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Appraisal of Environmental Health and Ecohydrology of Free-Flowing Aghanashini River, Karnataka, India

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Abstract: Rivers are vital freshwater resources that cater to the needs of society. The burgeoning population and the consequent land-use changes have altered the hydrologic regime with biophysical and chemical integrity changes. This necessitates understanding the land-use dynamics, flow dynamics, hydrologic regime, and water quality of riverine ecosystems. An assessment of the land-use dynamics in the Aghanashini River basin reveals a decline in vegetation cover from 86.06% (1973) to 50.78% (2018). The computation of eco-hydrological indices (EHI) highlights that the sub-watersheds with native vegetation had higher infiltration (and storage) than water loss due to evapotranspiration and meeting the societal demand. The computation of water quality index helped to assess the overall water quality across seasons. The study provides insights into hydrology linkages with the catchment landscape dynamics to the hydrologists and land-use managers. These insights would aid in the prudent management of river basins to address water stress issues through watershed treatment involving afforestation with native species, appropriate cropping, and soil conservation measures.

Keywords: eco-hydrological indices; flow regime; land use; multivariate analysis; water quality; water quality indices (WQI)

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1. Introduction

The aquatic ecosystem plays a vital role in sustaining ecological processes and the basic needs of society. Ecosystem quality varies due to natural processes (such as climatic factors, precipitation, soil erosion, weathering of rocks, soil quality, and watershed characteristics) and anthropogenic factors such as land-use changes, overexploitation of water resources, and agricultural practices [1,2]. During the twenty-first century, the planning, development, and management of aquatic resources relied on human-centric factors such as population, per capita water demand, agriculture production, and socio-economic activities [3]. Developing countries in the tropics have been facing water stress due to large-scale land cover changes from deforestation [4,5], unplanned developmental activities, and unprecedented and unscientific agriculture practices with extensive water abstraction [6–9]. The overexploitation of freshwater resources to cater to burgeoning societal needs has compromised the health and sustainability of resources in India and across the globe [10,11]. Anthropogenic activities coupled with skewed policies have resulted in the disappearance of pristine forests [12–14] in the catchment, affecting biogeochemical dynamics [4,15–17]. The structural changes in the catchment (landscape) have affected the functional aspects of ecosystems, thereby impairing the assimilative and supportive capacity [18,19] of fragile ecosystems. The impacts are evident with the recurring instances of droughts and floods and with the shortages of quality water affecting the regional economy and people's livelihoods [20]. The conservation of forests with native species in the catchment has helped sustain the hydrological regime and maintain biodiversity [21].

The integrity of the catchment of aquatic ecosystems decides water sustenance, as vegetation helps in retarding the velocity of water by allowing impoundment and groundwater recharge through infiltration. At the same time, another fraction returns to the atmosphere through evapotranspiration. Forests with native species of plants would aid as sponges, retaining and regulating the transfer of water between land and atmosphere [21]. The mechanism by which vegetation controls the flow regime is dependent on various bio-physiographic characteristics, namely, the type of vegetation, the species composition, maturity, density, structure, aerodynamic and surface resistance, root density and depth, and the hydro-climatic conditions [22]. The roots of diverse terrestrial vegetation provide habitats for diverse microflora and fauna, and with microbial actions, the soil has higher porosity or permeability, thereby enabling efficient infiltration. These functions depend on the diversity and maturity of the forests, and the density of plant species. This necessitates safeguarding and maintaining the existing native forest patches to sustain the hydrological regime, which caters to biotic (ecological and societal) demands. An undisturbed native forest has a consistent hydrologic regime with sustained flows during lean seasons [21,22].

Generally, ecosystems permit complex interactions among abiotic and biotic entities to recover from minor perturbations [21–23]. It is necessary to maintain the quantity, quality, and timing of flow [23,24], which is also known as ecological flow [25–27] across all segments of the riverine systems for the sustainable functioning of freshwater resources. This emphasizes understanding the hydrologic regime and the consumption behavior and transactions of resources among/between ecological and societal activities [28]. The hydrological regime sustaining the biotic components is referred to as an eco-hydrological footprint.

The physical, chemical, and biological characteristics of aquatic ecosystems are determined by water quality assessments [29]. The long-term and continuous monitoring of surface water bodies provides insights into the spatial and temporal variability in water quality [30,31]. Alterations in water quantity and quality govern the species composition, ecosystem productivity, and physiological conditions of aquatic organisms. Altered flows due to changes in ecosystem conditions influence the fish population, bringing about changes in habitat, food availability, community structure, composition, and behavior [32]. Pollutants such as heavy metals cause a severe threat to living organisms and humans as they are toxic and persist for a more extended period in nature, resulting in their bioaccumulation in the food chain [33,34].

Various statistical approaches have been adapted for interpreting water quality variables [35,36]. Furthermore, the computation of water quality indices (WQI) aid in understanding the suitability of water for anthropogenic purposes. Multivariate analysis such as cluster analysis (CA) and principal component analysis (PCA) aid in understanding spatial-temporal variations, a grouping of monitored stations, and identification of important factors that influences the quality of streams [37–40].

The Aghanashini River in the central Western Ghats is a free-flowing river that supports rich biodiversity and sustains people's livelihoods. The catchment of this river is witnessing land cover changes due to increasing societal demands. This necessitates understanding landscape dynamics with biodiversity, hydrologic regime, and water quality characteristics for the prudent management of fragile aquatic ecosystems.

The eco-hydrological footprint assessment of a river considers water availability, water quality characteristics, and water demand for the sustenance of biotic components. The objective of the current research is to assess the eco-hydrological footprint of the Aghanashini River basin at the sub-catchment level, considering various societal demands, ecological needs, and water availability. This entailed land use analysis; spatio-temporal analyses of annual rainfall data, hydrological and ecological footprint, the computation of eco-hydrological indices (EHI), eco-hydrological footprint, and water quality indices (through water quality assessment).

2. Materials and Methods

2.1. Study Area

Aghanashini is one of the few rivers flowing towards the west without major anthropogenic interventions (free-flowing river). Earlier studies confirm diverse flora and fauna along the riverscape [4,15,16,18,19,41] compared to the adjacent river catchments. This west-flowing river originates at Manjaguni and Shankara Honda (Sirsi) [20,41,42] and traverses a distance of 128 km [43] and joins the Arabian Sea. The catchment area of Aghanashini is about 1449 km^2 [42]. It is spread across the coastal and hilly agro-climatic zones in Siddapura, Sirsi, Ankola, and Kumta taluks of Uttara Kannada district [44]. The population has increased by 9.2% from 221,562 (2001) to 241,884 (2011) in the catchment [45]. The population is projected to increase to 264,137 by 2021. Elevation in the river catchment ranges between 0 and 786 m ASL. The undulating terrain of the Sahyadrian (Ghats) has denser stream networks, and the coastal regions have a sparse stream network with the broader riverbeds. The soil in the catchment is mainly clayey skeletal, loamy skeletal, along with clayey, fine, sandy, and loamy soils [46]. Figure 1 depicts the location of the Aghanashini River basin in Uttara Kannada district, Karnataka State, India, with the population density, topography, lithology, and agro-climatic zones. These spatial layers were generated using open-source GIS (QGIS) with the data compiled from the secondary sources (topographic maps of the Survey of India, Census data) and field data (collected using pre-calibrated handheld global positioning system (GPS)).

