Original Research Article

Stream flow trends analysis and its linkages with meteorological and anthropogenic factors in Ramganga River basin in North India

Abstract

Stream flow trend analysis of hydro-climatic variables such as stream flow, rainfall, and temperature provides useful information for effective water resources planning, designing, and management. Trends in observed stream flow at seven gauging stations in the Ramganga river basin of North India were assessed during the Mann–Kendall and Sen's slope for the 1981 to 2012 period. The relationships between trends in stream flow and rainfall were studied by correlation analyses. There was a gradual decreasing trend of annual, monsoonal, and winter seasonal stream flow ($p<0.05$) from the upstream to the downstream of the river and also a decreasing trend of crop seasonal and decadal moving averaged standardized anomalies of stream flow for the entire basin. The declining trend in the streamflow was attributed partly to the increased water withdrawal, to increased air temperature, to higher population, and partly to significant reducing trend of post monsoon rainfall especially at upstream and downstream. Upstream gauging station showed a significant decreasing trend of stream flow (-0.39 m^3/s/year) at annual scale, and this trend was attributed to the significant decreasing trend of catchment rainfall (-8.40 mm/year). Significant coefficient of positive correlation ($\rho=0.60$) between stream flow and catchment rainfall. The decreasing trend in stream flow and post-monsoon rainfall especially towards downstream area with concurrent increasing trend of temperature indicates a drying tendency of the Ramganga River basin. The results of this study may help stakeholders to design stream flow restoration strategies for sustainable water management planning of the Ramganga River basin.

Key words: Climate change, Mann-Kendall, Ramganga River basin, Streamflow trend

Introduction

Stream flow are defined as the flows required for the maintenance of the ecological integrity of rivers, their associated ecosystems, and the goods and services provided by them and to fulfill the aspirations of the people. stream flow represents an integrated process of atmosphere, hydrosphere, pedosphere and cryosphere in basin change and human activities (Barnett et al. 2005).With the rapid urbanization, expanding industrialization and increase in agricultural activities in the Ramganga river basin, the demand for water has increased manifold. Ecological degradation of Ramganga is also being attributed to the lean flows due to large scale abstractions for irrigation and increasing pollution of the river from multiple sources. This has been impacting the state of aquatic biodiversity present in the river along with the health of the local community members staying across the basin.

The variation in stream flow depends on several physical and hydrological processes of a basin and hence is likely to be affected by the magnitude and direction of climate change. The Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) mentions with high likelihood that the observed and projected increases in temperature and precipitation variability are the main causes for the reported and projected impacts of climate change on water resources, resulting in a significant impacton a river basin and associated river systems (Zhang et al. 2015). The water scenario of India, becoming critical as per capita availability of water has decreased from 2309 m^3 in 1990 to 1820 m^3 in 2001, and will reduce to 1140 m^3 by 2050 (Gupta and Deshpande 2004). The various developments made by human activity and hydro-climatic changes can alter the time series of a stream flow. Assessment of stream flow trends in long term is an important tool to detect any modification in hydrological systems as well as help decision makers with better planning (Chang, 2007). Furthermore, spatial-temporal and/or direction of trends could help guide water resource planners to devise adaptive management plans to deal with adverse changes (Abeysingha et al. 2015).

Several studies were reported on trend assessments at different scales for different parts of the world. But, there are very few literature published on stream flow studies in India at river basin scale, probably due to non-availability of long term stream flow data. Abeysingha et al. (2015) advocated that both climatic and anthropogenic factors are responsible for the decreasing trends in Gomti River stream flow. Fu et al. (2007) stated that climate variability had a significant impact on stream flow and it was sensitive to both precipitation and temperature in the Yellow River basin. Yang and Saito (2003) reported that, the reduction in the annual stream flow is due to water consumption, diversion and reservoir construction, which led to great environmental problems. Nune et al. (2012) tested the trends in rainfall and stream flow in Himayat Sagar catchment in southern India and showed large decline in stream flow without significant change in rainfall and then they attributed the stream flow trends to anthropogenic influences in the catchment. Panda et al. (2013) investigated the stream flow trends in the Mahanadi River basin in eastern India and linked the changes to El Niṅo-Southern Oscillation (ENSO). Bhutiyani et al. (2008) studied the changing stream flow patterns in the rivers of North Western Himalaya on a longer time scale of about 82 years. Their study showed a significantly decreasing trend in average annual and monsoon discharge in the Beas River and a decreasing but insignificant trend for the Ravi River in the last four decades of the last century. On the contrary, winter discharge in the Chenab River showed a statistically significant increase during those four decades. They attributed these changes to variability in snow and glacier melting.

