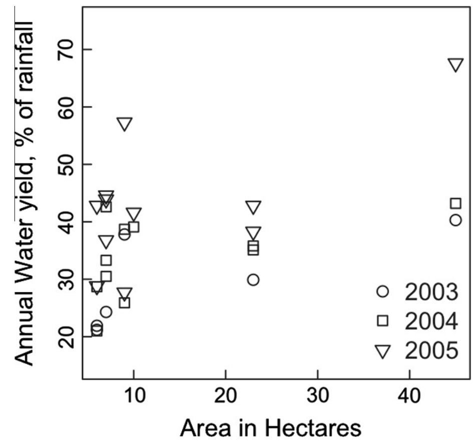

Fig. 3. The relationship between annual water yield and catchment area (as given in Table 1).

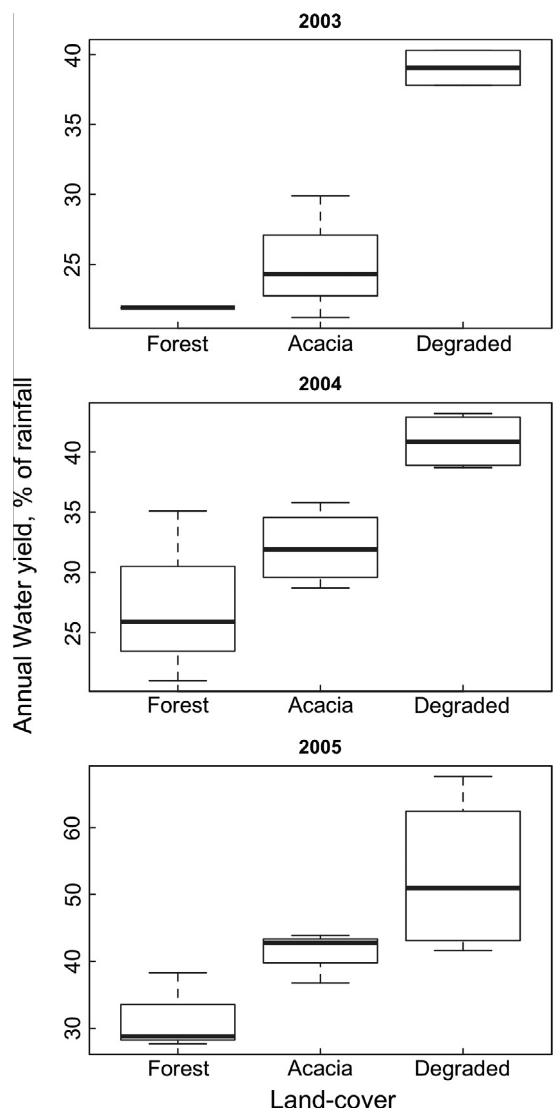

Fig. 4. The annual water yield for the different land covers.

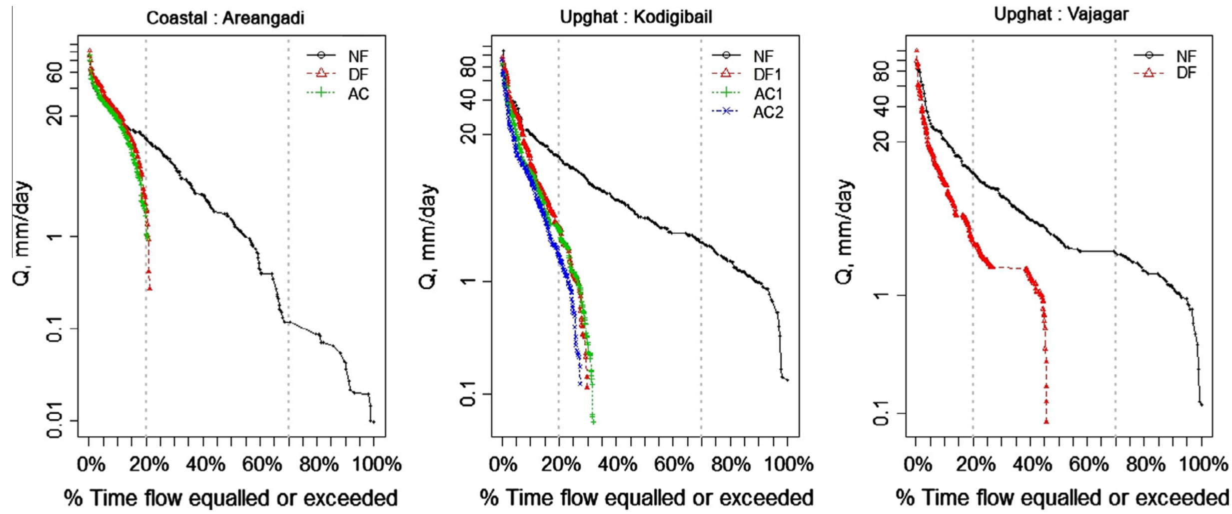

Fig. 5. The flow duration curves (FDC) of the Coastal and Up-Ghat basins. These are done on daily time-series data on a comparative basis across the land-cover types in each site using the entire period of record available and not including zero-flow values.