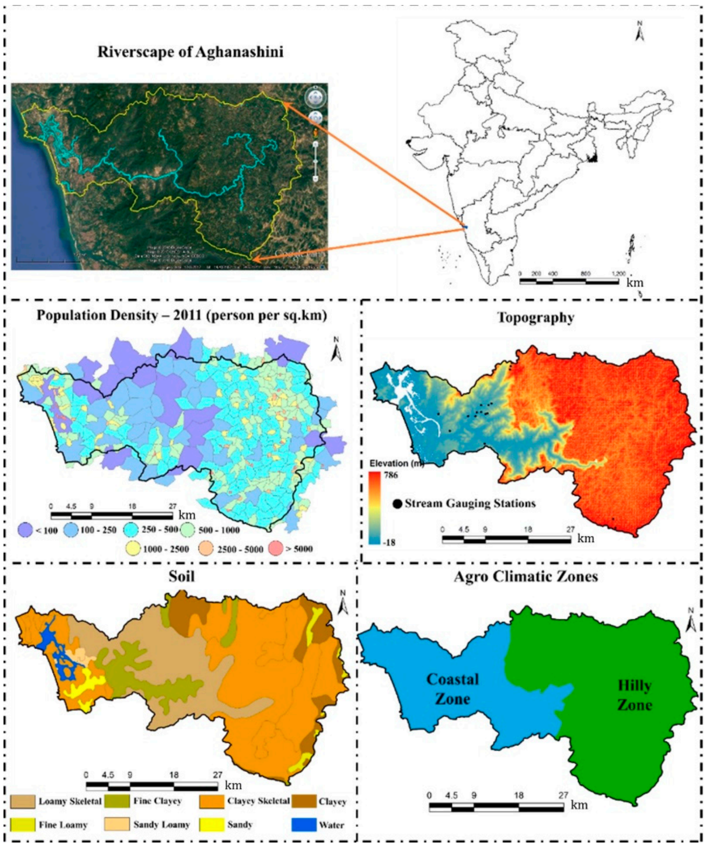


Figure 1. Aghanashini River catchment—population density, topography, soil, and agro-climatic zones.

2.2. Method

The data used for the analyses are listed in Supplementary Table S1, which were collected from the field (primary source), and secondary sources such as spatial data (Remote sensing data—RS) acquired at regular intervals through space-borne sensors [47], rainfall data [48–50], extra-terrestrial solar radiation and temperature data [51,52], temporal population data [45], livestock data [53], meteorological data [49], agriculture and crop information [44,50], topographic maps [43], virtual online remote sensing data [54,55], and catchment conditions [56]. Remote sensing data were preprocessed to eliminate positional errors, and geometric corrections were made using ground control points obtained from field (using GPS), the Survey of India topographic maps of Scale 1:50,000, and virtual earth databases [54,55]. Radiometric corrections were made to enhance the scene radiometric properties (contrast enhancement) for better interpretation of the data [57,58]. The protocol adopted for assessing the eco-hydrologic and environmental regimes (physicochemical and biological integrity) with the landscape dynamics in the Aghanashini River catchment is given in Supplementary Figure S1.

Fieldwork was carried out for 38 months (during June 2016 to May 2019) to understand the seasonal variability of the water quality and flow characteristics at sampling locations (Figure 2) in various streams across various micro-watersheds of the Aghanashini River basin in the Central Western Ghats. The data collected from the field include training data for land use analysis, flow dynamics, physical, chemical, and biological quality of water in the selected streams, hydrological regime, and ecological footprint. Flow dynamics (discharge) in select streams of the micro watershed were gauged monthly at sampling locations (Figure 2) using a current meter (or float based on site conditions) with the area velocity relationships and extrapolated to ungauged streams [56]. Water quality changes in relation to land use, flow regime, and across seasons are assessed at the sub-catchment level (Chandikaholé) through continuous field monitoring for 28 months of 9 streams.

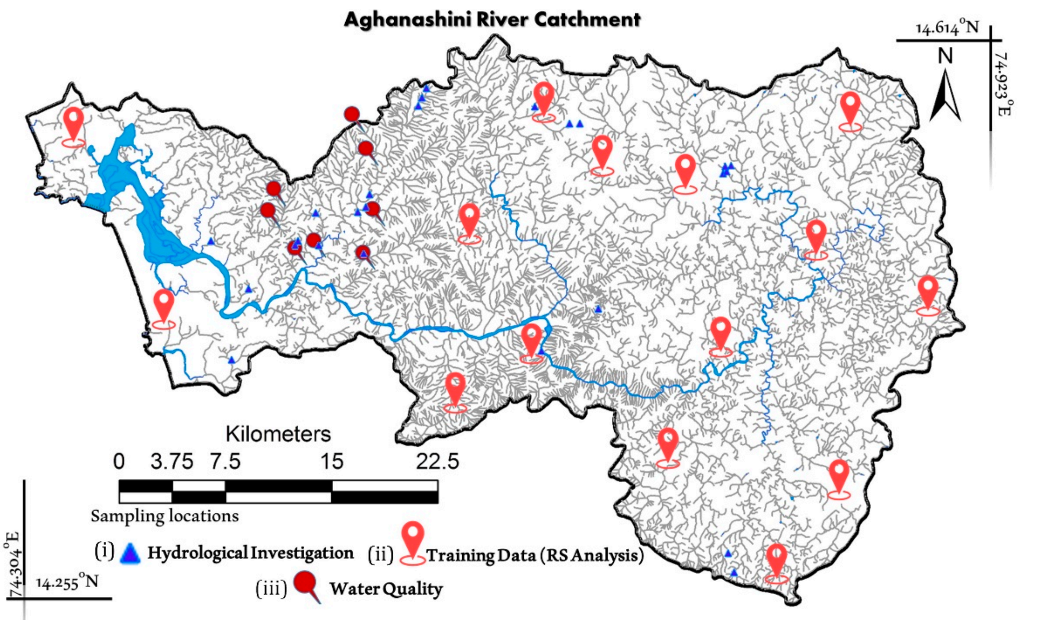


Figure 2. Locations of (i) gauging flow discharges, (ii) training data for remote sensing data analyses, and (iii) water sample collection (for assessing physical, chemical, and biological quality).