Analysis of hydro-climatic conditions at a regional scale may lead to loss of the spatial information of the variable. Therefore, it seems to be logical to analyze hydro-climatic variables at small scale (Rai et al., 2010). In this study, the Ramganga river basin is major tributary of the largest Ganga River basin was studied. We investigated trends in measured stream flow data, their spatial variation and the relations among observed changes in stream flow with rainfall and anthropogenic interventions.

Study area

The Ramganga, an alluvial river of the Indo-Gangetic Plain, is one of the important tributaries of the River Ganga. It is considered to originate near lower Himalaya at latitude 30^0 5’ N and longitude 79^0 16’ E at an altitude of about 3110 m above mean sea level. The river Ramganga joins the Ganga on its left bank at Kannauj in Fatehgarh district after traversing 596 km in south, south-east direction and the total area of Ramganga river basin has been estimated to be 58,869 km^2. The river flows initially in a south-western direction for about 32 km before it moves right and flows in a south westerly direction. Successively, through Almora and Garhwal district for about 112 km. In these two districts, the river flows thoroughly hill terrain and bounds in a number falls and rapids. The river emerges from the hills and enters in to the plains at Kalagarh near the border of Garhwal districts. At Kalagarh, a storage Dam has been constructed across the river. Beyond Kalagarh, the river flows in a south easterly direction through the districts of Bijnor, Moradabad, Badaun, Rampur, Bareilly and Shahjahanpur and finally joins the Ganga near about Kannauj in Fatehgarh district. Topography is undulating with higher elevation at upstream end of the basin and elevation ranges from 3473m to 113 m above msl. The climate of the basin is ranging from semi-arid to sub-humid tropical with average annual rainfall at different locations varying between 700 and 1200 mm. About 75% of total annual rainfall is received between June to September due to the South-West Monsoon (Rai et al., 2009). The RamgangaRiver is the main source of water supply to cities of Moradabad, Bijnor, Badaun, Bareilly, Kannauj and Shahjahanpur. A number of tube-wells have also been bored near the river-bed to exploit groundwater in the basin.

Material and Methods

Data set and data preprocessing

stream flow data were collected from the Central Water Commission (CWC), Government of India and their characteristics are shown in the Table 1. The CWC is the nodal agency in India to record, compute, quality check, and archive all river hydrological data. Due to limited availability of data, this study used monthly 10 daily average stream flow data of six gauging stations representing near natural flow. Figure 2, shows the original 10 daily stream flow data for different gauging stations used in this study. Length of the records varied with the gauging stations; however, 27 years data was obtained for the Dabri station near the outlet of the basin which represents the entire basin. Moreover, common period of records (1981-2012) were used to assess and compare the spatial distribution of the trend of stream flow and rainfall. Since we could not get sufficient number of stations for point rainfall and temperature data in the basin, monthly district rainfall (1981-2005) and temperature data (1981-2005) were downloaded from WRIS (Water Resources Information System), http://www.india-wris.nrsc.gov.inweb portal. The meteorological data were collected for 15 districts covering the whole basin. These districts are namely, Chamoli, Pauri-Garhwal, Almora, Bijnor, Champawat, Jyotiba Phule Nagar, Moradabad, Rampur, Udham Singh Nagar, Bareilly, Pilibhit, Badaun, Shahjahanpur, Etah and Hardoi.

In this study river basin was delineated using 90 m resolution SRTM data (Jarvis et al., 2008) set in ArcGIS and the total drainage area of the river was estimated to be 58,869 km^2 (Fig.1). Catchments with respect to seven gauging stations were also delineated using ArcGIS (Ver 9.3) and were overlaid with district boundaries (Fig. 2). District areas falling in respective catchment were determined by intersecting district boundary layer with catchment boundary layer. Different district areas falling in a catchment were normalized with respect to total catchment area and used as weight to calculate monthly average rainfall for that catchment. Using these weighted average monthly rainfall values total catchment wise seasonal rainfall for each of the crop seasons were calculated.