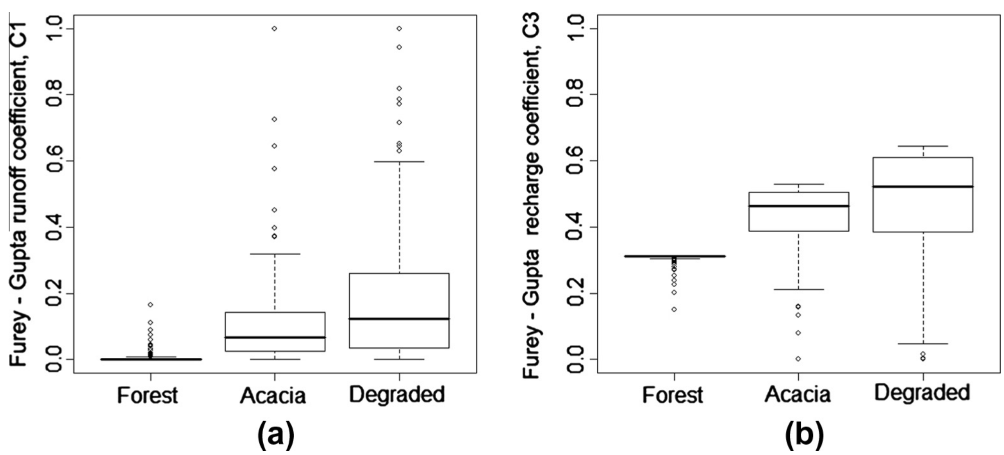

Fig. 6. The Furey Gupta filter coefficients, C1 (runoff) and C3 (recharge to ground-water), for the different land covers in the Coastal basins.

5.4. The Furey–Gupta filter analysis

It is encouraging that the rank order of the C2 coefficients (evapotranspiration plus some changes in storage), is in line with what would be expected, with the NF having the highest value (0.69) (Table 3). This Table 3 and Fig. 6 also show that the mean C1 is very low (0. 0067) under the Natural Forest and the highest under the Degraded Forest (0.21). The Acacia plantation also has a C1 value much closer to the DF1 basin with a mean of 0.10. Moreover in line with the findings of Furey and Gupta (2001) the variability (as shown by the standard deviation) in the mean C1 estimates remain high, most notably under the Natural Forest. The trend in these C1 estimates is what would be expected from with the previous hydraulic conductivity survey, that is, a greater frequency of overland flow in both the DF1 and AC1 basins (Bonell et al., 2010). Moreover this result is also in line with the higher Q_F(-quick flow)/Q (total flow) ratios from specific events, as determined from HYDSTRA, for the DF1 and AC1 (Krishnaswamy et al., 2012).

On the other hand, the median C3 (recharge to groundwater) was higher under DF1 and AC1 when compared to natural forest which is a surprising result. The box plots however show that there is a greater variability in C3 from storm to storm for DF1 and AC1 when compared to the Natural Forest. Thus despite the larger means and medians associated with the latter two basins, such variability *implies that groundwater recharge is inconsistent and more variable, especially under degraded forest*. Furthermore as C2 may include some temporary storage over shorter periods of time, it is likely to suppress somewhat the values of C3, especially for the less-disturbed forest catchment. The lower variability in C3 for NF1 suggests that this land cover has the most stable groundwater recharge mechanism. Such consistency in groundwater recharge maybe partly due the higher surface K_{fs} being receptive to higher infiltration in the Forest when compared to the other land covers. Further the duration of streamflow continued the longest within the Coastal forest after the summer monsoon had terminated, as indicated by the flow duration curves (Fig. 5), which favours the notion of a larger subsurface water storage capacity beneath the Forest. The latter would sustain AET and contribute towards the highest C2 value being associated with the NF1. In addition, the C3/C1 ratios are very similar for the degraded forest and the Acacia plantation with a low IQR (Table 3). These results are encouraging as they suggest a similar hydrogeology, hydro-pedology and climatic environment (Furey and Gupta, 2001). Conversely, the Forest is radically different with a C3/C1 ratio and an associated IQR that are two orders of magnitude higher.

Furthermore, the Natural Forest is also associated with the highest recession constant (0.98) and Q_B (0.95) respectively which, as one might expect, infers higher recharge to groundwater. The low standard deviation (SD) for C3 for this basin also lends confidence to this interpretation. Further this basin has also the advantage of being larger in area (23 ha) for groundwater storage. Nonetheless the proportion of Q as Q_B still remains at 0.55 or greater for DF1 and AC1 (Table 2), even after taking into account the larger SD in the C3 estimates and the basin areas (7 ha each) being smaller than the Forest. Such Q_B results indicate *that substantial groundwater recharge still occurs* under these land covers despite the lower surface K_{fs}.

However as the Forest is approximately three times larger in area when compared to the other two basins, the above conclusions about the relative role of land-cover needs to be made with some caution. Nonetheless all our analyses have been undertaken using depth units (mm) which takes care of some of the area effect and we are thus mostly attributing the differences in Q_B to land-cover rather than basin area.

5.5. The wet season water balances

Table 4 indicates that the percentage of precipitation as recharge to groundwater is highest in the Forest basins, followed by Acacia and Degraded Forest. This trend is consistent between the Coastal and Malnaad basins.

5.6. The water balance using the F–G C2 coefficient and Ledger (1975) AET estimates

Between 16 June and 26 July 2005, a total rainfall of 2181.6 mm was recorded and the respective total stream flows for NF1, AC1 and DF1 were 600.92 mm, 1073.89 mm and 1241.75 mm.