2.2.1. Land Use Dynamics

Land use analyses involved (i) generation of false-color composite (FCC) of remote sensing (RS) data (bands-green, red, and NIR). FCC helped in locating heterogeneous patches for choosing training polygons in the landscape; (ii) selection of training polygons covering 15% of the study area and polygons are uniformly distributed over the entire study area, covering all land use categories; (iii) loading these training polygons co-ordinates into pre-calibrated GPS; (vi) collection of the corresponding attribute data (land-use types) for these polygons from the field; (iv) supplementing this information with the data from the online data portal [54]; (v) 60% of the training data were used for classification; and (vi) the balance is used for validation or accuracy assessment. The land use analysis was performed using a supervised classification technique based on a Gaussian maximum likelihood algorithm with training data. Accuracy assessment (computation of Kappa statistics, overall accuracy, producer accuracy, and user accuracy) was carried out by comparing the classification output with the training data (field observations) collected using GPS [57–59].

2.2.2. Assessment of Hydrological Footprint, Ecological Footprint, and Eco-Hydrologic Footprint

Hydrological regime analyses involved the quantification of (i) run-off, (ii) infiltration, (iii) soil water availability, (iv) sub-surface (vadose) flow, (v) groundwater recharge, (vi) evapotranspiration (PET from vegetation), and (vii) assessment of the hydrologic regime as a function of various factors such as land use, precipitation, temperature, solar radiation, soil characteristics, geology, and topography [12,56,60,61]. Temporal rainfall data of all rain gauges in the catchment were compiled from India Meteorological Department (IMD) [49] and the Directorate of Economics and Statistics, GoK [50]. The average monthly and annual rainfall data [61,62] were used to understand the spatial pattern of rainfall in the study area to derive the gross yield and net yield by considering interception [56].

Stream gauging also aided in calibrating the run-off model at sub-basin levels. Run-off is computed by considering land use and rainfall based on the rational formula [56]. The physical parameters for water supply include run-off (overland flow), infiltration (subsurface and groundwater recharge), and soil water availability. After precipitation, a portion of the rainfall that flows in the streams is (i) surface run-off or direct run-off and (ii) subsurface run-off. Surface run-off refers to the portion of water that directly enters into the streams during rainfall, which is estimated based on the empirical relationships [9–11,21,22] considering run-off coefficient, depending on land uses [56].

The portion of water that enters the subsurface (vadose and groundwater zones) during precipitation depends on land cover in the catchment. During field monitoring of streams in the forested catchment, overland flow is noticed in streams only after the saturation of subsurfaces. The water stored in sub-surfaces will flow laterally towards streams and contribute to streamflow during non-monsoon periods, referred to as pipe flow (during post-monsoon) and base flow (during summer).

Water demand assessment included the societal (water for domestic purposes, agriculture, horticulture, livestock, and industrial) and ecological (to maintain the terrestrial and aquatic integrity) requirements. The societal water demand for agriculture, domestic, and livestock sectors was compiled from field observations and supplemented with secondary data from government agencies. Agriculture and horticulture demand were quantified considering crop types, cropping patterns, growth phase, and water requirements per crop. Domestic water demand was estimated considering daily water demand (Table S1). Similarly, water demand for livestock was quantified by considering animal type, population, and water requirements per animal (Table S1) [60]. Ecological (aquatic) water demand in the river is assessed by considering the flow regimes and biodiversity in micro-watersheds. Terrestrial water demand was estimated considering vegetation type-wise and actual evapotranspiration (AET) using the modified Hargreaves Method in the diverse landscape (details are given in Table S1).

Month-wise water availability and demand were computed to understand the eco-hydrological footprint. The eco-hydrologic footprint helps in understanding water-scarce deficit (supply < demand) and surplus (supply > demand) situations. The hydrological flow regime in each catchment was assessed based on field observations, and streams were categorized into four groups [60]: A (perennial streams with 12 months of adequate water), B (8 months), C (6–8 months), and D (4 months, only during the monsoon).

The ecological footprint was assessed considering biotic elements (biodiversity), i.e., flora and faunal species. The spatial distribution and species richness of plants and animals in the river catchment were compiled from the field (transect based quadrat sampling) and the published literature—books [12,20,63–67], conference papers [18,41,68,69], journals [4,15,16,18,19,41,60,70–74], and web portals [75,76].

The eco-hydrological footprint of the Aghanashini River was evaluated considering the seasonal variability of water availability and water demand. The eco-hydrological footprint, forest cover, flow regime, and species distribution were compared across sub-basins to understand the linkages and inter-relationships among hydro-ecological aspects. Based on these assessments, streams in a sub-catchment were considered for water quality assessment in relation to land use, flow regime, and other characteristics.

2.2.3. Water Quality Assessment

Water quality assessment was carried out in select streams of the Chandikaholé sub-catchment of the Aghanashini River basin (catchment id—8), and locations were chosen based on the eco-hydrological footprint, distribution of flora and fauna, and flow duration. The Chandikaholé stream originates near Yaana and joins the main river—Aghanashini at Bagribailu. Flow regime, water quality in the stream, and land uses were assessed in the micro- and macro-watersheds. Yaana, Nanalli, Beilangi, Mastihalla, and Harita are the micro-watersheds connecting Aanegundi (AGT1), whereas Aanegundi (AGT1 and AGT2) and Bialgadde (BGT) are the macro-watersheds. Aanegundi AGT1 and AGT2 join near Yaana Cross along the Sirsi-Kumta Road.

The streams in this catchment were monitored (Figure 2) for 28 months to understand the seasonal dynamics of water quality (18 physical and chemical parameters) at 9 sampling locations—Beilangi (BE), Yaana (YK), Nanalli (YNK), Harita (HA), Bialgadde (BGT), Aanegundi (AG), Aanegundi tributary 1 (AGT1), Aanegundi tributary 2 (AGT2), and Mastihalla (MH). Water temperature (WT—laboratory thermometer), dissolved oxygen (DO—Winkler's Method), discharge (current meter), electrical conductivity (EC), total dissolved solids (TDS), and pH (using Eutech: PCSTestr 35) were measured at the sampling location (on-site), while the other parameters such as total alkalinity (TA—titrimetric method); chemical oxygen demand (COD); biochemical oxygen demand (BOD); total hardness (TH) and calcium (Ca) using EDTA titrimetric method; magnesium (Mg); chloride (Cl—argentometric method); nitrate (phenol disulphonic acid method); orthophosphate (OP—stannous chloride method); sodium (Na) and potassium (K) using the flame emission photometric method were analyzed in the laboratory (off-site) according to the standard protocol [1,23,30,31,37,61]. Based on the temporal data, using a weighted arithmetic method, the water quality index (WQI) was computed [40,61,72] season-wise across sampling locations considering physicochemical parameters such as dissolved oxygen, electrical conductivity, total dissolved solids, pH, total alkalinity, total hardness, calcium, magnesium, chloride, and nitrate [40,61,72,73]. Water quality is graded as excellent (for WQI = 0 and 25); good (for WQI = 26–50); poor (for WQI = 51–75); very poor (for WQI = 76 and 100); and unfit for drinking (WQI > 100).

