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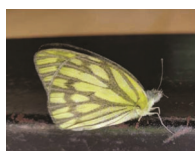
◄ COVER. Perennial stream amidst sacred grove at Vibuthi, Near Yana, Uttara Kannada District, Central Western Ghats. See page 1379.

Insights into riverscape dynamics with the hydrological, ecological and social dimensions for water sustenance

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Spatio-temporal patterns of four neighbouring riverscapes in the central Western Ghats, India through land-use analyses using temporal remote sensing data (1973, 2018), reveal a decline in evergreen forests (41%) and fragmentation of intact or contiguous forests (60%). Hydro-ecological footprint illustrates that catchment integrity plays a decisive role in sustaining water for societal and ecological needs. This is evident from the occurrence of perennial streams in the catchment dominated by native flora with forest cover greater than 60%, highlighting the riverscape dynamics with hydrological, ecological, social and environmental dimension linkages and water sustainability. This helps in evolving strategies to adopt integrated watershed management to sustain anthropogenic and environmental water demand.

Keywords: Biodiversity, eco-hydrological footprint, land use, lotic ecosystems, water quality.

RIVERINE ecosystems encompass ecological, social and economic processes (ecosystem functions) that interconnect biotic components and provide goods and services for the society. Degradation of these vital ecosystems has been the primary cause for increasing water insecurity, raising the need for integrated solutions to freshwater management. Sustainable management of freshwater flows is fundamental to the four dimensions of development, namely social needs, economic development, ecological integrity and environmental limits. However, unplanned developmental activities during the past four decades have been altering the land cover affecting physical integrity, bio-geochemical cycling, hydrological regimes, biodiversity, etc. This makes it necessary to understand: (i) the landscape dynamics and its relation with the hydrological and biological entities for determining the level of services provided by the ecosystem, and (ii) linkages of ecosystem structure with its functional capabilities, which are essential to frame appropriate management strategies towards mitigation of impacts.

Aquatic ecosystems are the destination of precipitation (surface and subsurface water) in the hydrological cycle, and are broadly categorized as lentic and lotic ecosystems. Lentic ecosystem refers to stationary or relatively still water bodies (such as lakes, ponds, etc.), while lotic ecosystem refers to flowing water (such as streams and rivers). Water sustenance in the aquatic ecosystems depends on the integrity of the catchment as vegetation helps in retarding the velocity of water by allowing impoundment and recharging of groundwater through infiltration. As water moves in the terrestrial ecosystem, part of it gets percolated, while another fraction gets back to the atmosphere through evaporation and transpiration. Forests with native vegetation act as a sponge by retaining and regulating the transfer of water between land and atmosphere[1,2]. The mechanism by which vegetation controls flow regime is dependent on various bio-physiographic characteristics, namely type of vegetation, species composition, maturity, density, structure, aerodynamic and surface resistance, root density and depth, hydro-climatic condition, etc. Roots of vegetation help in: (i) binding the soil, and (ii) improving soil structure by enhancing the stability of aggregates, which provide habitat for diverse microfauna and flora leading to higher porosity of soil, thereby making conduits for infiltration through the soil[3]. Native species of vegetation with the assemblage of diverse species help in recharging the groundwater, mitigating floods, and other hydro-ecological processes[4]. These functions augment with the age/maturity of the forests, their diversity, density of plant species, etc. In mature forests, streams are perennial with sustained yield (during all seasons), due to infiltration and storing of water in the subsurface (which gets released to the streams during the lean season). Also, the annual surface transpiration reduces with increase in understorey transpiration[5]. Revival of natural forest capabilities through reforestation or afforestation would take about 20–25 years in the tropical ecosystems and

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achievement of full potential about 40–50 years[6,7]. This necessitates safeguarding and maintaining the existing native forest patches to sustain hydrological regime, which caters to biotic (ecological and societal) demands. An undisturbed native forest has consistent hydrological regime with sustained flows during the lean season[8].

Aquatic ecosystems are the most threatened systems in India due to alterations in the landscape structure (changes in the land cover), anthropogenic inputs (disposal of untreated or partially treated wastewater), construction of reservoirs (altering the flow regime), water abstraction, river channelization (narrowing drains and concretization), etc. which in turn affect the physical and chemical integrity of the system. The spatial and temporal variability in freshwater stock with the burgeoning societal demands has resulted in anthropocentric regulation of river flow through construction of reservoirs, diversion works, etc. causing significant alterations in the hydrological regime and river morphology[9]. In general, dams are constructed for irrigation, hydroelectric power generation, domestic and industrial water supply, recreation and for controlling floods. Size and functionality of dams affect land use, livelihoods, local climate, hydrology and economy. Reservoirs and other storage structures, and diversion works have impacted the hydrological regime of rivers, which includes loss of interconnectivity along rivers, fragmentation of catchment, changes in hydrological processes, downstream erosion[10,11] and alterations in the flow regime of freshwater impacting downstream biota[12,13].

Ecological integrity of riverine ecosystem depends on river morphology, river connectivity, water quality[14–17], quantum, duration and velocity of water flow which influences the aquatic biodiversity. Ecosystem fragility refers to the extent to which a system experiences damage caused by sustained exposure to different stress agents that can cause environmental changes or changes in ecosystem functions[16,17]. Sustenance of water in the rivers, streams and wetlands during all seasons is crucial to maintain aquatic health and sustain biodiversity. The freshwater flows in terms of quantity and timing are essential to maintain the process and functioning of freshwater resources[18,19]. The health of a river (water body) deteriorates when the flow is either reduced or inhibited below a threshold required to sustain aquatic life[20] or environmental flow[20] (also known as ecological flow or instream flow or minimal flow). Maintaining environmental flow in streams and rivers is necessary to meet the needs of aquatic biota along with the societal demand[21], sustain the health of an aquatic system[22], manage flow and protect water bodies and river networks[23], maintain and enhance the ecological character and functions of floodplains, wetlands and riverine ecosystems which may be subject to stress from drought, climate change or water resource development[24,25].

Four river basins in the central Western Ghats with varied levels of anthropogenic stress have been chosen to understand the implications of large-scale changes in the respective landscape structures[27,28] on the hydrological regime, social needs, economic development, ecological integrity and environmental limits.

The Western Ghats (WG) are a range of ancient hills that run parallel to the west coast of India covering an approximate area of 160,000 km^2. They extend between 8°N and 21°N lat. and 73°E and 77°E long. The region is endowed with diverse ecological areas depending upon altitude, latitude, rainfall and soil characteristics[28]. The WG are among eight hot spots of biodiversity in India[29] and 36 global biodiversity hotspots[30] with exceptional endemic flora and fauna. Natural forests of the WG have been providing various goods and services[31], and are endowed with species of more than 4600 flowering plants (38% endemic), 330 butterflies (11% endemic), 156 reptiles (62% endemic), 508 birds (4% endemic), 120 mammals (12% endemic), 289 fishes (41% endemic) and 135 amphibians (75% endemic)[32]. Numerous streams originate in the WG, which drain millions of hectares area, ensuring water and food security for 245 million people, and hence the region is known as the 'water tower' of peninsular India. The region has tropical evergreen forests, moist deciduous forests, scrub jungles, sholas, savannas, including high-rainfall savannas of which 10% of the forest area is under legal protection. Areca nut, coconut, coffee, rubber, sugarcane and tea are the horticultural crops, and spices, paddy, cereals and cotton are major agricultural crops grown across the region.

The WG landscape consists of heterogeneous interacting dynamic elements with complex ecological, economic and cultural attributes. The interactions among the landscape elements result in the flow of nutrients, minerals and energy, which contributes to the functioning of the landscape. This complex interaction helps in the sustenance of natural resources through bio-geochemical and hydrological cycles. The changes in landscape structure have been altering the ecosystem functions.

The landscape in peninsular India with relic forests and perennial rivers has been catering to the societal water demand, while ensuring food security. The region is rich in biodiversity with numerous species of flora and fauna. Fragmentation of large contiguous forests to small and isolated forest patches either by natural phenomena or anthropogenic activities has led to drastic changes in the size of the forest patch, its shape, connectivity and internal heterogeneity, which restrict the movement of species leading to inbreeding among meta population with extirpation of the species.