Indicators Analysed

Following indicators were calculated from the data:

- Monthly mean stream flow: Mean of three decadal (10 daily) values of the month for a gauging station.
- Inter annual monthly mean stream flow: Monthly mean stream flow of the same month over the years (Jan $_{1982}$, Jan $_{1983}$, Jan $_{1984}$ ……) for a gauging station.
- Annual mean stream flow: Mean of twelve monthly mean stream flow values from January to December for a gauging station.
- Crop season mean stream flow: Mean of monthly mean stream flow values for *Rabi* crop season (November -March), *Kharif* crop season (July–October), and summer crop season (April –June), where the mean of *Rabi* crop season was based on December of the previous year and January, February and March of the following year.
- Decadal mean stream flow: Mean of ten year period stream flow i.e. 1981 to 1990 and 1991 to 2000 respectively
- Annual and seasonal mean temperature; Maximum and Minimum mean temperature for each of the six catchments.

Statistical Analysis

Monotonic trend of hydro-climatic data series in this study were tested using widely used trend detection methods of Mann-Kendall (MK) test (Mann 1945, Kendall 1975, Yue et al., 2002; Sharif et al., 2013, Abeysingha et al. 2015) and Sen’s slope estimator (Zhang and Lu 2009; Gautam et al., 2012).

Though the MK test is robust and very useful in many hydrological studies, the use of MK test for detecting trends may not always be ideal. That is because the MK test does not account for the serial correlation that very often exists in a hydrological time series (Hamed and Rao, 1998; Yue et al., 2002). The presence of serial correlation in a data set may lead to a misleading result interpretation because it enhances the probability of finding a significant trend, when actually there is an absence of a significant trend. As such, in our study, each time series was first checked to find whether a significant lag-one autocorrelation exists. If a time series did not exhibit a significant autocorrelation, the original MK test was used to analyze the data. When there was a significant lag 1 autocorrelation in a time series, we adopted Modified MK test proposed by Hamed and Rao (1998). All the hydro-climatic trends were evaluated at 0.05 and 0.1 significance levels ('p' values) as an indicator of the trend strength (Sharif et al., 2013).

The Standardized anomaly or 'Z-score' (subtracting the mean from the original value and then dividing it by the respective standard deviation) for each gauging station was calculated for streamflow and rainfall. This indicator minimizes the spatial bias and thus helps in comparing spatio-temporal variability in hydro-climatic parameters across the gauging stations of the basin. Non-parametric Spearman's rho correlation coefficient (ρ) was also used to find the prospective association of stream flow with rainfall. In order to reduce the random fluctuation and to derive overview of the entire basin, first smoothening of standardized anomaly in stream flow and rainfall were carried out on the basis of crop season and decadal and then compared.

Results

Before analyzing the trend in stream flow and rainfall, we tested the lag-one autocorrelation in all the time-series dataset (monthly, crop seasonal, decadal and annual) and about 8% of the tested series showed statistically significant autocorrelation at 5% significance level. Generally, monthly time series show a stronger autocorrelation compared to its annual time series (Hirsch and Slack, 1984) and we also observed significant autocorrelation only in monthly mean stream flow and crop seasonal mean stream flow.

In order to understand the overall behaviour of stream flow and rainfall of the basin, mean monthly stream flow and mean monthly rainfall of seven catchments were calculated over the period of 1981 – 2005 (Fig. 4). Most of the years in all gauging stations, the maximum mean monthly streamflow was in September, except Moradabad in August; whereas the maximum mean monthly rainfall occurred in July and August. This implies that most of the rainfall occurring in September may be contributing to streamflow. Of the seven gauging station the maximum stream flow was recorded at Bhakra Dhaneta station which is located at mid-stream (m/s)of the River basin and the lowest was at the Moradabad which is the most upstream (u/s) of the basin.

Trends in annual stream flow and rainfall

Figure 5 shows the trends of annual mean stream flow of the seven stations and annual rainfall of the corresponding seven catchments of Ramganga basin. The magnitude of the trend as Sen's slope and the Spearman's rho correlation coefficient (ρ) between stream flow and rainfall are also shown in Fig 5. There was a statistically significant decreasing trend in both stream flow and catchment rainfall at Moradabad and Dabri station as shown by negative Sen's slope values which are significant at p=0.05. This station is located in the most upstream (u/s) and downstream (d/s) of the Ramganga river basin. In contrast, all the other stations showed significant increasing trend of stream flow (positive values of Sen's slope) except Fatehganj gauging station, also represents decreasing trend in streamflow and rainfall. Considering the magnitude of the trend of annual stream flow and spatial distribution of gauging stations, it can be observed that declining trend of stream flow is increasing from the upstream (m/s) to the down-stream (d/s) of the river representing Moradabad to Dabri. The correlation analysis revealed a significant positive relation between stream flow and rainfall for the three stations over the study period. The highest ρ of 0.6 was obtained for Moradabad station, the most u/s station and the ρ values decreased as we move m/s to Ramnagar (ρ=-0.01), to Bhakra Dhaneta (ρ=-0.28),Kiccha Dhaneta (ρ = -0.26), Bareilly (ρ = -0.40) and then d/s to Dabri (ρ = -0.39). Figure 6 shows the relationship between standardized stream flow anomaly and rainfall anomaly at different stations across years. The significant linear relationship was observed between the two with intercept adjoining to zero and the strength of relation (R^2) shows decreasing trend from u/s to d/s.

