INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **38**: 2265–2279 (2018)
Published online 6 November 2017 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.5333

Regional climate trends and topographic influence over the Western Ghat catchments of India

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ABSTRACT: This study investigates the role of elevation stratification and climate change on the hydrology of Western Ghat catchments during the period from 1951 to 2013 using gridded data. The trend analysis of rainfall and temperature was conducted using the Mann–Kendall trend test, and the hydrological modelling of the rivers was conducted using the Soil and Water Assessment Tool (SWAT) model. To characterize the spatial distribution of rainfall and streamflow based on elevation stratification, contemporary rainfall zones were delineated and the response of each zone was evaluated. The results indicated that the maximum rainfall occurs at certain distance on the windward side from the crest of the Western Ghats. On the leeward side (eastern plateau), the rainfall is maximum at crest (Western Ghats) and decreases with distance. The rivers in the southern portion of the Western Ghats of India were highly vulnerable to changing climate followed by the central portion. The annual and monsoon rainfall in the southern river decreased at 0.43 and 0.30% decade^{-1} (1% significance level), respectively. The summer rainfall in the river of the central portion (Netravathi River) decreased at 0.44% decade^{-1}. The annual air temperature of the southern river catchment (Vamanapuram) increased at the rate of 0.12 °C decade^{-1} (at 0.1% significance level), and the air temperature of the central rivers increased at the rate of 0.09, 0.08, and 0.07 °C (0.1% significance level), respectively. The streamflow response of the southern and central rivers was discernible as the monsoon flow decreased at 37% decade^{-1} (0.1% significance level) in the southern river and 10% decade^{-1} (5% significance level) in the central river. Interestingly, the pristine Aghanashini River demonstrated resilience to climate change with an increase in annual rainfall and streamflow at 115 mm decade^{-1} (5% significance level) and 0.71 Mm^3 decade^{-1} (0.1% significance level), respectively.

KEY WORDS climate change; elevation stratification; Mann–Kendall; rainfall; resilience; streamflow; SWAT; Western Ghats of India

Received 2 March 2017; Revised 1 October 2017; Accepted 4 October 2017

1. Introduction

The rivers in the montane regions have pronounced hydrologic regimes and are concomitant with local weather and characteristics of regional climate (Stanford and Ward, 1993; Montgomery *et al.*, 1996; Church, 2015). The microclimatic properties mostly depend upon topographic features such as slope and aspect. The heterogeneous rainfall patterns along with physical habitats and vegetation are highly influenced by the varying topography in the mountain systems (Montgomery and Buffington, 1997; Niu and Yang, 2004; Beniston, 2006; Poulos *et al.*, 2012). The temperature and orographic effects of the montane regions influence the magnitude of precipitation, and studies report as much as five times more precipitation in the higher elevations (Sinclair, 1994; Katzfey, 1995a, 1995b; Rolland, 2003; Roe, 2005; Lundquist and Cayan, 2007; Minder *et al.*, 2010). The streams and rivers originating in the montane regions alternate between canyon and floodplain segments, and the local elevation, topography, and meteorological characteristics heavily influence the generation of streamflow (Hunsaker *et al.*, 2012).

The Western Ghats of India are pivotal in the moderation of tropical climate in the Indian region. The Indian monsoon is highly influenced by the Western Ghat mountains and its characteristic forest ecosystems. In addition, it is the best described tropical monsoon system. The mountains intercept the rain-bearing winds from the southwestern direction during late summer (June–September) and the region reveals extensive variation in the spatial distribution of rainfall. The understanding of weather conditions is quite challenging in the region due to the undulating terrain and lack of site-specific data. Several studies were conducted to understand the prevalent conditions and trend of climatic variables in the Western Ghats of India. The study by Kumar *et al.* (2010) revealed an increasing trend of annual rainfall along the northern and central portion of the west coast of India (by 7–8% decade^{-1}) and decrease by 1% decade^{-1} in the southern portion. The findings of the study were, however, limited due to less number of rain gauges in the northern and central portion. Jain and Kumar (2012) report a decrease in the annual rainfall as well as annual rainy days over the west coast of India. An attempt to study the trend of extreme rainfall over a

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river catchment of the Western Ghats revealed a decrease in the heavy precipitation events (intensity >100 mm) and increase in light showers (Babar and Ramesh, 2014). The study by Mudbhatkal *et al.* (2017) compared the hydrological impacts of climate change in west and east flowing rivers of the Western Ghats of India. The study revealed an increasing trend of rainfall and streamflow in an east flowing river and a decreasing trend of rainfall and streamflow in the west flowing river. The present study therefore examines the trend of climatic variables over river catchments representing the entire stretch of the Western Ghats of India.

The study by Bhowmik and Durai (2008) demonstrated the underestimation of rainfall over the Western Ghats in four models used by the India Meteorological Department (IMD). The study pressed the need for incorporating the influence of orography in the proverbial southwestern monsoon of India. The rainfall along the western coast of India is attributed to the Western Ghats, and the spatial distribution of rainfall over the region is demonstrated in the study conducted by Sijikumar *et al.* (2013). The study uses rainfall obtained from the Tropical Rainfall Measuring Mission (TRMM) and the simulations of the Advanced Research Weather Research and Forecasting (AR-WRF) model in demonstrating the spatial distribution. The numerical models of the European Centre for Medium-Range Forecasts (ECMWF) with the improvised topographic definition are quite reasonable in predicting heavy rainfall rates in the Western Ghats of India (Basu, 2005). Although the study evaluated the models of the National Centre for Medium Range Weather Forecasting (NCMRWF) and ECMWF and reported errors in the magnitude of heavy rainfall and rainfall forecast along ridgelines, the rate of rainfall was reasonably predicted. Hence, the present study examines the spatial distribution of rainfall considering the topography of the Western Ghats of India.

The correlation of the rain gauge station based on rainfall and elevation was attempted in a study by Raj and Azeez (2010), which illustrates the intensification of rainfall due to valleys, elevations, and topographical features in the Pallakad gap of the Western Ghats. The study also shows decreasing rainfall due to deforestation. The difficulty in relating topography with rainfall distribution and identification of homogeneous rainfall intensities in coastal districts of Karnataka and Kerala are reported by Simon and Mohankumar (2004) and Venkatesh and Jose (2007). The study by Simon and Mohankumar (2004) reports less than 75% rainfall from the southwestern monsoon on the leeward side of the apex regions. The lack of spatial coverage of rain gauges in the Western Ghats limits the study of rainfall in the rugged terrain, and a combination of satellite observations is attempted in the study of elevation dependence of rainfall (Bhowmik and Das, 2007; Tawde and Singh, 2015). The satellite-based rainfall products (such as TRMM) require regional-scale calibration and are able to detect the distribution of rainfall spatially, but the intensities of rainfall are underestimated along the coastal region of the Western Ghats (Mitra *et al.*, 2009). The streamflow records used in climate change studies for hydrologic model calibration and trend detection integrate the water from all of the tributaries across spatial and temporal distributions of precipitation and large variation in elevation and vegetation (Muttiah and Wurbs, 2002; Barnett *et al.*, 2004; Stewart *et al.*, 2005; Christensen and Lettenmaier, 2007; Hamlet and Lettenmaier, 2007; Rauscher *et al.*, 2008; Luce and Holden, 2009; Stewart, 2009; Fritze *et al.*, 2011; Tang and Lettenmaier, 2012). These streamflow records are very useful in understanding their integrated response, and the present study is an attempt to characterize streamflow generation in river catchments with a distinct change in the elevation profile.

The northern and central parts of the Western Ghats of India are predicted to be more vulnerable to climate change, and the temperature rise is expected to increase disproportionately higher than rainfall (Gopalakrishnan *et al.*, 2011), which supports the need for the present study in the evaluation of streamflow sensitivity to elevation and regional-scale warming. The present study examines the role of elevation stratification (topography) and climate change on the hydrological response of catchments. The investigation was conducted by focusing on (1) identification of the contemporary rainfall zones in one of the catchments (Aghanashini) using long-term meteorological variables from 1951 to 2013; (2) the trend analysis of meteorological variables in each rainfall zone and the streamflow pattern observed and the response of rainfall, temperature, and streamflow to elevation stratification and climate change; and (3) the extension of the investigation to five other river catchments along the Western Ghats of India starting from Gujarat state in the north to the southernmost river of Kerala state in the south. The investigation also focusses on the suitability of the regional network of weather stations and river gauges for predicting the hydrological impacts of climate change.

