Analysis of historical trends in hydrometeorological variables in the upper Cauvery Basin, Karnataka, India

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The present study examines the significance and magnitude of trends in the monthly rainfall, monthly mean maximum and minimum daily temperatures and streamflow in the Upper Cauvery Basin, Karnataka for a 30-year period, i.e. 1981–2010. Using observed data from 33 rain gauges, 6 climate stations and 4 stream gauging sites, statistical parameters –coefficient of variation (CV) and percentage departure have been calculated for average monthly values separately for three decades. As expected, CV of rainfall showed large variations from December to March, while the percentage departure also varies during these months for different decades. Statistically significant trend was observed in maximum temperature for Chikmagalur and Hassan stations. CV of minimum daily temperature showed large variability from November to March for all climate stations and also a significant increasing trend for Hassan and Bengaluru stations, while for Madikeri a decreasing trend was observed with a variation of –0.16°C/year. Not much variation was found for streamflow, except in K. M. Vadi and T. Narasipur gauge sites, which showed significant decreasing trend of –0.778 m^3/s/year. Long-range dependence analysis revealed a weak persistence for both rainfall and streamflow of the basin. Results provide information regarding historical climate trends in the Upper Cauvery Basin, which can form the basis for projecting likely future trends and preparing plans for climate change mitigation and adaptation.

Keywords: Climate change mitigation, historical climate trends, hydrometeorological trends, statistical analysis.

CLIMATE change impacts on water resources are likely to be most critical in river basins such as the Upper Cauvery Basin which is located in the humid tropics. Therefore, characterization of the impacts of climate change on the temporal and spatial distribution of available water resources is critical to ensuring sustainable development of water, land and other related natural resources. As a first step towards achieving this, it is necessary to create scenarios of possible future climatic conditions.

An important approach to characterizing and predicting future climatic conditions is through analysis of historical records of hydro-climatic variables such as air temperature, precipitation and streamflow. Various types of sophisticated statistical techniques/tools have been developed to identify the direction and magnitude of trends exhibited in long time-series of historical observations of hydro-climatic variables. Over the past few decades, several world-wide trend detection studies have been carried out at different temporal and spatial scales[1–5]. Several studies have been taken up in various regions of India to assess trends in hydro-climatic variables[6–9]. Jain *et al.*[10] provide a comprehensive review of studies taken up in India to analyse trends in temperature and rainfall in different hydro-climatic regimes. A few studies have also been taken up to evaluate trends in hydro-climatic variables in the Upper Cauvery Basin[11–13].

Most studies carried out earlier have implemented the conventional Mann–Kendall test to identify trends in datasets created for monthly or seasonal time steps. In this study, the seasonal Kendall test[14] has been implemented, thereby circumventing the need to separately analyse monthly or seasonal data. The seasonal Kendall test accounts for seasonality by computing the Mann–Kendall test on each of the months/seasons separately, and then combining the results. Also, few earlier studies have identified long-term persistence in time series of hydro-climatic variables. In this study, detrended fluctuation analysis (DFA) proposed by Kantelhardt *et al.*[15] has been implemented for detecting long-term persistence.

Cauvery is one of the major rivers which originates in the Western Ghats. The basin is flanked on the west by the Western Ghats and a large part of the river flow is derived from run-off generated on thickly forested mountain slopes. The Cauvery basin extends over four South Indian states of Kerala, Karnataka, Tamil Nadu and Puducherry. It is considered to be one of the most important river basins of peninsular India and caters to the water needs of millions of people in the region. Extensive development of water resources – both surface and groundwater has taken place in this river basin for several decades. Being one of the basins with the highest percentage of water resources utilization in the country, it is not surprising

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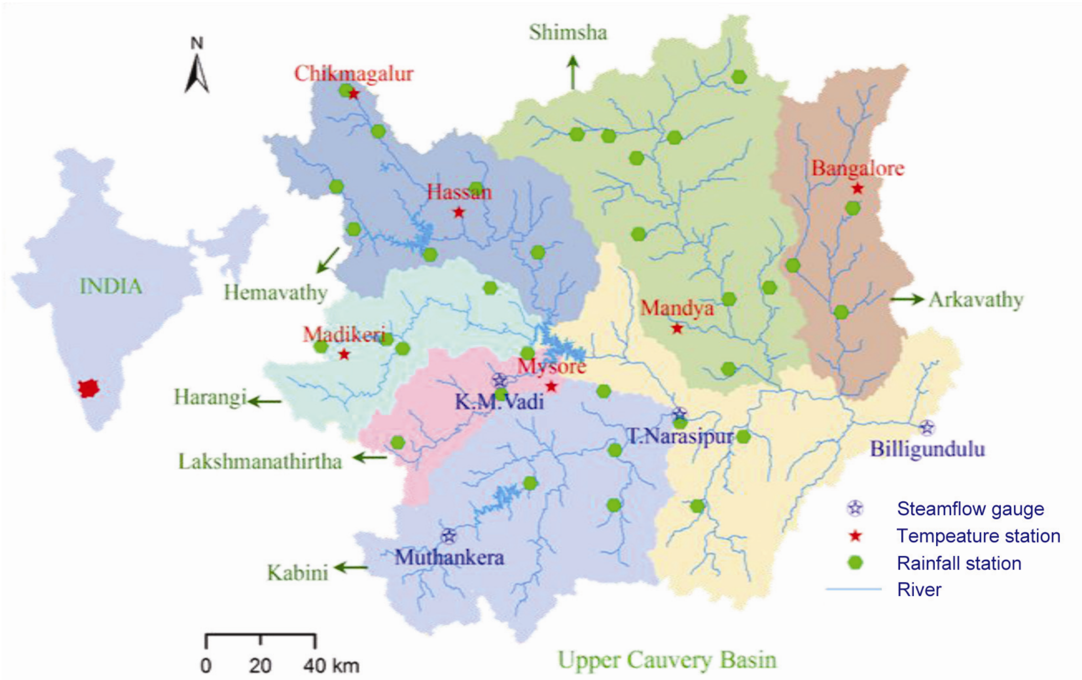

Figure 1. Location of rainfall, temperature and streamflow gauging stations used in the present study with their sub-basins.

that there is a longstanding dispute on water sharing among the riparian states.