Trends in mean crop seasonal stream flow and seasonal rainfall

Monotonic trends in stream flow and rainfall for three seasons (*Rabi*, *Kharif* and *summer* season) were analyzed for each of the catchment region and the results are shown in Figure 7. It shows that stream flow and rainfall patterns are characterized by marked seasonal differences. At the upstream(u/s) region of the Ramganga river basin, the relationship between crop seasonal stream flow and rainfall showed lowest in *Rabi* (ρ = 0.24) and *summer* crop season (ρ = 0.38) while in

Kharif crop season were highest (ρ = 0.51). However, at midstream (m/s) and downstream (d/s) catchment areas of Ramganga river basin showed negative relationship in *Rabi* crop season which represents the decreasing trend. The magnitude of declining trend of stream flow gradually increases from m/s to d/s over the monsoon season. This was consistent with the annual trend. It is important to note that almost all stations exhibited a decreasing stream flow trend during *summer* crop season; but in contrast, catchment rainfall also showed decreasing trend. *Kharif* crop season rainfall at all station (except Dabri) shows a decreasing trend and the statistically significant decreasing trends are observed in lower reaches of the basin.

Trend in decadal period, annual and crop seasonal mean streamflow

To study the stream flow trends at decadal, annual and crop seasonal periods for all the gauging stations in Ramganga river basin historical data was analysed. For the decadal period (1981-1990) the stream flow trend showed the decreeing trend at three gauging stations (Bhakra & Kiccha Dhaneta and Fatehganj) while all other stations showed increasing trend. The annual mean streamflow trends were showing decreasing trend at Moradabad and Dabri which is upstream (u/s) and downstream (d/s) gauging stations while at midstream (m/s) represented increasing trend in Ramganga river basin. On the basis of crop seasons, stream flow trends showed increasing trend in *Rabi* crop at all gauging station except Fatehganj. However, *Kharif* crop season represented decreasing trend at upstream gauging station (Moradabad), in midstream (m/s) gauging station (Bareilly); while Dabri gauging station showed increasing trend which is the most downstream (d/s) gauging station of Ramganga river basin.

Trends in monthly stream flow and rainfall

In order to understand the month-wise behaviour of stream flow, inter annual monthly mean flows were tested for trend using MK test and the Sen's slope (Table 2). Similarly, the inter annual mean monthly catchment rainfall was also analyzed (Table 2). The inter annual monthly stream flow showed decreasing trend in number of the months at different gauging station *i.e.* Moradabad, Bareilly, Kiccha Dhaneta (March –June); Fatehganj East (January- December). At the Bareilly gauging station significant decreasing trend were observed for the month of Jan – Mar. stream flow decreasing trend were also observed in different months, at gauging station Bhakra Dhaneta (June-September) and Ramnagar (January and April) respectively. In contrast the streamflow showed increasing trend in all the months at Dabri gauging station but none were statistically significant. The rainfall showed decreasing trend between Aprilto August months at all the four stations but none were significant except for the September month. During other months rainfall showed mixed trends but none were found to be significant.

Trends in air temperature

The trend analyses of annual and seasonal temperatures of the seven catchment over 25 years are summarized in Table 3. All catchment in the basin showed a significant increasing trend in mean annual and monsoon season temperatures. Even when we reduced the records to a common period of 1991 to 2005, the average air temperature of all catchments in the basin showed an increasing trend. Even though the winter average temperature also showed an increasing trend, it was not statistically significant.

Characterizing the drivers of trends in stream flow

In the present study, we could not quantitatively attribute different drivers for the detected trend of stream flow due to non-availability of long term relevant data set, but an attempt was made to qualitatively characterize the possible drivers of trends of stream flow.

