Journal of Hydrology 498 (2013) 191–209

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

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

Jagdish Krishnaswamy [a,*], Michael Bonell [b], Basappa Venkatesh [c], Bekal K. Purandara [c], K.N. Rakesh [a], Sharachchandra Lele [a], M.C. Kiran [a], Veerabasawant Reddy [d], Shrinivas Badiger [a]

[a] Ashoka Trust for Research in Ecology and the Environment (ATREE), Royal Enclave, Sriramapura, Jakkur Post, Bangalore 560 064, India
[b] The Centre for Water Law, Water Policy and Science under the auspices of UNESCO, University of Dundee, Dundee DD1 4HN, Scotland, UK
[c] Hard Rock Regional Centre, National Institute of Hydrology, Belgaum, Karnataka 590 001, India
[d] TERI, WRC, H. No. 233/GH-2, Vasudha Housing Colony, Alto Santa Cruz, Bambolim, Goa 403 202, India

ARTICLE INFO

*Article history:*
Received 8 October 2012
Received in revised form 7 June 2013
Accepted 19 June 2013
Available online 27 June 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Matthew Rodell, Associate Editor

*Keywords:*
Infiltration
Evapotranspiration
Groundwater recharge
Western Ghats
Hydrologic services
Tropical forests

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

* Corresponding author. Tel.: +91 80 23635555x209; fax: +91 80 23530070.
*E-mail address:* jagdish@atree.org (J. Krishnaswamy).

0022-1694/$ - see front matter 
http://dx.doi.org/10.1016/j.jhydrol.2013.06.034

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.