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The rain–runoff response of tropical humid forest ecosystems to use and reforestation in the Western Ghats of India

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SUMMARY

The effects of forest degradation and use and establishment of tree-plantations on degraded or modified forest ecosystems at multi-decadal time-scales using tree-plantations on the streamflow response are less studied in the humid tropics when compared to deforestation and forest conversion to agriculture. In the Western Ghats of India (Uttar Kannada, Karnataka State), a previous soil hydraulic conductivity survey linked with rain IDF (intensity–duration–frequency) had suggested a greater occurrence of infiltration-excess overland within the degraded forest and reforested areas and thus potentially higher streamflow (Bonell et al., 2010). We further tested these predictions in Uttar Kannada by establishing experimental basins ranging from 7 to 23 ha across 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. In total, 11 basins were instrumented (3 NF, 4 AC and 4 DF) in two geomorphological zones, i.e., Coastal and Up-Ghat (Malnaad) and at three sites (one Coastal, two Up-Ghat). The rainfall–streamflow observations collected (at daily and also at a 36 min time resolutions in the Coastal basins) over a 2–3 year period (2003–2005) were analysed.

In both the Coastal and Up-Ghat basins, the double mass curves showed during the rainy season a consistent trend in favour of more proportion of streamflow in the rank order DF > AC > NF. These double mass curves provide strong evidence that overland flow is progressively becomes a more dominant stormflow pathway. Across all sites, NF converted $28.4 \pm 6.41_{\mathrm{stdev\%}}$ of rainfall into total streamflow in comparison to $32.7 \pm 6.97_{\mathrm{stdev\%}}$ in AC and $45.3 \pm 9.61_{\mathrm{stdev\%}}$ in DF.

Further support for the above trends emerges from the quickflow ratio Q_F/Q for the Coastal basins. There are much higher values for both the DF and AC land covers, and their rank order DF > AC > NF. The quickflow response ratio Q_F/P is also the highest for the DF basin, and along with the Q_F/Q ratio, can exceed 90%. The corresponding delayed flow response ratios, Q_D/P clearly show the largest Q_D yields as a proportion of event precipitation from the Forest (NF1). The application of linear model supported these differences (e.g. 10–36% difference between NF and DF, $p < 0.001$) in the storm hydrologic response of the Coastal basins. The exception was Q_F/P where there was a higher uncertainty connected with inter-basin mean differences. Cross-correlation plots for rain–streamflow and corresponding lag regression models for three storm events in the Coastal basins suggested the existence of alternative stormflow pathways with multiple lags with peaks between ∼12 and 24 h in NF, compared to respective bimodal peaks at ∼1 and 16 h in AC and ∼1 and 12 h in DF. The long time lags for NF are suggestive of deep subsurface stormflow and groundwater as the contributing sources to the storm hydrograph. The short time lags in DF and AC are indicative of overland flow and so 'memory' of the previous degraded land cover is retained in AC as supported by previous hydraulic conductivity data. As potential and actual evapotranspiration is likely to be depressed during the monsoon, differences in streamflow and run-off responses between land-cover types is largely attributed to differences in soil infiltration and hydrologic pathways. Enhancing infiltration and reducing run-off in managed ecosystems should be explored in the terms of the context of other ecosystem services and biodiversity.

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1. Introduction

Previous work has highlighted a lack of drainage basin experiments to capture the hydrological responses to multi-decadal land degradation which is now the emerging reality of many humid tropic landscapes (Bruijnzeel, 1989, 2004; Bruijnzeel et al., 2004; Sandstrom, 1998; Giambelluca, 2002; DeFries and Eshleman, 2004; Holscher et al., 2004; Ziegler et al., 2004, 2007; van Dijk and Keenan, 2007; Ilstedt et al., 2007; Malmer et al., 2010). Similarly no such experiments have been established to monitor the hydrological impacts of 'forestation' (Scott et al., 2004) over 'degraded land' (Safriel, 2007) previously occupied by native tropical forests (Scott et al., 2004; Ilstedt et al., 2007; Lamb et al., 2005; Lamb, 2011). As part of the preceding scenarios, earlier work (Bonell et al., 2010; Bonell, 2010) noted that there is comparatively limited information in the humid tropics on the surface and sub-surface permeability of: (i) forests which have been impacted by multi-decades of human occupancy and (ii) forestation of land in various states of degradation. Moreover even less is known about the *dominant* stormflow pathways (as defined by Chappell et al. (2007)) or storm hydrograph characteristics (i.e., quickflow, delayed or baseflow; Chorley, 1978) for these respective scenarios.

Zhou et al. (2001) presented data from experimental first-order basins (up to 6.4 ha) in monsoonal southern China to study the impacts of rehabilitation of barren degraded land using eucalyptus (*Eucalyptus exerta*) as a plantation and separately, by under planting this eucalyptus with indigenous species. Within a 10-year period subsequent to 16 years of forestation, Zhou et al. (2001) noted that there was a progressive reduction in quickflow largely attributed to increasing macroporosity associated with the incorporation of biological matter. Although no soil hydraulic conductivity or hillslope hydrology data were presented, these writers remarked that the quickflow response was the highest from the degraded catchment due to surface soil crusting and showed no trend over the 10-year period, except being sensitive to rainfall variability. Similarly, work in very small basins (0.13–0.25 ha) over karst in Leyte, The Philippines (Chandler and Walter, 1998. Chandler, 2006) suggests that that pasture–fallow sites produced high volumes of infiltration-excess overland flow, *IOF* (70–80% of annual rainfall) compared with the minimal volumes of basin streamflow (~3% mostly from subsurface stormflow, *SSF*) from forest.

The above Asian studies are for the most part dealing with multi-decadal to century time scale, human impacted landscapes. In contrast there has been a concentrated effort on the impacts of forest conversion to pasture in the Amazon basin where such land cover changes are more recent. Whilst most of the work (reviewed in Bonell (2010)) has focused on point-scale, field saturated hydraulic conductivity (K_{fs}; Bouwer, 1966; Talsma and Hallam, 1980;Talsma, 1987) measurements; the work of de Moraes et al. (2006) was one of the first to present comparative hydrometric evidence (e.g. runoff plots, storm hydrograph response characteristics) from a forested (0.33 ha) and pasture basin (0.72 ha). Forest conversion to pasture 30 years ago had now clearly enhanced the occurrence of saturation-excess overland flow, *SOF* and further introduced *IOF* leading to higher proportions of total flow volumes as quickflow (2.7% forest *vis a vis* 17% pasture). A reduction in macroporosity beneath the pasture when compared with the forest, and a corresponding decrease in K_{fs} in the surface pasture soil, were the causal factors (de Moraes et al., 2006). Similar conclusions from a 3.9 ha basin in Rondonia which drained a cattle pasture were reported by Biggs et al. (2006). They noted quickflow was 16% of rainfall for a 10 rainstorm sample and ~50% of this quickflow resulted from *IOF*. Later Chaves et al. (2008) and Germer et al. (2010) reported on a combined hydrology–hydrochemistry study for respectively a forest (1.37 ha) and pasture (~20 years old, 0.73 ha) basin. These writers reported that overland flow (mostly *SOF*) dominated streamflow from the pasture in contrast to *SSF* in the forest supported by varying proportions of groundwater and soil water. Further evidence at larger scales in the Amazon basin that infer similar changes in the dominant stormflow pathway have also been presented (e.g., Costa et al., 2003; D'Almeida et al., 2007; Rodriguez et al., 2010).

Forest conversion, degradation and reforestation affect both infiltration and evapotranspiration, and there can be a trade-off between the two. These components are encapsulated in the *'infiltration trade-off'* hypothesis of Bruijnzeel (1989, 2004). In the context of this study, this hypothesis suggests that the ability of a degraded forest to allow sufficient infiltration (and thus groundwater recharge via vertical percolation) in the wet-season maybe impaired to such an extent, that the short and long-term effects on delayed flow after storms as well as on dry season flow would be detrimental, even after accounting for 'gains' from reduced evapotranspiration. Further such reductions in infiltration have the ability to change the dominant stormflow pathways (Chappell et al., 2007) on hillslopes from subsurface stormflow (*SSF*) to infiltration-excess overland flow (*IOF*). Under certain conditions and at 'local' scales, there is now emerging evidence in support of this hypothesis when concerning these changes in the storm runoff generation component.

Through the use of a *Comparative Catchment* approach (Blackie and Robinson, 2007), this work will present rainfall–streamflow data from 11 basins (⩽45 ha) in the monsoonal tropics to test hypotheses from an earlier survey of field, saturated hydraulic conductivity, K_{fs} in the Uttar Kannada district (Karnataka State) of the Western Ghats of India (Bonell et al., 2010). The locations of the experimental basins were guided by the landscape groupings of Gunnell and Radhakrishna (2001). Consequently three of the basins were located on the Coastal block and the remainder in the higher interior known as the Up-Ghat block or Malnaad. The rainfall–streamflow data analysed in this work was collected over a 2–3 year period (2003–2005) at a daily time resolution which was supplemented by 36 min data in the case of the Coastal basins.

As a result of degradation of forests over multi-decadal to century time scales, the land cover is complex in Uttar Kannada in common with other parts of the Western Ghats (Menon and Bawa, 1998; Seen et al., 2010). Patches of remnant natural forest, which are less disturbed and less used by people are at one end of the disturbance gradient and whilst at the other end, are a heterogeneous category of disturbed and heavily used forest (known as degraded forest). In addition a mix of State Government and community-based forestation programmes have been implemented for more than two decades within degraded forests and severely degraded, former forest-covered land (Pomeroy et al., 2003; Ramachandra et al., 2004). Consequently the Western Ghats (Karnataka State) provides a basis for evaluating land cover (LC) change impacts on streamflow hydrology at contrasting time scales linked with (i) forest land use and degradation, (ii) forestation over previously degraded land, relative to less used native forest and thus can address the hydrological knowledge gaps connected with these two scenarios (Ilstedt et al., 2007; Malmer et al., 2010). The impacts on the storm runoff hydrology of three of the more common land cover types namely, less disturbed natural–tropical evergreen Forest (NF), heavily impacted, degraded forest (DF) and former degraded land that has undergone 'forestation' (Scott et al., 2004) by way of *Acacia auriculiformis* plantations (AC) will be evaluated. The DF represents severely degraded, former evergreen forest, which has been converted floristically and architecturally into an open tree savanna.

1.1. Previous work relevant to the current study

Bonell et al. (2010) had previously provided K_{fs} data for five LCs (natural forests, degraded forests, acacia and teak plantations) and three soil groups, and linked such data with rainfall characteristics (IDF, intensity–duration–frequency). For extreme rainfalls with return periods of 1 in 1 year upwards, these writers inferred that *IOF* was a more dominant stormflow pathway on hillslopes than previously thought when concerning many of the land covers and for many of the return periods of rainfall. Significantly such an inference included some (but not all) of the less disturbed natural forests. Otherwise it was suggested that subsurface stormflow (*SSF*), supplemented by saturation overland flow (*SOF*), was the most prevalent.

One of the few other experimental basin studies previously undertaken in the Western Ghats was by Putty and Prasad (2000a), and later summarised in Putty (2006), based on first order basins (up to 8 ha in area) which were located south of Uttar Kannada within the Dakshina–Kannada district (near Talakaveri, annual rainfall ~6750 mm). Some of the conclusions of Bonell et al. (2010) aligned with the descriptions of Putty and Prasad (2000a). The latter, had noted the occurrence of *IOF* in the multi-decadal impacted, Kannike basin (2.8 ha) of mixed grassland and forestation where final soil infiltrability (Hillel, 1980) could be as low as 6 mm h^{-1}. However such *IOF* was supplemented *SOF* from riparian areas adjoining the stream (the Dunne mechanism, Dunne and Black, 1970) and more extensively on slopes, by an additional process termed *pipeflow overland flow*, *POF* (Putty and Prasad, 2000a). For the less disturbed, natural forest basin (8 ha), Putty and Prasad (2000a) noted that *SOF* is a significant contributor to stream discharge only during short duration events of higher rain intensity (~10–15 mm h^{-1}) and pipeflow is the major mechanism generating streamflow for the predominantly low rain intensity-longer storm durations. However these studies did not have detailed K_{fs} or stream hydrograph analyses and these aspects will be addressed in this study.

In the absence of detailed hillslope hydrology studies (a typical situation in most of the humid tropics), the work will analyze the rainfall–streamflow data using up to four analytical methods to assess if there is some coherence across the various interpretations of the results. These analyses will concurrently address the following questions:

1. What are the impacts of the three land covers on the stream discharge hydrograph components, *viz,* total flow, quickflow and delayed flow?
2. What *dominant* stormflow pathways can be inferred from the storm hydrograph characteristics and is there any agreement with the stormflow pathways, as suggested from the earlier K_{fs} survey linked with rain IDF (intensity–duration–frequency) (Bonell et al., 2010)?
3. What is the impact of forestation on the recovery of the rain–streamflow responses towards those observed under the less disturbed, natural forest?