If the reference AET for the wet evergreen forest is taken as 1.5 mm d^{-1} (Ledger, 1975) during the wet season, then the approximate AET over the 41 days period for the Forest (NF1) is 62 mm. Then applying Eqs. (3) and (4) provides the corresponding AET estimates for AC1 and DF1 (Table 5). Finally Table 5 shows the resulting water balance (using Eq. (2)) and the proportions of rainfall as recharge to groundwater. So the estimated rainfall as recharge over the 41 days in the Coastal basins is highest under Forest (69.63%), followed by Acacia (48.85%) and lowest under Degraded Forest (41.65%).

5.7. SWIM

Table 6 indicates that recharge to groundwater is also highest in the Forest (NF1), followed by Acacia and the Degraded Forest in the Coastal basin at an annual time scale. This agreement in rank order of recharge to groundwater, c.f., Tables 4 and 5, is despite the method being constrained by its one-dimensional assumption. The latter may also account for the radical differences in proportions of groundwater recharge when compared to the other approaches (Tables 4 and 5).

Table 5
The water balances of the coastal basins (16 June – 26 July 2005) using the Furey–Gupta C2 coefficients and using the mean daily actual evapotranspiration (AET) (Ledger, 1975) for the Forest as the scaling factor.

Land Cover	Rainfall (mm)	Stream flow (mm)	AET (mm)	Groundwater recharge (mm)	%Groundwater Recharge of Rainfall
NF1	2181.6	600.92	61.5[a]	1519.18	69.63
AC1	2181.6	1073.89	41.89[b]	1065.82	48.85
DF1	2181.6	1241.75	31.20[c]	908.66	41.65

[a] Based on a mean daily estimate from Ledger (1975).
[b] Calculated using Eq. (3).
[c] Calculated using Eq. (4).

Table 6
The Soil Water Infiltration and Movement (SWIM) model results for Coastal catchments for the period May 2004–April 2005.

Land-cover	Rainfall (mm)	Run-off (mm)	AET (mm)	GW recharge (mm)
Forest	3568.6	1001.7 (28.1%)	1555.0 (43.6%)	1647.3 (46.2%)
Acacia	3568.6	1409 (39.5%)	1312.9 (36.8%)	1404.4 (39.4%)
Degraded	3568.6	2058.7 (57.7%)	1215.8 (34.1%)	494.9 (13.9%)

Note: The percentages express the proportion of each water balance component of total rainfall.

5.8. Soil water hydraulic potential profiles and the zero flux plane

The profiles of soil water hydraulic potential with depth are shown in Figs. 7 and 8) for respectively the three Coastal basins and Kodigibail (Sites 1–3 and 6–9 in Table 1). The following features are evident:

- The hydraulic potential through the dry-season is higher under the forest at Kodigibail when compared to all other land-covers and basins. Moreover, the hydraulic potential under the Kodigibail forest is consistently maintained at a higher level between 0.60 and 1.20 m depth throughout the dry-season.
- There is evidence of the development of a ZFP in all the land-covers. The ZFP is more pronounced at shallow depths ($\leqslant$0.5 m) but it can also be detected at some sites even at greater depths ($\geqslant$1.2 m),e.g., Kodigibail forest. This suggests that soil water is being extracted from at least two parts of the deep profile to meet transpiration demand and as acknowledged above, will affect both the AET and drainage estimates.
- Table 7 shows the estimates of evapotranspiration and drainage for the Coastal basins for the period mid-December 2005 – mid-March 2006 where the ZFP is more marked. Further Table 7 refers to ZFP evident between 0.45 and 0.60 m and does not take into account any weaker reversals in hydraulic potential gradients at greater depths. *This period coincides with part of the dry season in the absence of any rainfall*. The ZFP was located at 0.45 m for natural and degraded forest and 0.6 m for Acacia. The evapotranspiration above the ZFP during the above period was 24.08 mm for Natural Forest, 34.80 mm for Degraded Forest and 32.58 mm for Acacia. The drainage for the period was 98.02, 66.92, and 70.91 mm respectively for Natural Forest, Degraded Forest and Acacia catchments.. As noted above, however, the deeper rooting patterns below the ZFP under the Natural Forest potentially introduces some unknown error into both the AET and drainage estimates.

Taking into account the above, two characteristics are evident. First, over this period the depths of the ZFP's are relatively fixed under all land covers and do not show temporal variability, and despite no rainfall occurring, and thus a simplified version of the ZFP Eq. (5)) was used (i.e., the rainfall and the 3rd term to account for a variable ZFP were both zero in Khalil et al., 2003). Second, the amounts of evaporation over three months are very low across all land covers (<34 mm), but as expected the rank order is NF > AC > DF. Conversely, the amounts of drainage are at least double the amounts of evaporation. One can conclude from these results that Forest at least must be drawing on much deeper subsurface water (>1.5 m depth) to meet its transpiration