Multivariate analysis of season-wise and sampling location-wise water quality data through Pearson's correlation coefficient (r), CA, and PCA was carried out using PAST software [35,37,42,61,62] to understand the contributing factors of pollution. PCA of water quality parameters [37] of nine streams was performed, and the scree plot shows principal components explaining variance. Components with an eigenvalue >1 were considered significant, while <1 were omitted from further analysis.

3. Results and Discussion

3.1. Land Use Dynamics

Land uses in the Aghanashini River catchment are depicted in Figure 3, and details with the accuracy of classification are listed in the Supplementary Table S2, which reveals a decline in forest cover from 86.06% (in 1973, 71.65% evergreen and 14.41% deciduous types) to 50.78% (in 2018, 23.95% evergreen and 26.83% deciduous).

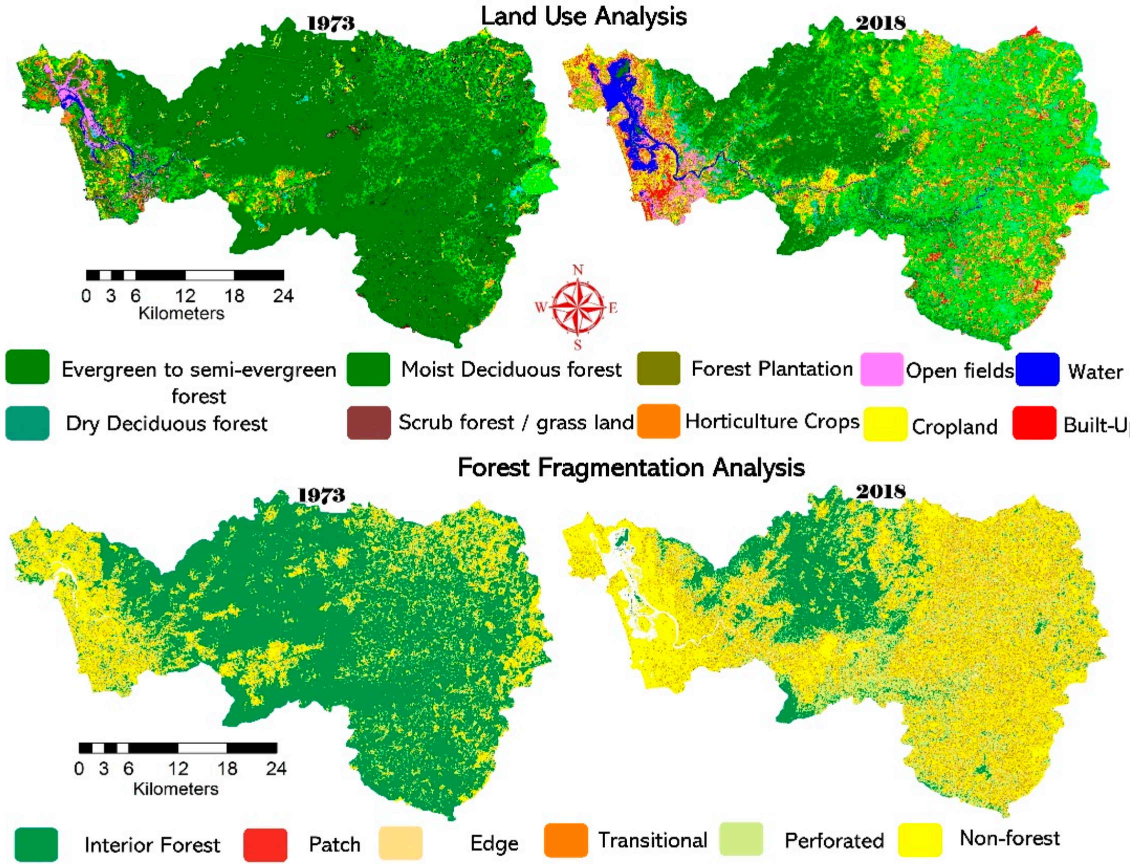


Figure 3. Land uses and extent of forest fragmentation in the Aghanashini River catchment.

The catchment is also witnessing the expansion of the commercial monoculture plantations (22.04%) of Acacia, Eucalyptus, and Arecanut, requiring a high quantity of water, evident from field observations of sustained water pumping and falling groundwater levels. Agriculture is practiced in the transition zones of Sirsi, the coastal areas of Kumta, followed by the Ghats, having patches of paddy cultivation (16.18%). Horticulture is prominent along the valley zones. Built-up areas constitute about 4.88% of the land use and are concentrated in towns—Kumta and Sirsi. Forest fragmentation analyses reveal a decline in interior forest cover from 66.30% (1973) to 17.76% (2018). The non-forest area now occupies about 49.34% (2018).

3.2. Assessment of Hydrological Footprint, Ecological Footprint, and Eco-Hydrologic Footprint

Spatio-temporal analyses show that annual rainfall ranges from <3000 mm in the transition zone to >5000 mm in the Ghats and about 4000 mm in coastal zones. Figure 4 depicts the variability in rainfall across space and time. The Southwest monsoon caters to more than 80% of the total, which occurs during June and September, with the highest precipitation during the month of July.