The Upper Cauvery Basin which forms a part of the larger Cauvery basin encompasses the state of Karnataka. The basin supports more than 20 million people. Agriculture in this basin provides livelihood to a large population and contributes significantly to the food production of Karnataka. More than 70,000 ha of land is irrigated from canals, groundwater wells and tanks. Water is also used for domestic, hydropower, tourism and industrial purposes. Due to rapid urbanization and industrial growth, the demand for water has increased significantly in the past two decades, which is likely to further increase the pressure on water availability from the surface as well as groundwater sources within the basin. The increased development of the upstream command areas, compounded by frequent monsoon failure, has resulted in overexploitation of groundwater for irrigation, domestic and industrial use. Also, changes in rainfall and climate patterns in the upstream area have led to frequent shortages of water for irrigation.

Climate changes in future are likely to further significantly affect the temporal and spatial distribution of water resources and thereby the sustainability of agriculture in the region. Therefore, there is an urgent need to characterize historical and recent trends in hydro-climatic variables so that further studies aimed at assessing agro-hydrological impacts and formulating mitigation measures for climate change will be benefited.

This study seeks to determine whether rainfall, maximum and minimum air temperature, and streamflow exhibit trends over a long time-period. Also, percentage departure in the monthly mean values of the variables considered has been characterized for different decades. In order to determine the existence of a trend and calculate the magnitude of trend in rainfall, streamflow and temperature data, the seasonal Kendall[14] and Sen's slope[16] estimators were used. To find out long-term persistence in the time-series data, DFA method was used[15].

Study area

The present study considers the Upper Cauvery Basin up to the Billigundulu gauge site with an upstream catchment area of 36,682 sq. km. The river originates at Talakadu at an elevation of 2028 m amsl and flowing in an eastwardly direction, reaches the Billigundulu site (257 m amsl). Annual rainfall in the basin varies from 621 mm in the lower reaches to 4137 mm in the mountainous uplands. The recorded mean maximum and minimum temperatures are 39.1°C and 4.8°C respectively. India Meteorological Department (IMD) and the Karnataka Irrigation Investigation Division have established climatic and rain-gauge stations in and around the basin. The Central Water Commission (CWC) has established stream-gauging sites in the Upper Cauvery basin. Data from 33 rain-gauge stations, 6 climate stations and 4 stream-gauging sites located within the Upper Cauvery Basin have been used in the analysis. Figure 1 shows their locations.

Seasonal Kendall method

The seasonal Kendall method[14] is a non-parametric test used for finding the significance of increasing or decreasing trends in time series. It accounts for seasonality by computing the Mann Kendall test on each of the seasons or months separately, and by combining the results. The Kendall statistic for each month S_i, is summed over the years (1 to m) to obtain the overall statistic S_k.

$$S_k = \sum_{i=1}^{m} S_i, \tag{1}$$

S_i is calculated by considering the variable Y (hydrometeorological data) and time T.

$$S_i = P_i - M_i, \tag{2}$$

where P is the number of times Y increases as the T increases and M is the number of times Y decreases as the T increases.

The distribution of S_k can be approximated quite well by a normal distribution with expectation (μ_{sk}) equal to the sum of the expectations (zero) of the individual S_i under the null hypothesis, and variance equal to the sum of their variances. Standardized S_k is evaluated against a table of the standard normal distribution.

$$Z_{sk} = \begin{cases} \dfrac{S_k - 1}{\sigma_{sk}} & \text{if } S_k > 0, \\ 0 & \text{if } S_k = 0, \\ \dfrac{S_k + 1}{\sigma_{sk}} & \text{if } S_k < 0, \end{cases} \tag{3}$$

Z_{sk} is overall Kendall statistic for different case of S_k values, where $\mu_{sk} = 0$

$$\sigma_{sk} = \sqrt{\sum_{i=1}^{m} (n_i/18)(n_i - 1)(2n_i + 5)}, \tag{4}$$

and n is the number of data points in the ith season.

If the calculated value of $|Z_{sk}| > Z_{\alpha/2}$, the null hypothesis is rejected at significance level α.

Sen's slope estimator

The magnitude of trend in time series can be determined using Sen's slope estimator[16]. This has been widely used to find the change in slope per unit time in the time series. In this method the slope (Q_i) of all data pairs is first calculated using eq. (5)

$$Q_i = \frac{x_j - x_k}{j - k}, \quad \text{for } i = 1,2,3, \ldots, N, \tag{5}$$

where x_j and x_k are data values at time j and k ($j > k$) respectively. The median of these N values of Q_i Sen's slope estimator is calculated as

$$Q = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} & \text{if } N \text{ is odd} \\ Q = \dfrac{1}{2}\left(Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]}\right) & \text{if } N \text{ is even.} \end{cases} \tag{6}$$

A positive value of Q indicates an increasing trend and a negative value indicates a decreasing trend in time series.

Detrended fluctuation analysis

Determination of trends in the hydro-meteorological time series is influenced by the existence of long-term persistence. The long-term persistence in time series can be quantified using DFA[15]. In DFA, the time series is initially integrated and the integrated time series is divided into sub-series of equal length m. In each sub-series local trend is estimated and this trend is subtracted from the sub-series to obtain a detrended sub-series. The root mean square fluctuation of the integrated and detrended sub-series is calculated using eq. (7)

$$F(m) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left[Y_k - y_m(k)\right]^2}. \tag{7}$$

The above equation is repeated for all sub-series data. The fluctuation can be characterized by a scaling exponent (d). The slope of linear relation of log$F(m)$ v/s log(m) gives the value of d. Using d, DFA exponent (α) is estimated as

$$\alpha = 2d - 1. \tag{8}$$

$\alpha \leq 0.5$ for uncorrelated time series, while $\alpha > 0.5$ indicates long-range correlation.