The impacts of unplanned developmental activities[26] are evident with: (i) the existence of barren hill tops, (ii) conversion of perennial streams to intermittent or seasonal streams, (iii) flash floods during monsoon and droughts during summer, (iv) pollution of ecosystems, (v) change in water quality, (vi) soil erosion and sedimentation[27], (vii) extinction of endemic flora and fauna, and (viii) loss
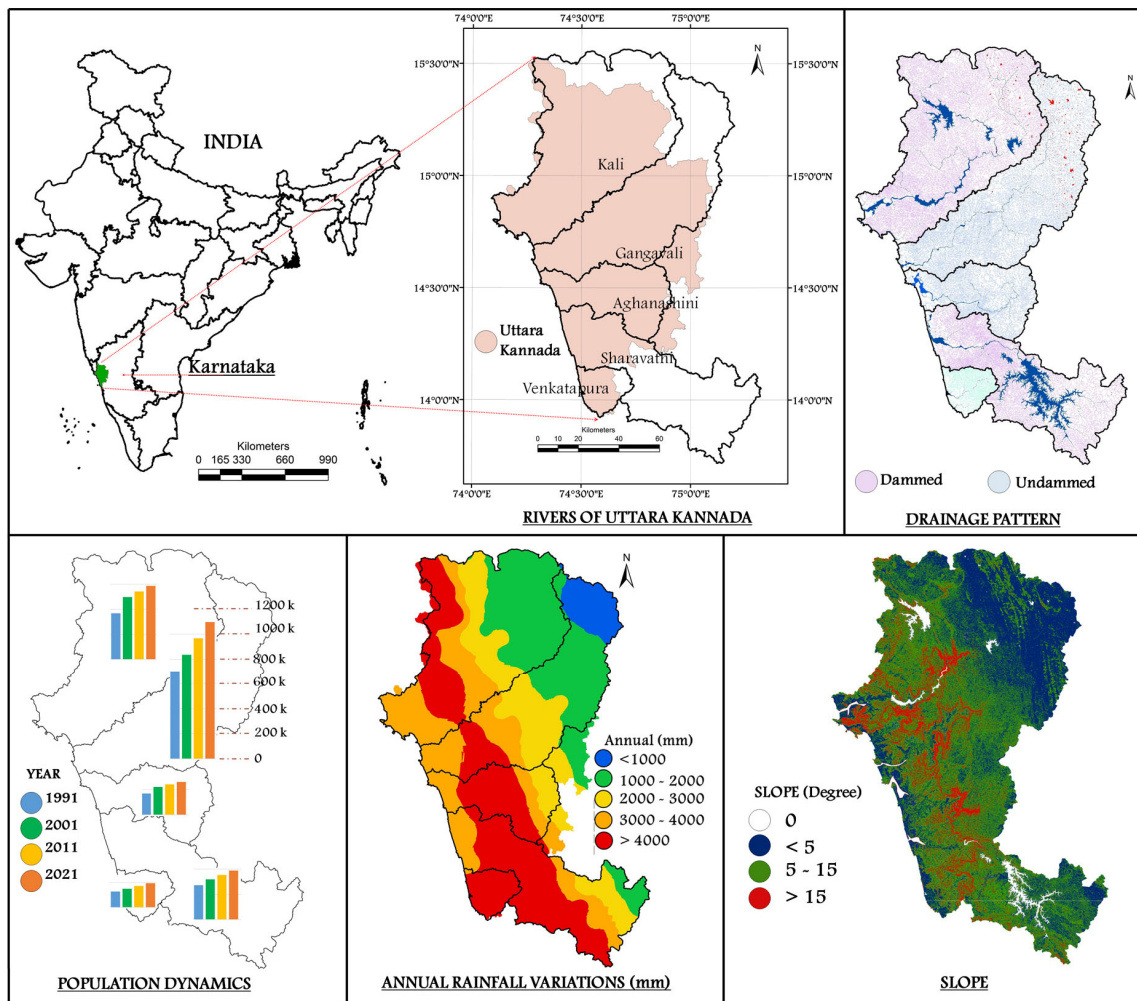
Figure 1. Study area.

of habitats, breeding grounds, etc. The region is ecologically fragile and vulnerable with high susceptibility to anthropogenic stress. This necessitates assessment of eco-hydrological footprint which will aid in the prudent management of fragile ecosystems to sustain: (i) natural flow regime, (ii) ecosystem goods and services, and (iii) livelihood of the people. The present study involves analysis of land-use dynamics with hydrologic regime to assess eco-hydrological footprints (water availability with demand to meet the societal and ecological needs), across the river scapes in the central WG with varied levels of anthropogenic stress. The results of the study could help evolve appropriate integrated management strategies to ensure sustenance of water, supporting biodiversity and people's livelihood.

Study area

Uttara Kannada district, Karnataka, located in the central WG (Figure 1), lies between 13.769°N and 15.732°N lat., and 74.124°E and 75.169°E long., covering an area of approximately 10,291 km². The district extends for a maximum length of 180 km along the N–S direction and a maximum width of 110 km along the E–W direction. The Arabian Sea borders it on the west creating a long, continuous and narrow coastline of 120 km. The district has varied geographical features with thick forests, perennial rivers and abundant flora and fauna. It falls in three agro-climatic zones – (i) the coastal region, which has a hot humid climate where rainfall varies between 3000 and 4500 mm; (ii) the Sahyadri interior region of the WG (500–1000 m elevation), in the south which is humid, where rainfall varies between 4000 and 5500 mm, and (iii) the plains on the east which are regions of transition that are dry, where rainfall varies between 1500 and 2000 mm. The district has four major rivers namely Kali with a catchment of 5085 km²; Gangavali (Bedthi; 3935 km²); Aghanashini (1448 km²) and Sharavati (3042 km²). Venkatapura, a relatively small river with a catchment of 460 km² and innumerable creeks is also found[33]. They all discharge into the Arabian Sea. These rivers are under various levels of stress like regulation of water flow for hydro-electric power generation (Kali and

Figure 2. Method adopted for the analyses of eco-hydrological footprint with forest transitions.

Sharavati rivers), and irrigation for the vast expanse of horticulture and monoculture plantations. Upper reaches of the Kali, Gangavali and Sharavati have a large number of interconnected lake systems (lentic ecosystems), while the WG are dominated by a dense drainage network.

As of 2018, Gangavali catchment has the highest population (1.01 million) followed by Kali (0.54 million), Sharavati (0.35 million), Aghanashini (0.24 million) and Venkatapura (0.17 million)[34]. Pop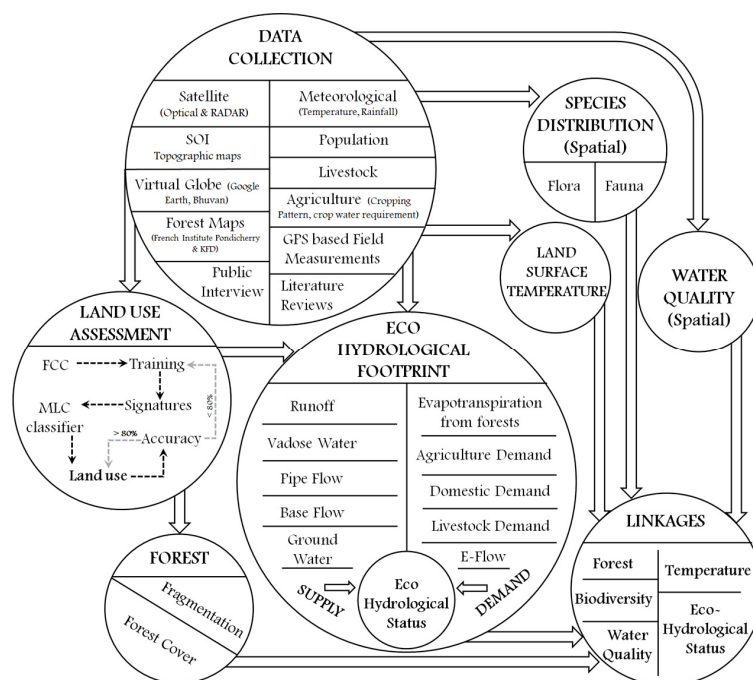ulation growth rate between 2001 and 2011 was highest in the Gangavali (15.3%), followed by Venkatapura (14.5%) and least in the Kali (8.9%). Venkatapura has the highest population density (377 persons/km^2), followed by Gangavali (258 persons/km^2) and lowest in the Kali (107 persons/km^2). Topographically, the coastal zone (in the west) and plain lands (towards the east) are flat with slopes (ranging up to 5°); the transition zones between the coast and the WG and the transition zones between the WG and eastern plain lands have slopes up to 15°. The WG have slopes greater than 15° (refs 35, 36). Interconnected lake systems in the plains were developed during the Kadamba (525–345 BCE) and Hoysala (AD 1063–1353) periods to cater to domestic and irrigation water requirements. This study is based on field ecological research carried out to understand the linkages of landscape dynamics with eco-hydrological footprints in the four major west-flowing river basins of Uttara Kannada district.

Data and methodology

Figure 2 describes the method adopted for assessing the role of landscape dynamics with ecological, hydrological and social dimensions in lotic ecosystems. This involves: (i) assessment of spatio-temporal patterns of land cover using multi-resolution remote sensing data, and (ii) assessment of eco-hydrological footprint through analyses of rainfall patterns and hydrological regime with the demand of biotic components.

Data collection

Optical satellite data from Landsat 1 MSS (1973), Landsat 8 OLI (2018) and topographic data from SRTM were downloaded from the United States Geological Survey (USGS)[37]. GPS-based field observations, Survey of India (SOI) topographic maps[36,38], French Institute, Puducherry maps[39], virtual earth data such as Google Earth[40], and NRSC Bhuvan[41] were used to geo-rectify and classify remote sensing data for identifying land-use categories. Long-term meteorological data such as temperature, rainfall and solar radiation were collected from Karnataka State Natural Disaster Monitoring Centre, Karnataka[42]; Directorate of Economics and Statistics, Government of Karnataka[43]; India Meteorological Department[44], and Food and Agriculture Organisation[45]. Population census data for 2001 and 2011 were collected from the Census of India[34]. Livestock data such as census and water requirement were collected from the Directorate of Economics and Statistics[43], District Statistical Office, Bengaluru[46], and through public interviews. Agriculture data such as the crops grown, cropping pattern, water requirement at different growth phases were collected from the District Statistical Office, Bengaluru[46], public interviews; online portals such as Raitamitra, iKisan, Tamil Nadu Agriculture

University, etc.[47–50] and published literatures. Field investigations in selected stream catchments were carried out for 24 months to understand the intra- and inter-variability of hydrological regime in the central WG and information regarding ungauged streams was compiled from the published literature. Steams were chosen based on land cover in the catchment as: (i) dominated by vegetation of native species to the extent of >60%; (ii) dominated by vegetation of monoculture species, and (iii) vegetation cover in the catchment <35%. This helped in understanding the natural flow regime of surface run-off, subsurface flows and infiltration dynamics to estimate the minimum flow to sustain aquatic life (also known as environmental flow or ecological flow)[51–55] for rivers in the central WG. Species composition and distribution pertaining to flora and fauna were mapped through quadrat-based transects in the field (representative regions across different forest types), biodiversity portals[56–58], Forest Department records[59] and published literature[60–71], and species distribution database was developed considering their occurrence[26,56–59,72–76], habitat (villages, transects, GPS coordinates, forest ranges), conservation status[77], etc. The spatial overlay of biodiversity information with the hydrological regime provided valuable insights on hydrological, ecological and biodiversity linkages with land-use dynamics across the four river basins with various levels of anthropogenic stress.