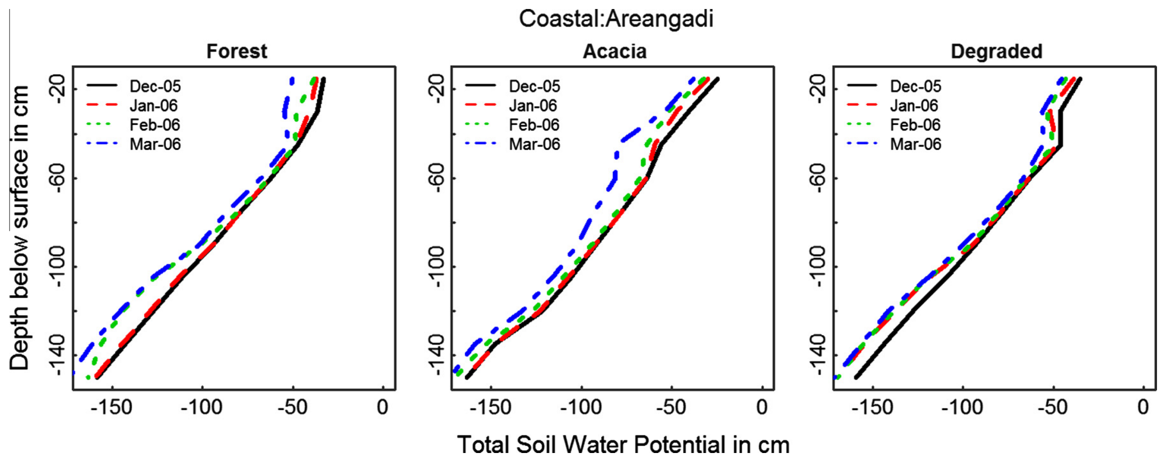

Fig. 7. The total soil water hydraulic potential (Φ) versus depth (z) relationsat selected dates during the dry season for the Coastal basins (Sites 1–3, Table 1, Fig. 1), where $\Phi = \Psi$ (matric potential) – z(gravitational potential), taking the surface as the reference datum.

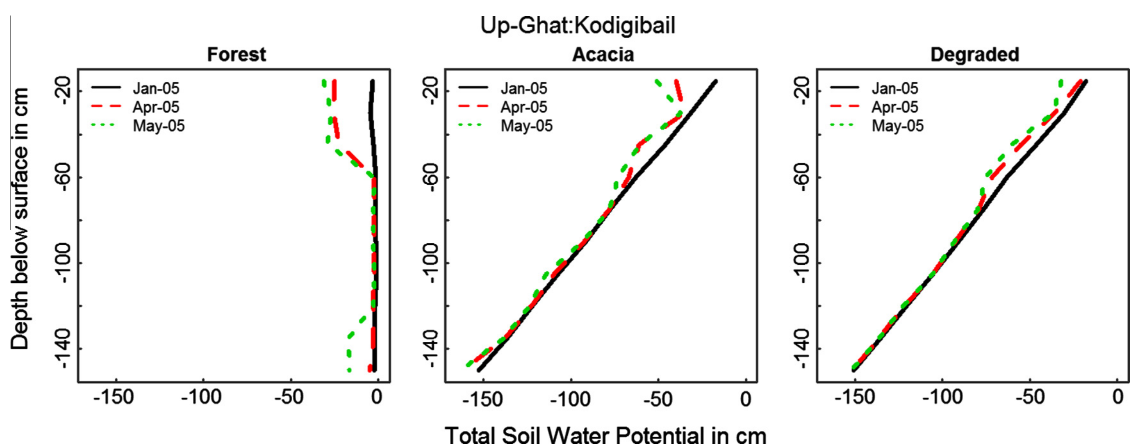

Fig. 8. The total soil water hydraulic potential (Φ) versus depth (z) relationsat selected dates during the dry season for the Up-Ghatbasins (Sites 6–9, Table 1, Fig. 1)where $\Phi = \Psi$ (matric potential) – z (gravitational potential), taking the surface as the reference datum.

Table 7
Estimated evaporation and drainage in the coastal basins, December 2005–March 2006, using the zero flux plane method (ZFP stationary at 0.45 m.depth for NF /DF and 0.60 m depth for AC).

Catchment	Total depth (m)	ZFP depth (m)	January-06	February-06	March-06	Totals
			Evaporation (mm)			
Degraded Forest	1.5	0.45	10.88	9.00	4.20	**24.08**
Forest	1.5	0.45	8.95	4.29	21.56	**34.80**
Acacia	1.5	0.60	8.16	7.68	16.74	**32.58**
			Drainage (mm)			
Degraded Forest	1.5	0.45	61.38	18.92	17.72	**98.02**
Forest	1.5	0.45	14.85	36.12	15.95	**66.92**
Acacia	1.5	0.60	14.75	28.61	27.55	**70.91**

demands. Bourgeon (1989) recorded many roots in a soil pit in this region under evergreen forest up to 1.2 m and beyond. Our field observations of soil exposures in the vicinity of the experimental basins also suggest Natural Forest rooting depths extend beyond 2 m (Krishnaswamy et al., 2012). As noted above, Kallarackal and Somen (2008) reported that Acacia rooting patterns are mainly in the upper 1 m, and further suggest their inability to tap deeper groundwater. Thus it appears that the Natural Forest has the greatest ability to support higher transpiration rates in the dry-season using deeper sources of water.

5.9. Dry-season flow in the larger catchments

The time-series of dry-season flow in the basins 1–2 km^2 downstream of the smaller instrumented basins indicates that flow is sustained longer into the dry-season in the basin with the highest percentage forest cover, that is, the Vajagar (Fig. 9, Table 2). On the other hand, the basin with the lowest forest cover, namely Nirmundagi (NRM), ranks second in sustaining flow the longest into the dry season. Another interesting feature is that the Kodigibail basin terminates flow early in the record, despite having the