Methodology

The hydro-climatic variables selected for analysis were daily maximum and minimum temperatures, rainfall depth and streamflow. Daily observations of these variables for the historical 30-year period, i.e. 1981–2010 were used and aggregated to monthly totals for rainfall depth and rainy days, and averages for temperature and streamflow. Statistical trend analysis of the selected hydro-climatic variables was carried out in four phases. In the first phase, the statistical parameters of coefficient of variation (CV) and percentage departure from the mean were calculated. The second phase involved identification

Table 1. Coefficient of variation (CV) for rainfall, maximum temperature, minimum temperature and streamflow

	CV											
Sub-basin	January	February	March	April	May	June	July	August	September	October	November	December
Rainfall												
Hemavathi	**0.26**	**0.36**	**0.19**	0.07	0.06	0.04	0.04	0.04	0.05	0.07	0.09	**0.21**
Harangi	**0.27**	**0.20**	**0.14**	0.07	0.05	0.04	0.03	0.03	0.04	0.22	0.08	**0.17**
Lakshmanathirtha	**0.30**	**0.26**	**0.16**	0.08	0.06	0.05	0.05	0.05	0.05	0.05	0.10	**0.22**
Kabini	**0.34**	**0.22**	**0.14**	0.07	0.06	0.05	0.05	0.05	0.06	0.06	0.10	**0.25**
Shimsha	**0.33**	**0.24**	**0.24**	0.09	0.06	0.08	0.07	0.06	0.06	0.05	0.09	**0.18**
Arkavathi	**0.71**	**0.28**	**0.16**	0.10	0.08	0.10	0.07	0.06	0.07	0.07	**0.11**	**0.21**
Upper Cauvery	**0.26**	**0.16**	**0.15**	0.05	0.04	0.04	0.04	0.03	0.04	0.04	0.07	**0.15**
Maximum temperature												
Station												
Chikmagalur	0.05	0.05	0.05	0.05	0.08	0.09	0.07	0.07	0.06	0.06	0.05	0.05
Hassan	0.07	0.06	0.06	0.07	**0.10**	**0.11**	0.09	0.08	0.08	0.07	0.07	0.07
Madikeri	0.06	0.06	0.07	0.07	0.09	0.09	0.07	0.08	0.08	0.07	0.06	0.05
Mandya	0.05	0.05	0.05	0.05	0.07	0.07	0.06	0.05	0.05	0.05	0.06	0.06
Mysuru	0.05	0.06	0.06	0.05	0.06	0.09	0.07	0.05	0.05	0.05	0.05	0.05
Bengaluru	0.06	0.06	0.05	0.05	0.06	0.06	0.06	0.05	0.05	0.05	0.06	0.06
Minimum temperature												
Station												
Chikmagalur	**0.11**	**0.11**	0.08	0.07	0.08	0.05	0.04	0.04	0.05	0.07	**0.11**	**0.12**
Hassan	**0.14**	**0.13**	**0.13**	0.11	0.10	0.11	0.07	0.06	0.07	0.07	**0.13**	**0.15**
Madikeri	**0.23**	**0.22**	**0.17**	0.10	0.07	0.06	0.05	0.05	0.06	0.09	**0.14**	**0.22**
Mandya	**0.16**	**0.17**	**0.15**	0.10	0.10	0.10	0.09	0.10	0.10	0.10	**0.12**	**0.16**
Mysuru	**0.13**	**0.12**	**0.11**	0.08	0.06	0.06	0.06	0.06	0.06	0.07	**0.10**	**0.13**
Bengaluru	**0.14**	**0.13**	**0.11**	0.07	0.06	0.05	0.04	0.04	0.04	0.06	**0.11**	**0.14**
Streamflow												
Site												
K. M. Vadi	0.07	0.08	0.07	0.07	0.05	**0.17**	**0.11**	**0.10**	**0.15**	**0.10**	0.07	0.05
Muthankera	0.02	0.02	0.08	0.04	0.09	0.05	0.03	0.02	0.03	0.02	0.02	0.03
T. Narasipur	0.04	0.05	0.02	0.02	0.03	0.07	0.04	0.03	0.03	0.03	0.02	0.02
Billigundulu	0.02	0.03	0.02	0.02	0.02	0.05	0.05	0.03	0.03	0.03	0.02	0.01

Values in bold indicate high CV more than 0.09.

of the significance of increasing or decreasing trend using the seasonal Kendall test[14]. In the third phase, the slope of a linear trend was calculated using Sen's slope estimator[16]. In the fourth phase, long-term persistence of time-series data was detected using DFA method[15]. With regard to rainfall depth, the analysis was performed separately for individual rain-gauge sites and also for areal rainfall calculated over six sub-basins (Figure 1).

Historical data of all the hydro-climatic variables were tested for consistency and missing records. Outliers were eliminated and missing data were filled-in using linear interpolation for temperature and streamflow variables, and nearest neighbour values for rainfall. Using a monthly time-step, basic statistical parameters of mean, standard deviation and CV were computed for each of the variables. Data for maximum and minimum temperature and rainfall were further segregated into the three decades – 1981–1990, 1991–2000 and 2001–2010. For these variables, percentage departure of monthly values was computed with reference to the mean for each decade. To determine areal average rainfall over each sub-basin, Thiessen polygon technique was used. In this study SWAT model[17] has been used for computing average areal rainfall for each sub-basin and for the entire basin using data from the respective rain-gauge stations.