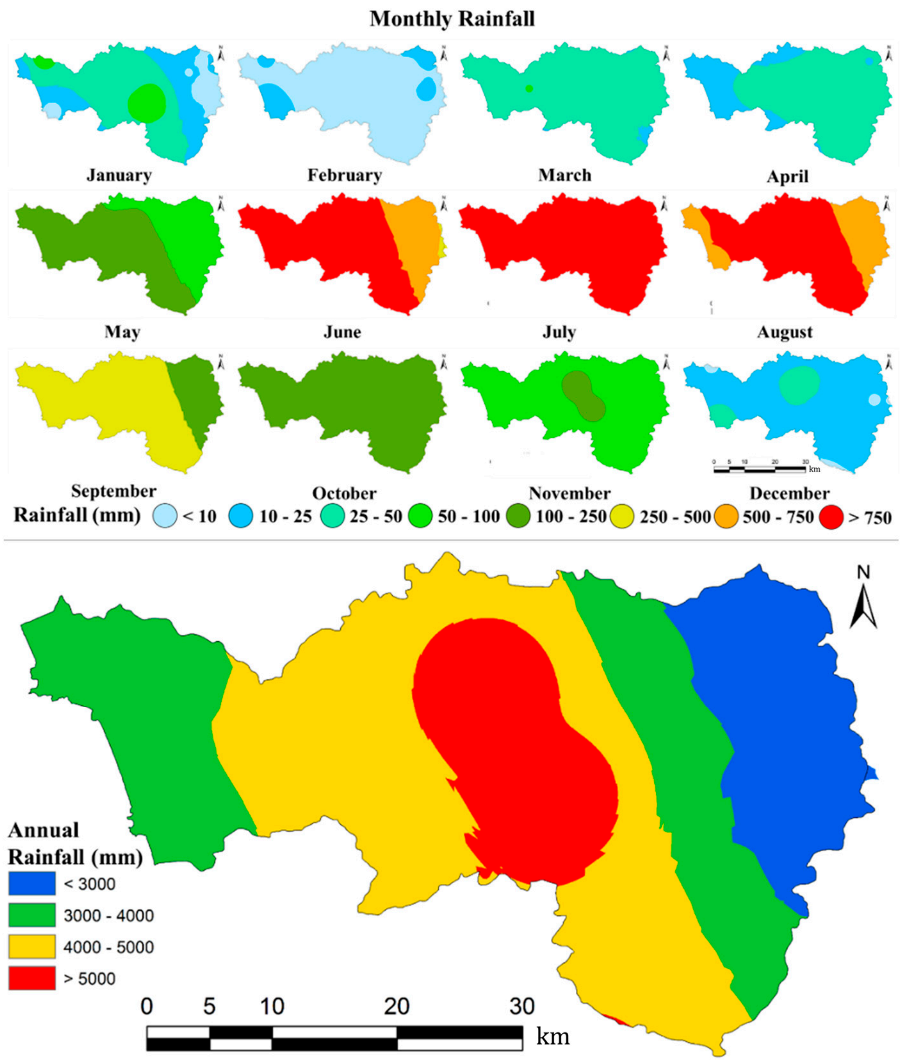


Figure 4. Spatio-temporal rainfall dynamics in the Aghanashini River basin.

Hydrological assessment in the Aghanashini River basin shows that gross annual rainfall in the catchment is about 3020 mm. Interception losses in the basin range between 651 mm and 1490 mm, with an average of 1042 mm. The Aghanashini River catchment has a forest cover of 60%. The run-off in the basin is about 766 mm, accounting for 1164 million cubic meters, and the balance is infiltrated, i.e., over 60% of the net rainfall is infiltrated, by the recharging subsurface (vadose and saturated zones) contributing to the subsurface flows (pipe flow and baseflow) during the non-monsoon period. Infiltration in the catchment is about 2412 million cubic meters, and the subsurface flow is about 455 million cubic meters, which caters to the water demand during all months.

The sector-wise water demand reveals that agriculture and horticulture sectors in the catchment require about 606 million cubic meter, domestic water (societal demand) is about 5.8 million cubic meter, and water required for livestock rearing is 3.8 million cubic meter. The environmental water demand includes terrestrial and aquatic ecosystems' demand. Terrestrial water demand is the water requirements of vegetation, i.e., AET from natural vegetation (forests), and is about 937 million cubic meter. The minimum water-sustaining biota during lean seasons in the aquatic ecosystem is about 483 million cubic meter, quantified based on field investigations, which constitutes about 30% of the total flow and is comparable to similar studies in the neighboring Sharavathi, Kali, and Gangavali river basins [21,26,41,60].

The assessment of the eco-hydrological footprint at the sub-catchment level was carried out considering (i) the biotic demands of blue water demand (agriculture, domestic, livestock, and aquatic ecological needs) and green water demand (evapotranspiration) and (ii) the hydrologic regime considering the surface (overland) flow and subsurface (vadose and saturated zones) flow (pipe and baseflow) [21].

The eco-hydrological analysis sub-basin wise in the Aghanashini River catchment indicates that native forests enable a higher infiltration compared to degraded landscapes, which is explained through eco-hydrological indices (EHI), presented sub-basin wise in Supplementary Table S3. Sub-watersheds with native vegetation have a higher EHI (greater than 1), indicating higher infiltration and storage than water withdrawal due to evapotranspiration, sufficient to meet societal water requirements. The study highlights that native vegetation forests play a decisive role in retaining the water in the catchment through infiltration to sub-surface regions, which helps cater to ecological and societal demands.

The eco-hydrological footprint in the Aghanashini River basin at the sub-catchment level is illustrated in Figure 5. The hydrological footprint shows the water scarcity situation in sub-catchment 1 (in the eastern transition zones towards Sirsi town). In contrast, sub-catchments in the Ghats and Coasts (i.e., 2 to 9) show sufficient water status, catering the societal (domestic, irrigation, horticulture, and livestock) and ecological needs. The dense forest cover of native species in hilly regions (Ghats) has enhanced the water retention capability (through infiltration), which caters to the respective sub-basins' societal and ecological water demand.

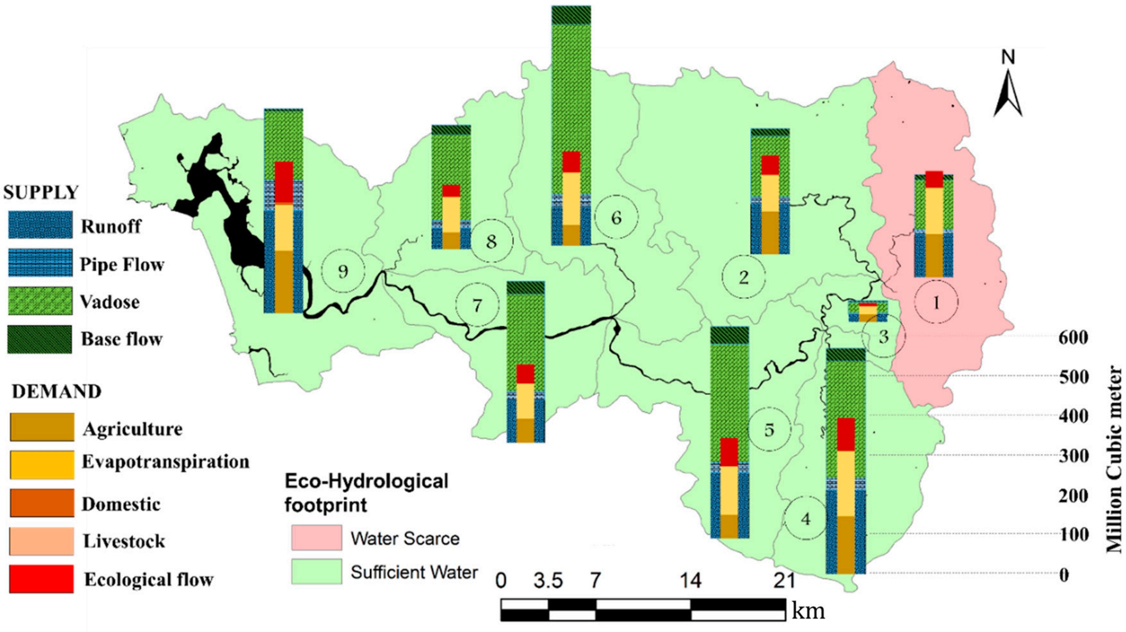


Figure 5. Eco-hydrological footprint of Aghanashini River.