2. Description of study area

2.1. Geology, landforms, soils and soil hydrology

The locations of the instrumented catchments are shown in Fig. 1. The two sets of sites are located in two distinct landforms: the Coastal plain and adjoining slopes and hilly Up-Ghat or Malnaad region. The geology is mainly Archaen-Proterozoic-Dharwad schist and granitic gneissic, meta-volcanics and some recent sediment in the coastal belt. Greywackes with lateritic caps are prevalent in a cross-section from the Western slopes to the Malnaad (Geological Survey of India, 1981).

Many of the upper geological sequences of this region are lateritised 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). Fig. 16b in Bourgeon (1989) provided a simplified latitudinal cross-section of the geology and location of laterite from the coast through to the Malnaad (incorporating Siddapur and Sirsi, 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 in Table 2 (Bourgeon, 1989).

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). 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 (Fig. 2). Further no detailed mapping of soil pipe occurrence was undertaken. However there was evidence of vertical macropore flow in soil exposures and an example is shown in Fig. 2.

2.2. Hydrogeology

Detailed hydrogeological surveys have not been done in the experimental basins. Even across the study area landscape such information is relatively sparse based on two phases of exploration with boreholes up 200 m depth (Central Groundwater Board, CGWB, 2008). 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 porous media with an effective porosity of 1–3% and contain groundwater. The transmissivity of aquifer material in 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 Uttar Kannada. In the post-monsoon, the

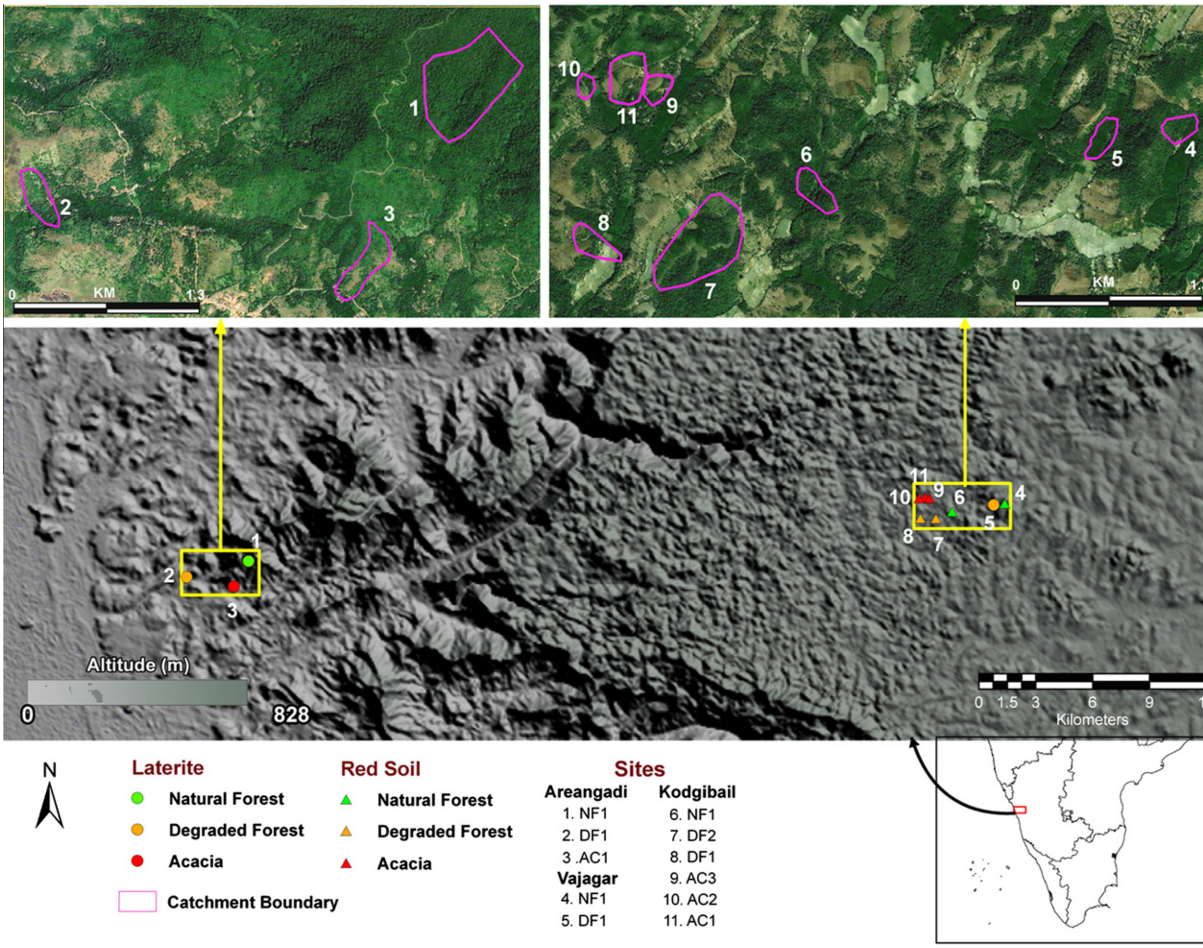

Fig. 1. The location, soil types and land covers of the research basins in the Western Ghats, Uttara Kannada District of Karnataka State.

prevailing depths within the Coastal and Malnaad areas were respectively 2–5 and 5–10 mbgl (CGWB, 2008).

2.3. 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 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 there is marked reduction in PET following the onset of the monsoon in June until its termination from October onwards (Hijmans et al., 2005). This 'dip' in PET is due to persistent high humidity and cloudiness with frequent rainfalls (Bourgeon, 1989; Hijmans et al., 2005).

The dry season lasts from 5 to 6 months and so during this time PET > rainfall. Annual mean temperatures range 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 coastal basins and 70% on the Malnaad slopes ((1960–1990), New et al., 1999).

Maximum rainfall intensities for a duration of 15mins 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). In a previous Western Ghats study, despite the high annual rainfalls and the long duration of storms, hourly and 15 min rain intensities >40mm h^{-1} contributed to not more than 15% of total rain and last a mere 2–5% of the total duration of events (Putty, 2006; Putty and Prasad, 2000a,b; Putty et al., 2000).

2.4. Aspects of vegetation and land covers

The 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 in the region (Pascal, 1982, 1984, 1986, 1988; Ramesh and Pascal, 1997; Ramesh and Swaminath, 1999). Within the framework of a highly fragmented land cover/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:

(i) 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.
(ii) Dominantly tree savannas (*Degraded Forest*, *DF*, *or Degraded*) that result from intense harvest of fuelwood, leaf and litter manure and grass, as well as intermittent fires (Rai, 2004;

Table 1
The physical characteristics of the experimental basins in the Up-ghat and Coastal regions.

No.	Site	Type	Area (ha)	Land cover type and 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*)
Malnad (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	Kodgibail	Natural Forest	6	NF1	540.14	7.56	2750	Red, Clayey-skeletal, kaolinitic, *Inceptisol* (*Ustoxic Dystropepts*)
7	Kodgibail	Degraded Forest1	9	DF1	522.16	4.76	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol* (*Ustoxic Dystropepts*)
8	Kodgibail	Degraded Forest2	45	DF2	536.50	5.10	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol* (*Ustoxic Dystropepts*)
9	Kodgibail	Acacia1	7	AC1	538.00	5.51	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol* (*Ustoxic Dystropepts*)
10	Kodgibail	Acacia3[b]	6	AC3	544.83	4.34	2948	Red, Clayey-skeletal, kaolinitic, *Inceptisol* (*Ustoxic Dystropepts*)
11	Kodgibail	Acacia2	23	AC2	544.10	3.36	2948	Red, Clayey-skeletal, kaolinitic, *Oxiso l* (*Ustoxic Dystropepts*)

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

Priya et al., 2007). These tree savannas were previously occupied by mostly evergreen and semi-evergreen forest prior to severe disturbance over decadel 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 3).

(iii) Exotic *Acacia auriculiformes* plantations planted since 1980 (*Acaicia*, *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 had further degraded to 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 range from to 7 to 12 years (Table 3).

Historically, people would have used and occupied the more ac*cessible s*ites, which are currently under degraded forests or are under restoration through establishment of tree plantations.

A description of the dominant vegetation types in the experimental basins are shown in Table 3. It should be noted that the Acacia plantations are not wholly monoculture but do incorporate a few other species.

2.5. Vegetation sampling and mapping exercise in the Malnaad

A vegetation sampling and mapping exercise was undertaken in selected Malnaad basins using 100 m × 20 m transects to enumerate tree species, tree girth, tree density and disturbance level (Table 3). Degraded forests still contained significant areas of dense tree vegetation. Further, pure grasslands in small patches exist and are dominated by *Themeda* sp. (Lele and Hegde, 1997). There was also significant difference in the species composition, tree density and basal area of different degraded basins, as well as between natural forests. However, both the NF basins clearly have the highest tree densities and basal areas compared to all other categories.

2.6. Tree root depths and surface K_{fs} across the land covers

Examination of selected soil exposures indicated that roots extended well beyond 2 m depth under the Natural Forest. For the young Acacia plantations most roots were ⩽1.5 m in 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.

Elsewhere Venkatesh et al. (2011) provided complementary evidence of the nature of rooting patterns. They observed that on the basis of soil moisture recessions most plant water use was confined to the upper soil layer (⩽0.5 m depth) in both the AC1 and DF1 Kodigibail basins (Table 1). This characteristic was attributed to the shallow rooting patterns in these two land covers. In contrast soil moisture recessions were evident throughout the profile down to 1.5 m depth in NF1 due to the greater depth of roots. This significant phase of moisture withdrawal occurred especially in the early stages of the post-monsoon season (Venkatesh et al., 2011), At such times, tree physiological activities take advantage of freely available, soil water combined with a more favourable meteorology that is, less cloudiness and a decrease in air humidity (Kallarackal and Somen, 2008).

The respective K_{fs} for the surface soils were in the range 26.4–187.8 mm h^{-1} for the natural forest compared to 26.8–61.0 mm h^{-1} under the *A. auriculiformes* plantations. The lowest surface K_{fs} occurred under the degraded forests being in the range of only 7.3–24.4 mm h^{1} (Bonell et al., 2010). Further details of the vertical changes in K_{fs} with depth are described in detail in Bonell et al. (2010).

2.7. The experimental basins

Additional details of the experimental basins (as shown in Fig. 1) are provided in Tables 1 and 3. The complex mosaic of

Table 2
Soil description of the evergreen forest in proximity to the Coastal basins (Bourgeon, 1989).

Village/location	Tulsani
Coordinates	Long: 74°33′25″E; Lat: 14°20′35″N
Altitude	110 m
Vegetation	Evergreen forest
Geology	Dharwar schists
Landscape unit	3, Ghats
Classification	Soil Taxonomy: *Indian* (*NBSSLUP*): Laterite; *USDA*: (Oxic) Eutropept; *French Classification*: Ferrallitic soil, weakly desaturated in B, rejuvenated, reworked.
From 0 to 10 cm	Slightly moist. Dark brown (7.5YR 4/4) moist. Humus. No effervescence. 50% of coarse elements, cobbles and gravels of highly weathered schist. Moderate crumb structure, 5 mm size. Coherent, plastic, very friable. Clay with medium sand. Very porous. Plentiful roots. Smooth transition in 2 cm
From 10 to 40 cm	Moist. Yellowish red (5 YR 5/6) moist. Humus. No effervescence. 80% of coarse elements, cobbles and gravels of highly weathered schist. Moderate subangular blocky structure, 8 mm size. Coherent, plastic, very friable. Clay with medium sand. Very porous. Plentiful roots. Smooth transition in 10 cm
From 40 to 120 cm and more	Moist. Yellowish red (5 YR 5/8) moist. Non-organic. No effervescence. 80% of coarse elements, stones, cobbles and gravels of highly weathered schist. Weak subangular blocky structure, 8 mm size. Coherent, plastic, very friable. Clay loam with fine sand. Very porous. Many roots

Fig. 2. A deeply weathered Red soil profile which is located near the Malnaad (Kodigibail) basins. The depth of the soil profile is in excess of 2 m depth and preferential wetting is also evident. Weathered rock is also visible in the right bottom corner.

land-cover and land-use made it difficult to identify homogeneous catchments of a sufficient area to be sure that inter-basin transfer of groundwater is potentially not significant, and the best possible catchments for a comparative study are less than 50 ha. In many basins the corresponding areas are ⩽10 ha as a result. On the other hand, these basin areas (Table 1) are of the same order of magnitude, or even one to two orders larger, when compared to other studies elsewhere (e.g., Chandler and Walter, 1998; Putty and Prasad, 2000a; Zhou et al., 2001; de Moraes et al., 2006; Chaves et al., 2008). Further because of their limited size, most basins did not have perennial flow. Any shortcomings of using basins of such small area will be later considered.