Results and discussion

Statistical analysis of hydrometeorological variables

Table 1 shows values of CV for monthly mean rainfall, maximum and minimum temperatures and streamflow data for the period 1981–2010. While Table 1 shows CV values for monthly rainfall averaged over each sub-basin and also for the entire Upper Cauvery Basin, Table 2 shows CV values for rainfall recorded at each rain-gauge station.

For all the sub-basins considerable variation was observed in rainfall during the winter season (December–March), ranging from 14% to as high as 71%. However, it must be noted that these months contribute less than

Table 2. Sen's slope, significant of trend using the seasonal Kendall method, detrended fluctuation analysis (DFA) exponent and CV for rain-gauge stations

Station	Sen's slope (mm/year)	*P*-value	Kendall's tau	DFA exponent Raw	DFA exponent Ds	CV January	February	March	April	May	June	July	August	September	October	November	December
Arkalgud	0	0.263	0.047	0.407	0.483	0.64	0.87	0.31	0.15	0.11	0.09	0.07	0.07	**0.11**	0.10	0.15	0.37
Begur	0	0.649	0.031	0.463	0.668	0.56	0.37	0.20	0.12	0.10	**0.11**	0.09	**0.11**	**0.10**	0.08	0.13	0.28
Belur	0	0.163	–0.050	0.684	0.784	0.41	0.52	0.24	0.12	0.10	0.08	0.09	0.08	0.10	0.10	0.16	0.32
Chamarajanagar	0	0.759	0.015	0.470	0.517	0.48	0.56	0.21	0.11	0.09	**0.13**	**0.12**	**0.12**	0.09	0.08	0.11	0.23
Chandrasekarpur	0	0.073	–0.057	0.585	0.531	0.47	0.52	0.35	0.18	0.12	**0.16**	**0.12**	**0.11**	**0.11**	0.11	0.15	0.35
Chikmagalur	0	0.499	0.021	0.429	0.550	0.49	0.51	0.24	0.13	0.10	0.08	0.09	0.08	**0.10**	0.09	0.15	0.30
Galibeedu	0	0.216	–0.040	0.291	0.457	0.42	0.27	0.19	0.13	0.08	0.04	0.03	0.04	0.06	0.07	0.12	0.25
Hallimysuru	0	0.331	0.040	0.468	0.630	0.45	0.59	0.31	0.13	0.10	**0.10**	0.08	0.09	**0.10**	0.08	0.15	0.34
Hanbal	0	0.796	–0.001	0.246	0.409	0.52	0.72	0.27	0.12	0.11	0.05	0.05	0.05	0.07	0.08	0.12	0.40
Harangi	0	0.753	–0.010	0.275	0.429	0.69	0.46	0.21	0.12	0.10	0.06	0.05	0.05	0.09	0.16	0.14	0.30
Hunsur	0	0.824	0.012	0.408	0.558	0.41	0.33	0.26	0.13	0.09	0.08	0.08	0.07	0.09	0.08	0.16	0.31
K. R. Nagar	0	0.867	0.008	0.422	0.614	0.47	0.41	0.28	0.14	0.10	**0.13**	**0.12**	**0.12**	**0.10**	0.09	0.15	0.30
Kikkeri	0	0.643	–0.001	0.319	0.471	0.68	0.49	0.31	0.14	0.10	**0.12**	**0.11**	**0.11**	**0.10**	0.09	0.14	0.38
Kollegal	0	0.448	–0.032	0.497	0.588	0.47	0.54	0.34	0.13	0.10	**0.15**	**0.13**	**0.11**	**0.10**	0.09	0.12	0.27
Kushalanagar	0	0.602	0.019	0.433	0.611	0.52	0.40	0.21	0.11	0.09	0.06	0.06	0.06	0.08	0.08	0.12	0.32
Maddur	0	0.279	–0.048	0.391	0.563	0.60	0.54	0.28	0.14	0.10	**0.14**	**0.11**	**0.10**	0.09	0.08	0.12	0.23
Malavally	–0.04	0.005	–0.086	0.438	0.507	0.54	0.48	0.28	0.14	0.10	**0.14**	**0.12**	**0.11**	**0.10**	0.09	0.12	0.22
Mayasandra	0	0.649	–0.008	0.381	0.415	0.61	0.56	0.71	0.20	0.13	**0.18**	**0.15**	**0.13**	**0.10**	0.10	0.18	0.40
Mysuru	0.04	0.113	0.053	0.447	0.629	0.69	0.49	0.25	0.12	0.10	**0.10**	0.09	0.09	0.09	0.08	0.13	0.24
Nagamangala	0	0.893	0.012	0.371	0.548	0.44	0.46	0.27	0.12	0.09	**0.14**	**0.12**	**0.11**	0.08	0.08	0.12	0.24
Nanjanagud	0	0.411	0.034	0.346	0.594	0.50	0.37	0.24	0.12	0.09	0.09	0.08	0.08	0.09	0.08	0.12	0.28
Nonavinakere	0	0.437	0.029	0.331	0.497	0.58	0.54	0.43	0.17	0.11	**0.14**	**0.13**	**0.10**	**0.10**	0.09	0.14	0.30
Ponnampet	0	0.622	0.021	0.342	0.454	0.47	0.45	0.20	0.12	0.10	0.07	0.06	0.06	0.07	0.08	0.14	0.33
Sargur	0	0.503	0.032	0.593	0.740	0.59	0.35	0.21	0.12	0.10	0.09	0.07	0.08	**0.10**	0.09	0.13	0.48
Shantigrama	0	0.204	–0.039	0.481	0.588	0.51	0.45	0.43	0.16	0.10	**0.10**	0.09	0.10	**0.10**	0.09	0.14	0.38
Sukravarsanthe	0	0.863	0.017	0.278	0.436	0.59	0.95	0.25	0.12	0.09	0.05	0.04	0.04	0.06	0.08	0.12	0.37
T. Narasipur	0	0.842	0.009	0.362	0.527	0.45	0.47	0.24	0.11	0.10	**0.12**	**0.11**	**0.10**	**0.11**	0.09	0.12	0.24
Tumkur	0	0.620	0.015	0.338	0.462	0.58	0.41	0.29	0.16	0.11	**0.11**	**0.10**	0.09	**0.10**	0.09	0.15	0.41
Turuvekere	0	0.547	–0.024	0.322	0.497	0.66	0.48	0.37	0.17	0.11	**0.14**	**0.11**	**0.10**	0.09	0.09	0.13	0.35