Land-use dynamics

Satellite data for 1973 and 2018 were resampled to 30 m resolution in order to maintain the same spatial resolution[78]. Training sites were developed based on field information (collected using pre-calibrated handheld GPS) and secondary data sources such as SOI topographic maps, vegetation map published by the French Institute, Puducherry and virtual globe datasets. The pre-processed satellite data were classified using supervised Gaussian maximum likelihood classification technique[79]. Also, 60% of the field data collected was used for classification, while 40% was used for accuracy assessment[80]. Additional training/field data were used and the process was repeated when classification accuracy was less than 80%. Land-use information of 1973 and 2018 were compared for assessing spatio-temporal patterns of landscape dynamics.

Forests

Spatial distribution of forests was extracted from the land-use information of 1973 and 2018. The binary maps of forest and non-forest areas were used for fragmentation analysis[81], which also emphasizes their relationship with biodiversity[82,83], climate change[84], etc. Forest fragmentation at pixel level was estimated based on an earlier proven protocol[85], by computing P_f (the ratio of pixels that are forested to the total non-water pixels in the window) and P_{ff} (the proportion of all adjacent (cardinal directions only) pixel pairs that include at least one forest pixel, for which both pixels are forested) indicators. Based on the level of fragmentation, forests were classified as interior (intact or contiguous), patch, transition, edge and perforated forests.

Species distribution and water quality

Water quality of the samples collated from field experiments at various locations in each of the river basins and also from the published literature[68] was analysed based on various physical, chemical and biological parameters. The surface water standards were used to define water quality status as highly polluted, polluted and non-polluted[68].

Temperature

Spatial patterns of temperature variation were computed based on mono window algorithm[86,87], using red, NIR and thermal IR (band 10) Landsat 8 data for 2018.

Eco-hydrological footprint

Eco-hydrological footprint of a river basin is computed through assessment of hydrological regime for sustaining vital ecological functions and appropriation of water by biotic components (including humans).

Biotic demand includes societal, terrestrial ecosystem demand and aquatic ecosystem demand (minimum flow required to sustain aquatic biotic components, also known as ecological flow). Societal demands include water requirement for agriculture, horticulture, domestic and livestock sectors[88–90]. Transpiration and evaporation from the forests alone have been accounted for under terrestrial water demand. Minimum flows (e-flows) to be maintained to sustain aquatic life were computed based on field observations[53–55,91,92], which show about 25% of annual flow needs to be maintained as natural flow regime during the lean season to maintain ecological integrity.

Natural water catering to societal and environmental needs depends on rainfall, land use, soil and lithological characteristics of the catchment (or watershed). Water supply in the catchments is considered as a function of overland flows, and subsurface (vadose and saturated zones) flows (pipe flow and base flow). Overland flows were monitored for 18 months at 12 locations across the river basins. They were estimated sub-catchment-wise for each river basin using the rational method[93], and the catchment coefficients for varied land uses were based on
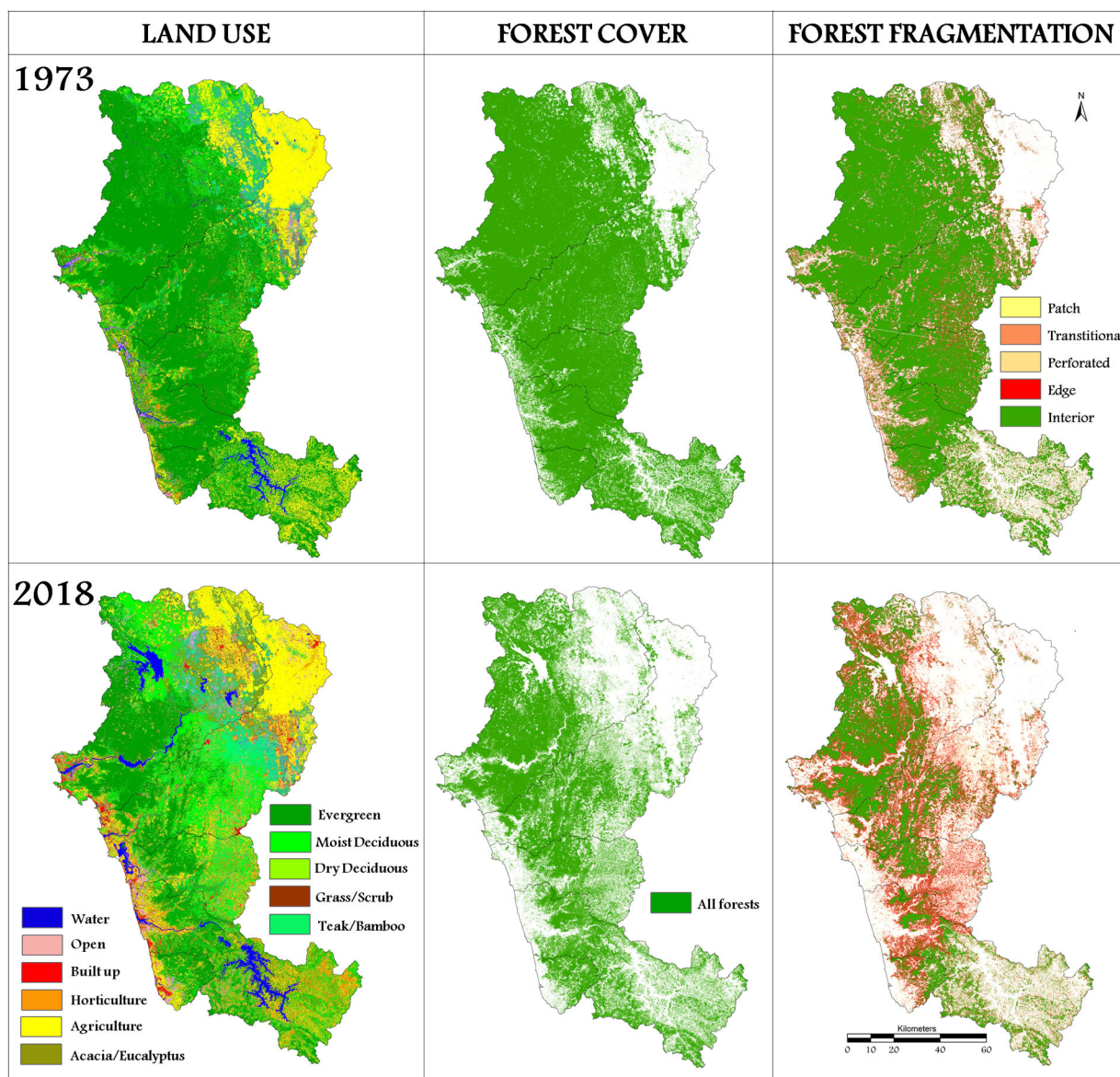
Figure 3. Dynamics in land use, forest cover and forest fragmentation across the west-flowing rivers of central Western Ghats, India.

field observations. Groundwater recharge was estimated using the Krishna Rao's equation, which holds good for Karnataka[51]. Subsurface flows were estimated based on the specific yield of rocks and porosity of soils[88]. Monthly supply (based on hydrological regime assessment) was compared with the biotic demands in order to understand the eco-hydrological status in every sub-catchment; ratio < 1 indicates deficit while ratio > 1 indicates surplus or sufficient situation.

Eco-hydrology and landscape structure linkages

Spatial variability and fragmentation status of forests, temperature, species distribution and water quality were compared spatially with the eco-hydrological status to understand the linkages of these variables with water sustenance.

Results and discussion

Status and transition of forest

These were evaluated through the assessment of land-use dynamics and fragmentation of forest landscapes using the temporal remote sensing data of 1973 and 2018. Figure 3 presents land-use dynamics with the fragmentation of forests across four major river catchments of Uttara Kannada district in the central WG. Figure 4 presents river basin-wise statistics. Land-use analyses using temporal remote sensing data reveal that the overall forest
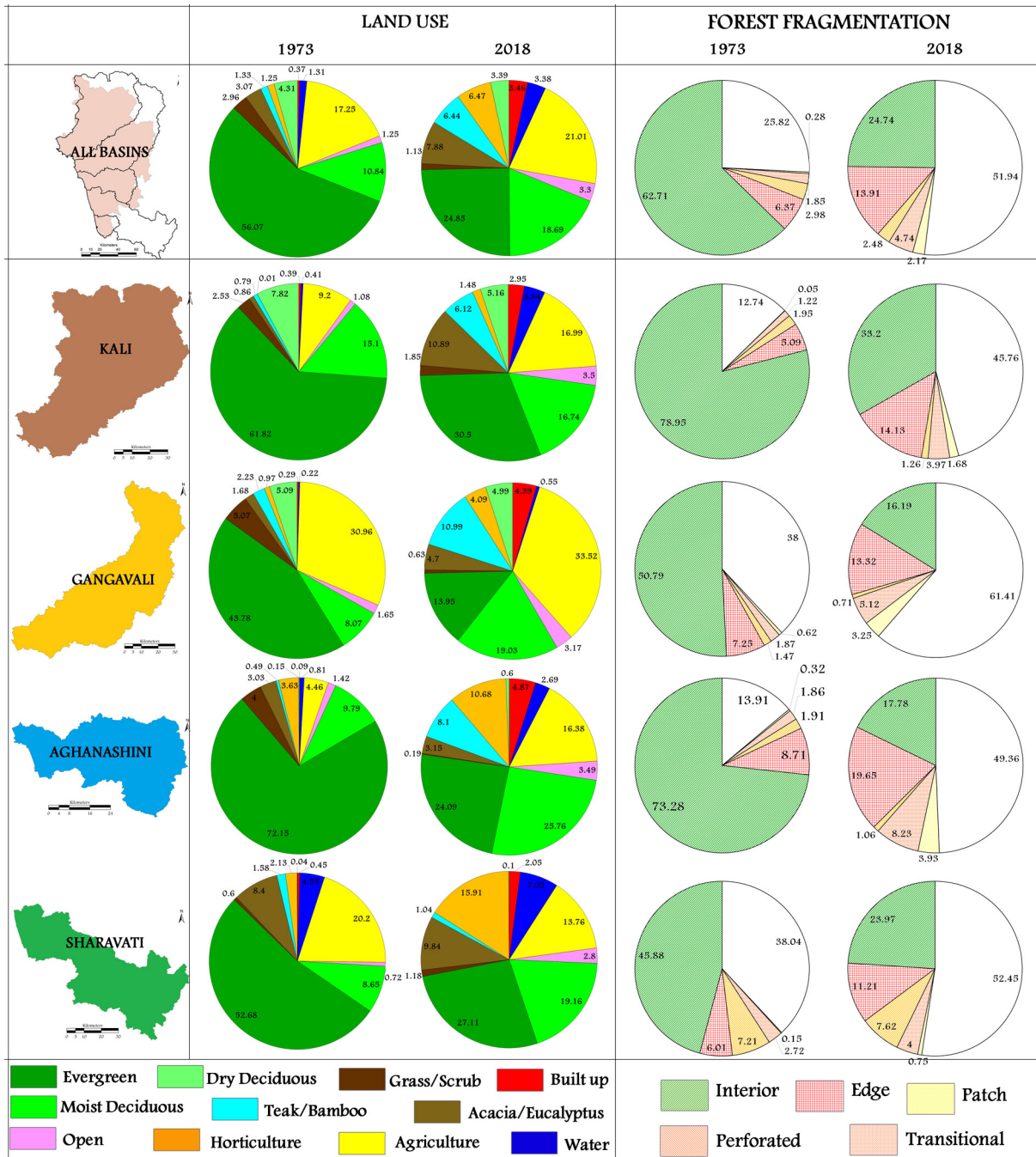
Figure 4. Land use and forest fragmentation dynamics.