Despite the higher elevations in the Malnaad (basin numbers 4–11, Table 1), the mean slope angles are low (⩽7.5°). It is also pertinent that the Vajgar basins 4 and 5 have different soils and higher elevations when compared to basins 6–11. By contrast the Coastal basins (Areangadi, basin numbers 1–3, Table 1) have higher mean slopes varying between ~10–17°. A riparian zone is more evident within the Coastal forest basin from the mid-stream profile towards the gauging station (NF1, Site 1). Whereas this feature is absent in the DF1 (Site 2) and AC1 (Site 3) and the convex hill slopes border the stream channel directly. Overall the Coastal forested catchment is characterised by steeper terrain, especially in upper parts of the basin, when compared to the other land-covers at Areangadi (Table 1).

3. Field methods and data

3.1. Rain–runoff instrumentation

Stream discharge in each catchment was measured using either weirs or stage-velocity-discharge methods. In addition all catchments in the Coastal zone (Areangadi) were instrumented with stage level, mechanical water-level recorders and an automatic rain gauge. As these three basins were spatially close together, the same data from the one automatic rain gauge was used. The latter was positioned so that it was <2 km from the boundaries of all these Coastal basins. In the Malnaad group, rainfall and streamflow 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 Up-Ghat (Malnaad), and for 2004–2005 for the three Coastal basins (Table 1). In addition for part of the summer monsoon of 2005 (16 June–26 July), 36 min (0.6 h) data was available for rainfall–streamflow for selected storms in the three Coastal catchments. Such information enabled us to monitor temporal changes in the rain–streamflow response following the onset of the monsoon until maximum basin wetness was attained. However there were equipment malfunctions within at least one of these basins during some of the rain events. This reduced the number of storms where streamflow was measured concurrently across all basins during a rain event to allow an intercomparison using time series methods. On the other hand, other analytical methods (discussed below) could be undertaken on all events. Further these equipment problems caused us to extend the rain–streamflow monitoring in the Natural Forest basin until 30 September 2005.

3.2. Permeability

In the three Coastal zone catchments and in a representative sub-set of basins in the Malnaad zone [i.e., Kodigibail basin nos. 6 (NF1), 7 (DF1), 9 (AC1); Vajagar basin nos. 4 (NF1) and 5 (AC1) in Table 1], field saturated hydraulic conductivity, K_{fs} was measured up to a soil depth of 1.5 m. For the surface and 0.1 m depth, the disc permeameter was used for the determination of soil K_{fs} (Perroux and White, 1988; McKenzie et al., 2002). A Guelph constant head well permeameter, CHWP (Mackenzie, 2002) measured subsoil K_{fs} at depth intervals 0.45–0.60 m, 0.60–0.90 m, 0.9–1.20 m and 1.20–1.50 m. When concerning the presentation of the results, the latter will be abbreviated from here-on using the lower depths, *viz*, 0.6, 0.9, 1.2, 1.5 m.

Table 3
Vegetation characteristics of the instrumented basins.

No.	Site	Type	Land cover type and code	Vegetation type and dominant tree species	Average tree density (per ha)	Average basal area ($m^2\ ha^{-1}$)
Coastal basins						
				Low elevation Evergreen and semi-evergreen forest		
1	Areangadi	Natural Forest	NF1	*Dipterocarpus indicus–Diospyros candolleana–Diospyros oocarpa* type	N/M	N/M
2	Areangadi	Degraded Forest	DF1	*Alseodaphne semicarpifolia*, *Lophopetalum wightianum*, *Ixora barcheata*, *Aporosa lindleyana*, *Hopea wightiana*, *Terminalia panniculata*, and *Terminalia alata*	N/M	N/M
3	Areangadi	Acacia	AC1	*Anacardium occidentale*, *Garcinia indica*, *Syzigium cumini*, *Buchanania lanzan*, *Holigarna aronottiana*, *Alseodaphne semicarpifolia*	N/M	N/M
Malnad (UP-GHAT)						
				Medium elevation Evergreen and semi-evergreen forests		
4	Vajgar	Natural Forest	NF1	*Persea macarantha–Diospyros* spp.–*Holigarna* type	485	3536
				Lophopetalum wightianum, *Alseodaphne semicarpifolia*, *Gymnonthra conariea*, *Sagereaea listari*, *Holigarna aronottiana*		
5	Vajgar	Degraded Forest	DF1	*Alseodaphne semicarpifolia*, *Lophopetalum wightianum*, *Ixora barcheata*, *Aporosa lindleyana*	615	1896
				Medium elevation Evergreen and semi-evergreen climax forests		
6	Kodigibail	Natural Forest	NF1	*Persea macarantha–Diospyros* spp.–*Holigarna* type	615	2632
				Gymnonthra conariea, *Sagereaea listari*, *Ixora barcheata*, *Holigarna aronottiana*		
7	Kodigibail	Degraded Forest1	DF1	*Alseodaphne semicarpifolia*, *Lophopetalum wightianum*, *Ixora barcheata*, *Aporosa lindleyana*, *Hopea wightiana*, *Terminalia panniculata*, and *Terminalia alata*	352 (DF1)	2099 (DF1)
		Degraded Forest2	DF2		N/M (DF2)	N/M (DF2)
8	Kodigibail	Acacia1 Acacia3	AC1 AC3	*Acacia auriculiformis*, *Anacardium occidentale*, *Garcinia indica*, *Syzigium cumini*, *Buchanania lanzan*, *Holigarna aronottiana*, *Alseodaphne semicarpifolia*	AC1-132	AC1-1068
9	Kodigibail	Acacia2	AC2	*Acacia auriculiformis*, *Buchanania lanzan*, *Holigarna aronottiana*, *Alseodaphne semicarpifolia*, *Syzigium cumini*	345	2053

Notes: (i) The above DF and AC sites originally belonged to evergreen and semi-evergreen forest type (Pascal, 1984, 1986, 1988). The vegetation cover later changed with the extent of degradation. There is no Leaf Area Index information. (ii) For selected Malnad basins, supplementary information on vegetation composition was obtained from a field survey in addition to taking tree density and basal area measurements. (iii) N/M – Not measured.

4. Analytical methods

4.1. Analysis of the rain–streamflow data

The rain–streamflow data were analysed using four methods, namely:

4.1.1. Double mass curves (cumulative rainfall (P_{cum}) and cumulative stream discharge (Q_{cum}) plots)

A double mass curve is a plot of cumulative values of one variable against the cumulative of another quantity during the same time period (Searcy and Hardison, 1960). This concerned an inter-basin comparison of cumulative rainfall (P_{cum}) and stream discharge (Q_{cum}) plots based on seasonal records at a daily time scale for both the Up-Ghat (Malnaad) and Coastal basins

4.2. Outputs from HYDSTRA – Coastal basins

When concerning the continuously monitored Coastal basins, HYDSTRA (2007, previously HYDSYS, 1991, now known as *Hydstra/Times Series Data Management*, 2007, http://www.kisters.com.au) was initially used as a quality control tool to screen the basic rainfall and streamflow data for errors. Subsequently for specific events and using HYDSTRA, the following outputs were produced, *viz*, total rainfall, P; maximum rainfall depths, P_i, over selected time increments, i; volumes of total streamflow, Q; quickflow, Q_F and baseflow, Q_B by event and the associated streamflow response ratios Q_F/P (*quickflow response ratio*), Q_F/Q and Q_B/Q. The stream hydrograph separation was undertaken following the approach of Moore et al. (1986) whereby a filtering algorithm is applied to hydrographs and separates the flow into "quick", "base" (or "delayed") flows based on certain objective criteria. Despite such filter approaches not being physically based, they are considered better (see review by Furey and Gupta (2001)) than the earlier graphical approaches (e.g. Hewlett and Hibbert, 1967). The streamflow response ratios were then compared across land covers using box plots.

4.2.1. Linear model/ANOVA

The various measures of hydrologic response derived from individual rainfall–streamflow events (% quickflow of total flow, % delayed flow of total flow, % quickflow of total rain, % delayed flow of total rain) within the Coastal basins, were compared across basins using linear model/ANOVA in R Statistical software (www.r-project.org). Mean values and standard errors were generated for each variable for each of the three land-cover types. Subsequently Tukey multiple comparisons of means (HSD, Honestly Significant Differences) were undertaken and 95% family-wise confidence levels generated for the differences.

4.3. Time-series lag analyses – Coastal basins

We used a time series methodology previously developed and applied for an Australian rainforest basin (Bonell et al., 1979, 1981) to compare differences in time lags between rainfall and the stream hydrograph by event and between land-cover. The varying time lags which are evident in the rainfall–stream hydrograph peaks within and between basins (and associated different land covers) suggest that possibly there are different dominant stormflow pathways.

The most general rainfall–streamflow (simulation) model, as used by Bonell et al. (1979) is of the form:

$$Y_t = \alpha + \beta_0 X_t + \beta_1 X_{t-1} + \dots \beta_i X_{t-i} + \varepsilon_t \quad (1)$$

where X_t is the deterministic input series $\log_{10}$(rainfall + 1) and Y_t is $\log_{10}$(stream discharge + 1) at time t. The ε_t is the error, which can have an explicit auto-correlated error structure such as an AR1 of the form:

$\varepsilon_{t=\gamma}\varepsilon_{t-1} + \eta_t$ i.e., $\varepsilon_{t-\gamma}\varepsilon_{t-1} = \eta_t$.

Or following Bonell et al. (1981) we further extended Eq. (1)) as a prediction (or forecasting) model in the form:

$$Y_t = a + \sum b_k Y_{t-k} + \sum c_k X_{t-k} + \varepsilon_t \quad (2)$$

where X_t is the deterministic input series (rainfall) and Y_t is stream discharge at time t and Y_{t-k} and X_{t-k} are the rainfall and stream discharge at time $t-k$. Autocorrelation in the error term, ε_t is similarly treated as described above (under Eq. (1)).

The log transform attempts to achieve normality and homoscedasticity (i.e., homogeneity of variance) of the residuals.

4.3.1. The physical interpretation of the lagged Y_t and X_t variables

The lagged X_{t-k} represent the "direct effect" of rainfall on the response variable, i.e. the stream variable, in the same way as understood for the simulation model in Eq. (1)) (Bonell et al., 1981).

The physical interpretation for the inclusion of any lagged Y_{t-k} in the prediction model (linked with Eq. (2)) reflects the "cumulative effect" of rainfall throughout the storm event. Such cumulative effects are in the context of the requirement for an available soil water store to be filled to capacity in the upper soil layers before any *SOF* can occur on the higher hillslope transects; *and/or* to cause shallow water tables within the lower areas (e.g. riparian zones) to emerge at the surface and thus trigger *SOF* (the Dunne mechanism, Dunne and Black, 1970).

4.3.2. Model selection procedure

We used for model selection, a rigorous information – theoretic approach that estimates likelihood (the probability of the data given by different models) as well as penalizes for model complexity or number of covariates used (Burnham and Anderson, 1998; Johnson and Omland, 2004; Hobbs and Hilborn, 2006). Models were compared and selected using the Bayesian Information Criteria (BIC). Along with AIC (Akaike Information Criteria), the use of the BIC is now increasingly favoured over the traditional regression measures such as R^2 and p-values, especially in bio-physical applications (Kashyap, 1977; Schwarz, 1978; Johnson, 1999; Hobbs and Hilborn, 2006). We used the BIC values, p-values and hydrologic logic to identify and select the best models from amongst the candidate models.

It is well known that when lagged endogeneous variables are included in the model that OLS estimation should not be used except when autocorrelation in the residuals is not significantly different from zero (Davidson and MacKinnon, 1993; White, 2001; Young, 2011). With our inclusion of the AR1 error adjustment, as outlined above, addresses such concerns. Otherwise approaches such as the Standard Instrumental Variable estimation (Young, 2011), or generalised least squares with auto-correlated error structure (Ebbes, 2007), are recommended.

The final models were therefore fitted using the GLS function in R (Pinheiro and Bates, 2000). These functions fit a linear model using generalised least squares (not least squares) and maximum likelihood estimation of coefficients. The errors are allowed to be correlated if needed with an explicit autoregressive structure as described earlier and parameter estimates are done using log-likelihood approaches.

The choice of how many and which rainfall-lag covariates to include was determined by a parsimonious, statistically and hydrologically informed model selection process. This involved looking at the cross-correlation plot between discharge and the rainfall, and the use of BIC criteria to select a subset amongst rainfall lag and flow lag covariates. The final models were those with positive rainfall lag covariates and both positive and negative flow covariates. However, in the interests of parsimony and with no loss of fit, we retained negative flow covariates only if there were significant (based on *p*-values) corresponding rainfall lag variables at that lag or earlier with a positive coefficient. This pruning was done after ensuring that the signs of the important rainfall terms did not change when the model was simplified and that there was no major loss of goodness of fit.