Raw, Raw time series; Ds, Deseasonalized time series. Values in bold indicate high CV.

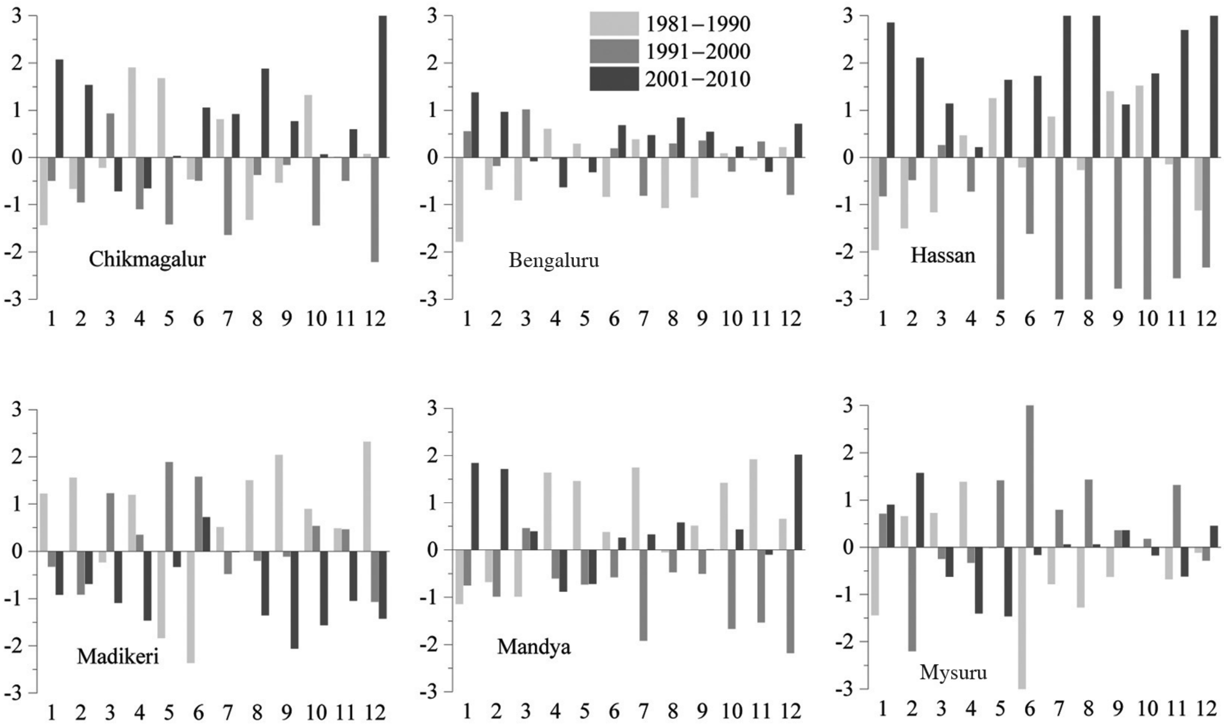

Figure 2. Percentage departure of monthly maximum temperature of different decades from 30 years normal value.

3% of the annual rainfall. Rainfall variability across the sub-basins is typically less than 10% during the other months, including the monsoon season (June–September). Maximum daily temperature displayed very small variability (5–10%) across all stations and months, with slightly higher CV values being recorded for the monsoon months (Table 1). On the other hand, minimum daily temperatures were more variable at all stations, especially during the winter months (November–February). Values of CV were also low for streamflow, except at the K. M. Vadi gauging station, where streamflow exhibited slightly higher variability, especially during the monsoon season (Table 1). As regards CV values for monthly rainfall at individual stations, Table 2 clearly highlights the fact that variabilities are much higher during all months of the year in comparison to those when the same rainfall is spatially averaged over sub-basins (Table 1). CV values for stations are particularly high during December–March, with highest variability of 95% being recorded at the Sukravarasanthe station in February. CV values start decreasing to about 5–15% from April onwards up to November. These results highlight the need to analyse historical rainfall records for individual stations rather than spatially averaged values, if the true variabilities are to be captured.

Figures 2–6 show the percentage departure of average monthly maximum and minimum daily temperatures and average monthly total rainfall and streamflow for three decades (1981–1990, 1991–2000 and 2001–2010) from their corresponding 30-year normal value. Considering maximum temperature, Figure 2 indicates that the departure for all stations and all decades is within ±3%. Except for the Hassan climate station, all other stations exhibit low departure during all months and all decades. The maximum daily temperature at the Hassan station appears to be lower than the normal value for all months during the decade 1991–2000, but during the more recent decade, i.e. 2001–2010, temperature appears to have increased during most of the months. At the Madikeri station, maximum temperature seems to have reduced during 2001–2010.