Streams were classified based on the duration of water flow and quantum as perennial (with 12 months of flow or Category A), intermittent (6–8 months of flow, Category B or C), and seasonal (4 months during the monsoon, Category D). The streams are perennial when their catchment is dominated by native species of vegetation (>60%). This is mainly due to infiltration or percolation in the catchment as the soil is porous with native species. Diverse microorganisms interact with plant roots and the soil, which helps transfer nutrients from the soil to plants and make the soil porous [21]. Soil samples of perennial stream catchments have the highest moisture content (61.47 to 61.57%), higher nutrients (C, N, and K), and lower bulk density (0.50 to 0.57 g/cc). In comparison, soil samples from intermittent and seasonal stream catchments had higher bulk density (0.87–1.53 g/cc) and relatively lower nutrients. Figure 5 confirms the role of native forests (contiguous or interior forests) in sustaining the water, evident from the occurrence of perennial streams compared to the intermittent or seasonal streams in the catchment dominated by degraded forest patches.

Flow assessment in sub-catchments of Aghanashini indicated that forests, monoculture plantations, and agriculture played a significant role in regulating the quantum and duration of flow in streams. In sub-catchment 1 (i.e., the transition regions near Sirsi town), the catchment is dominated by monoculture plantations. The flow duration in streams is 8 to 9 months (i.e., category B). In contrast, most of the streams in other sub-catchments had water for 12 months (perennial), highlighting the role of native vegetation (Figure 6) in sustaining water throughout the year. Hence, the study emphasizes the need to maintain native vegetation cover (of >50%) in catchments of streams and rivers to sustain water during all seasons.

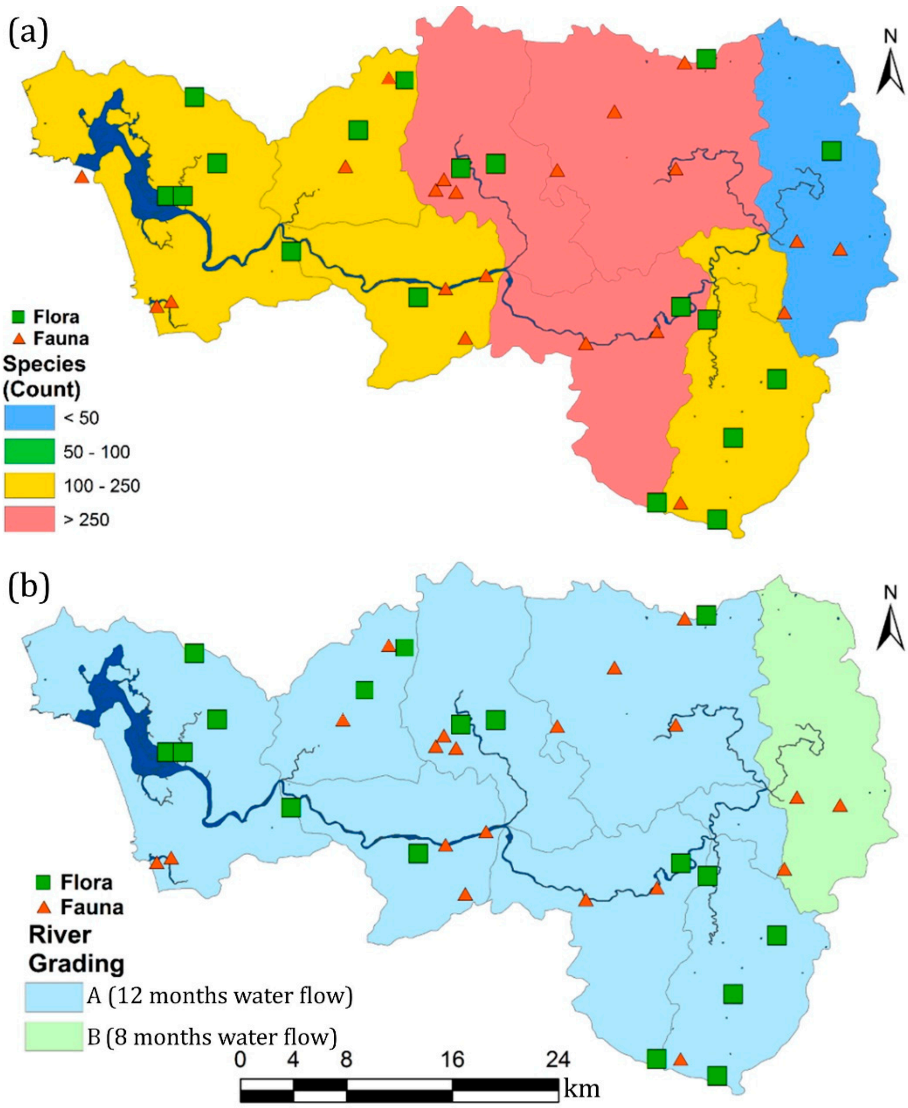


Figure 6. (**a**) Species distribution, (**b**) species distribution with the water availability—Ecology and hydrologic regime linkages in the Aghanashini River basin.

Figure 6 also depicts the distribution of endemic flora and fauna (threatened categories—critically endangered, endangered, vulnerable, and near-threatened) across sub-basins in the river catchment. Biodiversity, ecology, and hydrology linkages with the land-use dynamics in sub-catchments are evident from the comparative analyses of interior forest cover, flow duration, eco-hydrological footprint, and species distribution.

Contiguous forests with native vegetation species have aided in sustaining the water demand (ecological and societal) and supported diverse taxa, evident from the occurrence of rare and unique endemic and endangered taxa in the region. The river catchment with the numerous swamps (Myristica) and endemic taxa habitats constitute the hottest biodiversity hotspot. The current study conforms to the earlier research investigations across major rivers focusing on diatom species and land cover dynamics in the catchment [21]. The Aghanashini River basin supports the host of diverse epilithic diatoms: *Achnanthes minutissima*, *Achnanthidium* sp., *Brachysira neoexilis*, *Brachysira* sp., *Brachysira wygaschii*, *Cocconeis placentula*, *Cymbella* sp., *Eunotia minor*, *Eunotia rhomboidea*, *Fragilaria biceps*, *Fragilaria ulna*, *Gomphonema difformum*, *Gomphonemadi minutum*, *Gomphonema gandhii*, *Gomphonema parvulum*, *Gomphonema* sp., *Navicula cryptocephala*, *Navicula leptostriata*, *Navicula* sp., *Navicula symmetrica*, *Planothidium frequentissimum*, and *Planothidium* sp. [77,78]. The study highlights that the catchment's integrity determines the diatom species composition and water quality in the streams.