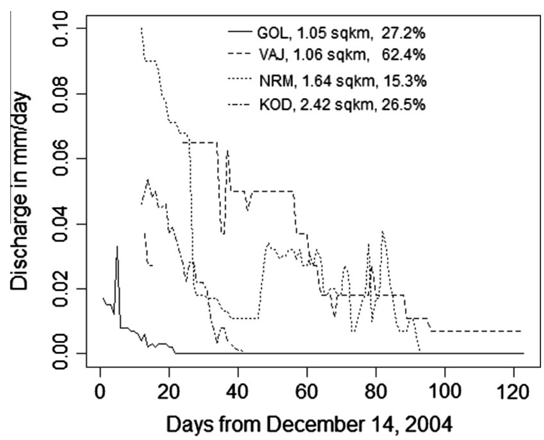

Fig. 9. Streamflow discharge in the larger catchments (shown in Fig. 1 and Table 2) duringthe early stages of the dry season. Area and % forest cover are indicated for each catchment. These higher order catchments are located downstream of the smaller and more homogeneous head-water catchments which are the main focus of the study.

advantage of the being the largest in area. On this basis, it could be inferred that Natural Forest is most influential on dry season flow when its areal coverage is very high.

6. Discussion

6.1. Groundwater recharge and the role of groundwater – a missing link

The independent results from the different water balance analyses suggest that groundwater recharge is substantial under all three ecosystems during the wet-season, and is the highest under Forest (46.2–69.6%), and is considerably lower under Acacia (39.4–56.4%) and Degraded Forests (13.9–44.6%). The main control on the amount of recharge in these high rainfall areas in the Western Ghats during the monsoon *is not the amount of actual evapotranspiration (AET)* (which is very limited by climatic conditions in the wet-season in all the three ecosystems) but by the soil hydraulic conductivity and the resultant partitioning of rainfall into quickflow, baseflow (delayed flow) and deep-percolation (see also Krishnaswamy et al., 2012). Moreover if one uses the Natural Forest cover over both the Laterites (*EutricNitosols* and *Acrisols*) and Red soils (*EutricNitosols*) as a baseline, the K_{fs} can be used as an indicator of the degree of degradation. It was reported (Bonell et al., 2010; Krishnaswamy et al., 2012) that the Degraded Forest and the Acacia plantations have up an order of magnitude decline in K_{fs} at the surface as result of human impacts at decadal to century time scales. *Nonetheless these results indicate that significant groundwater recharge seems to continue even under these more human – impacted land covers (AC, DF), despite some re-direction of rainfall as overland flow in response to land degradation.* The recharge process is nonetheless suggested to be complex, as indicated by the Furey–Gupta results when concerning the C3 coefficient. In that regard the larger inter–quartile variability shown in the C3 box plots for the more disturbed land covers (Degraded Forest, Acacia) as against those of the Natural Forest is critical. Such variability could be attributed to temporal changes of within - storm rain intensities. When the rain intensities are below the surface K_{fs} threshold for overland flow to occur, recharge dominates. Above this threshold a greater proportion of rain is re-directed laterally over the surface as overland flow and a lesser proportion is available for groundwater recharge. The negligible role of C1 for the Forest in conjunction with the low inter-quartile variability in the box plots for C3 indicates that groundwater recharge is *more consistent under this land cover.*

Furthermore the subsoil K_{fs} (geometric means ~10–20 mm h^{-1}) for all three Coastal basins are comparatively permeable down to 1.50 m depth when compared to other Laterite sites in the region (Bonell et al., 2010). These sub-soils are also more permeable than reports from other rainforest studies with 'Acrisol-type' soils in Australia (Bonell et al., 1981, 1998) and Peru (Elsenbeer and Lack, 1996) where the geometric mean K_{fs} are respectively one and two orders of magnitude lower than in the current study. Thus percolation to groundwater beneath both the DF1 and AC1 land basins would not be impeded, once rainwater entry through the lower surface K_{fs} had occurred. Thus recharge to groundwater can be maintained despite a reduction in surface K_{fs} in the two disturbed land covers. Under the Forest, the percolated water can still be intercepted for transpiration or storage (Fig. 9) and thus less is available for recharge for many events in spite of much higher infiltration. However the Forest has emerged as the most stable and consistent land cover to act as a "recharger" of groundwater. The latter is also reflected by the flow duration curves (FDC) where low flows occupy a much greater proportion of total flow from the Forest, when compared to the other land covers. Moreover such low flows are shown to be sustained for a longer period of time, especially in the Coastal region.

The preceding key attributes of the Forest (also previously noted by Roa-García et al., 2011) have important implications when concerning "provisioning" ecosystem services (MA, 2005) linked with a more reliable community water supply to downstream communities and agro-ecosystems such as Arecanut, home gardens and Paddy-rice. This work has shown that one cannot focus entirely on the surface hydrology to explain the impacts of land cover change. All our analyses based on different approaches have highlighted the importance of subsurface pathways and subsurface water bodies (including possibly deep groundwater) as contributing sources to streamflow. Thus at such small basin scales, in addition to surface changes in K_{fs} affecting stormflow pathways, runoff can also be affected by subtle differences in the hydrogeology by way of the jointing and fracturing within the underlying parent rock (as mentioned in CGB, 2008). Consequently, this work highlights the importance and the need for detailed knowledge not only on the evapotranspiration component of the water balance but also on the hydrogeology within the forest-land cover change debate – an issue commonly not strongly highlighted in the forest hydrology literature (e.g., Scott et al., 2004; Bruijnzeel, 2004). Consequently, there is a need for caution when attributing differences in the rainfall–runoff response to land cover change impacts on surface K_{fs} *per se* and that applies to the present study.