With regard to monthly average daily minimum temperature (Figure 3), departure is low at the Chikmagalur, Bengaluru and Mysuru climate stations during all months and all decades. While the Hassan and Mandya stations exhibit high departure in minimum temperature during all months, the Madikeri station shows high departure during the non-monsoon months only. Higher minimum temperature was recorded at the Hassan station during the decade 1991–2000 and lower temperatures was recorded during 2001–2010. On the other hand, the Mandya station experienced higher minimum temperature during all months of the decade 2001–2010 and lower temperature during 1981–1990.

From Figure 4, it can be seen that areal rainfall across the sub-basins exhibits high departure (exceeding ±50%) during the non-monsoon months for certain decades. However, departure in rainfall is quite low during the

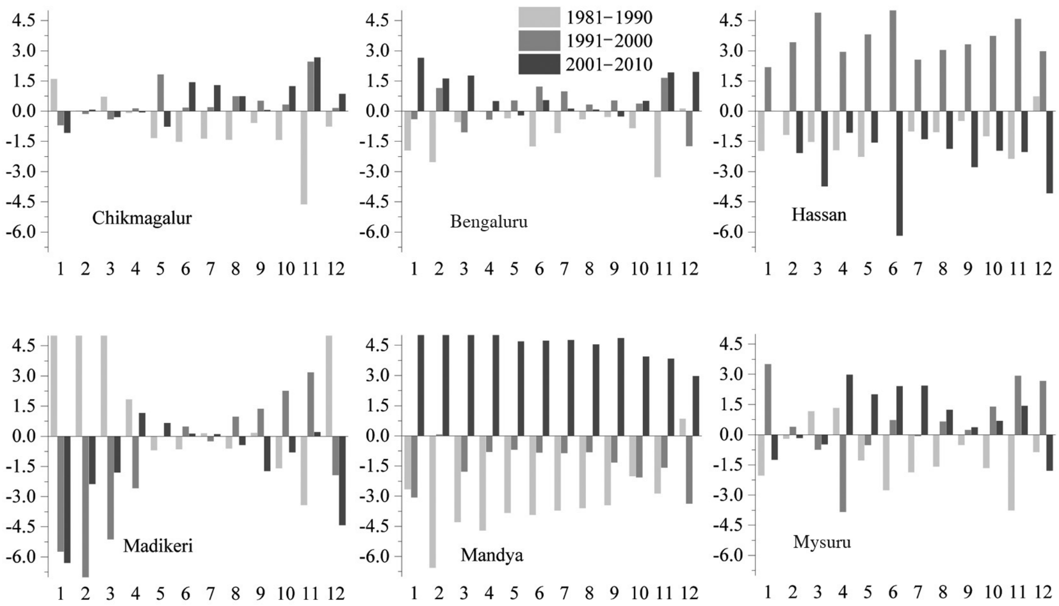

Figure 3. Percentage departure of monthly minimum temperature of different decades from 30 years normal value.

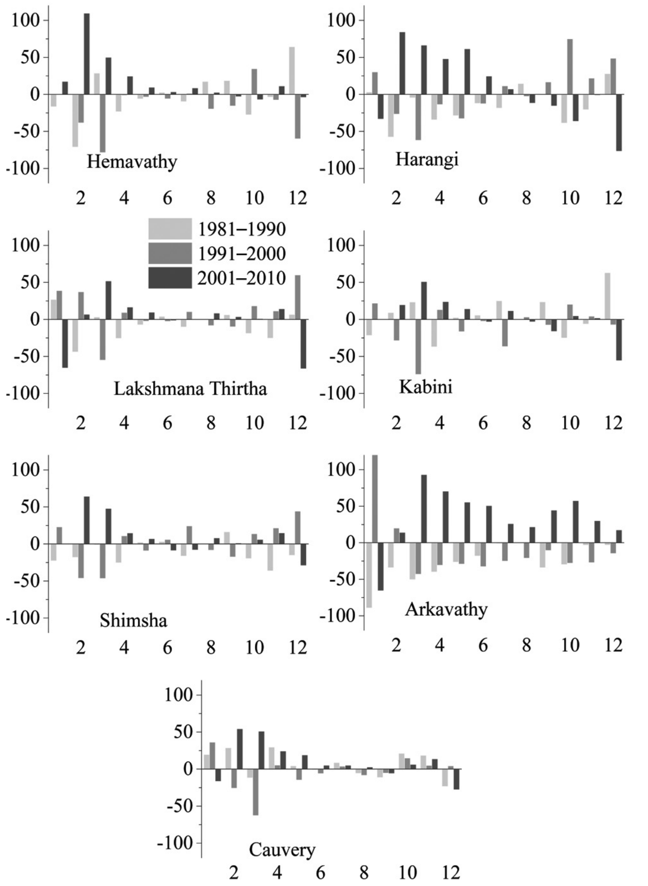

Figure 4. Percentage departure of monthly rainfall of different decades from 30 years normal value.

monsoon season for all the sub-basins, except Arakavathi, where non-negligible departure occurred even during the monsoon months.

Similar behaviour of low departure during monsoon months and somewhat high departure during the summer months can be seen with regard to rainfall at all individual rain-gauge stations (Figure 5).

Trend analysis of hydrometeorological time series

Tables 2 and 3 present results of trend analysis (Sen's slope, *P*-value and Kendall's tau) with regard to rainfall at individual stations and areal average rainfall for each of the sub-basins. No statistically significant trend is observed at any of the rain-gauge stations. Among the six sub-basins, Arkavathi shows significant increasing trend at 5% significance level. No trend is observed for the other sub-basins. Regional Sen's slope analysis for monthly rainfall over the entire Upper Cauvery Basin shows trend of 0.005 mm/year; but this is not statistically significant at 5% significance level.

Table 3 also shows results of the seasonal Kendall and Sen's slope analysis performed for monthly average daily minimum and maximum temperatures. Among the six climatic stations, Hassan shows statistically significant increasing trend for both minimum and maximum temperature. The Chikmagalur station shows significant increasing trend for maximum temperature, but there is no significant trend for minimum temperature. The Bengaluru station exhibits significant increasing trend in minimum temperature with no significant trend for maximum temperature. The Madikeri station shows significant decreasing trend for minimum temperature at 5% significance level.