2. Regional setting of the study area

The Western Ghats of India are the mountain ranges along the west coast of the Indian subcontinent. The ranges of the Western Ghat extend from 8°30′N to 21°0′N and 73°0′E to 77°30′E starting from Gujarat state in the north to Tamil Nadu in the south. These ranges pass through the states of Gujarat, Maharashtra, Goa, Karnataka, Kerala, and Tamil Nadu for a length of approximately 2300 km and are as wide as 100 km at some places. Five rivers were selected for investigation representing the north, central, and southern parts of the Western Ghats of India (Figure 1). The Purna River originates in the Western Ghats region of Maharashtra and flows through the Maharashtra and Gujarat states of India to join the Arabian Sea. It is one of the northernmost rivers of the Western Ghats of India. The river traverses over a length of 180 km and spreads over 1655 km^2 and is gauged at Mahuva.

The second river is Aghanashini (Tadri), which is an independent west flowing river originating from the Western Ghats of India in Karnataka. The Aghanashini River is

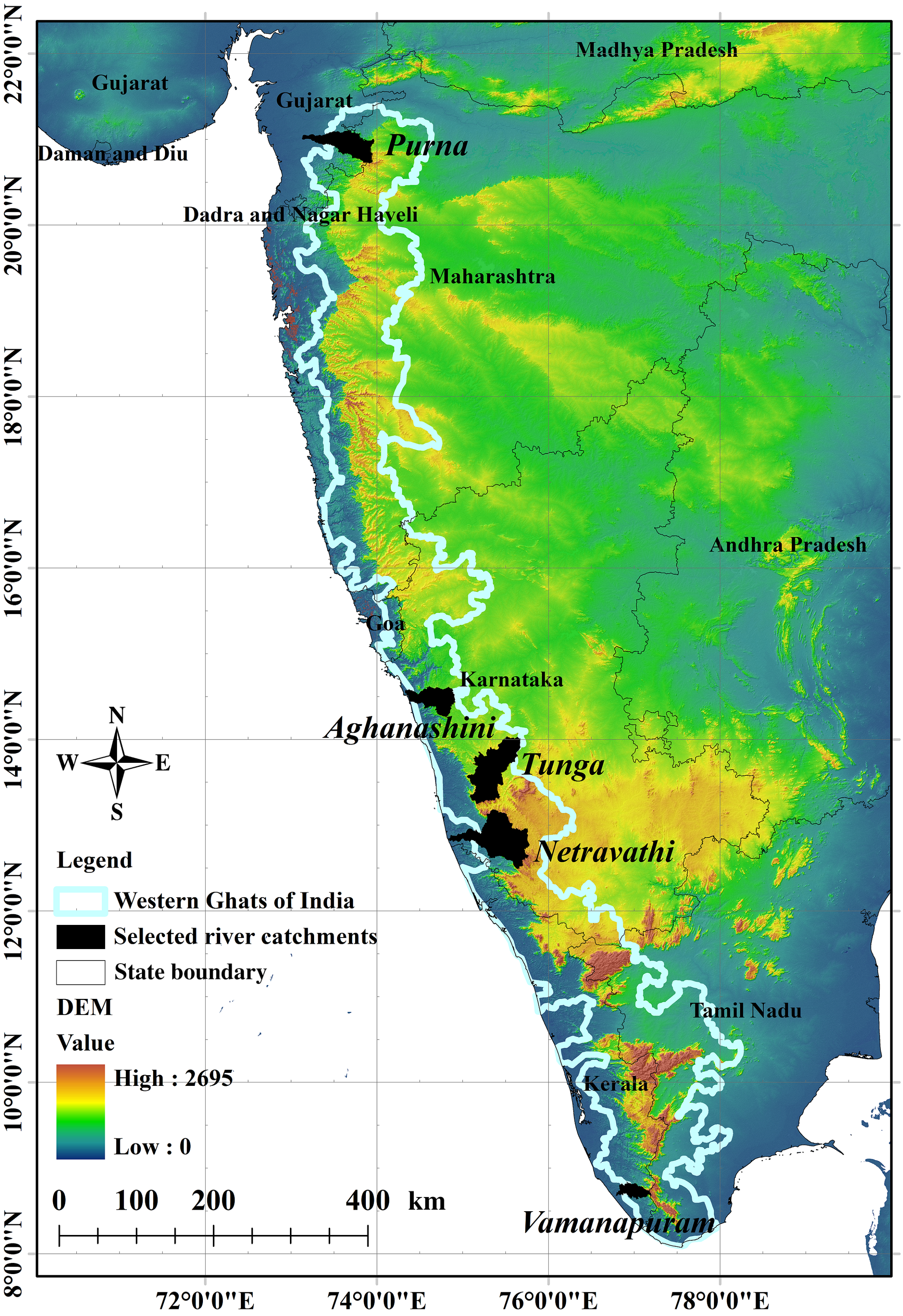

Figure 1. Location map of the rivers in the Western Ghats. [Colour figure can be viewed at wileyonlinelibrary.com].

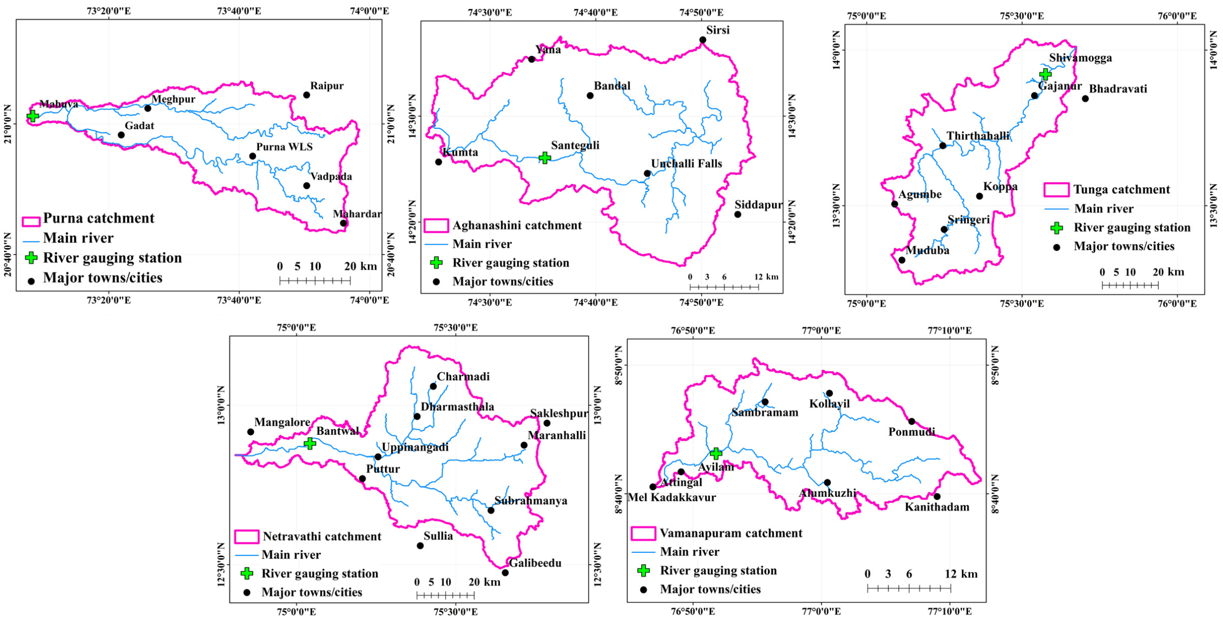

Figure 2. Major drainage of Western Ghat rivers. [Colour figure can be viewed at wileyonlinelibrary.com].

the main focus of this study. The river originates in Gadihalli (Sirsi taluk) at an elevation of 700 m above mean sea level (msl) and flows approximately 117 km before joining the Arabian Sea. The Aghanashini River is gauged at Santeguli and has no major diversions, dams, withdrawals, or industrial establishments, and there is little alteration of the landscape (1.5% built-up area). The mainstream of the Aghanashini is one of the longest free-flowing and most pristine west flowing rivers along the west coast of India.

The third river, Tunga, is a tributary of the Tungabhadra River in the Krishna basin. Tunga is an east flowing river originating in the Western Ghats at the Chikmagalur district of Karnataka and is gauged at Shivamogga. The river has a catchment area of 2922 km^2 and flows for 150 km before it merges with Bhadra River (another tributary of the Krishna River). The Netravathi River is the other west flowing river considered in the southern part of the Karnataka state. The river flows for approximately 125 km before joining the Arabian Sea and has a catchment area of 3351 km^2 and is gauged at Bantwal. The Vamanapuram River is the southernmost river catchment considered in the Western Ghats of India in Kerala. It is also the southernmost west flowing river of Kerala state with a catchment area of 541 km^2 and is gauged at Ayilam. The river joins Kadinamkulam Lake after flowing for 90 km. The drainage map of the river catchments is presented in Figure 2.