The goal was to achieve the simplest regression model which could enable us to assess the relative influence of rainfall lag at various time-steps on streamflow response. Once the final model was reached, we checked for autocorrelation in the residuals. If needed autocorrelation was explicitly addressed by including an autocorrelated error structure, as outlined above, as part of the model definition. Comparisons between models with and without autocorrelation were done using likelihood-based diagnostics. Although there are autoregressive and moving average approaches depending on the structure, we chose the first order autoregresive as the most parsimonious choice consistent with the error structure.

We recognize that interpretation of multiple regression coefficients will be difficult when lagged variables are included and we have used the regression models to confirm the interpretation of the cross-correlations lags rather than emphasis on the coefficients. In summary, the steps taken in the work was first to produce cross-correlations between rain and streamflow by storm event for the each basin/land cover type for the detection of time lags followed by regression analyses described above to further strengthen inference on rainfall–streamflow dynamics. Subsequently a brief comparison between the simulation model (based on Eq. (1)) and the prediction model (Eq. (2)) results will be made.

4.3.3. Comparisons between the Coastal basins and NE Australia

The environmental circumstances in the present study are very different from the NE Queensland, Australia work in terms of the synoptic climatology and rainfall characteristics. On the other hand, both the Australian and the current study basins share a seasonal concentration of rainfall and thus have in common near saturated soil profiles at such times (Bonell et al., 1981, 1998; Venkatesh et al., 2011). In addition, the permeability (depth) profiles (discussed below) have some similarities between the two geographic areas, especially the Forest (NF). These suit the application of the time series model as well as being a comparative study.

5. Results

5.1. The soil hydraulic conductivity profiles

The K_{fs} (depth) profiles as shown in Fig. 3 follow the description previously outlined by Bonell et al. (2010). The Forest profiles are typical of the 'Acrisol-type' (Elsenbeer, 2001; Chappell et al., 2007) which encourages a subsurface stormflow, *SSF* dominant pathway (supplemented by saturation excess overland flow, *SOF*) on hillsides (Elsenbeer, 2001; Chappell et al., 2007). Further there is clear reduction in K_{fs} at the surface when concerning the Degraded Forest and the Acacia plantations. Such a reduction in K_{fs} is confined to the upper 0.2 m layer of soil in line with the description for other sites in the study area (Bonell et al., 2010) as well as findings elsewhere (Hamza and Anderson, 2005; Zimmermann et al., 2006; Zimmermann and Elsenbeer, 2008). The occurrence of *IOF* is possible at such sites. The same effect of land-cover on K_{fs} is consistently observed even in the Malnaad basins (Fig. 3b and c) in spite of differences in soil type.

With the possible exception of one basin each at respectively Kodigibail (DF1) and Vajagar (DF1), the subsoil K_{fs} overall remains comparatively high and in excess of 10 mm h^{-1} across the remaining sites (Fig. 3). The high subsoil K_{fs} must contribute to the rapid translation of the wetting fronts of soil moisture (Venkatesh et al., 2011). It should be noted that the different soil groups are represented across land-covers in Vajagar (Table 1) whereby the Forest and the Degraded Forest are underlain respectively by Laterite and Red. But despite the Red soil group being the more inherently permeable, the impact of long-term forest degradation has reduced the surface K_{fs} (Bonell et al., 2010).

5.2. The double mass curves ($P_{cum,}$ Q_{cum})

5.2.1. The Kodigibail and Vajagar Up-Ghat basins

The double mass curves are initially shown for the Up-Ghat (NF1, DF1, DF2, AC1, AC2, AC3) basins at Kodigibail (Fig. 4a–c). Despite the varying period of record (Fig. 4), the different basin areas and the variation in total rainfall (i.e. 2252–3663.4 mm), the rank order in percentage (%) of rainfall emerging as streamflow between the basins remains consistent. The lowest streamflow occurs from the Forest and the highest from the Degraded Forest. The Acacia Plantations occupy an intermediate position. For 2004 and 2005 when higher rainfalls occurred, the proportion of streamflow increases across all land covers but is particularly higher in the Acacia plantations, i.e. AC 1 to 3.

The above trends in streamflow production continues with the Vajagar NF1 and DF1 basins (Fig. 5a and b). The Forest covered basin consistently supplies lower streamflow when compared to the Degraded Forest, and these circumstances occur despite differences in soil type and K_{fs} between these basins (Table 1, Bonell et al., 2010).

5.2.2. The Coastal basins (Areangadi)

There is a subtle difference between the Coastal Basins and the Up-Ghat basins. Towards the end of the summer monsoon, stream discharge in the Forest continues whereas flow in both the Acacia and Degraded Forest basins has terminated (Fig. 6a and b). The larger basin area of the Forest is likely be one of the reasons why such a continuation of stream discharge is favoured (Table 1). Thus there is a change in the rank order in percentage (%) of rainfall emerging as streamflow, i.e. DF > NF > AC. However for the bulk of the rainy season, the rank order of streamflow is DF > AC > NF and this is consistent with the Up-Ghat basins.

5.2.3. Comparison between the Up-Ghat and Coastal basins

Overall the double mass curves indicate that there is remarkable consistency in the rank order of basin streamflow yields despite varying monsoon rainfall totals and basin areas. Further the percentages (%) of rainfall emerging as streamflow were similar between years except for 2005 in the Up-Ghat basins. For the latter, all land covers had higher streamflow coefficients in response to the higher summer monsoon rainfall total of 3663.4 mm.

Subsequently the basins identified with the three respective land covers were grouped together across the two geomorphological zones. Overall NF converted a mean of $28.4 \pm 6.41_{\mathrm{stdev\%}}$ of rainfall into total streamflow in comparison to $32.7\_ \pm 6.97_{\mathrm{stdev\%}}$ in AC and $45.3 \pm 9.61_{\mathrm{stdev\%}}$ in DF.

5.3. Hydrologic dynamics across land-covers within the Coastal Basins

Focus is now confined to the Coastal basins where continuous records are available to apply HYDSTRA for specific rain events and the application of the ANOVA to ascertain any significant differences in selected HYDSTRA variables. Later for three rain events,

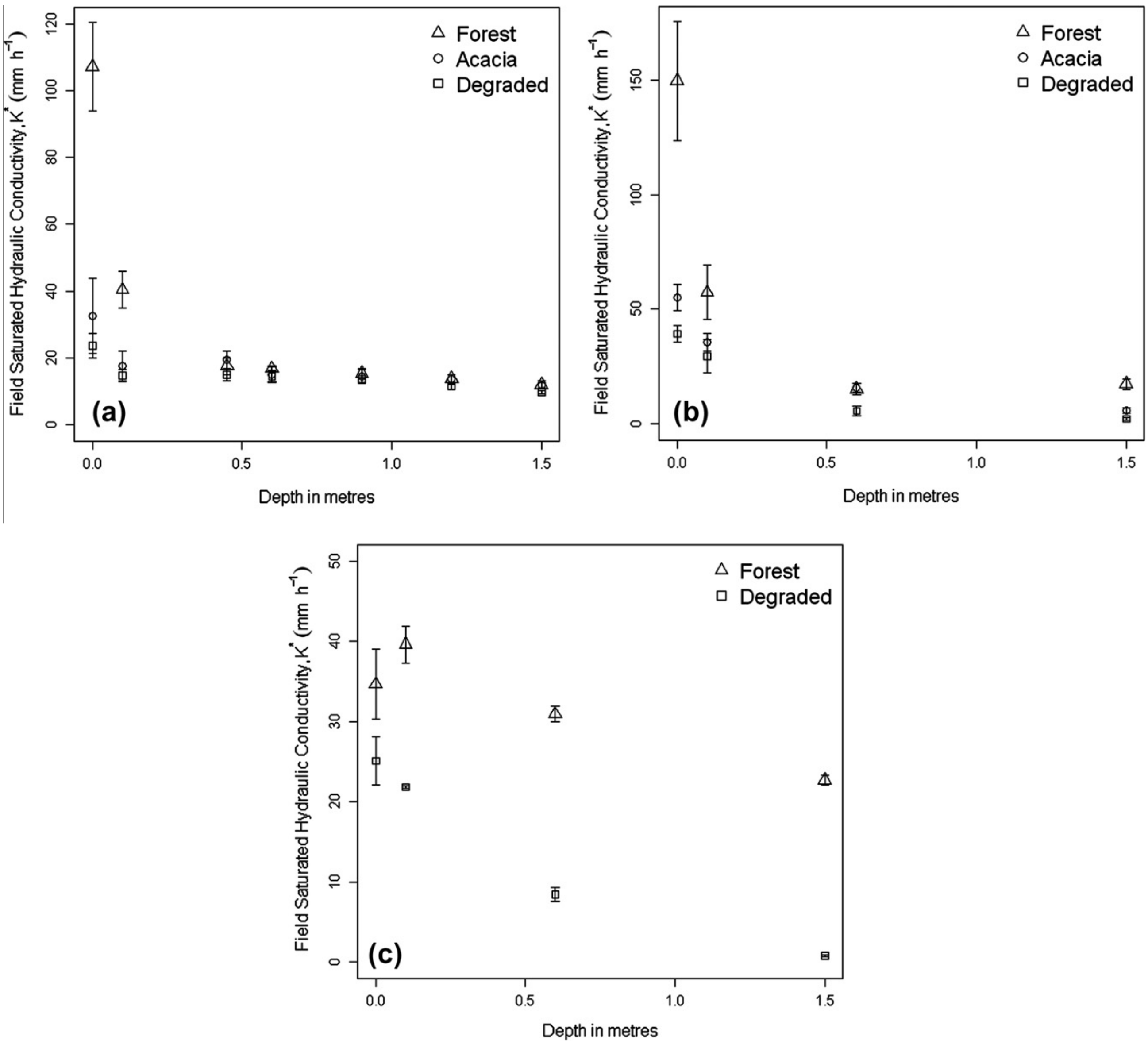

Fig. 3. The field saturated hydraulic conductivity K_{fs} and standard deviation against depth (z) for the three sites: (a) Areangadi, (b) Kodigibail and (c) Vajagar.

the results from the application of time series-lag regression analyses will be examined.

5.3.1. A comparison of the storm rainfalls and streamflow characteristics for selected events in the Coastal basins

A summary of the hydrograph separation results for the above storms using HYDSTRA are presented in Table 4 and the response characteristics also summarised as box plots (Fig. 7). It should be noted that when concerning Table 4, the Event numbers are the same rain storms but the rainfall totals and event definition (start/end times of quickflow) differs between the three basins due to the storm hydrograph separation procedure, as followed by HYDSTRA. Further within Table 4, there are six proportions exceeding 100% when concerning Q_t/P and Q_f/P, which at face value are physically unrealistic, and four of these are associated with the NF basin. The same issue was noted for a tropical forest basin towards the end of a long duration monsoonal event in north east Australia (Bonell et al., 1991 reproduced in Bonell (2010)). A causal factor put forward to explain such proportions (>100%) is the delayed release of groundwater from subsurface stores of large capacity (Bonell et al., 1991). The latter explanation is also offered here linked with the fissured hydrogeology.

Table 4 also shows the rain events that were selected for later application of the time series analyses where rain–streamflow records were complete. Moreover the nature of hydrograph separation using HYDSTRA causes the duration of quickflow (and thus in some cases, total rainfall) not to be identical across the land covers within a particular event. Further for the smaller storms, the Forest basin proved less sensitive in the streamflow response compared with the other two land covers. That is, HYDSTRA did not detect any streamflow peak to apply hydrograph separation. This aspect also contributed to the uneven sample sizes in Table 4.

Storm totals can be as high as 653 mm but the durations for the larger events (>130 mm) commonly vary between ~2–9 days. By contrast, the maximum 30 min and 1 h rain intensities are comparatively low (equivalent hourly rates $\leqslant$40 mm h^{-1}) except for one Event shown as 3NF/4AC/6DF (maximum 30 min, 72.5 mm h^{-1}) in Table 4. All these rain characteristics fall in line with the descriptions of Putty and co-workers (Putty et al., 2000; Putty and Prasad, 2000a,b; Putty, 2006).