cover in the district has declined from 74.19% (1973) to 48.04% (2018), with the loss of evergreen forests from 56.07% to 24.85%. The loss of forest cover is due to developmental activities with aggravated anthropogenic activities[94] such as (i) construction of dams along River Kali post-1975, without appropriate rehabilitation and catchment restoration measures, (ii) increase in monoculture plantations such as teak, eucalyptus, acacia by the Forest Department as part of social forestry scheme, (iii) conversion of area under forests to agriculture, horticulture or private plantations[82,95], (iv) increase in built-up

area, (v) setting up of forest-based industries, and (vi) nuclear power plant at Kaiga in the midst of evergreen forests[75].

Fragmentation process involves alteration in the structure and composition of native forests through the division of contiguous forests into smaller non-contiguous fragments with a sharp increase in the edges. This will have detrimental effects such as disruption in bio-geochemical cycling, nutrient and water cycling, ecological processes, forests and further land-use changes. About 64,355 ha of forest land has been diverted for

various non-forestry activities (such as paper industries, hydroelectric and nuclear power projects and commercial plantations) during the last four decades[75]. Hence, the terrestrial forest ecosystems in Uttara Kannada district, central WG have been experiencing fragmentation of contiguous forests, evident from the decline of interior or contiguous forests from 62.71% (1970) to 24.74% (2018), and consequent increase in patch, transitional, edge and perforated forests. This has led to the loss of connectivity of natural/native vegetation and straying of wild animals into human habitations. Instances of human–animal conflicts has increased. There is also extirpation of genes due to higher inbreeding, loss of biodiversity, absence of native pollinators, etc. Spurt in urban growth is witnessed in and around major towns such as Sirsi, Siddapura, Karwar, Hubli, Ankola, Kumta, Honnavar, Dandeli, etc. Encroachment of forest lands of the order of 7072 ha (ref. 75) and conversion to agriculture, horticulture and private plantations is prevalent throughout the district (except those designated as protected areas) across all agro-climatic zones (coast, Western Ghats (hilly zones), plains and transition zones).

River basin-wise land-use analysis (Figure 4) reveals that anthropogenic activities involving monoculture (both forest plantation and horticulture) plantations and exploitation of timber in the Aghanashini river basin have led to the decline in forest cover from 86.08% (1973) to 50.65% (2018), followed by river basins of Kali (37.8%), Gangavali (37.7%) and Sharavati (23.3%).

Evergreen forest cover in Aghanashini riverscape has declined from 72.15% (1973) to 24.09% (2018), while moist deciduous forest cover has increased from 9.79% to 25.76% during this period. While there has been a sharp increase in agricultural activity from 4.46% to 16.38% in the coastal regions, in the WG and transition zones to the east, horticulture practices (areca nut gardens) have increased from 3.63% to 10.68%, especially along the river valleys and stream courses. Urban growth has picked up as indicated by increase in built-up area from 0.1% to 4.87% in the proximity of the coast (Gokarna and Kumta) and along the WG (Sirsi). There has been a reduction in the interior forest cover from 73.28% to 17.78%, with increase in edge forests (from 8.71% to 19.65%) and transitional forests (from 1.86% to 8.23%).

Construction of a series of dams in the Kali river basin at Supa, Kodasalli, Kadra, etc. has resulted in loss of forest cover (from 87.26% to 54.24%) and in particular evergreen forests (from 61.82% to 30.5%)[52]. Due to availability of water and lack of appropriate regulatory mechanisms, there have been encroachments into the forests in the eastern part of the catchment (near Hubli and Belgaum) leading to increase in agricultural and horticulture activities (17.02%–22.15%). Overall, the forest cover in Kali river basin has reduced. Infrastructure activities (Karwar, Hubli–Dharwad) have boosted the growth of urban areas from 0.39% to 2.95%. All these pressures

have reduced the contiguous, native, intact forests from 78.95% to 33.2% in the Kali river basin.

Similar levels of anthropogenic stress were witnessed in the Sharavati river basin, which has led to the decline in forest cover from 61.97% to 47.55% with the loss of evergreen forests (from 52.68% to 27.11%) and a two-fold increase in deciduous forests. Human–animal conflicts have increased due to the disruption of animal movement paths with the decline of contiguous forests from 45.88% to 23.97% and loss of fodder, water, etc. with decline of native vegetation. There has been an increase in urban spaces (0.45%–2.05%), and horticulture lands (2.13%–15.91%). There was also a decline in agricultural practices in Sharavati river basin with large-scale conversion of paddy fields into cash-crop fields like areca gardens.

Eco-hydrological footprint

Assessment of eco-hydrological footprint at sub-catchment level across the four major river basins of Uttara Kannada district was carried out considering: (i) biotic demands: blue water demand (agriculture, domestic, livestock, aquatic, ecological needs), green water demand (evapotranspiration), and (ii) hydrological regime considering surface (overland) flow and subsurface (vadose and saturated zones), flow (pipe and base flow) (Figure 5). The societal and environmental water demand was highest in Kali (7075 M.m^3), followed by Gangavali (5501 M.m^3), Sharavati (4827 M.m^3) and Aghanashini (2204 M.m^3). Upper reaches in all these basins have witnessed major land-use changes with increase in agricultural and horticultural areas, and sustained water demand throughout the year. Analysis of water demand based on cropping pattern (agriculture and horticulture) indicates that the Gangavali river basin has the highest demand (2597 M.m^3), followed by Kali (2272 M.m^3), Sharavati (1975 M.m^3) and Aghanashini (765 M.m^3).

Based on flow, streams have been classified into three categories as perennial (with 12 months flow), intermittent (6–8 months flow) and seasonal (four months flow, only during monsoon). Figure 6 confirms the role of native forests (contiguous or interior forests) in sustaining perennial stream flow. Intermittent or seasonal streams are found in areas with the catchment dominated by degraded forest patches. The streams are perennial when the catchment is dominated by vegetation (> 60%) of native species. This is mainly due to infiltration or percolation in the catchment, where the soil is more porous in areas with native species. Diverse microorganisms in the soil interact with plant roots, which help in the transfer of nutrients from the soil to plants, and maintains soil porosity or premeability. Analyses of soil sample from the catchments of perennial and intermittent streams reveal that soils in the perennial stream catchments have highest moisture content (61.47%–61.57%), higher nutrients
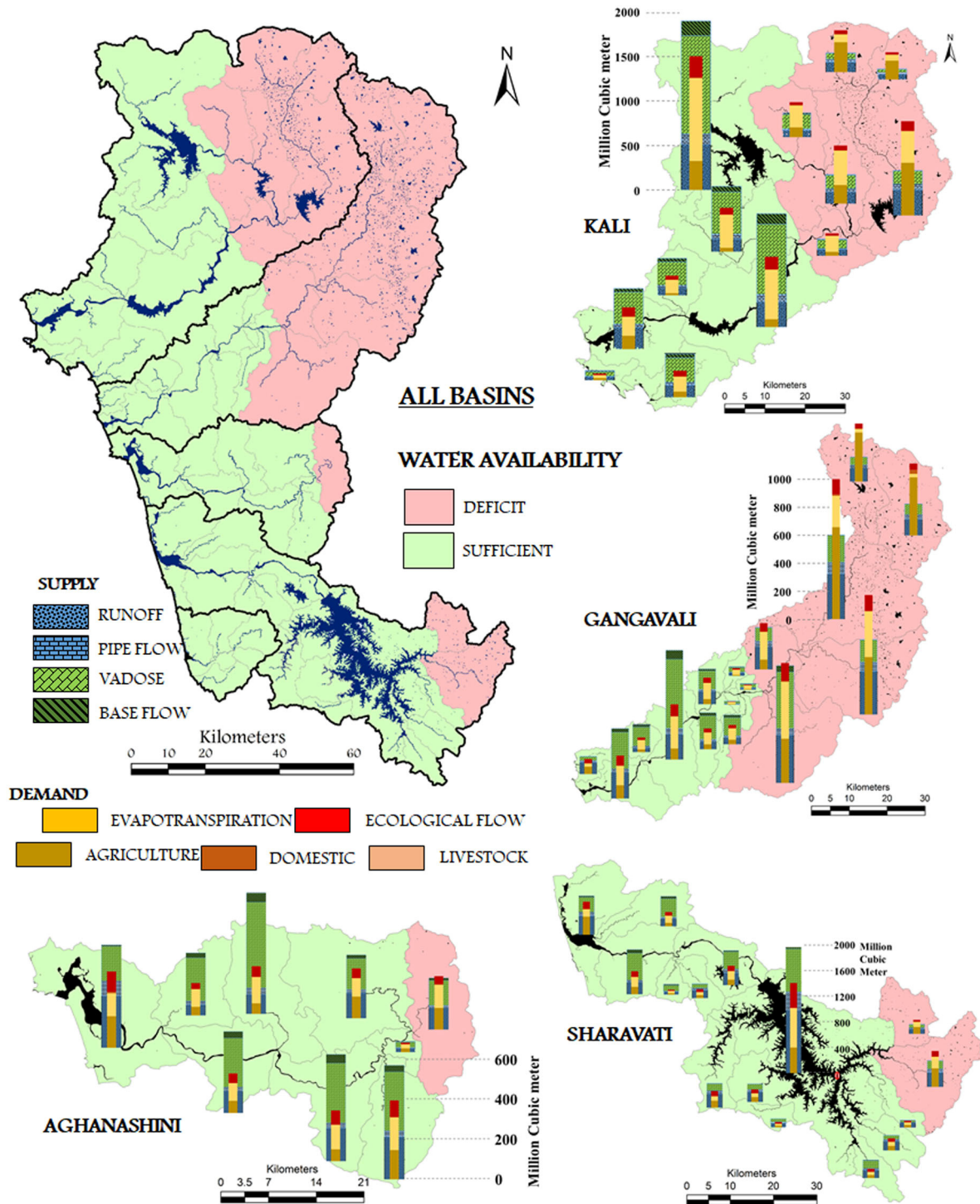
Figure 5. Eco-hydrological footprint (water availability) across the basins.