The land use and land cover change were studied for three decades from 1985 to 2005 (Figure 3). The accuracy of the land use data (for the year 2005) was evaluated using ground truth data and random field samples. The Cohen's kappa accuracy and user's accuracy between reference points and map were determined using the confusion error matrix. The kappa accuracy across all the selected catchments was 0.94 and an overall mapping accuracy of 94% was achieved. Except for barren and wasteland, most of the land use land cover classes had accuracy higher than 90%. The dominant land use in the Purna catchment was found to be deciduous broadleaf forest (26% of the catchment area) followed by agriculture (26%). The catchment area of the Aghanashini River is dominated by evergreen broadleaf forests (34.5%), followed by deciduous forests (17%) and mixed forests (26.5%). The urban settlements account for 1% of the catchment area. The Tunga catchment is dominated by agriculture (25%), followed by shrub land (25%), evergreen broadleaf forests (16%), and plantations (16%). The urban settlements in the Tunga catchment have been rapidly increasing (0.4–2%) across the three decades of study. The catchment area of the Netravathi River has primarily plantations (44%), evergreen broadleaf forests (24%), and deciduous forests (14.5%). The dominant land use in the Vamanapuram catchment is plantations (67.5%), followed by evergreen forests (16.5%). Urban settlements have increased from 1.6 to 3.3% in the catchment.

3. Data sources and methodology

The gridded data on precipitation (0.25 × 0.25°) and temperature (1 × 1°) were procured from the IMD. The processing of the gridded data may be found elsewhere (Pai *et al.*, 2014). The discharge data were obtained from the India Water Resources Information System (www.india-wris.nrsc.gov.in/wris.html). The number of grid points available for rainfall data analysis in the Purna, Aghanashini, Tunga, Netravathi, and Vamanapuram was 20, 9, 24, 27, and 9, respectively. The rainfall data for the Aghanashini catchment were procured from the Water Resources Development Organization (WRDO), Government of Karnataka, India. All of the data were available on a daily time step.

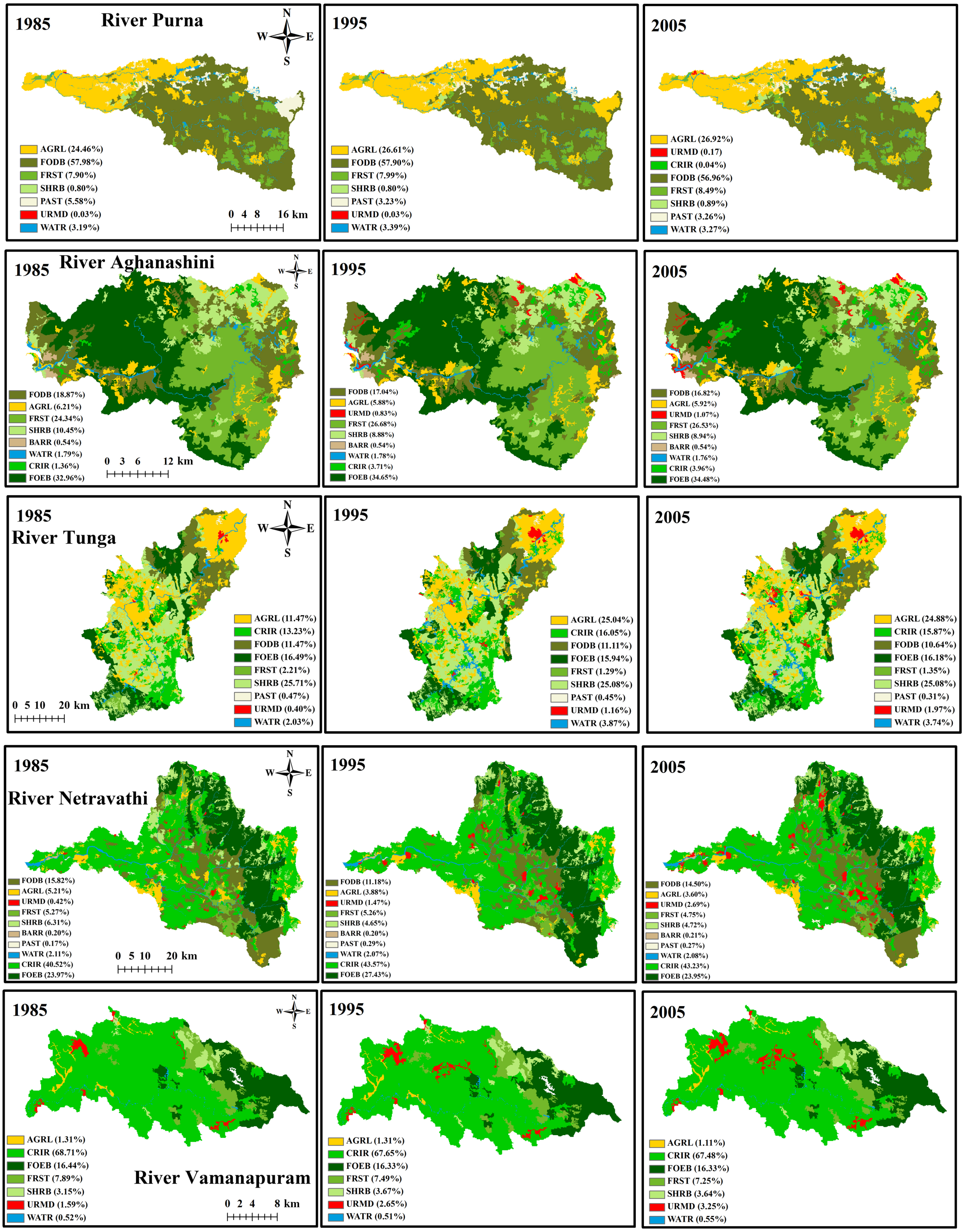

Figure 3. Land use and land cover in river catchments of the Western Ghats. [Colour figure can be viewed at wileyonlinelibrary.com].

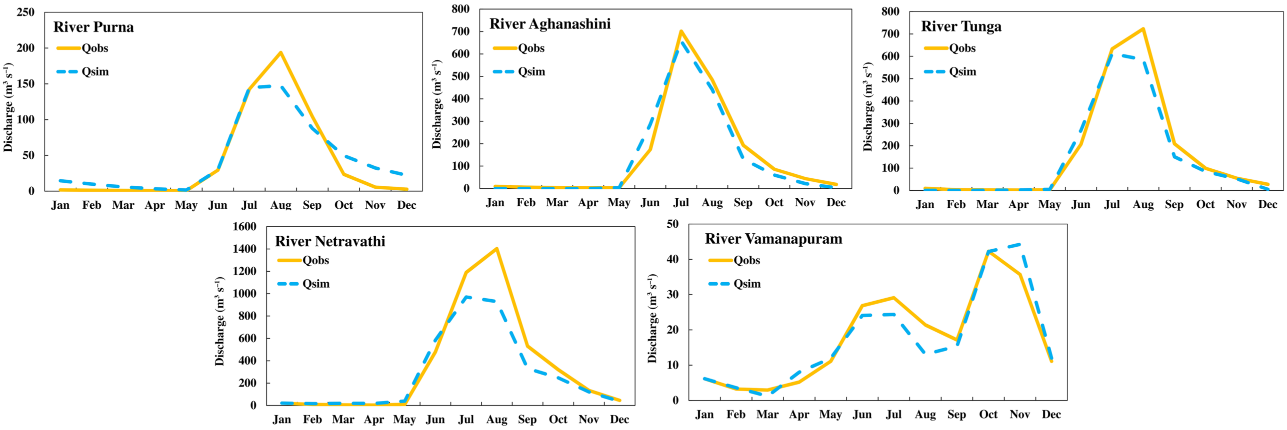

Figure 4. Performance of SWAT model during calibration period. [Colour figure can be viewed at wileyonlinelibrary.com].