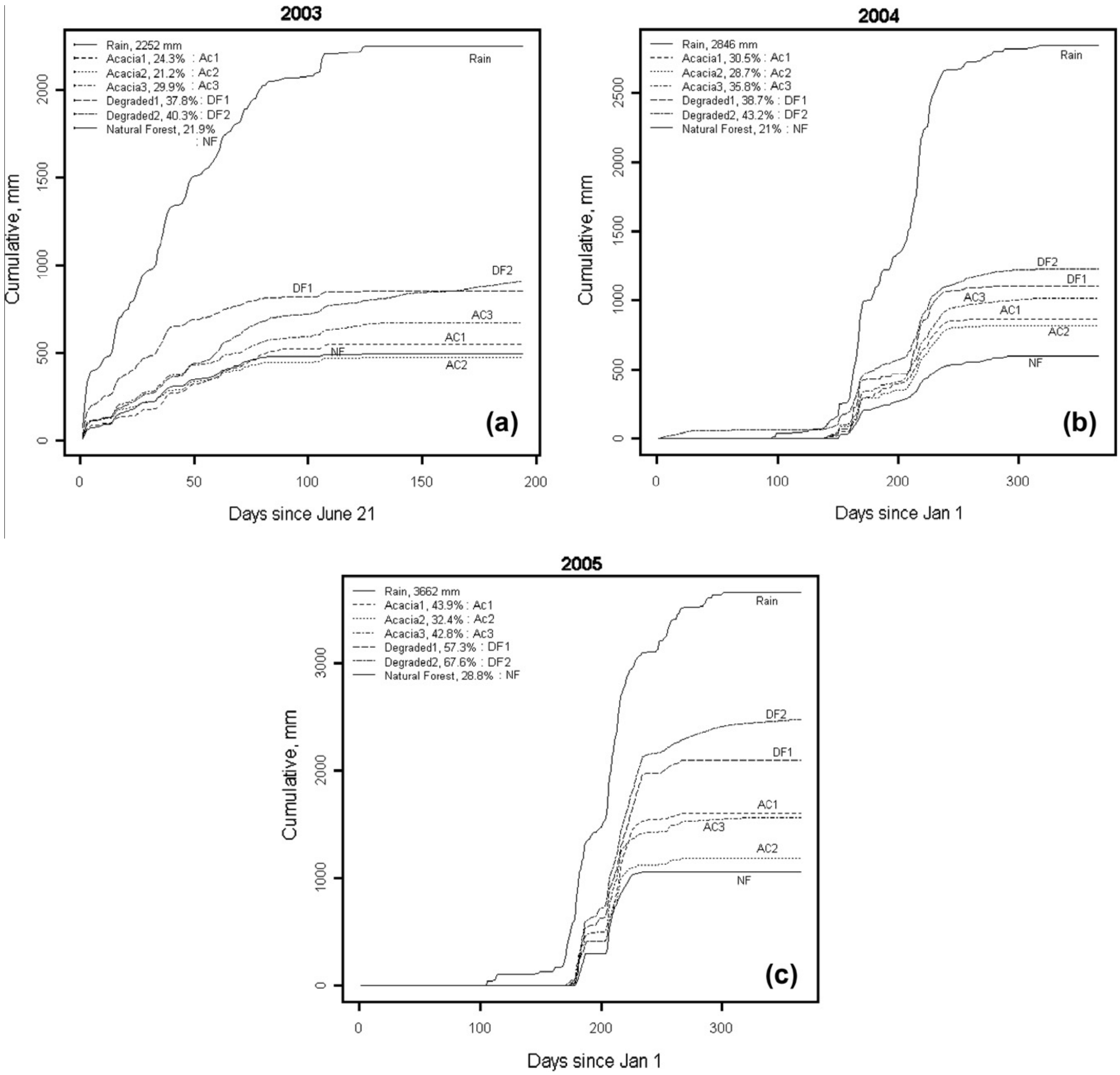

Fig. 4. The double-mass plots, P_{cum} (Q_{cum}), for the Up-Ghat Kodigibail basins for the years 2003 (a), 2004 (b) and 2005 (c).

The proportion of total flow (Q) as quickflow (Q_F) (Fig. 7a) shows a clear trend. By far the highest Q_F/Q percentage (median in excess of 90%) emanates from the DF basin (Table 4, Fig. 7a), thus suggesting overland flow occurrence and minimal contributions from deep groundwater (as shown from the inverse % for Q_D, Table 4 and Fig. 7b). The Forest has the lowest proportion of Q being represented by Q_F (and in turn greater than 50% of Q_D, Table 4) whilst the median of the Acacia Plantation occupies an intermediate ranking (Fig. 7). As expected, the highest quickflow response ratios (Q_F/P up to 90% in Table 4, Fig. 7c) are associated with the Degraded Forest in line with the *a priori* inferred, dominant *IOF* stormflow pathway (Bonell et al., 2010). On the other hand, there are surprisingly only marginal differences between the box plots (Fig. 7c) for the Acacia and the Forest with the middle inter-quartiles in the 20–40% range of Q_F/P. This suggests that apart from surface changes in K_{fs} between land covers, there could be other influences controlling storm streamflow which will be examined below.

5.3.2. The means and standard errors of the hydrologic response characteristics of the storm events

When concerning Table 5, there is a clear trend for Q_f/Q_t, Q_d/Q_t and Q_d/P with the Forest having the expected lowest (i.e., Q_f/Q_t) and highest percentages (i.e., Q_d/Q_t, Q_d/P). The converse applies to the Degraded Forest with the Acacia basins occupying an intermediate rank position. However when concerning the quickflow response ratio (Q_f/P), a different ranking exists with a surprising reversal between the Forest and Acacia. Thus the lowest percentage exists for the Acacia basin whilst the Forest occupies an intermediate ranking. The highest Q_f/P for the Degraded is what would be expected. On the other hand, the standard errors for Q_f/P are much higher than for the other response variables and so caution in interpretation of this particular ranking across land covers is required.

The above point is emphasised in the box plots (Fig. 7). When concerning the Forest for Q_f/P, there is greater dispersion and more

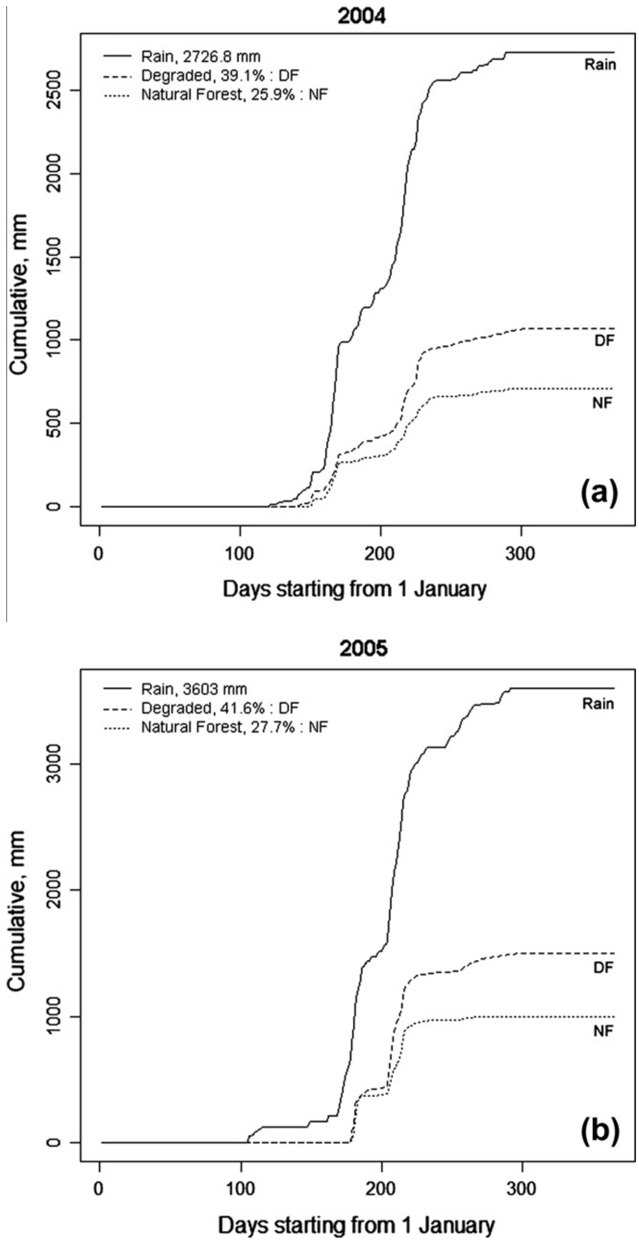

Fig. 5. The double-mass plots, P_{cum} (Q_{cum}), for the Vajagar Up-Ghat basins for the years 2004 (a) and 2005 (b).

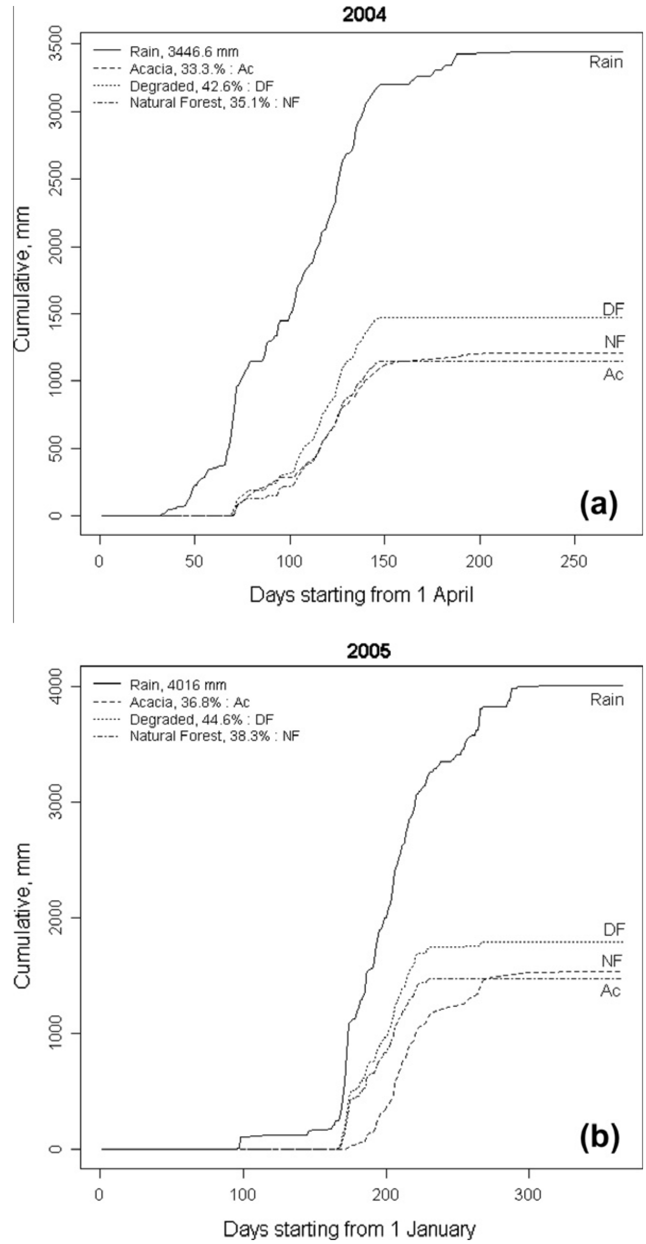

Fig. 6. The double-mass plots, P_{cum} (Q_{cum}), for the Coastal basins (Areangadi) basins for the years 2004 (a) and 2005 (b).

specifically a greater spread of the lower quartile. Moreover the medians between Forest and Acacia are not that radically different. Furthermore Fig. 7 also highlights there is greater dispersion for other response variables (Q_f/Q_t, Q_d/Q_t) for Acacia which are not apparent from the standard errors in Table 5. The same comment applies to Q_d/P for the Forest.

5.3.3. The application of linear model/ANOVA

Table 6 provides further insights into the differences in hydrologic response. There are sizeable differences in % means (15–40) between all basin pairings across the four response variables, with the exception of $Q_d/P\%$ between Acacia and Degraded.

With the exception of Q_f/P, there is a very high certainty of difference based on adjusted p between the Forest and Degraded basins for the other response variables. There is also a high certainty of difference between the Forest with the Acacia. Excluding the $Q_d/P\%$ as above, adjusted p indicates a high certainty of difference between the Acacia–Degraded also exists when concerning $Q_f/Q_t\%$ and $Q_d/Q_t\%$.

It is pertinent that the adjusted p show that there is a low to very low certainty of differences between all combinations of basin pairings when concerning Q_f/P.

5.3.4. Time series analysis: Rain–streamflow cross-correlations

Data connected with the storm events *1DF/1AC/1NF (16–25 June 2005)*, No. *3DF/2AC/2NF* 2 (*29 June–2 July 2005*) and *9DF/8AC/4NF* (*19–26 July 2005*) (Table 4) were available for all three basins to enable a comparison of the rain–streamflow responsiveness. For reasons of simplification, the above storms will be referred from hereon as respectively, Event 1, 2 and 3.

Two of these events (*Event 1*, range 653–656.5mm; *Event 3*, range 403–430 mm, Table 4) were typical of the long duration storms associated with the SW monsoon. Further the respective maximum 30 min and 1 h rain intensities for the above storms (40 mm h^{-1}, 34.3 mm h^{-1}; 38.3 mm h^{-1}, 32 mm h^{-1}, Table 4) were

Table 4
The outputs using HYDSTRA for the Coastal Basins - rainfall characteristics and hydrologic response variables.