Water withdrawal from the basin (surface water) has major influence on the stream flow. As most of the basin area is under agricultural land-use with rice and wheat as dominant crops in *Kharif* (June – October) and *Rabi* (November-March) seasons, respectively, we analyzed the trends in irrigated area of the basin. Total irrigated areas under rice and wheat crops in major parts of the basin over 1993-94 to 2012-13 period are shown in Figure 11. Over the study period, the increase in irrigated area is 68% for rice and 22% for wheat. Figure 11 clearly shows an increasing trend in irrigated area under both the crops, implying that irrigation water consumption in the basin increasing continuously over time, which might have also negatively influenced the flow of water in the river. The Table 4 shows the population of the districts of Ramganga River basin in 1991 and 2011 and the percentage change over this period. It indicates that the population has increased by 21 % and specifically districts such as Bareilly and Moradabad showed higher increment (36% and 38%) in population. Increased population indirectly implies increased water demand over the study period which might have also impacted the river stream flow negatively.

Discussion

Climatic change impacts on stream flow

stream flow is an important component of fresh surface water resource that is crucial for human societies and natural ecosystems. Climate change and anthropogenic intervention is the main cause to explain change in stream flow of river basin. In general, stream flow is positively related with precipitation but negatively correlated with temperature (Fu et al., 2007; Xu et al., 2010). Melting glacier and precipitation in the high mountain regions are the main water resources of the semi-arid areas in northern India. Increasing air temperature induced more glacier and snow melting during the past decades which contributed significantly to the increasing stream flow in river basin. From monthly changes of average streamflow data, the impact of climate change can be seen more clearly in the Ramganga river basin. Taking the stream flow of the Bhakra Dhaneta (BD) station as an example (Figure 5), stream flow increased in the spring. The spring season(March to May), is the snow melting season, and the rising stream flow can be attributed to higher temperature. There is hardly any runoff generated in the m/s and d/s of Ramganga basin due to low precipitation and high evapotranspiration, and the change in precipitation does not affect stream flow. In addition, precipitation decreased in most of the months of all catchment areas of Ramganga river basin from upstream to downstream region, which showed that the impact of the precipitation change on the stream flow is negligible. Moreover, the relationships between stream flow and air temperature are different in the m/s and d/s of Ramganga river basin. Higher air temperature could lead to higher actual evapotranspiration which resulted in the decrease of streamflow.

Anthropogenic impacts on stream flow

stream flow is the most important water resource that sustains irrigated agriculture in the Ramganga river basin. During the last several decades, the hydrological regime of the Ramganga river basin had been strongly affected by extensive human activities. They impacted the surface water stream flow. During the study period, we observed a significant decreasing trend of stream flow, particularly on annual scale, at Moradabad station which is located at the u/s of the basin. A similar significant decreasing trend was observed for the Moradabad catchment rainfall, especially on annual scale. Therefore, decreasing trend of stream flow in u/s of the river is primarily attributed to the high human activities occurred in the upstream region of Ramganga river basin. Milliman et al. (2008) concluded that trends in annual stream flow for many rivers primarily were driven by changes in precipitation. It is further evident by statistically significant correlation coefficient between stream flow and rainfall ($\rho = 0.56$) at this station. In addition, Gregory et al. (2012) examined the actual evapotranspiration, runoff, and potential evapotranspiration for the past century by using a monthly water-balance model and their analysis indicated that precipitation has been the primary driver of variability in runoff.

In contrast, we found a gradual decreasing trend of annual mean stream flow, monthly stream flow and crop seasonal stream flow from u/s to the d/s area of the river. However, annual and monsoon season catchment rainfall of the respective catchments show significant decreasing trends. The decreasing trend of stream flow for the entire basin was further corroborated by significant decreasing trend rainfall. In contrast, rainfall over the basin showed decreasing trend for *Rabi* crop season ($p \leq 0.05$), and *Kharif* crop season ($p \leq 0.05$). Regarding the trends in crop seasonal distribution of rainfall, we found that the summer crop season rainfall is increasing significantly, particularly in the month of May. In contrast, post monsoon rainfall is decreasing significantly especially the d/s area. It indicates that there may be an apparent shifting in timing of monsoon season, i.e. early onset and early withdrawal. Moreover, the monsoon season rainfall is also increasing significantly for the entire basin. Even with increased rainfall, the decreasing trends in stream flow indicate that the rate of water withdrawal from the basin is much higher than the runoff generated from increased rainfall.