(C, N and K) and lower bulk density (0.50–0.57 g/cm³). Compared to this, soils in the catchment of intermittent and seasonal streams have higher bulk density (0.87–1.53 g/cm³) and relatively lower nutrient content. Due to this, water infiltrates and fills the underlying zones vadose and saturated zones in the catchments of perennial streams.

The region receives rainfall for about four months and the surface run-off during monsoon is due to precipitation. After the monsoon recedes, the water stored in the vadose and saturated zones flows laterally towards the stream for about 6–8 months (as pipe flow in the post-monsoon period of four months and base flow during summer). Water infiltration allows storage in the saturated
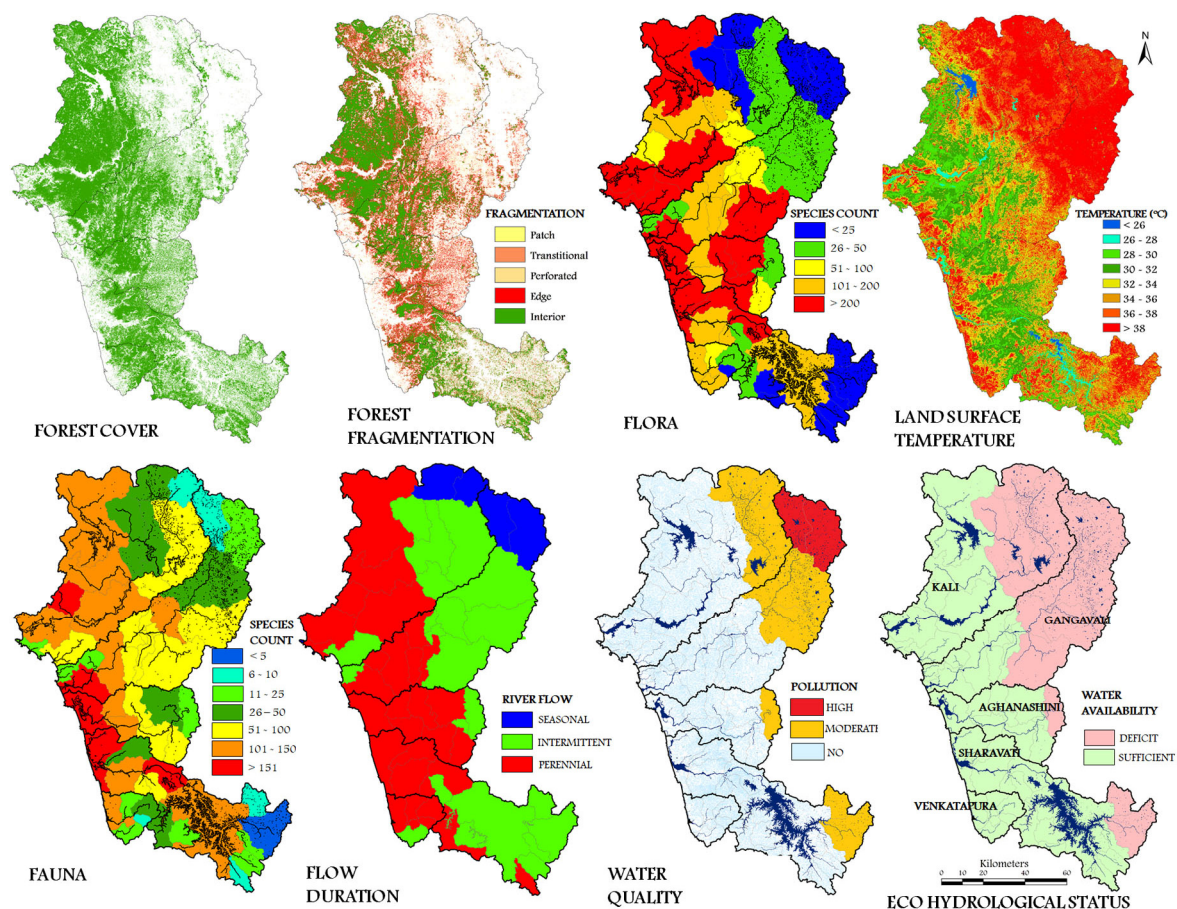
Figure 6. Eco-hydrology and forest linkages.

and vadose zones, which is crucial for sustenance of water in the streams during lean season. This emphasizes that vegetation helps in retarding water flow in the catchment by allowing infiltration. Contiguous forests of native species moderate the local climate (through transpiration) and also act as a sponge by retaining water, which is released slowly to the streams during the lean season, thereby sustaining water availability in the catchment to meet biotic needs throughout the year. Streams in the catchment dominated by a single species (monoculture plantations) had adequate flow for 6–8 months. This is mainly because of lower infiltration due to higher bulk density of soil and also because litter of monoculture plants requires longer time for degradation. Water availability for four months is observed in the streams of the degraded catchment with vegetation cover less than 30%.

At the sub-catchment level across all four river basins, field investigations confirmed higher infiltration (almost twice) compared to transpiration in sub-catchments with intact forests of native species. There was increase in surface water flow (during monsoon) and reduced flow (or no flow) during non-monsoon in the sub-catchments associated with degraded and altered landscapes, changes in the physical properties of soil and local temperature. The

land-use alterations due to intense societal pressures with increasing water demands have led to negative eco-hydrological footprint with water scarcity ranging between 4 and 8 months.

Assessment of eco-hydrological status confirms the role of forests with native species in retaining water (in the catchment), which is available to meet the demands throughout the year.

Field ecological survey through quadrat-based transects (156) along with opportunistic studies yielded 1068 species of flowering plants representing 138 families. Of these, 278 were tree species (from 59 families), 285 were shrubs species (73 families) and 505 were herb species (55 families). Moraceae, the family of figs (*Ficus* spp.), which constitutes keystone resource for animals, was represented by maximum tree species (18), followed by Euphorbiaceae (16), Leguminosae (15), Lauraceae (14), Anacardiaceae (13) and Rubiaceae (13 species). Shrub species richness was represented by Leguminosae (32 species), Rubiaceae (24) and Euphorbiaceae (24 species). Among herbs, grasses (Poaceae) were the most specious (77 species), followed by sedges (Cyperaceae) with 67 species Orchids (Orchidaceae) were found in good numbers[96,97]. The flora in the contiguous forests of the district

included the most threatened and vulnerable species such as *Wisneria triandra*, *Holigarna beddomei*, *Holigarna grahamii*, *Garcinia gummi gutta*, *Hopea ponga*, *Diospyros candolleana*, *Diospyros paniculata*, *Diospyros saldanhae*, *Cinnamomum malabatrum*, *Myristica malabarica* and *Psydrax umbellate*. Wildlife included predators such as tiger (*Panthera tigris*), leopard, wild dog (dhole) and sloth bear. Prey animals like barking deer, spotted deer (*Axis axis*), wild boar, sambar (*Cervus unicolor*), gaur (*Bos gaurus*) were also found.

Figure 6 shows forest status (forest cover, fragmentation) in relation to temperature, flora, fauna, water quality, flow duration and eco-hydrological status across the river basins. The correlation among these variables is evident from the occurrence of: (i) endemic species of flora (100 species per sub-basin), (ii) fauna (50 species per sub basin), (iii) occurrence of perennial streams, (iv) good water quality, (v) moderate temperature, and (vi) sufficient water availability in the catchments with contiguous intact native forests. On the contrary, degraded landscape supports lower floral (<50 species) and faunal (<25 species) diversity. Societal activities in the upper reaches (of rivers) towards the transition zones and plain lands were higher compared to the WG. Absence (minimally present) of intact mature forests in the socially active regions has led to decline in river flow (seasonal or intermittent flow). The rivers in these regions (upper reaches) have been polluted with domestic sewage, agricultural run-off and industrial effluents. The temperatures in altered catchments with degraded landscapes are higher across all agroclimatic zones.

Information related to biodiversity and ecology of the region was compiled through literature review and field measurements. Ecologically sensitive regions (ESRs) were delineated based on the geoclimatic, land, ecological and hydrological parameters (Figure 7)[98]. Comparing ESR with the eco-hydrological status (Figure 6) confirms the ecological sensitivity linkages with the hydrological regime of a region. This is evident form the presence of perennial streams (in ESR 1 and 2), when the catchment dominated by the native plant species cover (>60%) with abundance of endemic species. This highlights the linkages of hydrology, biodiversity and ecology with land-use dynamics in a riverscape.