The hydrologic modelling of the catchments was conducted using the Soil and Water Assessment Tool (SWAT) hydrologic model. The digital soil map provided by the Food and Agricultural Organization was used for the extraction of soil characteristics of the catchment. The SRTM digital elevation model (DEM) with a resolution of 90 × 90 m was used for the creation of the stream network, delineation of the watershed, and to study the characteristics of the slope gradient. The SWAT models for all of the selected rivers were calibrated and validated on a daily time step using discharge data. A split-sampling and cross-validation technique (Bennett *et al.*, 2011) was employed in the calibration and validation of the models. The performance of the SWAT model was assessed using four evaluation metrics to represent the performance of the model across various statistical indices. The coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NSE) were used to assess the goodness of fit. The *R*-factor represented the degree of uncertainty and the percent bias (PBIAS) assessed the tendency of the simulation compared to the observed streamflow (Abbaspour, 2013).

The details of the calibration and validation of the SWAT models are provided in Figure 4 and Table 1. Figure 4 compares the annual cycle of streamflow for the observed (Qobs) and simulated (Qsim) data during the calibration period. The minor deviations observed in the hydrographs might be introduced by the hydrological model. The NSE values across all of the five catchments ranged between 0.71 and 0.87 for the calibration period and between 0.70 and 0.87 for the validation period (Table 1). The NSE values indicate a good fit of the model as the calibration was carried out on a daily scale and represents a good quality of the meteorological inputs. The *R*-factor for the nine catchments ranged from 0.05 to 0.37, which indicated a good strength of calibration.

The spatial distribution of rainfall was analysed, and the entire Aghanashini catchment was divided into three rainfall zones. The identified rainfall zones were subjected to trend analysis using distribution-free nonparametric methods. This was carried out because the hydrologic time series are often non-normally distributed, and misleading results are encountered upon the use of parametric methods in hydrologic time series (Hirsch *et al.*, 1992; Salas, 1993). The modified Mann–Kendall trend test (Hamed and Ramachandra Rao, 1998) was used in the trend detection of the present study, and the Sen's slope estimator was used to estimate a robust magnitude of the monotonic trend (Sen, 1968).

4. Results and discussion

4.1. Elevation-based stratification of rainfall

The SRTM DEM (Figure 5(a)) revealed that the Aghanashini catchment is characterized by flat plains on the west (area bounded between 74°20′N and 74°30′N) with a typical elevation not exceeding 10 msl. The central portion of the catchment is characterized by a 116-m elevation drop and steep slopes, and the eastern portion has a comparatively lesser slope at higher elevations. The temporal variation of the rainfall in the Aghanashini River was similar to other coastal rivers originating in the Western Ghats. The months of June and July receive the

Table 1. Performance of SWAT hydrological model during calibration and validation (daily streamflow).

State	Catchment name	Calibration period	NSE (calibration)	Validation period	NSE (validation)	*R*-factor
Gujarat	Purna	1971–1990	0.79	1991–2000	0.70	0.36
Karnataka	Aghanashini	1989–1996	0.84	1997–2002	0.85	0.04
	Tunga	1973–1992	0.87	1993–2000	0.87	0.07
	Netravathi	1980–1995	0.85	1991–1995	0.87	0.37
Kerala	Vamanapuram	1990–2005	0.71	2006–2011	0.83	0.05

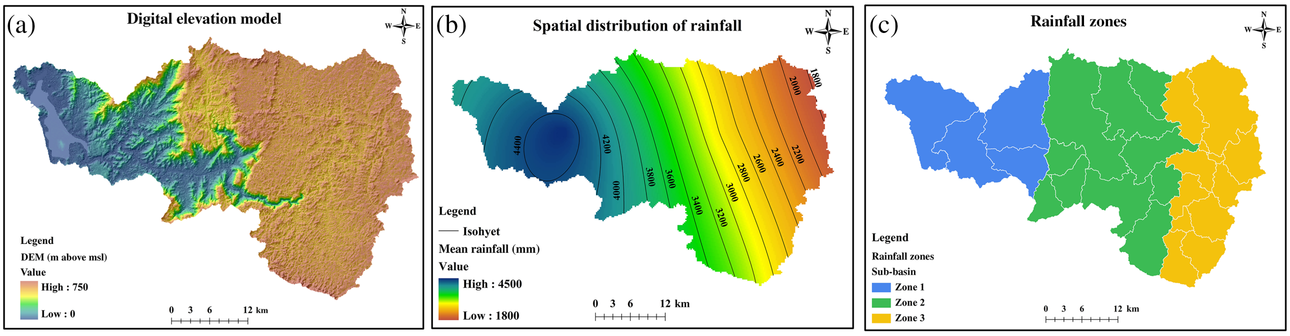

Figure 5. (a) DEM, (b) spatial distribution of rainfall, and (c) rainfall zones of the Aghanashini River catchment. [Colour figure can be viewed at wileyonlinelibrary.com].

heaviest rainfall events, whereas August and September receive moderate rainfall and the intensity and magnitude of rainfall gradually decrease after September.

The spatial distribution of long-term annual average rainfall over the Aghanashini catchment presents interesting results as shown in Figure 5(b). The catchment was spatially divided into three zones of rainfall, and the nomenclature for the rainfall zones was in accordance with the annual rainfall (Figure 5(c)). Zone 1 is the portion of the catchment receiving the highest average annual rainfall (between 3600 and 4500 mm). Zone 1 starts at the lowest elevation of the catchment (i.e. the confluence of the river with the Arabian Sea) and continues up to the flat plains (an average slope of 3.3 $\mathrm{m\,km^{-1}}$) of the catchment. The land use and land cover in the portion of the catchment are mainly deciduous forests, built-up areas, and agriculture. Zone 2 is the area of the catchment that receives an average annual rainfall of 2800 to 3600 mm. This portion extends from the flatter plains to the top of Unchalli falls and is densely populated by evergreen broadleaf forests followed by agriculture along the river banks. Zone 3 is the portion of the Aghanashini catchment that is from the top of Unchalli falls to the highest elevation in the catchment. Because of the high elevations, the portion is dominated by mixed forests and shrublands and receives the least amount of rainfall (average annual rainfall varying between 1800 and 2800 mm). Data from three rain gauges were available in Zones 1 and 3, and data from two rain gauges were available for Zone 2. In addition to the rain gauges, three rainfall data points of IMD gridded rainfall data were available in each of the zones for statistical analysis.

Because of the nonlinear temperature dependence of the saturation pressure, the maximum intensity of rainfall in the Aghanashini catchment was found to be at some distance from the crest on the windwards side. Similar results were observed by Das (1968), which suggested a peak of the monsoon in the Western Ghats of India to be approximately 50 km on the windwards side from the crest. The spatial distribution of rainfall over other river catchments of the Western Ghats are presented in Figure 6. The peak of rainfall in the west flowing Purna (Figure 6(a)) and Netravathi (Figure 6(c)) Rivers and the Vamanapuram catchments (Figure 6(d)) were at some distance from the crest of the Western Ghats on the windward side, whereas the east flowing Tunga River (Figure 6(b)) received maximum rainfall at the crest and the rainfall decreased towards the leewards side from the Western Ghats. In comparison with the results of the Aghanashini River with the other rivers of the Western Ghats, it was found that the observations of Das (1968) are limited to the windward side of the Western Ghats. It may also be noted that the broad mountains of the Western Ghats in Karnataka receive more rainfall on the windwards side (Tawde and Singh, 2015). Consequently, the leeward sides receive rainfall at lower intensities (<4 $\mathrm{mm\,day^{-1}}$).

4.2. Trend analysis of precipitation and temperature

The trend analysis of the meteorological variables was carried out in two stages. First, the analysis was conducted for the entire Aghanashini catchment to ascertain the prevalent trends, and then the analysis was conducted for the each of the three zones to evaluate the response of climate change and the elevation profile along the course of the river. The trend analysis was also conducted for the four principal seasons in India: monsoon (June–September), post-monsoon (October–November), winter (December–February), and summer (March–May). The results of the modified Mann–Kendall revealed that the average rainfall over the Aghanashini catchment has been increasing at a rate of 115 $\mathrm{mm\,decade^{-1}}$ (5% significance level) from 1951 to 2013. The monsoon and post-monsoon seasons contribute to approximately 96.25% of the total rainfall in the catchment. As per the IMD, rainy days are defined as daily rainfall of >2.5 mm. The number of rainy days over the entire catchment was found to be 129 $\mathrm{days\,year^{-1}}$. The number of rainy days along the western coast of India is generally 140 $\mathrm{days\,year^{-1}}$ (Jain *et al.*, 2007), and the results obtained in the present study were found to be in concurrence with several studies that state an increasing trend of rainfall in the west coast with a decreasing number of rainy days (Khan *et al.*, 2000; Shrestha *et al.*, 2000; Mirza, 2002; Lal, 2003; Min *et al.*, 2003; Goswami *et al.*, 2006; Dash *et al.*, 2007; Kumar *et al.*, 2010).