These opposite trends observed between the stream flow and rainfall in majority of basin area suggests that endogenous changes in the catchment dominant over the exogenous (climate) changes. Nevertheless, the d/s catchments showed a statistically significant decreasing trend of rainfall during the *Rabi* crop season ($p \leq 0.1$). Moreover, we observed statistically significant correlation between catchment rainfall and stream flow at different gauging stations of the basin. Since the significance of this correlation decreased from u/s to d/s, driving forces other than rainfall may be playing a dominant role in the d/s area of the basin. The decreasing trend of stream flow in the d/s areas of the river may be partly caused by the variations in rainfall and partly by other anthropogenic factors. Human activities such as increased water consumption, land use and land cover changes caused by forest disturbance, soil and water conservation projects, new dam construction and city expansion etc., resulted in significant hydrological alteration (Li et al., 2007; Wei and Zhang, 2010).

Maurya (2013) in his study on environmental implications of anthropogenic activity on Ramganga River morphology at Moradabad and Bareilly showed that the water of Ramganga is used for Industrial purpose located in nearby area and the Ramganga barrage is used to manage the river water level in Moradabad during the summer season. Moreover irrigated area of the basin has substantially increased during 1993/94 to 2013/14(Fig. 11). In addition, population growth over the basin (21% between 1991 and 2011) indicated the commensurate increase in abstraction of river water. Hence, all these factors might have resulted in increased water withdrawal and thus causing decreasing trend of stream flow especially in the d/s area of the basin. Nune *et al.* (2012) also found declining trend in stream flow without significant changes in precipitation in the Himayat Sagar catchment in India over a period of 24 years (1980 to 2004). They also attributed the stream flow trends mainly to anthropogenic factors, such as, changes in land use, watershed development, ground water abstractions and storage. Lloyd (2010) by examining the Breede River flows in South Africa over the past 43 years, found decreasing stream flow trend in most of the gauging stations and concluded that changes in land use, creation of impoundments, and increasing abstraction have primarily been responsible for changes in the observed flows.

We also observed that air temperature of the entire basin has increased at a rate of 0.01^{0}C/year during the study period (Table 3). Hingane et al. (1985) also found that mean annual temperature to be increasing over the north central and northeastern regions of India during 1901-1982. This increasing trend of air temperature increased the atmospheric water demand through higher evaporation and evapotranspiration. The increasing trend in temperature might also be a factor contributing to the increased water loss from the basin and decreasing trend in stream flow. Zhang et al. (2014) also reported significant upward trend of annual mean temperature and potential evapotranspiration in Xitiaoxi River basin in China which were partly responsible for significant downward trend of annual stream flow from 1975 to 2009.Abeysingha et al. (2015), advocated that the average air temperature of all catchment of Gomti river basin showed an increasing trend leading to reduction in stream flow.

Decreased stream flow in Ramganga River especially during the dry season might affect the aquatic biodiversity of the river and areas in its periphery, recharging capacity of the groundwater and natural purification capacity of the river water. In addition, decreased streamflow might affect the rituals related to river water as Ramganga River is also a tributary of holy Ganga River. Lokgariwar et al. (2014) pointed out the importance of including the cultural water requirement in assessing environmental flow. Decreased stream flow also showed the need of assessing the environmental flow requirement for Ramganga River including the cultural water flow.

Overall it can be clearly seen that the Ramganga River basin is showing a drying tendency at Moradabad (u/s) gauging station, Fatehganj (m/s) gauging station and Dabri (d/s) gauging station and the decadal trend and crop seasonal showed statistically significant downward trend of the streamflow. The decreasing rainfall during summer crop season and *Kharif* crop season are of little consequence. Both climatic and anthropogenic factors were responsible for the decreasing trend in stream flow, though it is difficult to quantify contribution of each of the individual factors.

It may be pointed that this study has certain shortcomings. One of the major was non-availability of uniform long period records of stream flow and rainfall for the basin. The length of records in the study varied from 21 to 30 years. Rainfall records, covering a period over 30 years, were considered to be long enough for a valid mean statistics (Kahya and Kalayci 2004) while a minimum record length of 25 years ensured statistical validity of the trend results in a climate change research (Burn and Elnur, 2002). In order to ensure validity of trend results, we tested the annual mean trend, decadal and crop seasonal averaged standardized anomaly for the entire basin as well as for each station. The streamflow decreasing trends at Moradabad (u/s) gauging station, Fatehganj (m/s) gauging station and Dabri (d/s) gauging station all these cases enhance the confidence in the results. Therefore, the current analysis certainly provides important insights into the likely hydrological scenario of Ramganga river basin for water managers to initiate suitable remedial plans.