People's livelihood and eco-hydrological status of a catchment

A comparative assessment of people's livelihood has been made with soil water properties and availability of water in the respective catchment. The result shows that, catchments with >60% vegetation with native species have higher soil moisture and groundwater compared to the catchments (of seasonal streams) during dry spell of a year. The higher soil moisture due to availability of water

during all seasons facilitates farming of commercial crops with higher economic returns to farmers, unlike those farmers who face water crisis during the lean season. The study emphasizes the need for conservation by maintaining native vegetation in the catchments, highlighting its potential to support people's livelihood with water conservation at local and regional levels. Both plantation and agricultural crops have been considered for valuation in select catchments of perennial and seasonal streams. Plantation crops (viz. areca nut, coconut, banana, beetle leaf and pepper) are the major income-generating products in the catchment areas of perennial streams. In this sector a gross average income of Rs 311,701 ha^{-1} yr^{-1} (during 2009–10) was generated from plantation crops as against an average expenditure of Rs 37,043 ha^{-1} yr^{-1} (mainly for plantation maintenance), yielding a net profit of Rs 274,658 ha^{-1} yr^{-1}. On the contrary, in the catchment of seasonal streams (where both plantation and rice fields were considered for income calculation), the average gross income generated was Rs 150,679 ha^{-1} yr^{-1} against expenditure for plantation maintenance and field preparation of Rs 6474 ha^{-1} yr^{-1}.

Faunal diversity and total economic value

The presence of contiguous or intact forests with native species maintains the natural flow conditions and water
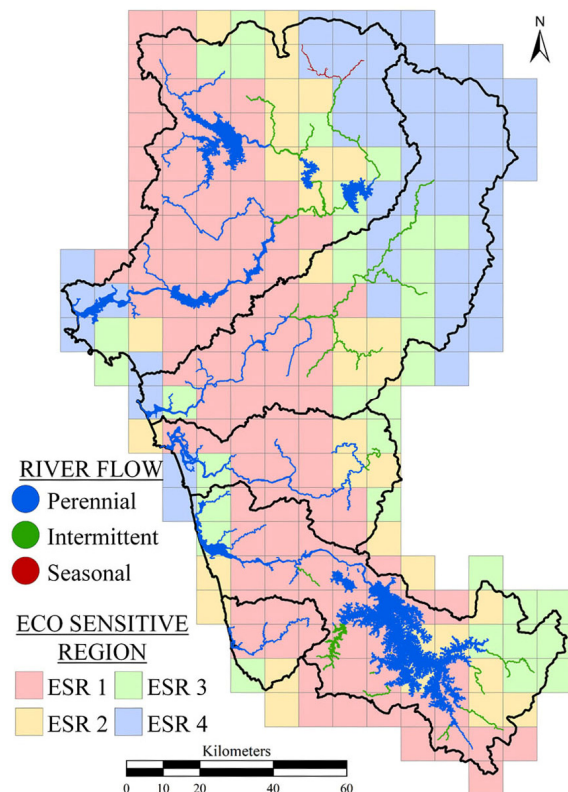

Figure 7. Ecologically sensitive regions in Uttara Kannada district, Karnataka, India.

Table 1. Estuarine faunal diversity and total economic value (TEV)[65,71,84,100]

River basin	Dams	Fishes (sp. count)	Gastropods/bivalves (sp. count)	TEV (Rs in million/ha/yr)
Kali	Six reservoirs	61	7	2.5
Gangavali	Presence of small check dams	55	6	2.6
Aghanashini	Presence of small check dams	86	7	5.0
Sharavati	Three reservoirs	43	2	1.3

quality. Alteration in the natural flow regime through construction of reservoirs for impounding water and releasing according to societal needs has led to an imbalance in the ecosystem, loss of habitat, alteration of water quality, etc. Altogether 61 fish species from 47 genera and 38 families were recorded from the Kali estuary. Gangavali had 55 species of fish from 46 genera and 39 families. Aghanashini had the highest diversity of fishes; 86 species belonging to 66 genera and 47 families, while Sharavati had the lowest with 43 species from 25 genera and 24 families[60,99]. High diversity in Aghanashini estuary is obviously due to preservation of relatively better natural condition of the river, unaffected by dams or other major developmental projects. However, shell and sand mining which have intensified in recent decades, have a telling effect on estuarine fish population and livelihood based on them[60].

The estuaries of the four rivers under discussion spreading across 7,549 ha area support significantly the employment sector in the district, accounting for about 2,092,000 fishing days/yr, benefiting an estimated 3086 families of estuarine fishermen, generating 277 days of fishing work per year and generating an income of Rs 88,157/ha/yr. This is significant, considering that income is only due to fishing efforts without any external input . This is because mechanized fishing is not practised in the estuaries of the district. The estuarine area required for fishing is 0.56 ha per head in Gangavali and Aghanashini (both are without dams), 1.58 ha in Kali and a whopping 4.72 ha in Sharavati (impacted by a series of hydroelectric projects).

Table 1 lists estuarine faunal diversity with the total economic value, which highlights the importance of maintaining natural flows to sustain estuarine biodiversity and ecosystem goods and services. Natural flows are regulated in the Kali and Sharavati rivers with reservoirs built across them for producing electricity at Supa, Kodasalli, Kadra (Kali) and Linganmakki (Sharavati). Controlled flows alter the salinity and nutrient levels in the estuaries, which results in the lowering of goods and services as evident from the total economic value (TEV) per hectare. TEV is 1.2 million rupees (Sharavati) and 2.5 million rupees (Kali) compared to 5 million rupees per hectare per year in Aghanashini or 2.6 million rupees per hectare per year in the Gangavali. Gangavali and Aghanashini rivers are devoid of reservoirs and the flow in these rivers is natural. This ecology also has led to higher diversity of bivalves, which consist of about 13 species in Gangavali and 86 species in Aghanashini[65].

The study reiterates the need for maintaining the natural flow regime and prudent management of watershed to (i) sustain higher faunal diversity, (ii) maintain the health of the water body and (iii) sustain people's livelihood with higher revenues. The study negates the current decision-makers' approach with the assumption 'freshwater flowing into the sea is a waste of a precious natural resource', and highlights the importance of maintaining forests with native vegetation in the catchment areas to sustain water quality and quantity of the rivers during all seasons. The unregulated flow in rivers can maintain the health and biodiversity in the downstream regions, including coastal waters, wetlands (mangroves, seagrass beds, floodplains), and estuaries.

Conclusion

Watershed of a river plays a vital role in sustaining the hydrological regime. Analysis of landscape dynamics across the west-flowing major rivers of Uttara Kannada district (Central WG), reveals degradation of forests from 74.19% (1973) to 48.04% (2018) with loss of evergreen forests from 56.07% to 24.85% due to large-scale developmental activities such as construction of dams, power projects, forest based industries – paper mills, expansion of roads, urbanization, encroachment for horticultural and agricultural practices. The forests are currently confined to the WG and protected areas.

Alterations of landscape structure in the catchment areas influence the hydrological regime leading to variations in the hydrological status. Assessment of sub-basin-wise eco-hydrological footprint across river basins with varied levels of anthropogenic stress emphasizes the role of forests on infiltration and evapotranspiration capabilities. Sub-basins with forest cover with higher proportion of native species have higher eco-hydrological index, suggesting that the availability of water can satisfactorily maintain biotic demands, whereas sub-basins dominated by monoculture have low index which indicates water scarcity. Inter-annual variability of water availability and demand footprints indicate that the sub-basins between coasts and the WG have perennial river streams, whereas transition zones between the WG and plains towards the east show deficit of water for 6–10 months in a year with intermittent and seasonal flow. Occurrence of streams with 12 months flow in ESRs (1 and 2) confirms the linkages of hydrological regime with ecological sensitivity of a region. This highlights that streams are perennial in

the catchments with native forest cover >65% having higher proportion of endemic plant species. The significance of land cover with native undisturbed forests (interior forests) in maintaining flow regime in the rivers, micro-climate and biodiversity is evident with the comparative analysis of temperature, biodiversity, water quality, forests and hydro-ecological flows. The catchments with perennial rivers support rich biodiversity with higher number of species of both flora and fauna.

Assessment of spatial patterns of biodiversity across the four river basins reveals the occurrence of endemic flora and fauna in the catchments with perennial streams. Similarly, aquatic diversity across these four river estuaries indicates that due to the natural flow regime, Aghanashini has the highest diversity followed by Gangavali, Kali and Sharavati, which have altered salinity conditions due to river flow that is regulated by reservoirs.

Anthropogenic activities (industries, horticulture, etc.) in the upper reaches of rivers have a negative impact on the pristine nature of water, i.e. high pollution levels have been observed in the catchments with towns/cities with high population (Hubli, Dharwad, Sirsi, Sagar) and industries (Dandeli). Forests help in remediation and maintenance of water quality in the downstream regions. They also help in moderating micro-climate as evident from the lower surface temperatures in forested catchments compared to the degraded landscapes. Regulation of water flow in the river impacts people's livelihood downstream, as evident from the lowered values of ecosystem goods and services as in Kali and Sharavati estuaries (TEV <2.5 million rupees/yr/ha) compared to river basins with natural flow as in Aghanashini estuary (with the higher fish diversity and TEV of >5 million rupees/yr/ha).

The study provides insights on the role of native vegetation in (i) sustaining water availability during all seasons to meet biotic demands, (ii) supporting rich endemic biodiversity, (iii) maintaining water quality through bioremediation, (iv) promoting higher ecosystem goods and services, and (v) supporting livelihood of people dependent on indigenous resources. Understanding these linkages would help the planners/decision-makers with valuable knowledge for integrated river-basin management in an era dominated by indiscriminate development of river catchment areas involving enhanced deforestation, frequent instances of altering natural regime, inappropriate cropping and poor water efficiency.