The higher and consistent recharge under natural forest at smaller spatial scales leads to longer dry-season flows in basins downstream as supported from measurements of dry-season flow in downstream basins of 1–2 km^2. For the specific examples used here only such conclusions apply where forest cover *exceeds* 60% of basin area. However in the absence of other replication studies in the Western Ghats such a figure cannot be taken as universal. Nonetheless qualitative observations on the duration of stream flow within higher order stream networks downstream during the study also suggested that substantial recharge occurs in less disturbed catchments. Thus dry-season flows in these less disturbed basins are more sustained within the long dry season. Elsewhere James et al. (2000) also reported similar characteristics from a comparative, small catchment study (0.15–2.95 km^2) within the Western Ghats of Kerala. The densely forested basins produced streamflow ranging from 24.2 to 32.8 mm/unit area in contrast to 1.6–6.4 mm/unit area in "partially exploited" basins and 0 mm/unit area from "fully exploited" basins during the January–May period (James et al., 2000).

The importance of groundwater is also suggested by the ZFP results. Despite potential violation of one ZFP method assumption (*viz*, soil water extraction by roots is mostly confined to above the zero flux plane in the Natural Forest), nonetheless only very small amounts of soil water (<35 mm) in the top 1.5 m of the soil profiles are suggested as contributing towards AET during the protracted dry season. Such small amounts of soil water use must be made up by much larger contributions from deeper groundwater to meet transpiration-physiological demands notably beneath the forest. Some support for the latter comes from the previously mentioned study in the Kodigibail basins by Venkatesh et al. (2011). These writers reported that the use of soil moisture for physiological activities in the Acacia and Degraded Forest was mostly confined to the upper layer (up to 0.50 m depth) due to the shallow nature of the rooting systems, notably beneath the Acacia (Kallarackal and Somen, 2008). Further the upper layer is also more favoured as a soil water source for physiological activities, especially during the early part of the post monsoon season when water is freely available (Kallarackal and Somen, 2008). Furthermore, the maintenance of high soil water hydraulic potentials throughout the dry-season beneath the Kodigibail forest is also interesting. This could be potential evidence of hydraulic redistribution of moisture from deeper to shallower soil by tree-roots, as reported by Prieto et al., 2012), and the process merits a deeper study.

6.2. The '*infiltration-evapotranspiration trade-off*' hypothesis: a perspective from this study

In the model simulations of Van der Weert, 1994, (reviewed in Bruijnzeel, 2004), the indications were that delayed flow would not be affected if the 'surface runoff coefficients' (i.e. infiltration-excess overland flow) remain below 15% of rainfall. If the latter however, attains 40% then delayed flow (dry season flow) would be halved (Bruijnzeel, 2004). When concerning the heavily-impacted Coastal basins, the estimated overland flow from the F-G analyses (C1 coefficient, max 0.21) lies in- between these 15% and 40% limits, as mentioned by Bruijnzeel (2004).

This analysis however does indicate aspects which support the '*infiltration-evapotranspiration trade-off*' hypothesis. These include the following points:

- From the F–G analysis, there is a reduction in delayed flow of 40% between the Forest and the degraded forest, and conversely an increase in Q_F of 40%.
- Groundwater recharge is the highest for the Forest (natural forest, NF1), followed by AC1 (*Acacia auriculiformis* plantation) and lowest for DF1 (degraded forest) using three independent techniques to estimate the water-balance
- A comparison of the frequency duration curves (FDC) across land covers also suggests less groundwater recharge and baseflow within the disturbed land covers and a greater potential for infiltration excess-overland flow. Thus in the more disturbed land covers (DF, AC), the occurrence of sustained low flows do not occur in contrast to the Forest FDC.
- Elsewhere (Krishnaswamy et al., 2012) it was noted that there is a shift from long to the shorter time lags in rainfall-runoff when comparing the Natural Forest with the AC and DF land covers for specific rain events. Such changes infer reduced infiltration and an 'apparent' transformation from a previously dominant and slower stormflow pathway emanating from subsurface sources towards a more rapid surface pathway. This aspect supports the earlier conclusions from the soil hydraulic conductivity survey (Bonell et al., 2010).

The data from Krishnaswamy et al. (2012) clearly indicates that annual recharge from natural forests can range from 259 mm (rainfall 2252 mm) to nearly 1000 mm when the rainfall is over 4000 mm. On the other hand, there is also evidence that recharge to deeper soil water and groundwater stores still remains significant under all three ecosystems, including the Degraded Forest and the Acacia plantation. The latter are contrary to what might be expected for the 'degraded scenario' of the '*infiltration-evapotranspiration trade-off*' hypothesis (Bruijnzeel, 2004). In terms of this extra recharge not being reflected in the rain-runoff totals, this paradox may be explained by scale. One is dealing here with very small headwater basins. Thus there remains the strong possibility that some of the recharge in the monsoon maybe contributing to a much deeper, regional groundwater flow and storage in the ecosystem that extends well beyond the topographic boundaries of these small basins, as supported by perennial or longer duration flows in higher order catchments downstream that supply water to downstream agro-ecosystems (Fig. 9) .Thus such regional groundwater sustains vegetation water use and other ecosystem services in the dry season.

A principal message from this study is that to make significant progress in the humid tropics on this land cover change – hydrological impacts issue, such basin studies need to be coupled with parallel, hydrogeology, soil moisture and eco-physiological investigations. Further such studies ideally should be undertaken at larger scales subject to the constraint of land cover fragmentation.