The rainfall statistics and the results of a modified Mann–Kendall test for annual and seasonal rainfall over the three rainfall zones of the Aghanashini catchment are given in Table S1, Supporting information. Of the

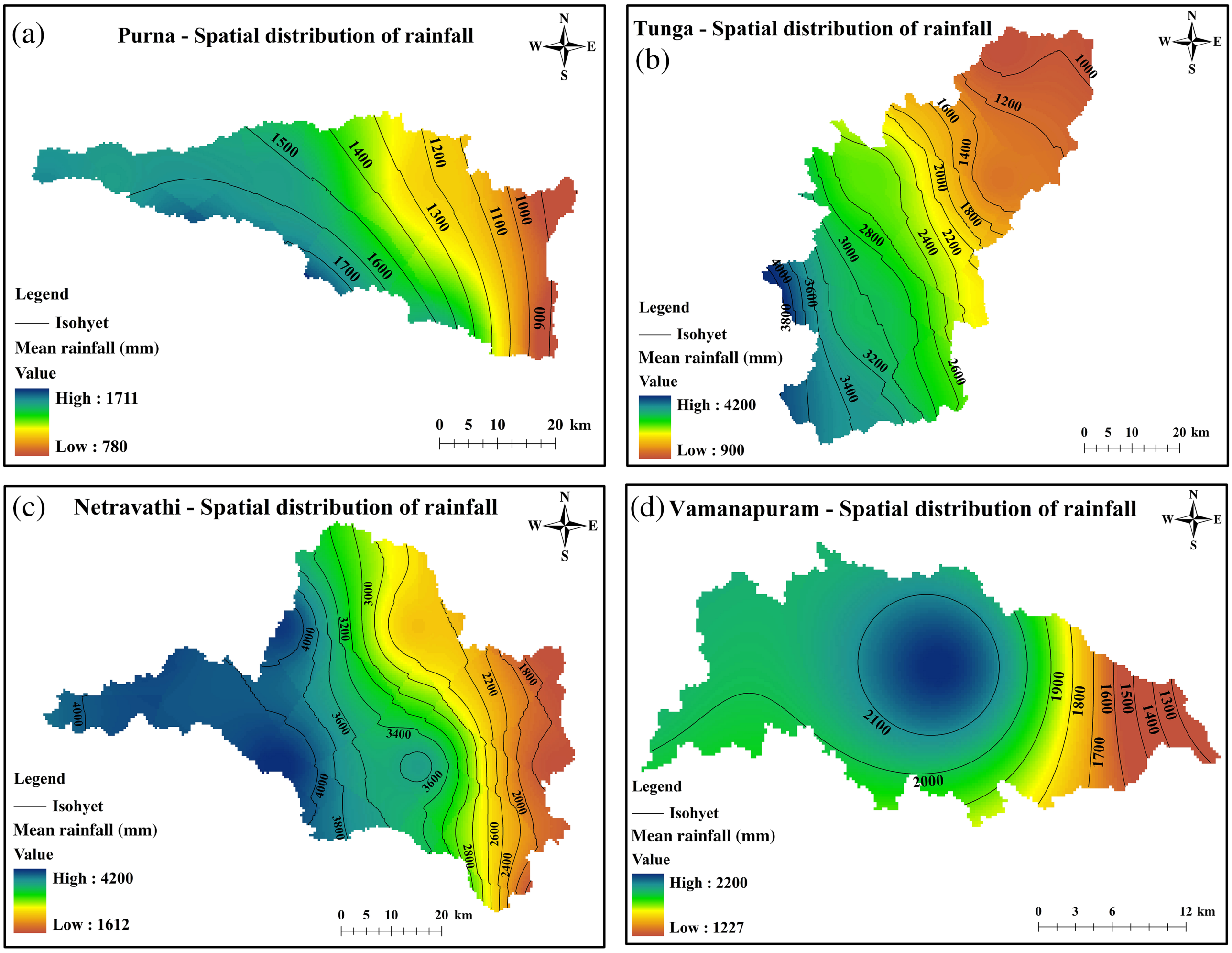

Figure 6. Spatial distribution of rainfall in the rivers (a) Purna, (b) Tunga, (c) Netravathi, and (d) Vamanapuram. [Colour figure can be viewed at wileyonlinelibrary.com].

three zones, two zones showed an increase in annual as well as monsoon rainfall. Zone 1 is the western portion of the river catchment, and it was observed to have a maximum increase in annual and monsoon rainfall. The annual rainfall showed a very prominent increase (at the 0.1% significance level) of 226 mm decade^{-1} in the 63 years from 1951 to 2013. The rate of increase was approximately 6% of annual average rainfall. The analysis of intra-annual fluctuation of rainfall showed that the monsoon season (June–September) contributes to 92% of the rainfall in Zone 1, which is increasing at 6% decade^{-1}. The increase in the average annual rainfall may be attributed to the increase in rainfall during the monsoon. The winter has no contribution to the annual rainfall, whereas the post-monsoon and summer months contribute to approximately 8% of the rainfall in the zone. No changes with regard to trend were observed during the post-monsoon and summer months. Zone 1 received 127 rainy days, which is the major contributor of available water in the catchment.

Zone 2 is the portion of the catchment with the 116-m drop in elevation. The average rainfall in the zone was 2800 mm with a maximum contribution from the monsoon months (90% of the annual rainfall). The results of the trend analysis in Zone 2 were quite similar to Zone 1 with an increase of 3% decade^{-1} (75 mm decade^{-1}) in the monsoon rainfall. This, in turn, has led to an increase in the annual rainfall by 72 mm year^{-1} (3% of annual rainfall). Interestingly, the number of rainy days in the zone was 116 year^{-1}. Zone 3 was found to have the least rainfall in the catchment with an average annual rainfall of 1445 mm and 100 rainy days per year. No trend could be established for the annual and monsoon rainfall in Zone 3. The winter and summer rainfall contribute to 8.5% of the total rainfall in the zone. An increasing trend was detected during winter, and a decreasing trend was observed during summer. The change in the rainfall during winter and summer was meagre ($<$0.6%) and was found to be negligible compared to the total rainfall.

The mechanism of distinct stratification of rainfall in the Aghanashini catchment may be understood from studies conducted earlier in the Western Ghats region. In the reaches of the Western Ghats having gradual slopes, the slopes tend to deflect the rain-bearing mass of air upwards after striking the barrier by providing a stable ascent. In the case of mountains with high elevation and abrupt changes

Table 2. Trend analysis of rainfall over rivers of the Western Ghats.

River	Rainfall time series	Mean rainfall (mm)	Statistic value	Sen's slope estimator (mm decade^{-1})	Trend
Purna	Annual rainfall	1445	−0.15	4.84 (0.33)	No trend
	Monsoon Rainfall	1371 (94.85)	0.01	0.40 (0.02)	No trend
	Post-monsoon	60 (4.15)	0.23	0.63 (0.04)	No trend
	Winter rainfall	04 (0.30)	−0.35	0.00	No trend
	Summer rainfall	10 (0.70)	_−2.66***_	_1.10_ (0.07)	Decreasing
Tunga	Annual rainfall	2188	0.18	0.30	No trend
	Monsoon rainfall	1791 (81.89)	−0.08	0.23	No trend
	Post-monsoon	222 (10.16)	0.06	0.05	No trend
	Winter rainfall	15 (0.66)	1.02	0.05	No trend
	Summer rainfall	159 (7.28)	−1.61	0.83	No trend
Netravathi	Annual rainfall	2932	−0.37	12.57 (0.43)	No trend
	Monsoon rainfall	2382 (81.24)	−0.50	18.45 (0.63)	No trend
	Post-monsoon	300 (10.23)	0.06	0.83 (0.03)	No trend
	Winter rainfall	22 (0.74)	0.70	0.57 (0.02)	No trend
	Summer rainfall	228 (7.79)	−1.66*	12.90 (0.44)	Decreasing
Vamanapuram	Annual rainfall	_1746_	_−2.66***_	_7.55 (0.43)_	Decreasing
	Monsoon rain	_764 (43.78)_	_−2.98***_	_5.19 (0.30)_	Decreasing
	Post-monsoon	502 (28.76)	−0.33	0.36 (0.02)	No trend
	Winter rainfall	139 (7.97)	−0.15	0.07	No trend
	Summer rainfall	_340 (19.49)_	_−2.23**_	_1.96 (0.11)_	Decreasing

Values in parenthesis denote percentage of annual rainfall. Italic indicates statistically significant values. *10% significance level. **5% significance level. ***1% significance level.

in slope (such as the Aghanashini catchment with an elevation drop at Unchalli), the abrupt change in elevation tends to suppress the rainfall in the lower reaches. This may be because the abrupt upwards slopes are unable to provide a stable ascent for the incoming air parcel to deflect upwards after striking. While the mountainous barriers act as sources of heat in producing convection cells and converging the air mass at the crest, the abrupt and steep slopes stunt the ascent of rain-bearing clouds by collision and coalescence, which leads to higher rainfall at the foot of the mountain (Elliott and Shaffer, 1962; Sarker, 1966; Grossman and Durran, 1984; Ogura and Yoshizaki, 1988; De and Dutta, 2005).