Streamflow data were analysed for the four gauge sites in the Upper Cauvery Basin to quantify the magnitude of trend; the results are presented in Table 3. The T. Narasipur

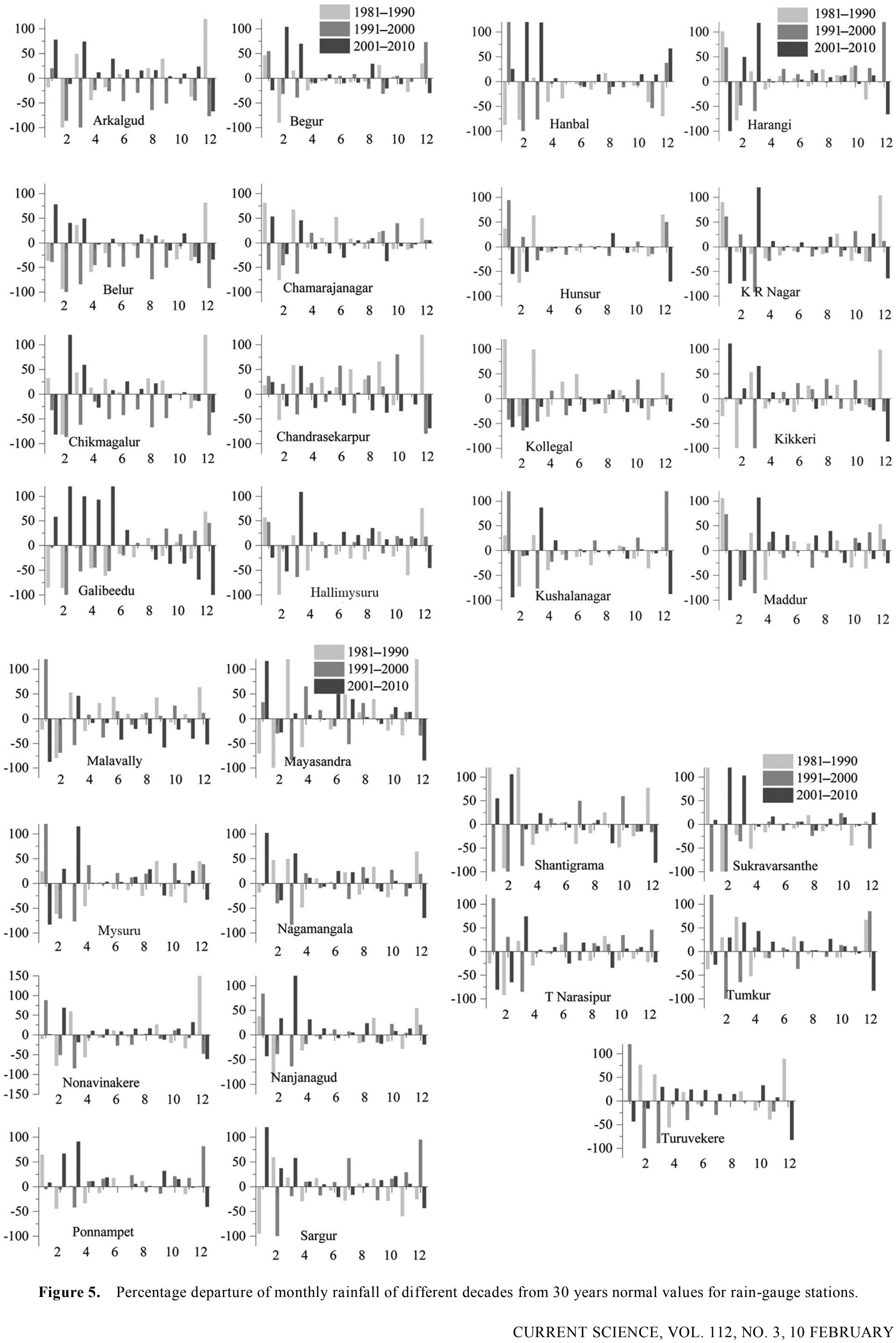

Figure 5. Percentage departure of monthly rainfall of different decades from 30 years normal values for rain-gauge stations.