6.2.1. Infiltration-evapotranspiration trade-off: a dynamic process?

The ''infiltration-evapotranspiration trade-off'' conditions are not static for an ecosystem but are a dynamic function of its evolving biomass and structure and the prevailing land-use, all of which influences at any time the infiltration characteristics in relation to the prevalent rainfall regime as well as its evapotranspiration levels (Fig. 10). Our study shows that these conditions can change from storm to storm within a monsoonal season as well as across monsoon seasons (Krishnaswamy et al., 2012). In addition, climate change is likely to further increase the frequency of higher intensity rainfall in the Western Ghats and other parts of India (Rakhecha and Soman, 1994; Lal et al., 2001; Goswami et al., 2006 and Pattanaik and Rajeevan, 2010). This scenario suggests that many ecosystems which are currently just above or at the threshold of the ''*infiltration-evapotranspiration trade-off*'' levels of K_{fs} will be tipped over to a condition that enhances overland flow at the expense of deep percolation. Furthermore certain soil types and land-covers are particularly sensitive to overland flow occurrence (Bonell et al., 2010). We illustrate the trajectory of forest degradation and land-use and land-cover change in relation to the ''*infiltration evapotranspiration trade-off*'' *hypothesis* and changes in the rainfall intensity regimes using a conceptual diagram, as shown in Fig. 10, which is based on insights gained from this study. As an example, converting natural forest into other categories implies changes in both infiltration characteristics and evapotranspiration, and in the case of tree-plantations it would be a function of tree-density and age. Grazing may further reduce infiltration compared to well-maintained grassland. We further note that natural forest may be able to cope with increased rain intensities in the future compared to the other land-cover types. The overall impact of these various trajectories on hydrologic functions and services is also scale dependant as mentioned earlier.

6.3. Infiltration-evapotranspiration trade off: some implications for forest ecosystem restoration and services

A fundamental message of the work is the need to protect and safeguard the natural forests in headwater areas. Such steps are

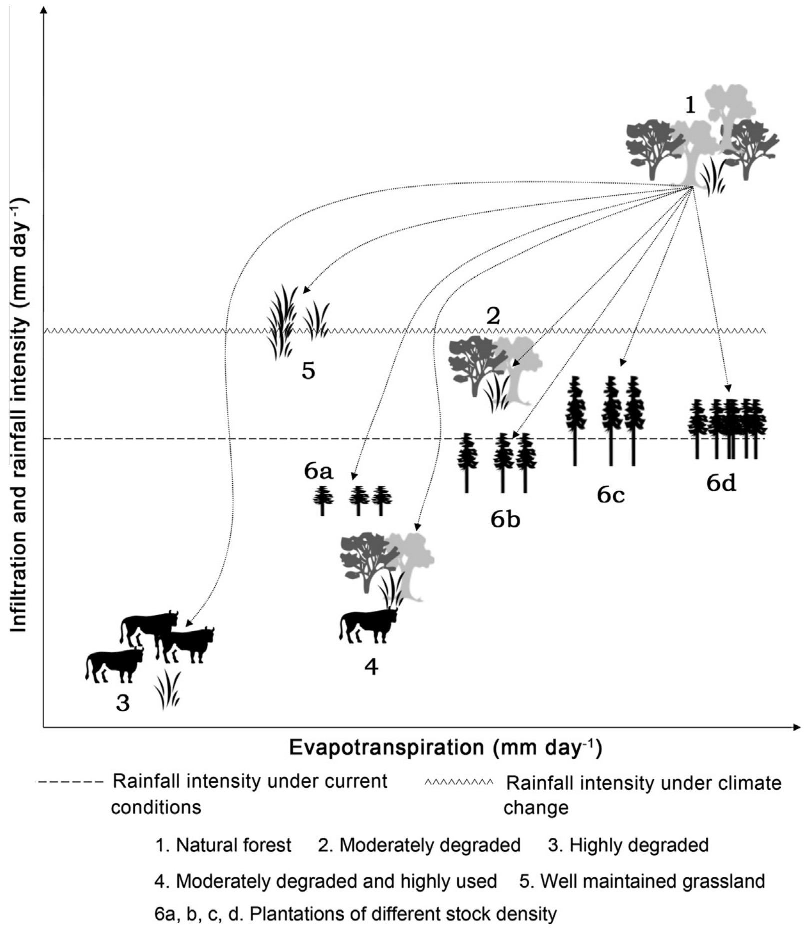

Fig. 10. A conceptual diagram ofthe Evapotranspiration-infiltration 'trade-off' as applicable to the study sites and also linked with the hypothesis of Bruijnzeel (1989, 2004). For example conversion of natural forest (1) to over-grazed grassland (3) will reduce both evapotranspiration and infiltration considerably, whereas some young, fast-growing plantations of high density (6d) may match the natural forest (1) in evapotranspiration but will have reduced infiltration. If rainfall intensity exceeds the infiltration the land-cover types are prone to infiltration-excess over run-off and recharge to ground-water will decrease. Under climate change, increase in rainfall intensities will enhance this vulnerability, with consequent changes to hydrologic services.

critical in ensuring that low flows are sustained during the long dry season and thus allow the natural forests to maintain low flows as key "provisioning" ecosystem services (MA, 2005) linked with a more reliable community water supply. It is also evident that the time to recover anywhere close to the natural forest hydrological characteristics (i.e., water balance, FDC) by way of forestation using Acacia may take several decades, or if not at all. The latter is because monocultures for example do not encourage the same diversity of soil biology and ecology (and thus enhanced macro-porosity and resulting effects on infiltration) (Rossi and Blanchart, 2005; Bonell et al., 2010). Despite the paucity of direct measurements of AET of *Acacia sp.* /*Eucalyptus sp* under humid tropic conditions, the AET of the young and vigorously growing plantations will also possibly be higher than the Natural Forest on the basis of work elsewhere (see review of Scott et al., 2004).