The Purna, Tunga, and Netravathi Rivers did not portray statistically significant changes in the trend of annual and seasonal rainfall (Table 2). However, the rainfall during summer was observed to be decreasing in the Purna and Netravathi Rivers. The rainfall during the summer season showed a decrease of 0.44% of mean rainfall per decade (13 mm decade^{-1}) in the Netravathi River. It may be noted that these three rivers are solely dependent on the southwestern monsoon of India. The Vamanapuram River in the southern part of the Western Ghats has the influence of the southwest as well as the northeast monsoons. Approximately 44% of the total rainfall in the catchment is contributed by the southwestern monsoon (June–September), and 29% of the rainfall is contributed by the northeast monsoon (October–November). The results of the trend analysis showed that the rainfall during June–September (the monsoon season) is decreasing at 0.30% decade^{-1} (5 mm decade^{-1} at the 1% significance level), which indicated a weakening of the southwest monsoon in the southern parts of the Western Ghats. The number of rainy days in the Purna, Tunga, Netravathi, and Vamanapuram River catchments was found to be 84, 142, 160, and 149 days, respectively. This leads to the inference that the central and southern portions of the Western Ghats receive higher events of rainfall, but the rainfall intensity is decreasing over time. The observations from the study also indicate decreasing rainfall towards the southern part of the Western Ghats.

The temperature in the Purna River catchment did not show any significant change in the temperature regime. The temperature over the Aghanashini catchment was found to be increasing at a rate of 0.07 °C decade^{-1} (0.1% significance level) (Table 3). The rise in temperature may be attributed to changes in the global concentration of greenhouse gasses. The intra-annual trend analysis showed that the most significant increase in mean temperature is during the monsoon months with a temperature rise of 0.08 °C decade^{-1} (0.1% significance level). The winter and summer months revealed an increase of 0.06 and 0.08 °C decade^{-1} (1% significance level), respectively.

An increase of 0.09 and 0.10 °C decade^{-1} (0.1% significance level) was observed in the annual and monsoon temperatures of the Netravathi catchment, and the Tunga catchment showed an increase at a rate of 0.08 °C. The Vamanapuram catchment revealed an increase in annual temperature of 0.12 °C decade^{-1}. The maximum rate of increase was found to be as high as 0.13 °C decade^{-1} (0.1% significance level) during the monsoon season of the Vamanapuram River catchment. A similar increase in the temperature was observed across all of the seasons, which indicated that the central and southern rivers of the Western Ghats of India are more vulnerable to climate change and rising temperatures than the northern rivers of the Western Ghats. The study by Gopalakrishnan *et al.* (2011) reported the central part of the Western Ghats of India (in Karnataka) to be more vulnerable to climate change due to a rise in temperature by almost 3 °C. The

Table 3. Trend analysis of temperature over rivers of the Western Ghats.

River	Temperature time series	Mean temp (°C)	Statistic value	Sen's slope estimator (°C decade^{-1})	Trend
Purna	Annual temperature	26.85	0.90	0.002	No trend
	Monsoon temperature	28.08	1.21	0.003	No trend
	Post-monsoon temperature	26.50	1.32	0.007	No trend
	Winter temperature	22.49	0.06	0.000	No trend
	Summer temperature	29.74	0.64	0.002	No trend
Aghanashini	Annual temperature	_25.88_	_4.02***_	_0.07_	Increasing
	Monsoon temperature	_25.27_	_3.46***_	_0.08_	Increasing
	Post-monsoon temperature	_25.76_	_2.56*_	_0.10_	Increasing
	Winter temperature	_24.57_	_2.78**_	_0.06_	Increasing
	Summer temperature	_28.08_	_2.88**_	_0.08_	Increasing
Tunga	Annual temperature	_24.31_	_4.38***_	_0.08_	Increasing
	Monsoon temperature	_23.48_	_3.71***_	_0.09_	Increasing
	Post-monsoon temperature	_23.93_	_3.27**_	_0.09_	Increasing
	Winter temperature	_23.31_	_3.42***_	_0.09_	Increasing
	Summer temperature	_26.69_	_2.66**_	_0.08_	Increasing
Netravathi	Annual temperature	_24.04_	_5.34***_	_0.09_	Increasing
	Monsoon temperature	_23.36_	_4.50***_	_0.10_	Increasing
	Post-monsoon temperature	_23.58_	_3.82***_	_0.11_	Increasing
	Winter temperature	_22.93_	_3.90***_	_0.09_	Increasing
	Summer temperature	_26.39_	_3.14**_	_0.09_	Increasing
Vamanapuram	Annual temperature	_27.02_	_5.92***_	_0.12_	Increasing
	Monsoon temperature	_26.93_	_5.23***_	_0.13_	Increasing
	Post-monsoon temperature	_26.37_	_4.82***_	_0.11_	Increasing
	Winter temperature	_26.11_	_4.78***_	_0.11_	Increasing
	Summer temperature	_28.46_	_3.90***_	_0.12_	Increasing

Italic indicates statistically significant values. *5% significance level. **1% significance level. ***0.1% significance level.

present study confirms the results of Gopalakrishnan *et al.* (2011) and further indicates that the southern portion of the Western Ghats (Kerala and Tamil Nadu) has a higher potential to rise in temperature along with the central portion. It is important to note that the relationship of air temperature and the thermal regime of the rivers has been found to be a function of the stream type and time scale (Stefan and Preud'homme, 1993; Pilgrim *et al.*, 1998; Erickson and Stefan, 2000; Webb *et al.*, 2003; Caissie, 2006; Ahmadi-Nedushan *et al.*, 2007).

The perturbations of a warmer air temperature are likely to increase the river temperature of the Aghanashini River and would affect the aquatic habitat attributes, fisheries, and ecological health of the wetlands. Studies have demonstrated that the reduction in the streamflow of rivers adversely affects the river temperature and that evaporative cooling minimizes the effect of higher air temperatures on the water temperature (Hockey *et al.*, 1982; Dymond, 1984; Bartholow, 1991; Caissie *et al.*, 2005). The reduction in streamflow of the Aghanashini River through excessive withdrawal (irrigation) and/or diversion (hydro power) would lead to deterioration of the general health of the riparian ecosystem.

4.3. Response of streamflow to climate change and elevation stratification

This section discusses the sensitivity of streamflow to elevation stratification and highlights the characteristics of streamflow in each of the contemporary rainfall zones of the Aghanashini River. The Aghanashini River is rich in terms of ecology and conservation of wetlands, and the changes in climate over the Aghanashini catchment would exert an influence on the local patterns of streamflow. To assess the response of streamflow to climate change, the flow from each zone was subjected to trend analysis. It was observed that the demarcated contemporary rainfall zones would have a different meaning on the streamflow characteristics as the mechanism of streamflow is highly dependent on the time of concentration. In essence, the demarcated Zone 1 would represent the characteristics of the complete Aghanashini catchment (100% of the catchment area). Zone 2 represents the combined response of Zones 2 and 3 (which is 79.5% of the catchment area), and Zone 3 is standalone and represents 32.5% of the catchment area.

The results of the modified Mann–Kendall test for streamflow in the zones of the Aghanashini catchment are presented in Table S2. The annual streamflow of the entire Aghanashini catchment (Zone 1) was increasing and indicated more availability of water in the river. The decadal increase in the streamflow was estimated at 7.5% of the mean flow (0.7 $\text{Mm}^3\,\text{decade}^{-1}$ at the 0.1% significance level). The monsoon flow indicated a decadal increase of 21.5% of the mean flow (2 $\text{Mm}^3\,\text{decade}^{-1}$ at the 0.1% significance level). Zone 2 represented 79.5% of the catchment area and also indicated an increase in the annual and monsoon flow with magnitudes of 5.3 and 15.7%, respectively, of the mean flow of Zone 2 (0.34 and 1 $\text{Mm}^3\,\text{decade}^{-1}$ at the 1% significance level). Zone 3 was found to have an increase in annual flow by 3% and monsoon flow by 14.5% (0.14 and 0.38 $\text{Mm}^3\,\text{decade}^{-1}$ at 5% significance level). Although there was an increase in streamflow in all three zones of the Aghanashini catchment, it is important to note the change in the

Table 4. Trend analysis of streamflow in the rivers of Western Ghats.