Conclusions

Ramganga is an important major tributary of the Ganga River which irrigates large tracts of wheat and rice area and supports a huge human population. This study on the annual and crop seasonal trends in stream flow of Ramganga river basin showed that there is a drying tendency of basin stream flow, especially in the downstream areas. This is despite the fact that there is a decreasing trend in crop seasonal rainfall. The study indicated that both climatic and anthropogenic factors are responsible for the decreasing trends in Ramganga river stream flow. Amongst the climatic factors, a significant increasing trends in air temperature and significant decreasing trends in rainfall are the important ones. Among the anthropogenic factors, the increasing trends in crop area under irrigation and about 21% growth in population over 30 years period may have been responsible for increasing water withdrawal from the basin. The decreasing trends in stream flow may become more pronounced under future trends of climate change and increasing population of the region.

Unless immediate remedial measures are not initiated, the decreasing trends in Ramganga river basin stream flow is likely to adversely impacts the aquatic biodiversity of the river and areas in its periphery, recharging capacity of the groundwater and natural purification capacity of the river water. It may results in compromising the food security of the region, livelihood and other entitlements of a large population. So, this study point to an urgent need for holistic water management planning in this basin by undertaking practices at different spatial scales that may able to reserve the drying trends by increasing use efficiency of river water in various sectors.

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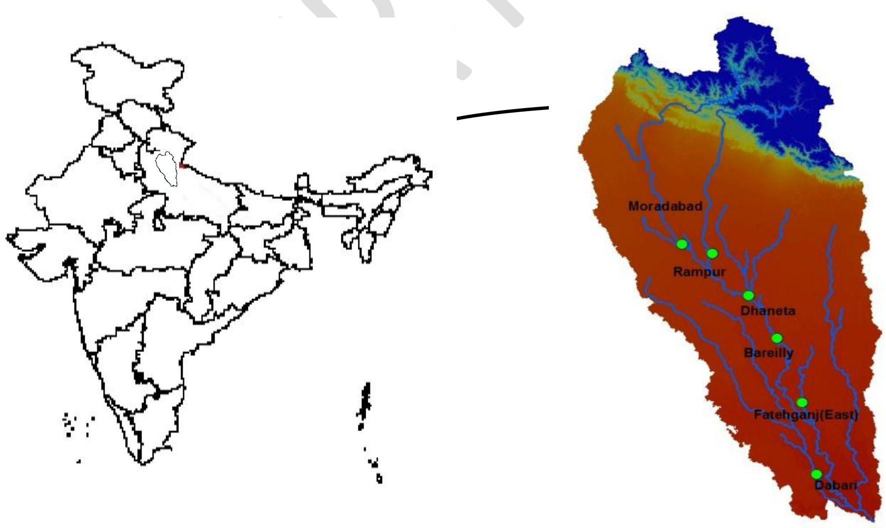