The study highlights the vital ecological function of a riverscape in sustaining the hydrological regime when covered with vegetation of native species. The presence of perennial streams in sub-catchment dominated by native vegetation contrasts the seasonal streams in the catchment dominated by anthropogenic activities with monoculture plantations. Hence, the premium should be towards conservation of forests with native species in order to sustain water and biotic diversity in the water bodies, which are vital for food security. There exists a chance to restore the lost natural evergreen to semi-evergreen forests through appropriate conservation and management practices. Eco-hydrological assessment across riverscapes of varied levels of anthropogenic stress highlights the water retention capability of a riverscape dominated by vegetation of native species to sustain the local societal and ecological demands, which is useful in the integrated management of riverscapes (watershed, catchment or basin) in India by the respective government agencies.

1. Bruijnzeel, L. A., Hydrological functions of tropical forests: not seeing the soil for the trees? *Agric. Ecosyst. Environ.*, 2004, **104**, 185–228.
2. Lana-Renault, N., Latron, J., Karssenberg, D., Serrano-Muela, P., Regüés, D. and Bierkens, M. F. P., Differences in stream flow in relation to changes in land cover: a comparative study in two sub-Mediterranean mountain catchments. *J. Hydrol.*, 2011, **411**, 366–378.
3. Bargués Tobella, A. *et al.*, The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. *Water Resour. Res.*, 2014, **50**, 3342–3354.
4. Mackey, B., Watson, J. and Worboys, G. L. G., Connectivity Conservation and the Great Eastern Ranges Corridor, Department of Environment, Climate Change and Water, New South Wales, Sydney, Australia, 2010.
5. Vertessy, R. A., Watson, F. G. R. and O'Sullivan, S. K., Factors determining relations between stand age and catchment water balance in mountain ash forests. *For. Ecol. Manage.*, 2001, **143**, 13–26.
6. Pugh, D., How forests regulate streamflows, 2014, pp. 1–8; https://d3n8a8pro7vhmx.cloudfront.net/ncec/pages/50/attachments/orignal/1422089907/How_Forests_Regulate_Streamflows.pdf?1422089907
7. Kuczera, G., Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. *J. Hydrol.*, 1987, **94**, 215–236.
8. Pearce, A. J., Rowe, L. K. and O'Loughlin, C. L., Hydrologic regime of undisturbed mixed evergreen forests, South Nelson, New Zealand. *J. Hydrol. (New Zealand)*, 1982, **21**, 98–116.
9. Mehta, R., Jain, S. K., Rathor, D. S. and Garvit, K., Hydrological impacts of dams: a review. *Int. J. Water Resour. Environ. Manage.*, 2012, **3**, 75–97.
10. Tiemann, J. S., Gillette, D. P., Wildhaber, M. L. and Edds, D. R., Effects of lowhead dams on riffle-dwelling fishes and macro-invertebrates in a Midwestern river. *Trans. Am. Fish. Soc.*, 2004, **133**, 705–717.
11. Tiemann, J. S., Dodd, H. R., Owens, N. and Wahl, D. H., Effects of lowhead dams on unionids in the Fox River, Illinois. *Northeast. Nat.*, 2007, **14**, 125–138.
12. Jansson, R., Nilsson, C. and Renöfält, B., Fragmentation of riparian floras in rivers with multiple dams. *Ecology*, 2000, **81**, 899–903.
13. Nilsson, C. and Berggren, K., Alterations of riparian ecosystems caused by river regulation. *Bioscience*, 2000, **50**, 783–792.
14. Jain, S. K., Assessment of environmental flow requirements. *Hydrol. Process.*, 2012, **26**, 3472–3476.
15. Salik, K. M., Hashmi, M. Z.-R., Ishfaq, S. and Zahdi, W.-Z., Environmental flow requirements and impacts of climate change-induced river flow changes on ecology of the Indus Delta, Pakistan. *Reg. Stud. Mar. Sci.*, 2016, **7**, 185–195.
16. Bunn, S. E. and Arthington, A. H., Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environ. Manage.*, 2002, **30**, 492–507.

17. Poff, N. L. *et al*., The natural flow regime: a paradigm for river conservation and restoration. *Bioscience*, 1997, **47**, 769–784.

18. Peñas, F. J. *et al*., Estimating minimum environmental flow requirements for well-mixed estuaries in Spain. *Estuarine Coastal Shelf Sci.*, 2013, **134**, 138–149.

19. Kimmerer, W. J., Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. *Estuaries*, 2002, **25**, 1275–1290.

20. Brown, C. and King, J., *Environmental Flows: Concepts and Methods*, Water Resour. Environ. Tech. Note C.1., The World Bank, 2003, 1st edn.

21. Hughes, D. A., Providing hydrological information and data analysis tools for the determination of ecological instream flow requirements for South African rivers. *J. Hydrol.*, 2001, **241**, 140–151.

22. Yang, F., Xia, Z., Yu, L. and Guo, L., Calculation and analysis of the instream ecological flow for the Irtysh River. *Proc. Eng.*, 2012, **28**, 438–441.

23. Chen, H. and Zhao, Y. W., Evaluating the environmental flows of China's Wolonghu wetland and land use changes using a hydrological model, a water balance model, and remote sensing. *Ecol. Modell.*, 2011, **222**, 253–260.

24. Sims, N. C. and Colloff, M. J., Remote sensing of vegetation responses to flooding of a semi-arid floodplain: implications for monitoring ecological effects of environmental flows. *Ecol. Indic.*, 2012, **18**, 387–391.

25. Dyson, M., Bergkamp, G. and Scanlon, J. (eds), *Flow – The Essentials of Environmental Flows Gland Switz. IUCN*, International Union for Conservation of Nature and Natural Resources, Switzerland, 2013, 2nd edn.

26. Ramachandra, T. V. and Bharath, S., Geoinformatics based valuation of forest landscape dynamics in Central Western Ghats, India. *J. Remote Sensing GIS*, 2018, **7**.

27. Ramachandra, T. V., Vinay, S. and Subash Chandran, M. D., Quantification of annual sediment deposits for sustainable sand management in Aghanashini river estuary. *J. Environ. Manage.*, 2018, **206**, 1263–1273.

28. Gunnel, Y. and Radhakrishna, B. P. (eds), *Sahyadri: The Great Escarpment of the Indian Subcontinent*, Geological Society of India, Bangalore, 2001.

29. International Union for Conservation of Nature, 2019.

30. Conservation International, Hotspots, 2002; https://www.conservation.org/priorities/biodiversity-hotspots

31. Ramachandra, T. V., Soman, D., Naik, A. D. and Subash Chandran, M. D., Appraisal of forest ecosystems goods and services: challenges and opportunities for conservation. *J. Biodivers.*, 2017, **8**, 12–33.

32. Daniels, R. R. J. and Venkatesan, J., *Western Ghats – Biodiversity, People, Conservation*, Rupa & Company, 2008.

33. Suryanath, U. K. (ed.), *Uttara Kannada District Gazetteer*, Government of Karnataka, 1985; http://gazetteer.kar.nic.in/

34. Office of the Registrar General and Census Commissioner, Census of India. Ministry of Home Affairs, Government of India, 2011.

35. Jarvis, A., Reuter, H. I., Nelson, A. and Guevara, E., SRTM 90 m Digital Elevation Database v4.1. Cgiar-Csi, 2008.

36. Survey of India, Topographic maps. Department of Science and Technology, 2018; www.surveyofindia.gov.in

37. USGS, Earthexplorer. United States Geological Survey, 2000; https://earthexplorer.usgs.gov/

38. Survey of India, Nakshe. Department of Science and Technology, 2018; soinakshe.uk.gov.in

39. Pascal, J. P., *Explanatory Booklet on the Forest Map of South India*, French Institute of Pondicherry, Puducherry, 1986.

40. Google, Google Earth, 2018; https://www.google.com/earth/

41. National Remote Sensing Centre, Bhuvan, Indian Space Research Organisation, Government of India, 2016; bhuvan.nrec.gov.in

42. Department of Science and Technology, Karnataka State Natural Disater Monitoring Centre, Government of Karnataka, 2007; ksndmc.org/default.aspx

43. Directorate of Economics and Statistics. Government of Karnataka, 2017; des.kar.nic.in

44. India Meteorological Department, Hydrometerological Services, Ministry of Earth Sciences, Government of India, 2018.

45. FAO, Meteorological data, Food and Agriculture Organization, Rome, 2017; fao.org/home/en

46. District Statistical Office, *District Statistics at a Glance*, Bengaluru, 2016; http://districts.nic.in/

47. Karnataka State Department of Agriculture, Raitamitra, 2017; http://raitamitra.kar.nic.in/

48. Department of Economics and Statistics, Season and Crop Report Tamil Nadu 2009–2010, Chennai (India), 2011.

49. Ikisan Agri-Informatics and Services Division, Nagarjuna Fertilizers and Chemicals Ltd, Hyderabad, 2017; https://krishijagran.com/list-of-irrigation-companies/ikisan/.

50. Tamil Nadu Agricultural University, TNAU Agritech Portal, Tamil Nadu Agricultural University, http://www.tnau.ac.in/

51. Ramachandra, T., Vinay, S. and Bharath, H. A., Environmental flow assessment in a lotic ecosystem of central Western Ghats, India. *Hydrol. Curr. Res.*, 2016, **7**, 1–14.

52. Ramachandra, T. V., Vinay, S., Bharath, S. and Shashishankar, A., Eco-hydrological footprint of a river basin in Western Ghats. *Yale J. Biol. Med.*, 2018, **91**, 431–444.

53. Putty, M. R. Y. and Prasad, R., Understanding runoff processes using a watershed model – a case study in the Western Ghats in South India. *J. Hydrol.*, 2000, **228**, 215–227.

54. Ramachandra, T. V, Hydrological responses at regional scale to landscape dynamics. *J. Biodivers.*, 2014, **5**, 11–32.

55. Vinay, S. *et al.*, Hydrological regime in sacred groves and non-sacred groves of Central Western Ghats. In Lake 2016: Conference on Conservation and Sustainable Management of Ecologically Sensitive Regions in Western Ghats, Moodbidri, Dakshina Kannada, Karnataka, 2016.