River	Streamflow time series	Mean flow (Mm^3)	Statistic value	Sen's slope estimator (Mm^3 decade^{-1})	Trend
Purna	Annual streamflow	3.97	−0.64	0.06 (1.51)	No trend
	Monsoon streamflow	8.77	−0.46	0.12 (3.02)	No trend
	Post-monsoon flow	3.61	−0.37	0.03 (0.75)	No trend
	Winter streamflow	1.36	−0.19	0.01 (0.25)	No trend
	Summer streamflow	0.32	−0.05	0.00	No trend
Tunga	Annual streamflow	13.63	0.77	0.21 (1.54)	No trend
	Monsoon streamflow	36.55	0.52	0.34 (2.49)	No trend
	Post-monsoon flow	6.73	−0.43	0.10 (0.73)	No trend
	Winter streamflow	0.24	1.53	0.01 (0.07)	No trend
	Summer streamflow	_0.51_	_−2.06**_	_0.03 (0.22)_	Decreasing
Netravathi	Annual streamflow	25.51	_−1.70*_	0.65 (2.54)	Decreasing
	Monsoon streamflow	_63.43_	_−2.25**_	_2.51 (9.83)_	Decreasing
	Post-monsoon flow	17.03	1.06	0.36 (1.41)	No trend
	Winter streamflow	_2.50_	_2.08**_	_0.09 (0.35)_	Increasing
	Summer streamflow	2.81	0.15	0.02 (0.07)	No trend
Vamanapuram	Annual streamflow	_2.32_	_−3.21***_	_0.41 (17.67)_	Decreasing
	Monsoon streamflow	_3.63_	_−3.91****_	_0.86 (37.06)_	Decreasing
	Post-monsoon flow	_4.11_	_−2.09**_	_0.39 (16.81)_	Decreasing
	Winter streamflow	0.58	0.52	0.02 (0.86)	No trend
	Summer streamflow	_1.10_	_−2.85***_	_0.16 (6.89)_	Decreasing

Values in parenthesis denote percentage of annual streamflow. Italic indicates statistically significant values. *10% significance level. **5% significance level. ***1% significance level. ****0.1% significance level.

significance level. The portion of the catchment at a higher elevation has the least statistical significance, and the significance increases in the downstream direction. The results are quite concurrent with increased rainfall over the catchment. In the rivers with a mid to high range of elevation stratification, the increase in temperature is related to changes in the frequency and magnitude of flows and the probability of flash floods is higher (Hassan *et al.*, 2006; Goode *et al.*, 2013).

The impacts of climate change on water availability in the Western Ghat river catchments were clearly evident in the rivers considered in this study. The Purna, Tunga, Netravathi, and Vamanapuram Rivers are not as pristine as the Aghanashini River. The Purna River did not reveal variation in the trend of streamflow over the 63-year period from 1951 to 2013 (Table 4). In the Tunga River, it was observed that the streamflow during summer is decreasing at a rate of 0.22% (0.03 Mm^3 decade^{-1}). This change in the streamflow during summer could be attributed to the rise in mean temperature over the catchment by 0.08 °C decade^{-1}. Although there have been anthropogenic interventions in the Tunga River, such as the Upper Tunga dam, the impact of climate change was found to be worse on the Netravathi and Vamanapuram Rivers. The annual streamflow in the Netravathi River was observed to decrease by 2.54% decade^{-1} (0.65 Mm^3 decade^{-1} at the 10% significance level). The monsoon season revealed a maximum decrease in the streamflow at a rate of 10% decade^{-1} (2.51 Mm^3 decade^{-1}). Similar decrease in the historic trend of rainfall and streamflow in the river Netravathi was reported by Mudbhatkal *et al.* (2017). The study further assessed the impact of climate change on the river Netravathi using the Representative Concentration Pathway 4.5 (RCP 4.5) scenario and demonstrated the long-term persistence of streamflow in rivers. Although there was a decrease in the trend of historic rainfall, the rainfall during forecasted scenario did not exhibit high variability. The higher intensity rainfall was found to decrease in the future leading to decrease in the streamflow.

The Vamanapuram River was the most affected river in the five catchments considered in the present study. The annual streamflow was found to be decreasing at a rate of 18% decade^{-1} (0.41 Mm^3 decade^{-1}). The monsoon streamflow was found to decrease at a rate of 37% decade^{-1} (0.86 Mm^3 decade^{-1} at the 0.1% significance level). The decrease in monsoon streamflow may be considered a signal of a weakening southwest monsoon in the southern portion of the Western Ghats of India. The post-monsoon season was also found to have a decreasing streamflow rate at 17% decade^{-1} (0.39 Mm^3 decade^{-1} at the 5% significance level), which indicated that the north-eastern monsoon has little influence on the streamflow of the Vamanapuram River. The streamflow during summer was reduced at a rate of 7% decade^{-1} (0.16 Mm^3 decade^{-1} at the 1% significance level). From these observations, it was evident that the rivers in the northern portion of the Western Ghats were found to be less affected by climate change compared to the southern rivers.

The temporal evolution of the river discharge was examined using the annual discharge for each of the river catchments in the period from 1951 to 2013. The inter-annual variability of the streamflow provided an insight into the flow regime of the rivers (Figure 7). The shift in flow regime was very evident in the Aghanashini River, with mean flow increasing from approximately 8 to 11 Mm^3. However, the mean flow decreased from approximately 4 to 1.5 Mm^3 in the Vamanapuram River. Studies have demonstrated that the changing rate of water in the stream channels is linked to an influence on the phenological

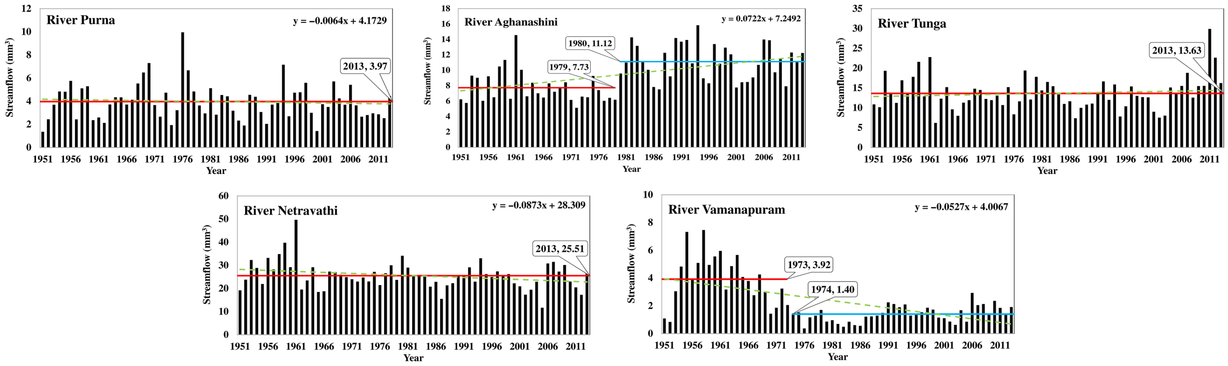

Figure 7. Streamflow regime in rivers of the Western Ghats. [Colour figure can be viewed at wileyonlinelibrary.com].

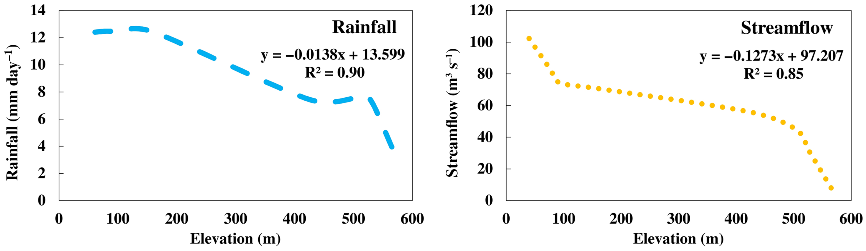

Figure 8. Relation of rainfall and streamflow to elevation in the Aghanashini catchment. [Colour figure can be viewed at wileyonlinelibrary.com].

events of ecosystem components and increased scouring of the stream bed, especially during the winter season (Hauer *et al.*, 1997; Rieman *et al.*, 2007; Davis *et al.*, 2013; Goode *et al.*, 2013; Isaak and Rieman, 2013). These changes in the flow regimes of the Aghanashini and Vamanapuram Rivers may possibly modify the patterns of bed scour and sediment transport. Although there were changes to streamflow in the Purna, Tunga, and Netravathi Rivers, a shift in flow regime could not be detected.