Overall, the management of ecosystems in the Western Ghats needs to take into account the possibility of shifts in hydrologic pathways in the future (Fig. 10) and to local and downstream ecosystem services, such as baseflow of rivers sustaining coastal ecosystems and livelihoods. Furthermore, the planned reforestation and restoration of 6 Million hectares by the Government of India under the Green India Mission initiative (http://www.pib.nic.in/release/release.asp?relid=36449) needs to consider the consequences for hydrologic services under different hydro-climatic conditions. The remarks of Chazdon (2008) that when concerning approaches to restoring forest ecosystems, these "depend strongly on levels of forest and soil degradation, residual vegetation, and desired restoration outcomes" also apply to the hydrologic consequences of such impacts, as highlighted in this work. This study has revealed the potential of certain tropical landscapes characterized by a combination of geo-physical, bio-physical and land-use history to respond hydrologically to forest use, degradation and reforestation in support of the "*infiltration-evapotranspiration trade-off*" hypothesis. The positive role of upstream natural forest in recharging groundwater in the monsoon for downstream sustenance of communities and ecosystems in the Western Ghats is suggested. The implications of these findings, however, remain preliminary. The nature of land cover fragmentation has been a severe constraint in terms of confining such basins studies to comparatively small scales. The critical issue of 'upscaling' results from this type of work still remains a global challenge if it is to realise the objective of comprehensively contributing towards a hydrological basis linked with "provisioning" ecosystem services (Costa et al., 2003; Bruijnzeel, 2004; D'Almeida et al., 2007; MA, 2005; Elmqvist et al., 2010; Rodriguez et al., 2010).

7. Conclusions

Through the use of various analytical techniques, the work established some support for the infiltration-evapotranspiration 'trade-off' hypothesis up to basin scales of $\sim$2 km^2. Conclusions from the small basin studies (⩽23 ha) which can be grouped under 1–4 are as follows:

- The frequency–duration–curves (FDC) of streamflow showed the existence of much longer durations of low flows from Forest in contrast to the Acacia and Degraded Forest. These low flows also occupy a large proportion of total Q. Flows below 20 mm day^{-1} in the Coastal, 40 mm day^{-1} in Kodigibail and 80 mm day^{-1} at Vajgar are the approximate thresholds for departure of the Forest from the other land-covers. In contrast, most of the stream discharge emerging from the Acacia and Degraded Forest is associated with storm events coupled with the more flashy nature of the hydrograph responses and very low Q in between storms (as reported in Krishnaswamy et al., 2012). In combination, the latter two factors results in a FDC biased towards the ⩽20% of the flow spectrum.
- The above flashy nature of hydrograph responses is reflected in higher C1 estimates (overland flow) for the Acacia and Degraded Forest basins based on the Furey–Gupta analysis. Such findings are in line with the previous hydraulic conductivity survey that inferred a greater frequency of infiltration-excess overland flow within these land covers (Bonell et al., 2010). Moreover this result is also in line with the earlier reports of higher Quickflow (Q_F)/total storm (Q) ratios based on hydrographs for specific events for the Degraded Forest and Acacia (as described by Krishnaswamy et al., 2012). Thus the *Acacia auriculiformis* plantations still retains a 'memory' of the storm hydrograph characteristics described above for the Degraded Forest.
- The independent results from the application of three different water balance approaches, which included the use of two modeling techniques (Furey –Gupta, SWIM), all suggest a consistent ranking in priority of groundwater recharge, viz, Forest > Acacia > Degraded Forest. In terms of percentage of rainfall as groundwater recharge however there is some variation, partly due to the assumptions in the methods adopted. Thus for Forest the percentage of rainfall as groundwater recharge ranged from 46.2% to 69.6%, under Acacia (39.4–56.4%) and Degraded Forests (13.9–44.6%). Nonetheless overall, groundwater recharge is substantial under all three ecosystems in the wet-season and is attributed to the specific caveat of soils and hydrogeology found in this environment namely the comparatively high subsoil hydraulic conductivities (Bonell et al., 2010) as well as the nature of the hydrogeology (i.e., fractured rock aquifers). Once rainwater penetrates the surface soil layers of lower permeability in the disturbed land covers, substantial recharge to groundwater can occur. Not all this recharge however becomes streamflow within the headwater experimental basins (which are intermittent), but instead it is considered to emerge downstream in higher-order sub-basins from regional groundwater (point 5 below).
- The zero flux plane analysis highlighted the very low amounts of soil water (< 34 mm) from the top 1.5 m layer across all land covers which were able to service the needs of transpiration and other physiological activities during the dry season. It is suggested that deeper subsurface water sources (deeper soil moisture and groundwater) must compensate for such low amounts in the shallow surface layers. Such findings highlight the importance and need of hydrogeology knowledge which is commonly not mentioned in the context of the infiltration-evapotranspiration 'trade-off' hypothesis.
- Finally at the ~2 km^2 basin scale, there is a suggestion of low flows being sustained into the dry season even where the Forest cover exceeds 60% of basin area, thus providing further support for the trade-off hypothesis. Further replications of other similar work are still required in order to derive a more regional figure for the Western Ghats.

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