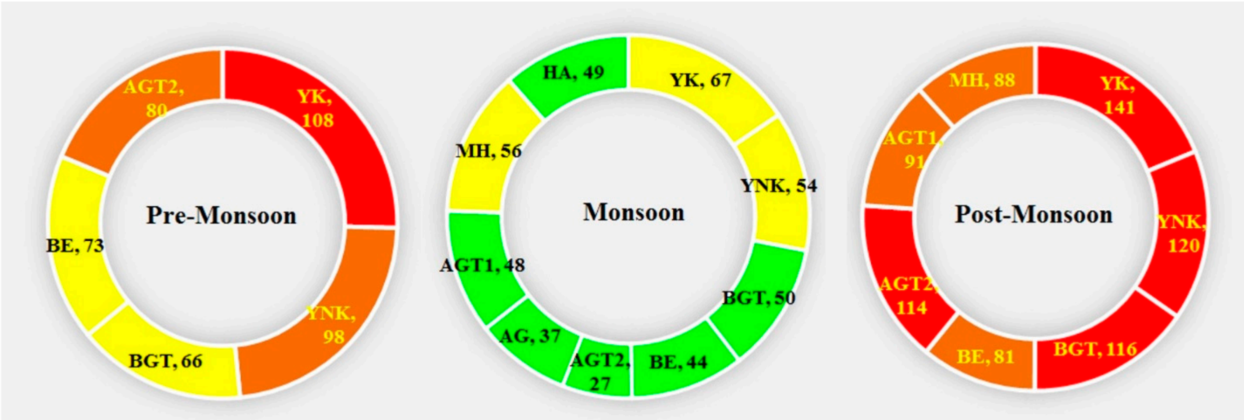
3.3. Assessment of Water Quality and Composition

The physicochemical assessment (18 parameters) reveals that the water quality parameters varied across sampling stations during the study period. The average values of physicochemical parameters at different sampling sites are presented in Supplementary Table S4. Yaana (YK) has the highest pH, total alkalinity, total hardness, calcium, and magnesium among the sampled locations. In contrast, AG has the least TDS, EC, total alkalinity, pH, total hardness, calcium, magnesium, and nitrate. Variations in pH depend on the amount of carbonate, bicarbonate, and free carbon dioxide in the water [79]. An increase in the number of ions increases the TDS, EC, and total hardness. The increase in total solids concentration is attributed to clay and silt particles in stream water [80]. Higher alkalinity in water indicates higher amounts of hydroxides, carbonates, nitrates, phosphates, and sulphates [81]. Dissolved oxygen in water bodies depends on temperature, streamflow, aeration, photosynthetic rate, and the presence of organic matter [82,83]. Orthophosphate and nitrate are limiting nutrients that decide the productivity of freshwater ecosystems. An increase in nitrate and phosphate occurs due to inputs from nearby agricultural fields, and an increase in water velocity at the downstream improves water quality [84].

Pearson's correlation coefficient (r) was computed with *p*-values to understand the relationship among physicochemical parameters [85], which reveals that TDS is strongly positively correlated with EC, pH, total hardness, total alkalinity, calcium, and magnesium (refer Supplementary Table S5). TDS increases with EC because the charged ions (cations and anions) conduct electricity [86]. Correlation analyses reveal that (i) EC is positively correlated with pH, total alkalinity, total hardness, calcium, and magnesium; (ii) pH is positively correlated with total alkalinity, total hardness, calcium, and magnesium; and (iii) total alkalinity are positively correlated with total hardness, calcium, and magnesium. Hardness is caused by cations such as calcium and magnesium and anions such as carbonate, bicarbonate, and chloride. BOD and COD are used to assess organic matter present in both suspended and dissolved forms in water [87].

Wide seasonal variation is observed in the physicochemical parameters across monitored locations. Parameters such as turbidity, DO, orthophosphate, BOD, and COD were high during monsoon due to turbulence and the transport of sediments through run-off. In contrast, the pH was alkaline in the post-monsoon season due to the photosynthetic activities of algae. Water temperature, total alkalinity, total hardness, calcium, magnesium, and chloride were high in the pre-monsoon with high evaporation and low water level. The varied water quality across seasons in monitored locations is due to changes in water quantity, flow, weather, and land use in the catchment.

Figure 7 provides the season-wise WQI of monitored streams. During the monsoon season, YK, YNK, and MH showed poor water quality [87–89]. Other sites such as BGT, BE, AGT2, AG, AGT1, and HA showed good water quality [90–92]. Monitoring sites YK, YNK, BGT, and AGT2 showed a water quality status unsuitable for drinking [92,93], whereas sites such as BE, AGT1, and MH showed inferior water quality in the post-monsoon season [87,92]. YK reflected a water quality status unfit for drinking [94,95]; BE and BGT had poor water quality [95,96]; and YNK and AGT2 had inferior water quality during the pre-monsoon season [97,98]. Increased pollutants, reduced river flow, and agricultural run-off govern stream water quality [97,99,100].



Colour Code					
WQI	0–25	26–50	51–75	76–100	>100
Water Quality Status	Excellent water quality	Good water quality	Poor water quality	Very poor water quality	Unsuitable for drinking

Figure 7. WQI of monitored streams during pre-monsoon, monsoon, and post-monsoon seasons.

Cluster analysis (CA) grouped sampling sites based on the similarity of water quality [101,102]. Hierarchical cluster analysis [103–105] yielded a dendrogram (Figure 8) that grouped nine sampling sites into three clusters (G1, G2, and G3) based on the similarity of their physicochemical characteristics. Here, G1 has less polluted stations such as YNK, BGT, AGT2, AGT1, and MH, with a lower quantum of all parameters except sodium. G2 has moderately polluted stations such as BE, AG, and HA with higher physicochemical parameters (such as WT, turbidity, COD, BOD, chloride, orthophosphate, and potassium), and discharge. Station G3 (YK) has higher values for physicochemical parameters (such as EC, TDS, pH, total alkalinity, total hardness, calcium, magnesium, DO, and nitrate) due to the inherent catchment properties. Yaana [YK] is a tourist location prone to unregulated anthropogenic activities and waste (liquid and solid) mismanagement.