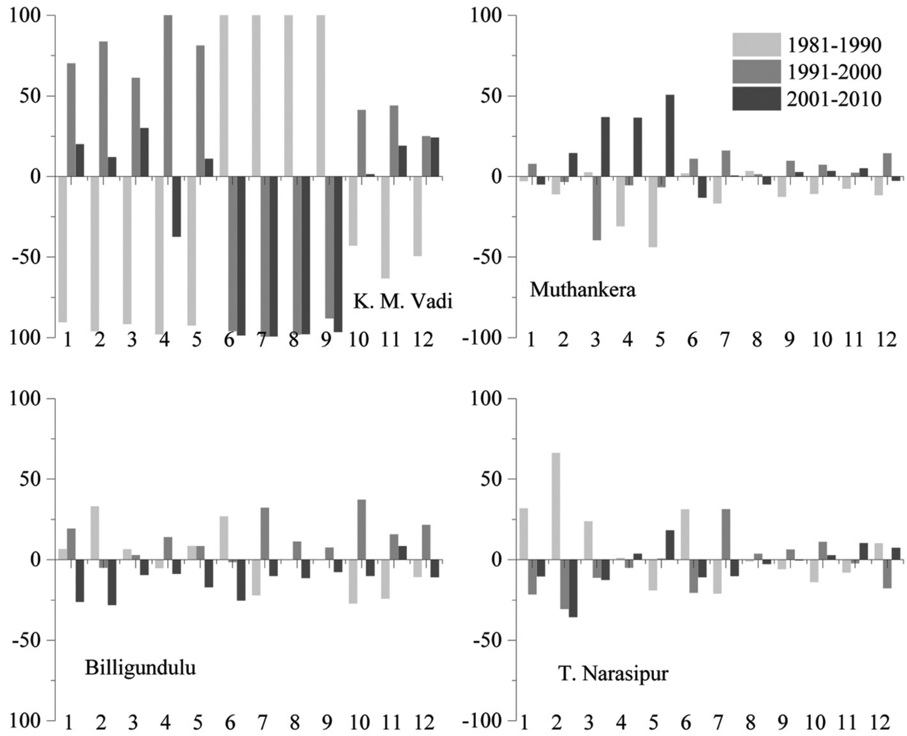

Figure 6. Percentage departure of monthly streamflow of different decades from 30 years normal value.

Table 3. Sen's slope and significant of trend using the seasonal–Kendall method for rainfall, temperature and streamflow

Sub-basin	Sen's slope (mm/year)		*P*-value		Kendall's tau	
Rainfall						
Hemavathi	0.00		0.456		–0.29	
Harangi	0.08		0.481		0.027	
Lakshmanathirtha	0.05		0.344		0.036	
Kabini	0.04		0.416		0.031	
Shimsha	0.00		0.631		–0.018	
Arkavathi	0.37		0.0002		**0.166**	
Upper Cauvery	0.06		0.462		0.029	
	Sen's slope (°C/year)		*P*-value		Kendall's tau	
Station	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Maximum and minimum temperature						
Chikmagalur	0.04	0.01	0.0001	0.566	**0.162**	0.020
Hassan	0.02	0.04	0.0001	0.0001	**0.153**	**0.153**
Madikeri	–0.02	–0.04	0.928	0.0001	0.003	**–0.164**
Mandya	0.00	0.00	0.292	0.637	0.036	–0.016
Mysuru	0.02	0.01	0.007	0.193	0.094	0.045
Bengaluru	0.00	0.02	0.563	0.0001	0.020	**0.229**
Site	Sen's slope (m^3/s/year)		*P*-value		Kendall's tau	
Streamflow						
K. M. Vadi	0.00		0.055		0.072	
Muthankera	0.98		0.978		0.001	
T. Narasipur	–9.34		0.0004		**–0.160**	
Billigundulu	–9.92		0.273		–0.056	

Values in bold indicate high significant trend in rainfall and temperature.

Table 4. DFA exponent α, for monthly rainfall and streamflow time series

	DFA exponent (α)	
	Raw time series	Deseasonalized time series
Rainfall		
Hemavathi	0.40	0.59
Harangi	0.31	0.52
Lakshmanathirtha	0.38	0.58
Kabini	0.46	0.67
Shimsha	0.25	0.51
Arkavathi	0.57	0.68
Upper Cauvery	0.36	0.60
Streamflow		
Site		
K. M. Vadi	0.43	0.41
Muthankera	0.38	0.46
T. Narasipur	0.50	0.56
Billigundulu	0.55	0.58

gauge site shows significant decreasing trends at 5% significance level for streamflow. The T. Narasipur gauge site indicates an annual decrease of –0.778 $m^3/s/year$ in the period 2001–2010. No significant trend is observed for the other three gauge sites.

Long-term persistence in hydrometeorological time series

To check whether hydrometeorological time series exhibit long-range dependency or not, the DFA method was applied. Monthly rainfall and streamflow data for the period 1981–2010 were used for this purpose. The long-range dependence was checked for raw and deseasonalized time series. From Table 4, a weak persistence can be observed for rainfall and streamflow raw time series using the DFA method, although slightly stronger persistence is evident for the deseasonalized time series. The DFA exponent (α) for rainfall is in the range 0.27–0.57 and for streamflow it is 0.38–0.55 for the raw time series. The DFA exponent (α) ranges between 0.52 and 0.68 for rainfall, and between 0.41 and 0.58 for streamflow when the deseasonalized time series is considered.

Summary and conclusion

Historical records of hydroclimatic variables in the Upper Cauvery Basin were analysed to identify possible changes and trends over the 30-year period, i.e. 1981–2010. The variables analysed were monthly averages of daily maximum temperature, daily minimum temperature, rainfall depth and streamflow recorded at 33 rain-gauge stations, 6 climate stations and 4 stream-gauging stations located within the basin. In addition to analysing rainfall at individual rain-gauge stations, areal rainfall depths for six sub-basins and the entire Upper Cauvery Basin were also computed and subjected to analysis. For each of the variables, historical data were analysed to compute CV and percentage departure in monthly mean values from the normal values separately for three different decades. In order to determine the existence of a trend and calculate magnitude of trend in these variables, the seasonal Kendall[14] and Sen's slope[16] estimators were used. To find long-term persistence in the time-series data, DFA method was used[15].

Overall, monthly rainfall over sub-basins and also at individual stations did not exhibit statistically significant trends using any of the methods employed. However, somewhat large values of CV and departure were noted for rainfall in the non-monsoon months. Not much variation was observed for maximum daily temperature, except in May and June for the Hassan climate station. Statistically significant trend was observed in maximum temperature only for Chikmagalur and Hassan stations. CV of minimum temperature showed large variability from November to March for all climate stations and also a significant increasing trend for Hassan and Bengaluru stations, while for Madikeri a decreasing trend was observed with a variation of –0.16°C/year. Not much variation was found for streamflow, except for the T. Narasipur gauge site which showed a significant decreasing trend of –0.778 $m^3/s/year$. Long-range dependence analysis indicated a weak persistence for both rainfall and streamflow. Results of this study can provide important inputs to climate/hydrology modellers and also to decision-makers concerned with developing adaptation/mitigation plans for climate change.

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