Event	Rainfall characteristics				Q_t/P	Q_f/Q	Q_f/P	Q_d/P	Q_d/Q
	Duration (days)	Max.30 min (mm h^{-1})	Max.60 min (mm h^{-1})	Total P (mm)	%	%	%	%	%
Degraded									
Event 1DF[a]	8.68	40.0	34.3	653.0	70.26	78.33	55.03	15.23	21.67
Event 2DF	1.63	14.2	9.2	33.0	39.24	93.51	36.70	2.55	6.49
Event 3DF[a]	2.88	16.7	13.3	71.0	84.54	94.32	79.73	4.80	5.68
Event 4DF	4.33	22.5	16.5	135.5	82.12	94.00	77.19	4.93	6.00
Event 5DF	1.17	5.8	3.5	13.0	32.15	92.82	29.85	2.31	7.18
Event 6DF	1.96	72.5	47.2	219.8	32.31	92.93	30.02	2.28	7.07
Event 7DF	3.46	40.0	33.3	70.0	105.90	85.71	90.77	15.13	14.29
Event 8DF	3.08	23.3	18.3	51.0	81.27	90.54	73.59	7.69	9.46
Event 9DF[a]	5.75	38.3	32.0	403.2	62.81	78.43	49.27	13.55	21.57
Acacia									
Event 1AC[a]	9.32	40.0	34.3	656.5	60.13	64.51	38.79	21.34	35.49
Event 2AC[a]	2.71	16.7	13.2	71.0	47.89	92.91	44.49	3.39	7.09
Event 3AC	4.75	22.5	16.4	189.5	64.95	86.44	56.14	8.81	13.56
Event 4AC	1.63	72.5	47.1	175.0	26.38	89.80	23.69	2.69	10.20
Event 5AC	3.04	40.0	33.1	121.5	36.93	69.27	25.58	11.35	30.73
Event 6AC	1.42	6.7	5.0	8.0	22.50	28.89	6.50	16.00	71.11
Event 7AC	1.54	23.3	18.3	42.5	37.91	56.36	21.36	16.54	43.64
Event 8AC[a]	6.10	38.3	31.7	402.7	50.64	72.44	36.69	13.96	27.56
Natural Forest									
Event 1NF[a]	9.32	40.0	34.3	656.5	5.70	47.90	2.73	2.97	52.10
Event 2NF[a]	2.71	16.7	13.2	71.0	141.96	75.49	107.17	34.79	24.51
Event 3NF	5.71	72.5	47.1	232.0	69.18	65.19	45.10	24.08	34.81
Event 4NF[a]	7.92	38.3	31.7	429.9	59.37	47.37	28.12	31.25	52.63
Event 5NF	7.75	24.2	15.2	183.9	88.83	52.38	46.53	42.29	47.62
Event 6NF	17.33	30.0	22.8	188.0	67.62	38.14	25.79	41.83	61.86
Event 7NF	9.13	25.0	15.0	157.5	51.43	41.30	21.24	30.19	58.70
Event 8NF	2.29	13.3	10.6	37.1	39.35	37.19	14.64	24.72	62.81
Event 9NF	7.50	23.3	16.9	84.5	162.15	67.76	109.87	52.28	32.24

Note: P – Total precipitation by total storm event (mm), Q – Total stream discharge (mm), Q_f – quickflow (mm), Q_d – delayed flow (mm).
[a] Storms used in the time series analyses.

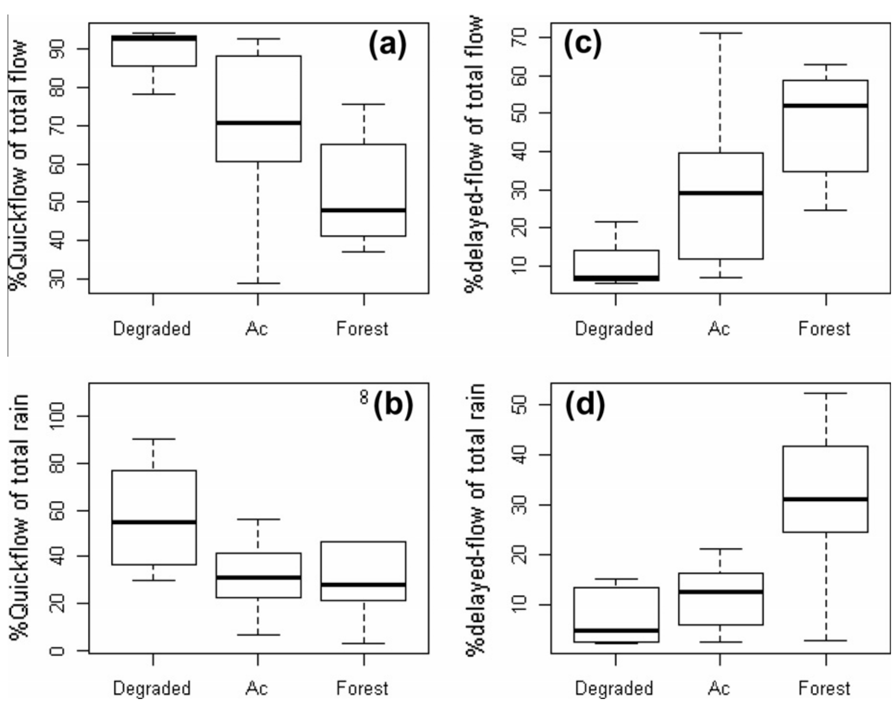

Fig. 7. Box plots showing for storm events (Table 4) occurring in the Coastal basins using HYDSTRA: the % quickflow, Q_F/Q (a),% delayed flow (baseflow)/total flow, Q_B/Q (b),% quickflow/total rain, Q_F/P (c) and % delayed flow/total rain, Q_{DF}/P (d).

also typical of the ranges cited by Putty and co-workers (Putty et al., 2000; Putty and Prasad, 2000a,b; Putty, 2006). Event 2 by contrast was weaker with a total rainfall of 33.0mm and maximum 30 min and 1 h rain intensities of only 14.2 mm h^{-1} and 9.2 mm h^{-1} respectively. Further Event 1 was the first major event during the opening stages of the summer monsoon. The other two events were typical of those that occur once basin antecedent soil moisture attains optimal wetness, similar to the description of Venkatesh et al. (2011) for the Kodigibail basins.

The cross-correlations for these events are shown respectively in Figs. 8–10 and one lag unit represents a time increment of 0.6 h. There is some consistency in the distribution of peak coefficients for both the Degraded Forest and the Acacia Plantation in spite of the noted differences in rainfall characteristics. The highest cross-correlations occur with short time lags (0–2 time units) which suggest the existence of comparatively a faster delivery mechanism of stormflow to the stream hydrograph. Further secondary peaks are also are shown, most notably in the AC basin, which vary between lag 20 and lag 60 (12–36 h) which could be reflecting a slower stormflow pathway.

The Forest by contrast shows less consistency between the three storms in the distribution of peak lags. Multiple peak lags are shown for Event 1 from lag 1 (which has the highest cross-correlation coefficient) up to ~lag 75 (45 h) which could be due streamflow emanating from multiple sources and pathways during the opening phase of the monsoon. For Events 2 and 3 more distinct peak lags are evident, although in the former the coefficients take the form of a flatter peak ~lag 30–40 (18–24 h). For Event 3 when more optimal, catchment wetness exists, the peak lag is shorter and more distinct at ~lag 15 (8 h).

Thus overall the Forest is much less responsive when compared to the other land covers and much slower (multiple) pathways of streamflow are indicated.

5.3.5. Time series: Lag regression analysis

Table 7 summarizes the outputs using the simulation model (Eq. (1)) and Figs. 8–10 include the summary of the forecasting/prediction model (Eq. (2)).

For the Forest there are multiple rain lags, and the overall description for the cross-correlation coefficients above is reflected again in these results. A series of longer response delays occur when compared to the other two land covers which suggest multiple contributions from subsurface sources. For Events 1 and 2 there is also shorter response at lag 1, c.f., the cross-correlation, which could be a secondary contribution from the riparian zone which exists in this basin. It is pertinent that the zero time lag for rainfall is never selected for the Forest but almost always for the other two land covers.

By contrast the Degraded Forest and Acacia either show two groups of significant rainfall variables respectively that favour either short and longer lags or short rain lags only (i.e., Event 1, DF; Event 2, Acacia). These results again confirm the trends as shown in Figs. 8–10 for the cross-correlations. The inclusion of short-term rainfalls (in most cases at rain RF_{t-0}) with a separate group of longer rain lags infers the juxtaposition of a more rapid pathway of stormflow delivery with the slower, subsurface sources of streamflow characterised by the Forest.

Table 5
The means and standard errors of the hydrologic response characteristics for the storm events in the Coastal basins.

	Catchment type		
	Degraded	Acacia	Natural forest
$\frac{Qf}{Qt}$, %	$89.0 \pm 7.15_{se}$	$70.1 \pm 5.20_{se}$	$52.5 \pm 7.15_{se}$
$\frac{Qf}{P}$, %	$58.0 \pm 13.58_{se}$	$31.7 \pm 9.88_{se}$	$44.6 \pm 13.58_{se}$
$\frac{Qd}{Qt}$, %	$11.0 \pm 7.15_{se}$	$29.9 \pm 5.20_{se}$	$47.5 \pm 7.15_{se}$
$\frac{Qd}{P}$, %	$7.6 \pm 4.67_{se}$	$11.8 \pm 3.40_{se}$	$31.6 \pm 4.67_{se}$

Notes: P = Precipitation (mm), Q_f = total quick flow (mm), Q_t = total streamflow (mm), Q_d = delayed flow (mm), se = standard error.

5.3.5.1. Brief comparison with the simulation model results.

Figs. 8–10b–f summarize the model fit to the stream hydrograph and the corresponding outputs using Eq. (2)).

Overall when concerning the selected rain variables, the trends as outlined above are reflected again in the equations associated with this model. However with the introduction of the "cumulative effect" of previous rainfalls on regolith available storage capacities (in the form of previous runoff variables or lagged Y_{t-k}) reduces the number of rainfall lags and makes the previous interpretations more clear. The importance of antecedent storage capacities (i.e., the inclusion of several lagged RO_{t-k}) is also more evident in this study and especially for the Forest than when compared to NE Queensland rainforest (Bonell et al., 1981). On the other hand, for the Degraded Forest (Event 1) has a very simple model, not too different from those reported in the Australian study. Only two short-term rainfall variables are significant, i.e., RF_{t-0} and RF_{t-1} as well as RO_{t-1}. In the absence of riparian zone, this result suggests *IOF* occurrence (as well as *SOF*) on the hillslopes which is controlled by short-term, changes in rainfall intensities. Similarly remarks apply to Event 3 for DF and also Event 2 for Acacia except both equations also incorporate a longer rainfall lag as well.

6. Discussion

6.1. Land cover change impacts on the basin water yield and storm runoff hydrology

When concerning total streamflow yield, overall the double mass curves, Q_{cum} (P_{cum}), at the seasonal time scale show that the highest streamflow yields are in the order DF > AC > NF for both the Coastal and Malnaad (Up-Ghat) basins. The same conclusions emerge when the records from both the Malnaad and Coastal basins are combined. Despite the caution expressed earlier in terms of the problems of using small area basins (e.g., subsurface exchange of groundwater across basin boundaries defined by surface topography), such consistency in rain–streamflow trends is encouraging. Nonetheless because total evapotranspiration was not directly measured on site to factor that component into a water balance, these double mass curves *per se* do not provide conclusive

Table 6
Tukey's multiple comparison differences of means for the Coastal storm events along with lower and upper 95% bounds and adjusted *p*-values.

	Difference	Lower 95%	Upper 95%	p Adjusted
Q_f/Q_t%				
Degraded–Acacia	18.88	0.97	36.78	0.0375
Natural Forest–Acacia	−17.55	−35.45	0.35	0.0554
Natural Forest–Degraded	−36.43	−53.80	−19.06	0.0000
Q_f/P%				
Degraded–Acacia	26.36	−7.63	60.36	0.1498
Natural Forest–Acacia	12.92	−21.08	46.92	0.6138
Natural Forest–Degraded	−13.44	−46.42	19.54	0.5717
Q_d/Q_t%				
Degraded–Acacia	−18.88	−36.78	−0.97	0.0375
Natural Forest–Acacia	17.55	−0.35	35.46	0.0554
Natural Forest–Degraded	36.43	19.06	53.80	0.0001
Q_d/P%				
Degraded–Acacia	−4.15	−15.86	7.55	0.6529
Natural Forest–Acacia	19.84	8.13	31.55	0.0009
Natural Forest–Degraded	23.99	12.64	35.35	0.0001

Notes: P – Total precipitation by total storm event (mm), Q_t – total stream discharge (mm), Q_f – quickflow (mm), Q_d – delayed flow (mm).