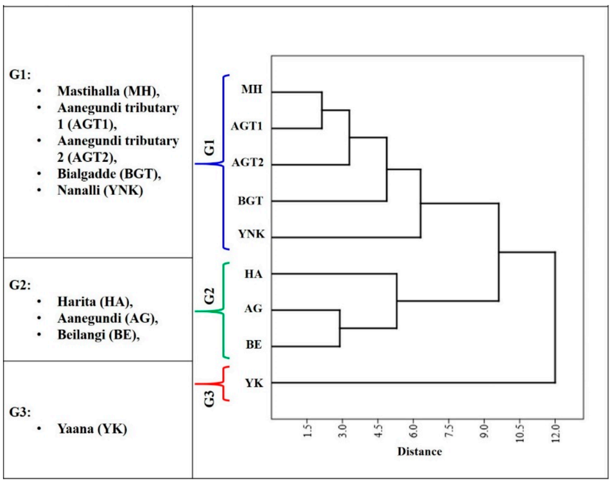


Figure 8. Dendrogram highlighting grouping of monitored streams based on physicochemical characteristics.

PCA was performed considering 17 variables, which include (i) physicochemical parameters, (ii) land use (Built-up: BU; Evergreen Forest: EF; Deciduous Forest: DF; Forest Plantation: FP; Horticulture: Horti and Agriculture: Agri), and (iii) catchment characteristics (Flow Duration: FlowD) (Supplementary Table S6). The PCA yielded four principal components, which accounted for 90.68% of the total variance. The first component, PC1 explained about 49.75% of the total variance and had positive loading on EC, pH, DO, total alkalinity, total hardness, evergreen forest, and flow duration (Table S6), whereas there was negative loading on the deciduous forest. The decomposition of litter and the leaching of ionic contents (Na^+, K^+, Mg^{2+}, Ca^{2+}, and Cl^-) in forested watersheds alter the stream water quality [106]. These ions increase the EC, hardness, alkalinity, and pH of water, which favors algae growth and eventually increases DO levels. The second component, PC2 explains about 23.05% of the total variance and has positive loadings on nitrate, built up, orthophosphate, and turbidity, whereas it has negative loadings on forest plantation. This is attributed to pollution from domestic sewage that increased the nutrient levels. The third component, PC3, was responsible for 11.35% of the total variance and had positive loadings on agriculture, horticulture, BOD, and COD. This factor represented pollution from untreated/raw non-point domestic discharge that increased organic matter levels. The fourth factor, PC4, was responsible for 6.54% of the total variance and had positive loadings on agriculture, orthophosphate, and DO. This factor highlights pollution due to agricultural run-off. The input of pesticides and synthetic fertilizers from agricultural fields altered the chemical integrity of pristine water resources, affecting the hydrology and ecology [66]. The land-use changes with enhanced anthropogenic activities have altered run-off patterns and flow regimes [107–109]. Vegetative cover, topography, slope, and quantum of rainfall in a catchment decide flow in streams [108,110–114], evident from the increased annual surface run-off of 45 $\pm$ 14% with the conversion of forest landscape to other land uses (decline of forests by 49.34% with an increase in built-up, and open area).

4. Conclusions

Riverine ecosystems are disturbed by human interference. The current study affirms that burgeoning anthropogenic activities resulted in the loss of contiguous interior forest cover, leading to forest fragmentation and the decline of ecologically sensitive habitats. The area under non-forest has increased to 49.34% (in 2018). Field investigations and subsequent data analyses reveal that factors such as the type of forest cover, monoculture plantation, and agriculture played a crucial role in sustaining the water in the ecosystem, evident from the flow regime. The sub-watersheds in Aghanashini with native vegetation had higher eco-hydrological indices (EHI). The eco-hydrological footprint assessment at the sub-watershed level reveals that native vegetation forests in the catchment sustain water. The relationship is evident from water availability during all 12 months in streams with a native vegetation cover of >60% in the catchment, compared to the seasonal streams in the catchment with a vegetation cover of <30%. The study highlights that streams are perennial in the catchment with a native forest cover of >60% and a higher number of endemic plant species, confirming the linkage between ecology and hydrology with land-use dynamics. The hydro-ecological investigation provides invaluable insights into the need for integrated approaches in river basin management in an era dominated by mismanagement of river catchments with the enhanced deforestation process, inappropriate cropping, and poor water use efficiency. The premium should be on conserving the remaining evergreen and semi-evergreen forests, which are vital for water security (perennial streams) and food security (sustenance of biodiversity).

Pearson's correlation coefficient revealed a high correlation among ionic parameters. The WQI results represented in a single number enabled the assessment of overall water quality during the monsoon, post-monsoon, and pre-monsoon seasons. Multivariate statistical approaches applied to water quality data of streams in Chandikaholé's sub-catchments of the Aghanashini River basin helped to understand pollution sources and site suitability. Streams were categorized as less polluted, moderately polluted, and highly polluted sites based on their similarities in the water quality variables after the cluster analysis. A principal component analysis revealed that EC, pH, DO, total alkalinity, total hardness, evergreen forest, and flow duration play a crucial role in streams. The current study provides insights into the role of forests with native species in sustaining the local demand by maintaining the hydrological regime and preserving water quality, which is helpful in the watershed (catchment or basin) management by the respective government agencies.

The research outcome helps in developing the appropriate mitigation measures to maintain river basins' ecological and hydrological integrity to sustain water. In addition, it helps in communicating with the public and decision makers to implement prudent management of the catchment through participatory approaches involving all stakeholders.

The current study is based on monitoring a free-flowing river in the Western Ghats, with the hot moist sub-humid climate regime (with a catchment of 1449 km^2), which has to be validated for the larger spatial extent river catchments covering diverse agroclimatic regime. The next phase of the research focuses on applying this protocol for the Krishna River catchment with the wider agroclimatic regime and across administrative regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14060977/s1, Figure S1: Method for eco-hydrological and environmental regime assessment; Table S1: Details of data with sources; Table S2: Category-wise land use (with accuracy assessment) and forest fragmentation extent (in percentage); Table S3: Sub-basin wise forests and eco-hydrological status; Table S4: Average values of physicochemical parameters at different sampling sites; Table S5: Correlation coefficient matrix of water quality parameters of streams; Table S6: Loadings of 17 variables extracted from PCA.

Author Contributions: T.V.R. designed the experiments, finalized field experiments, funding acquisition, writing of the manuscript, editing, and final review; V.S. collected experimental data of hydrologic regime, spatial data analyses, a draft of the part of the manuscript; A.K.S. and S.V. collected field data (water quality), field samples analyses, data analyses, writing a part of the manuscript; B.S. carried out land use and fragmentation analyses using remote sensing data, compiled flora and fauna details, and wrote those sections in the manuscript; B.H.A. completed the manuscript writing, and review. All authors have read and agreed to the published version of the manuscript.

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