56. India Biodiversity Portal, The Western Ghats; https://indiabiodiversity.org/

57. Avibase – the world bird database, 2003; https://avibase.bsc-eoc.org/avibase.jsp?lang=EN

58. ENVIS, CES, IISc, Sahyadri: Western Ghats Biodiversity Information System, 1995; http://wgbis.ces.iisc.ernet.in/biodiversity/

59. Karnataka Forest Department e-portal, Government of Karnataka, 2018; https://aranya.gov.in/

60. Mahima, B., Nayak, V. N., Subash Chandran, M. D. and Ramachandra, T. V., Fish distribution dynamics in the Aghanashini estuary of Uttara Kannada, west coast of India. *Curr. Sci.*, 2014, **106**, 1739–1744.

61. Mahima, B., Nayak, V. N., Subash Chandran, M. D. and Ramachandra, T. V., Impact of Hydroelectric dams on fisheries in the Sharavathi estuary of Uttara Kannada District. In Lake 2012: Conference on Conservation and Management of Wetland Ecosystems, Kottayam, Kerala, 2012.

62. Mahima, B., Nayak, V. N., Subash Chandran, M. D. and Ramachandra, T. V., Inventory of fishes of Gangavali estuary in Uttara Kannada, Karnataka state. *J. Mar. Biol. Assoc. India*, 2016, **58**, 69–74.

63. Ramachandra, T. V. *et al.*, Integrated ecological carrying capacity of Uttara Kannada district, Karnataka, Sahyadri Conservation Series 47, ENVIS Technical Report 87, 2014.

64. Balachandran, C., Dinakaran, S., Subash Chandran, M. D. and Ramachandra, T. V., Diversity and distribution of aquatic insects in Aghanashini River of Central Western Ghats, India. In Lake 2012: Conference on Conservation and Management of Wetland Ecosystems, Kottayam, 2012.

65. Ramachandra, T. V., Subash Chandran, M. D., Joshi, N. V. and Bhoominathan, M., Edible bivalves of Central West Coast, Uttara

Kannada district, Karnataka, India, Sahyadri Conservation Series 17, ENVIS Technical Report 48, Bangalore, 2012.

66. Boominathan, M., Subash Chandran, M. D. and Ramachandra, T. V., Economic valuation of bivalves in the Aghanashini Estuary, west coast, Karnataka, Sahyadri Conservation Series 9, ENVIS Technical Report: 301, Bangalore, 2008.

67. Ramachandra, T. V., Rao, G. R., Vishnu, D. M. and Subash Chandran, M. D., Forest trees of Central Western Ghats, ENVIS Technical Report 121, Bangalore, 2017.

68. Ramachandra, T. V., Subash Chandran, M. D., Joshi, N. V., Karthik, B., Sameer, A. and Vishnu, D. M., Ecohydrology of lotic ecosystems of Uttara Kannada, Central Western Ghats, Sahyadri Conservation Series 14, ENVIS Technical Report 40, Bangalore, 2012.

69. Karthik, B. and Ramachandra, T. V., Water quality status of Sharavathi River Basin, Western Ghats, Sahyadri Conservation Series 6, ENVIS Technical Report 23, Bangalore, 2006.

70. Amit, S. Y. *et al.*, Ecological status of Kali River flood plain, ENVIS Technical Report 29, Bangalore, 2008.

71. Ramachandra, T. V., Vinay, S., Bharath, S. and Bharath, H. A., Profile of rivers in Karnataka, Sahyadri Conservation Series 71, ENVIS Technical Report 129, Bangalore, 2017.

72. Kumar, U., Chiranjit, M. and Ramachandra, T. V., Multi resolution spatial data mining for assessing land use patterns. In Data mining and warehousing, Sudeep Ela. CENGAGE Learning, Delhi, 2015, pp. 97–138.

73. Lillesand, T. M., Kiefer, R. W. and Chipman, J. W., *Remote Sensing and Image Interpretation Lloydia Cincinnati*, Wiley, New York, USA, 2004, 7th edn.

74. Bharath, H. A., Vinay, S., Chandan, M. C., Gouri, B. A. and Ramachandra, T. V., Green to gray: Silicon Valley of India. *J. Environ. Manage.*, 2018, **206**, 1287–1295.

75. Ramachandra, T. V., Bharath, S., Rajan, K. S. and Subash Chandran, M. D., Stimulus of developmental projects to landscape dynamics in Uttara Kannada, Central Western Ghats. *Egypt. J. Remote Sensing Space Sci.*, 2016, **19**, 175–193.

76. Haddad, N. M. *et al.*, Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci. Adv.*, 2015, **1**, 27.

77. Jha, C. S., Goparaju, L., Tripathi, A., Gharai, B., Raghubanshi, A. S. and Singh, J. S., Forest fragmentation and its impact on species diversity: an analysis using remote sensing and GIS. *Biodivers. Conserv.*, 2005, **14**, 1681–1698.

78. Laurance, W. F., Laurance, S. G. and Delamonica, P., Tropical forest fragmentation and greenhouse gas emissions. *For. Ecol. Manage.*, 1998, **110**, 173–180.

79. Ramachandra, T. V., Bharath, S. and Subash Chandran, M. D., Geospatial analysis of forest fragmentation in Uttara Kannada District, India. *For. Ecosyst.*, 2016, **3**, 15.

80. Sreekantha, Gururaja, K. V. and Ramachandra, T. V., Nestedness pattern in freshwater fishes of the Western Ghats: an indication of stream islands along riverscapes. *Curr. Sci.*, 2008, **95**, 1707–1714.

81. Ramachandra, T. V., Vinay, S. and Aithal, B. H., Environmental flow assessment in a lotic ecosystem of Central Western Ghats, India. *Hydrol. Curr. Res.*, 2016.

82. Ramachandra, T. V. *et al.*, Sacred groves (Kan forests) of Sagara taluk, Shimoga district, Sahyadri Conservation Series: 54, ENVIS Technical Report 102, Bangalore, 2016.

83. Karnataka Biodiversity Board, Government of Karnataka, 2018.

84. Ramachandra, T. V., Subash Chandran, M. D., Joshi, N. V., Mahima, B., Prakash, N. M. and Srikanth, N., Estuarine fish diversity and livelihood in Uttara Kannada district, Karnataka state, Sahyadri Conservation Series 34, ENVIS Technical Report 64, Bangalore, 2013.

85. IUCN, The IUCN red list of threatened species, 2019; https://www.iucnredlist.org/

86. Wang, F., Qin, Z., Song, C., Tu, L., Karnieli, A. and Zhao, S., An improved mono-window algorithm for land surface temperature retrieval from Landsat 8 thermal infrared sensor data. *Remote Sensing*, 2015, **7**, 4268–4289.

87. Ramachandra, T. V., Bharath, S. and Nimish, G., Modelling landscape dynamics with LST in protected areas of Western Ghats, Karnataka. *J. Environ. Manage.*, 2018, **206**, 1253–1262.

88. Ramachandra, T. V. *et al.*, Water bodies of Uttara Kannada, Sahyadri Conservation Series 44, ENVIS Technical Report 81, Bengaluru, 2014.

89. Vinay, S., Bharath, S., Bharath, H. A. and Ramachandra, T. V., Hydrologic model with landscape dynamics for drought monitoring. In Joint International Workshop of ISPRS VIII/1 and WG IV/4 on Geospatial Data for Disaster and Risk Reduction, Hyderabad, 2013.

90. Ramachandra, T. V., Nagar, N., Vinay, S. and Bharath, H. A., Modelling hydrologic regime of Lakshmanatirtha watershed, Cauvery river. In 2014 IEEE Global Humanitarian Technology Conference – South Asia Satellite, GHTC-SAS 2014, 2014, pp. 64–71.

91. Vinay, S. *et al.*, Landscapes and hydrological regime linkages: case study of Chandiholé, Aghanashini,. In National Seminar for Research Scholars 2017, Bangalore, 2017.

92. Johansson, E. L., Fader, M., Seaquist, J. W. and Nicholas, K. A., Green and blue water demand from large-scale land acquisitions in Africa. *Proc. Natl. Acad. Sci. USA*, 2016, **113**, 11471–11476.

93. Mutreja, K. N., *Applied Hydrology*, Tata McGraw-Hill, New Delhi, 1995, 4th edn.

94. Ramachandra, T. V., Setturu, B., Rajan, K. S. and Subash Chandran, M. D., Modelling the forest transition in Central Western Ghats, India. *Spat. Inf. Res.*, 2017, **25**, 117–130.

95. Ramachandra, T. V., Subash Chandran, M. D., Joshi, N. V. and Bharath, S., Fragmentation of Uttara Kannada Forests, Sahyadri Conservation Series 29, ENVIS Technical Report 57, Bangalore, 2013.

96. Ramachnadra, T. V., Subash Chandran, M. D., Rao, G. R., Vishnu, D. M. and Joshi, N. V., Floristic diversity in Uttara Kannada District, Karnataka. In *Biodiversity in India* (eds Pullaiah, T. and Sandhya Rani, S.), Regency Publications, New Delhi, 2015, 1st edn, pp. 1–87.

97. Rao, G. R., Krishnakumar, G., Dudani, S. N., Chandran, M. D. S. and Ramachandra, T. V., Vegetation changes along altitudinal gradients in human disturbed forests of Uttara Kannada, Central Western Ghats. *J. Biodivers.*, 2017.

98. Ramachandra, T. V., Bharath, S., Subash Chandran, M. D. and Joshi, N. V., Salient ecological sensitive regions of Central Western Ghats, India. *Earth Syst. Environ.*, 2018, **2**, 15–34.

99. Mahima, B., Nayak, V. N., Subash Chandran, M. D. and Ramachandra, T. V., Impact of hydroelectric projects on finfish diversity in the Sharavathi River estuary of Uttara Kannada District, central west coast of India. *Int. J. Environ. Sci.*, 2014, **5**.

100. Ramachandra, T. V., Subash Chandran, M. D., Joshi, N. V, Rakhi, R. K., Prakash, N. M. and Sumesh, N. D., Valuation of estuarine ecosystem, Uttara Kannada District, Karnataka, Sahyadri Conservation Series 27, ENVIS Technical Report 45, Bangalore, 2013.