The response of rainfall and streamflow to elevation stratification was studied for the Aghanashini River. The statistical relationship of rainfall and streamflow to the elevation of the Aghanashini catchment is presented in Figure 8. The highest rainfall over the Aghanashini catchment was observed at the lower elevation and the rainfall reduced with increase in elevation. The rainfall reduces to less than 6 mm day^{-1} after confronting the mountainous barrier at Unchalli falls (which is at an elevation of 500 m). The streamflow was more at lower elevation than at the higher elevation. This could be attributed to the fact that streams contributing to the flow are lesser in the higher elevation and the more streams join as the river flows. The lags between percentiles of rainfall and streamflow were used as the evaluation metrics for assessing the storage of precipitation and the conversion of rainfall into streamflow. The lags between the 25th percentiles of rainfall and streamflow provide insight into how quickly the rainfall is converted into streamflow. The catchments dominated by high rainfall events (such as the Aghanashini) exhibit seasonal variation in base flow and changes in the timing of rainfall transformation into streamflow over the catchments that have an influence on the water quality and the rate of chemical weathering (Tennant *et al.*, 2015). Therefore, it was deemed essential to analyse the variation of the rainfall to streamflow channel routing in the different elevation zones.

In order to analyse the variation of rainfall to streamflow channel routing in different elevations zones, the cumulative distribution for the delivery of rainfall and streamflow in the Aghanashini catchment were plotted (Figure 9). It may be noted that the values have been computed by considering daily mean rainfall and streamflow for 63 years (1951–2013). The x-axis represents the months of the year and the y-axis represents the percentage of annual rainfall in each month. The cumulative distribution is separately plotted for each rainfall zone, and the thick portion of the plot indicates a higher inter-quartile range. In the Aghanashini River, the lag time between the rainfall event and resulting run-off for the catchment was found to be directly proportional to the elevation. The lags for Zones 1–3 were found to be 10, 20, and 30 days, respectively (Figure 9). These lags are influenced by factors such as topography because steeper slopes are associated with the quicker delivery of rainfall into streamflow. This is also true for the intensity and duration of rainfall, which affects groundwater storage and base flow. The shorter lags in Zones 1 and 2 may be due to the steep slope in Zone 2. The intensity of heavy rainfall events (>100 mm) and the number of rainy days in Zones 1 and 2 are more than in Zone 3. Similar lag times were observed in four rain-dominated catchments of the United States (Tennant *et al.*, 2015).

5. Conclusions

The present study is focused on the response of streamflow and characterization of rainfall to climate change and

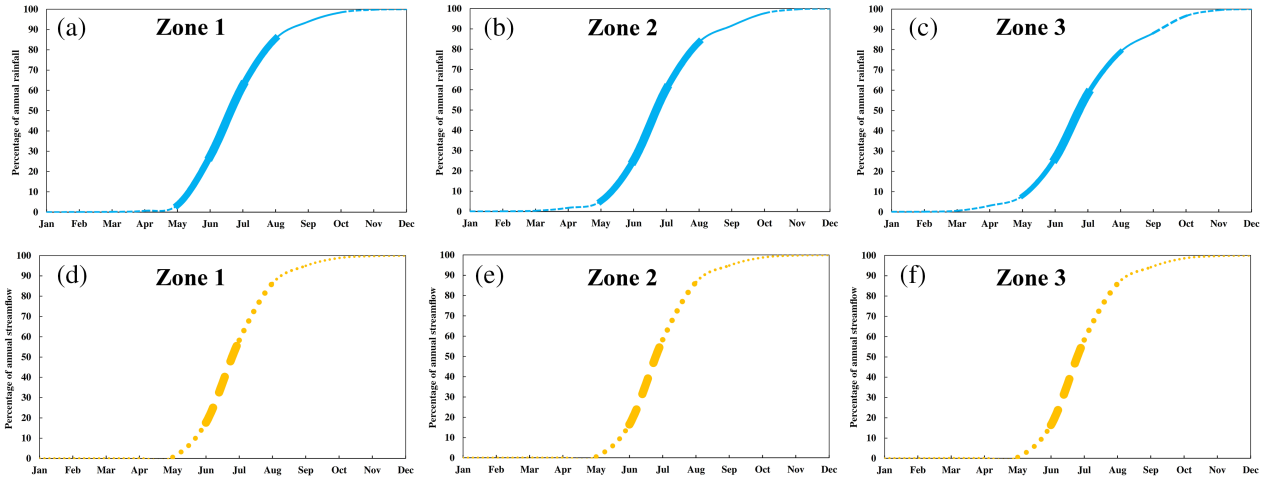

Figure 9. Cumulative distribution plots for rainfall and streamflow in the Aghanashini catchment. [Colour figure can be viewed at wileyonlinelibrary.com].

elevation stratification. The Aghanashini River is an ideal catchment for such investigations due to its pristine regime and the 116-m drop in elevation during the course of river flow. Three rainfall zones were identified within the catchment based on rainfall, and land use and land cover were distinct in each of the three zones as a result of rainfall. The three zones also had distinct elevation profiles. Additionally, four rivers along the Western Ghats range were compared to highlight the significance of the Aghanashini River. The long-term climatic variables (1951–2013) were subjected to a modified Mann–Kendall trend test, and the magnitude of the trend was quantified by the Sen's slope estimator. The hydrologic modelling of the river catchments was conducted using the SWAT hydrologic model.

The analysis of the spatial distribution of rainfall showed that the maximum intensity of rainfall is not at the crest of the Western Ghats but at a distance from the crest on the windward side. The leeward side of the Western Ghat receives quite a bit less rainfall compared to the windward side. This is especially true in the Western Ghats of Karnataka state. The rainfall in the Western Ghats was found to be decreasing from north to south. No change in the trend of rainfall was detected in the northern rivers of the Western Ghats. The Aghanashini River demonstrated resilience to climate change with an increase in rainfall (6% decade^{-1}). The average number of rainy days (>2.5 mm rainfall per day) in the Aghanashini catchment was 129, and the rainy days in the rainfall zones decreased with the increase in elevation. The central and southern portions of the Western Ghats receive a higher number of rainy days, but the intensity and magnitude of rainfall have been decreasing over the years from 1951 to 2013. The southernmost Vamanapuram River showed a statistically significant decrease in the annual, monsoon, and summer rainfall at rates of 0.43, 0.30, and 0.11%, respectively. The southern portion of the Western Ghats (Kerala and Tamil Nadu) has a higher rate of increase in temperature than the northern (Gujarat) and central (Karnataka) portions. The rate of increase is as high as 0.13 °C decade^{-1} (Vamanapuram River catchment). Anthropogenic interventions in the form of excessive withdrawal (for irrigation) and/or diversion (for hydropower), especially in the southern rivers of the Western Ghats, are bound to disrupt the health of the riparian ecosystem.

The impacts of climate change on the water availability in the southern portion of the Western Ghats were quite discernible. The mean annual flow in Vamanapuram was found to be decreasing at a rate of 18% decade^{-1}, followed by the Netravathi River, which showed a decreasing rate of mean annual flow of 2.5% decade^{-1}. The central and southern rivers are more vulnerable to climate change, and the Aghanashini River showed better resilience in coping with the rising temperatures. A shift in flow regime was detected in the Aghanashini and Vamanapuram Rivers. The mean flow of the Aghanashini River increased from 8 to 11 Mm^3 and decreased from 4 to 1.5 Mm^3 in the Vamanapuram River. These observations stress the need for better management practices in the southern rivers of the Western Ghats of India. It may, however, be noted that the rivers demonstrate natural variability and the changes in the past may not entirely hold good in the future. The elevation dependence of the streamflow in the Aghanashini catchment is quite distinct. The streamflow consistently increased throughout the catchment at varying rates along each rainfall zone (because each rainfall zone has a distinct elevation profile). The lag time between the rainfall event and streamflow was assessed, and it was found that the higher elevations of the catchment require more time for the generation of streamflow. Therefore, it is concluded that the elevation stratification (topography) also plays a key role in understanding the changes in the regional climate of tropical montane rivers.

Supporting information

The following supporting information is available as part of the online article:

Table S1. Trend analysis of rainfall over zones of the Aghanashini catchment.

Table S2. Trend analysis of streamflow in zones of the Aghanashini catchment.

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