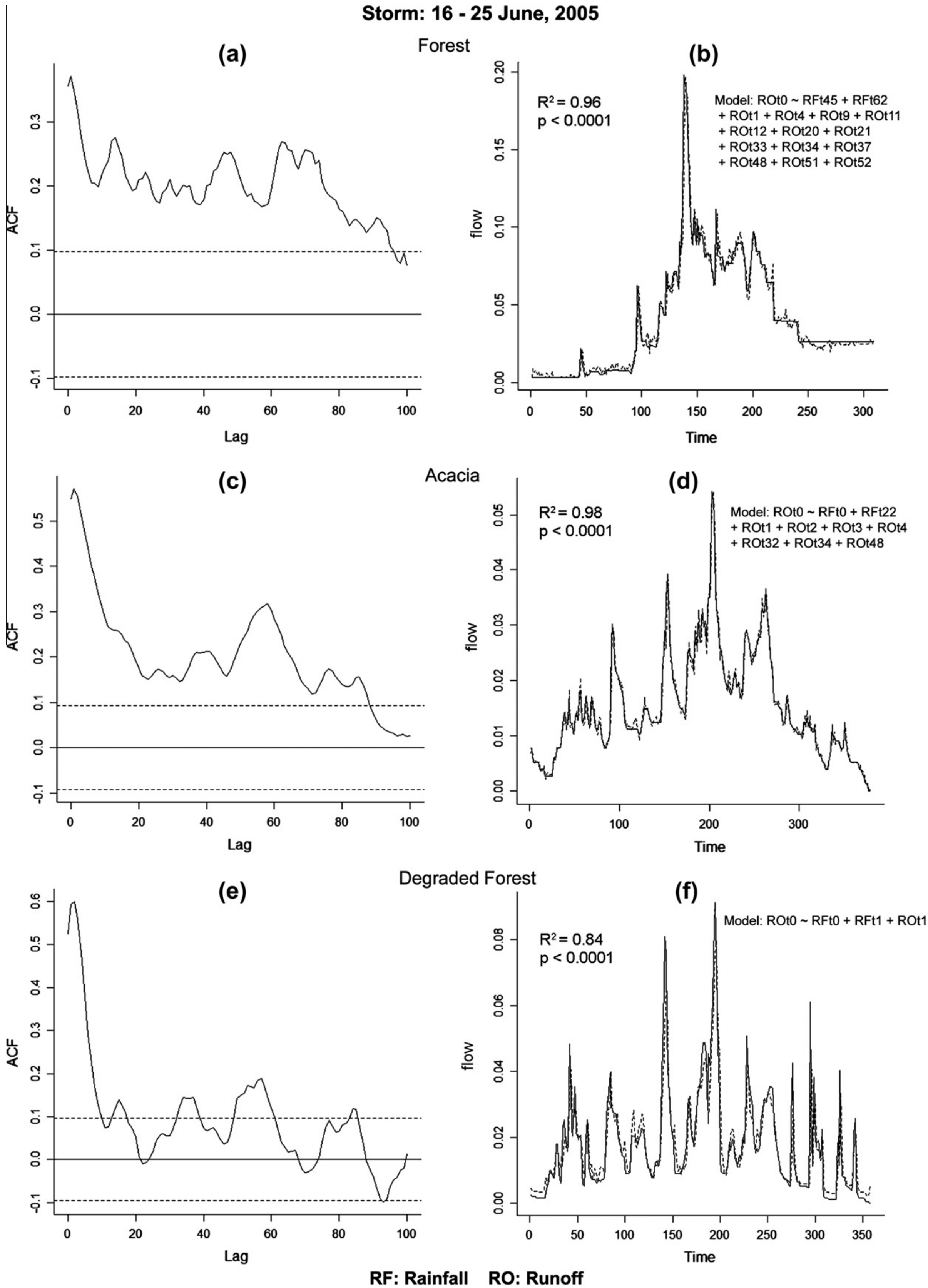

Fig. 8. Coastal basins: The cross-correlation coefficients and time series-regression models (Eq. (2)) for the Forest (NF1), Acacia (AC1) and Degraded Forest (DF1) for the Event 1 (16–25 June 2005). *Note:* 1 lag unit is equal to 0.6 h and the time is expressed in lag units.

proof that overland flow progressively becomes a more dominant stormflow pathway in the reverse basin order NF < AC < DF.

On the other hand, there is also additional support for overland flow probably becoming more dominant, when concerning the Q_F/

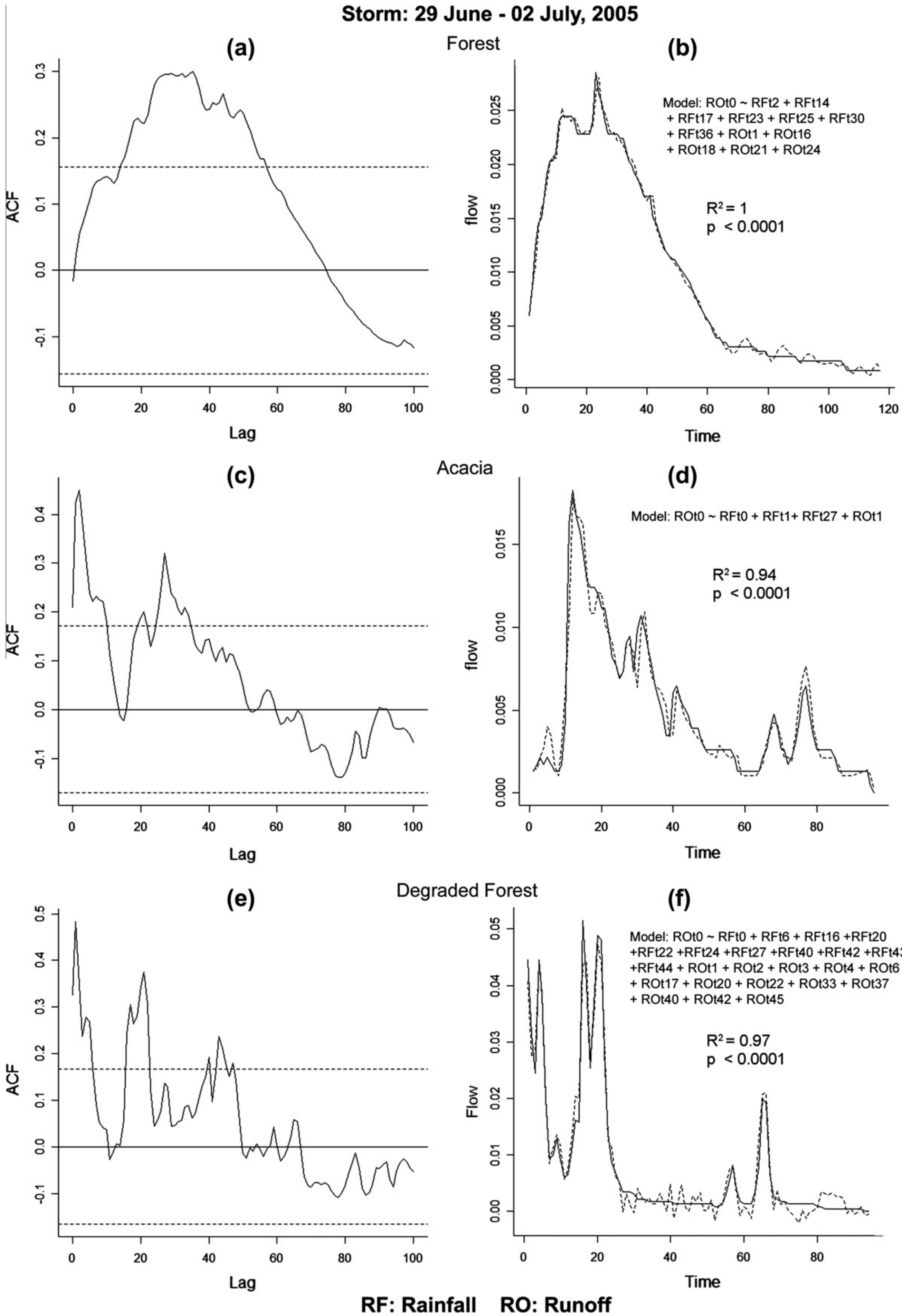

Fig. 9. Coastal basins: The cross-correlation coefficients and time series-regression models (Eq. (2)) for the Forest (NF1), Acacia (AC1) and Degraded Forest (DF1) for the Event 2 (29 June 2005–2 July 2005). *Note:* 1 lag unit is equal to 0.6 h and the time is expressed in lag units.

Q ratio by storm event from HYDSTRA for the Coastal basins. For most events, there are much higher values for this runoff ratio for DF and AC, and again, all are in the same rank order NF < AC < DF as for the seasonal double mass curves. Even more

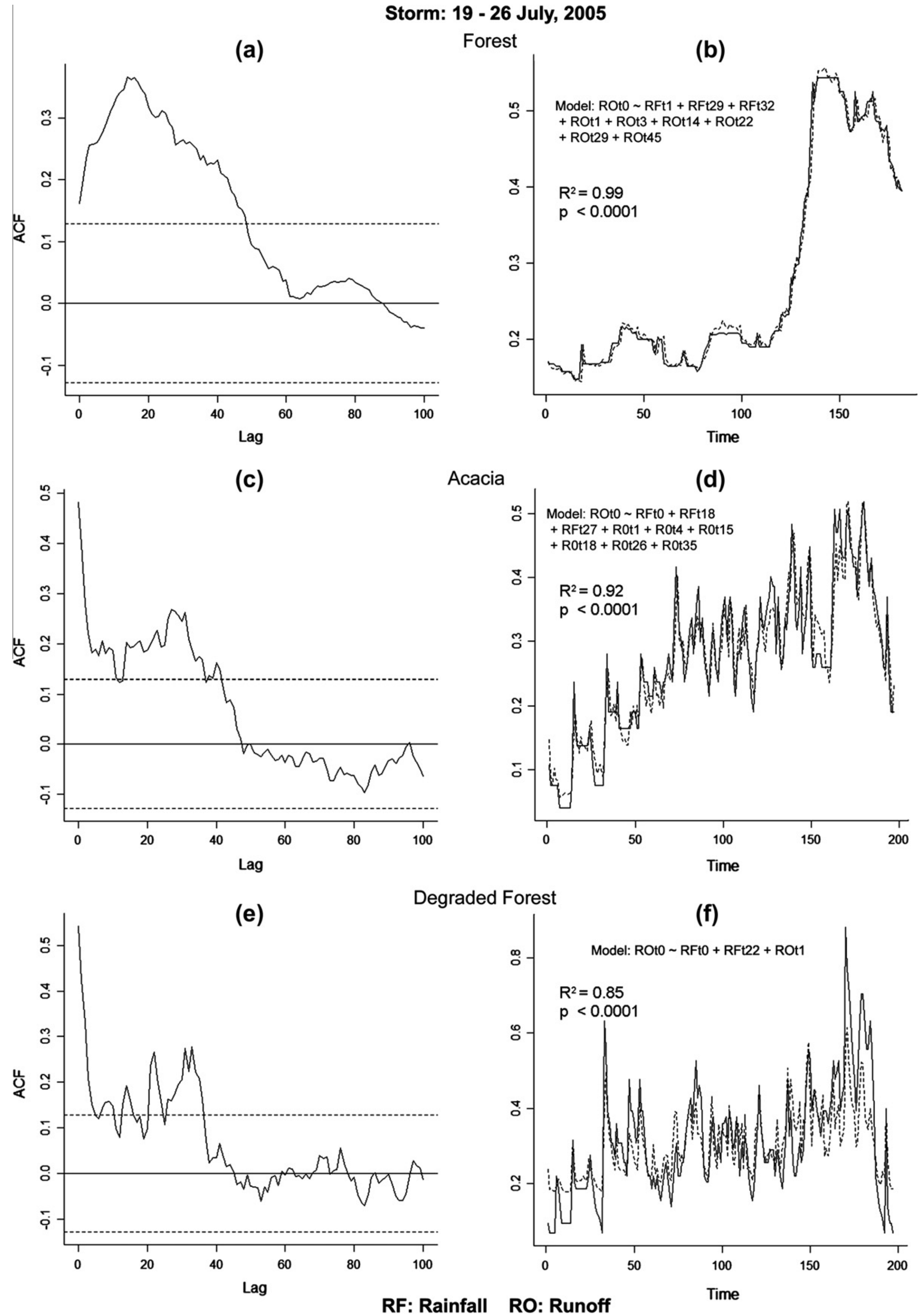

Fig. 10. Coastal basins: The cross-correlation coefficients and time series-regression models (Eq. (2)) for the Forest (NF1), Acacia (AC1) and Degraded Forest (DF1) for the Event 3 (19–26 July 2005). *Note:* 1 lag unit is equal to 0.6 h and the time is expressed in lag units.

remarkable is that the Q_F/Q can exceed 90% in the DF basin in selected events. By contrast the Q_F/P ratios are less consistent, with the Acacia rather than the Forest having the lowest mean value. The larger area of the Forest basin may be a cause for this inconsis-

Table 7
Streamflow–rainfall regression model terms using rain lag variables.

Event	Model Regression		
	Forest	Acacia	Degraded
Event 1; 16–25 June	Runoff = rainfallt1 + rainfallt14 + rainfallt36 + rainfallt48 + rainfallt63 + rainfallt74	Runoff = rainfallt0 + rainfallt1 + rainfallt3 + rainfallt26	Runoff = rainfallt1 + rainfallt2
Event 2; 29 June – 02 July	Runoff = rainfallt1 + rainfallt4 + rainfallt6 + rainfallt9 + rainfallt11 + rainfallt13 + rainfallt15 + rainfallt17 + rainfallt19 + rainfallt20 + rainfallt22 + rainfallt24 + rainfallt26 + rainfallt27 + rainfallt28 + rainfallt29 + rainfallt30 + rainfallt31 + rainfallt32 + rainfallt33 + rainfallt34 + rainfallt35 + rainfallt36 + rainfallt37 + rainfallt38 + rainfallt40 + rainfallt42 + rainfallt44 + rainfallt46 + rainfallt48 + rainfallt50 + rainfallt51 + rainfallt52 + rainfallt53 + rainfallt55 + rainfallt56 + rainfallt58 + rainfallt60	Runoff = rainfallt2 + rainfallt0	Runoff = rainfallt0 + rainfallt1 + rainfallt4 + rainfallt6 + rainfallt16 + rainfallt17 + rainfallt20 + rainfallt22 + rainfallt40 + rainfallt43 + rainfallt45
Event 3; 19–26 July	Runoff = rainfallt11 + rainfallt14 + rainfallt16 + rainfallt19 + rainfallt36 + rainfallt38 + rainfallt43	Runoff = rainfallt0 + rainfallt1 + rainfallt25 + rainfallt40	Runoff = rainfallt0 + rainfallt1 + rainfallt2 + rainfallt22 + rainfallt34

tency. On the other hand, the statistical analyses showed that there was a low to very low certainty in difference between the three basins when concerning Q_F/P. When concerning the remaining hydrologic response variables, there is mostly a high level of certainty in statistical differences between pairs of basins (land cover types).

The corresponding delayed flow response ratios, Q_D/P clearly show the much larger Q_D yield as a proportion of event precipitation from the Forest in contrast to the DF and AC basins. The same trend applies to Q_D/Q.

Furthermore the more responsiveness of rain–streamflow time lags from the time series analyses provide further support for a faster dominant storm flow pathway being associated with the DF and AC basins. The regression equations for both the prediction and simulation models are much simpler (notably for the Acacia Plantation) and favour short time lags. Moreover the structure of these regression equations are not too dissimilar from those reported from the NE Queensland tropical forest where shallow *SSF* (supplemented by *SOF*) was the dominant stormflow pathway (Bonell et al., 1979,1981). On the other hand, these results do not give any indication of the spatial and temporal extent of this dominant stormflow pathway. Further the time unit of 0.6 h remains comparatively coarse compared with other tropical hillslope hydrology studies (e.g., reviewed in Bonell (2004)) and even some humid temperate work (Dunne, 1978; Anderson and Burt, 1990) to suggest that the responsiveness of these disturbed basins are not that radically different from many other studies.

It is clear that the impacts of multi-decadal to century time scale degradation or use have reduced surface permeability and so infers that there has been some redirection of the dominant stormflow pathways from previously *SSF* and vertical percolation (Forest) in favour of enhanced *IOF* in the Coastal DF and AC basins. Consequently despite some recovery in surface K_{fs} in the Acacia plantations, the impacts of long-term degradation *a priori* still persist as a 'memory' in the streamflow response. In China, Zhou et al. (2001) also noted the continued retention of more compacted areas in a basin which had previously undergone forestation over more than 20 years previously.

Land cover is thus an important control on streamflow despite two different soil types (Red, Laterite) being represented in the study. The higher volumes of seasonal streamflow and quickflow by event from long-term degradation supports the conclusions from the previous hydraulic conductivity survey that enhanced *IOF* occurs (supplemented by *SOF*) (Bonell et al., 2010). Similar conclusions were also suggested elsewhere (Chandler and Walter, 1998; Zhou et al., 2001; Costa et al., 2003; Bruijnzeel, 2004; Scott et al., 2004; Chandler, 2006; Zimmermann et al., 2006; de Moraes et al., 2006; Chaves et al., 2008; Zimmermann and Elsenbeer, 2008, 2009). Furthermore even though we could not study pipeflow, this work adds much more detail on the storm hydrograph response characteristics impacted by different land covers and thus extends the earlier descriptions given in Putty and Prasad (2000a).

The current results contrast with those from selected controlled experiments in both the humid tropics and the humid temperate latitudes (e.g. Swank et al., 1988; Bruijnzeel, 1990, 1996; Andreassian, 2004; Grip et al., 2004; Brown et al., 2005). In such cases for the most part the soil hydraulic properties at the surface in disturbed basins have retained enough of the pre-disturbed soil hydraulic characteristics, i.e. the 'good' condition status of Bruijnzeel (2004), so the storm runoff process has not been radically altered. In addition, it is evident that several decades will still be required for the rain–streamflow response of forested degraded land (i.e. by way of *A. Auriculiformis* plantations) to return towards the 'background' levels of the Forests. Although the more limited of soil biology associated with these plantations, in contrast to the natural forests, maybe a constraint to complete recovery of the hydraulic conductivity of these soils and thus the storm runoff generation process (Bonell et al., 2010). In the meantime the runoff generation process remains similar in the Acacia plantations to that found in the Degraded Forest.

Overall there is support from this study for the the 'degraded scenario' of the 'infiltration trade-off' hypothesis of Bruijnzeel (2004) *when concerning the storm runoff generation part of this hypothesis.* At these small basin scales, the surface reduction in soil K_{fs} under the DF land cover, and its persistence in the AC plantations, have clearly enhanced both seasonal streamflow yields and quickflow by rain event. It is to be noted that although this study does not address evapotranspiration and water-balance aspects, we suggest that as potential and actual evapotranspiration are likely to be depressed in the monsoon period when relative humidity is high, differences in stream flow and run-off between land-cover types during the wet-season are largely attributed to soil infiltration and hydrologic pathways.

6.2. A comparison of quickflow response ratios linked with synoptic climatology

The quickflow response ratios for the Coastal NF basin are much lower than those reported from north-east Queensland tropical rainforest (e.g. Q_F/P up to 56%) where the Lyne and Hollick (1979) hydrograph separation method was also used (Howard et al., 2010). Aside from differences in soil permeability, a key difference concerns the prevailing short-term rainfall intensities. They are much weaker in the Western Ghats when compared to the Australian study even if the daily totals are comparable (Putty et al., 2000; Putty, 2006; Bonell et al., 2004). The north-east Queensland rainforest is frequently impacted by tropical depressions and cyclones (Bonell et al., 2004; Bonell and Callaghan, 2008) whereas at the synoptic scale, rainfall in the study area emanates more from 'surges' in the wind streamlines of the south-west monsoon. Further orographic uplift of this deep (up to 6 km) and moist, airflow with the topographic barrier of the "Western Ghats-Central Sahyadri" accentuates precipitation. It is this mechanism which is a key driver for the occurrence of such high daily rainfalls (Gadgil and Joshi, 1983; Singh, 1986; Gunnell, 1997).

By contrast the hydrologic response variables associated with quickflow, as reported for the Coastal basins by event, are much higher than the reports from the Amazon basin studies (Biggs et al., 2006; de Moraes et al., 2006; Chaves et al., 2008). Aside from some differences in soil hydraulic conductivity (Bonell et al., 2010), the synoptic climatology is also very different between the two locations. It is not monsoonal in the Amazon basin in the strict sense of cross-equatorial flow over a large latitudinal range (Sadler et al., 1987). Moreover there are a very different suite of rain-producing systems and associated rainfall characteristics in the Amazon basin (Greco et al., 1990; Garstang et al., 1994; Garreaud and Wallace, 1997; reviewed in Bonell et al. (2004)). In addition, land degradation is more recent associated with the above Amazon basin studies (Biggs et al., 2006; de Moraes et al., 2006; Chaves et al., 2008).

6.3. The time series analyses and the roles of deep subsurface flow and groundwater

In the Coastal basins the time series analyses also indicated substantial time lags by event in rain–streamflow within the NF basin, and thus deeper, slower pathways being the dominant contributor to the storm hydrograph. Furthermore there was an interesting retention of this characteristic of a longer time lag in the human-impacted AC and DF basins, despite the emergence and juxtaposition of much shorter time lags as well. In contrast no such long time lags were detected in the NE Queensland tropical rainforest study (Bonell et al., 1979, 1981). Thus the more responsive storm hydrographs connected with the latter study (dominated by surface/shallow subsurface streamflow sources, *SOF* and *SSF*), contrasts with the much slower storm hydrograph responses in the NF basin. Much deeper sources of streamflow are suggested via deep *SSF* and groundwater pathways. Remarkably this same characteristic is still retained even within the DF and AC basins, and this is despite human impacts on the surface soils up to a century time scale. Moreover the simulation model indicated larger available storage capacities in the regolith and thus their greater role in the storm runoff generation process in contrast to the NE Queensland tropical rainforest study (Bonell et al., 1981).

One explanation for the above hydrological characteristics is that the subsoil K_{fs} (geometric means ~10–20 mm h^{-1}) for all three Coastal basins are comparatively permeable down to 1.50m depth when compared to other Laterite sites in the region (Bonell et al., 2010). Moreover these sub-soils are more permeable than those in the similar 'Acrisol-type' soils of the Australian study (Bonell et al., 1981, 1998) where the geometric mean K_{fs} is an order of magnitude lower. Elsewhere in a similar soil 'Acrisol-type' associated with a Peru study (Elsenbeer and Lack, 1996) there is a lower two order of magnitude difference in subsoil K_{fs}. Consequently available soil water storage capacities would be higher under the Forest and in the sub-soil away from the human-impacted surface soil layers. Further percolation to groundwater beneath both the DF and AC land basins would not be impeded, once rainwater entry through the lower surface K_{fs} has occurred. Thus recharge to groundwater, albeit in different proportions of total event rain, can be maintained despite a reduction in surface K_{fs} in the two disturbed land covers. Furthermore in the absence of detailed catchment surveys, the contributions of pipeflow towards a deeper *SSF* pathway cannot be excluded, on the lines of the description by Putty and Prasad (2000a).

The above findings highlight the need for detailed hydrogeology information when concerning rain–streamflow comparative studies linked with LC change. Moreover in addition to evapotranspiration and surface changes in K_{fs}, streamflow could potentially be also be affected by subtle differences in the hydrogeology by way of the jointing and fracturing within the underlying parent rock (as mentioned in CGWB (2008)) at such small basin scales. Despite such concerns the overall trend in streamflow yields (DF > AC > NF) for the Coastal basins are in line with the Malnaad basins.

7. Conclusions

Following the three questions posed *a priori* the conclusions are:

1. When compared to the less disturbed, baseline evergreen forest the impacts of multi-decadel degradation of forests results in enhanced total stream discharge and quickflow both seasonally and by storm event. Conversely base (delayed) flow is reduced.
2. The work supports earlier conclusions from the hydraulic conductivity survey (Bonell et al., 2010) which suggested that the occurrence of overland flow may have increased as a result of long-term forest degradation. Such comments also apply to (re) forested, former "degraded" land using *A. auriculiformis* plantations. Acacia plantations may thus not be very effective in restoring hydrologic functions in the short-term.
3. On the other hand there is evidence of contributions from deeper, subsurface sources to the storm hydrograph (more associated with the baseline evergreen forest) still continuing under the degraded forest and Acacia plantations. This is partly attributed to the sub-soils being comparatively permeable when compared to other studies. Despite some recovery in the surface hydraulic conductivity, the rain–streamflow response charac-

teristics of the *A. auriculiformis* plantations still retains a 'memory' of the storm hydrograph characteristics described above for the Degraded Forest.

4. As potential and actual evapotranspiration is likely to be depressed during the monsoon, differences in streamflow and run-off responses between land-cover is largely attributed to differences in soil infiltration and hydrologic pathways.
5. Hydrologic functions and services should be viewed in a larger frame-work of multiple ecosystem services and biodiversity of these ecosystems and land-management options to increase infiltration should be explored within this context of trade-offs and synergies at various spatial and temporal scales.

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