Figure 1. Location of the study area

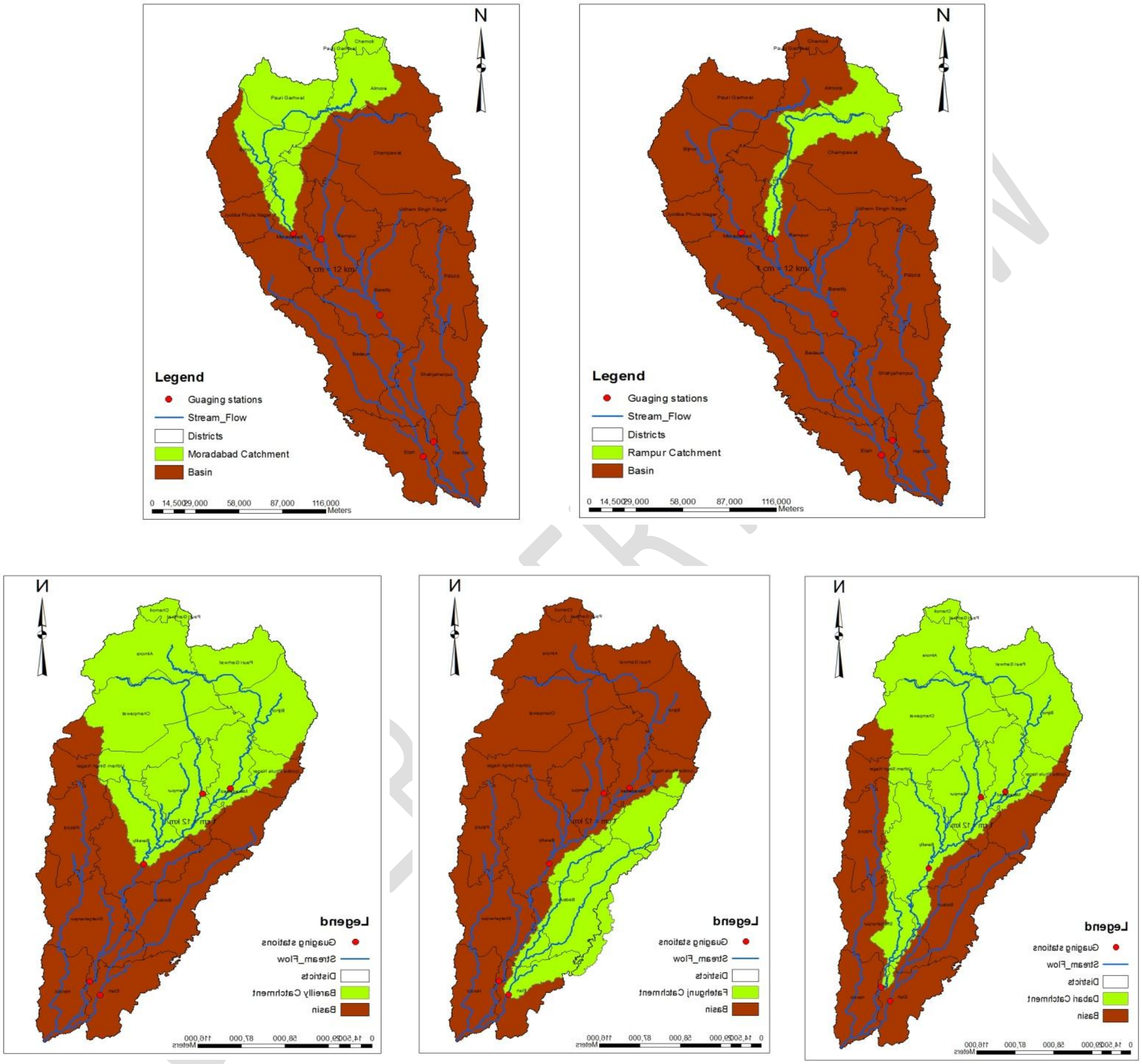
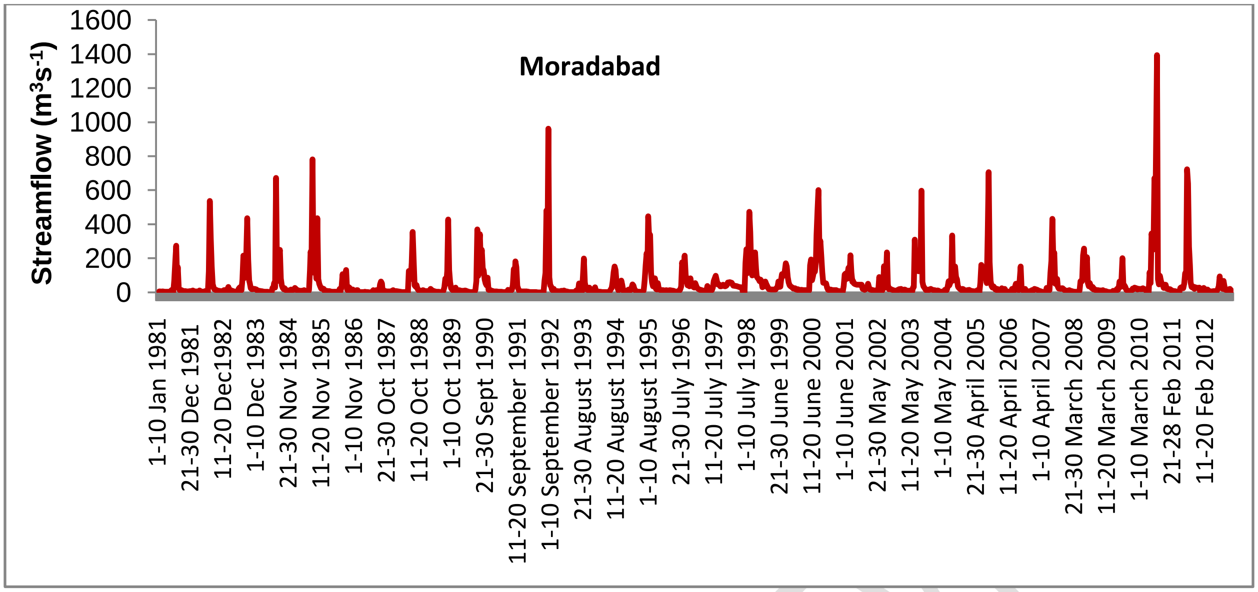
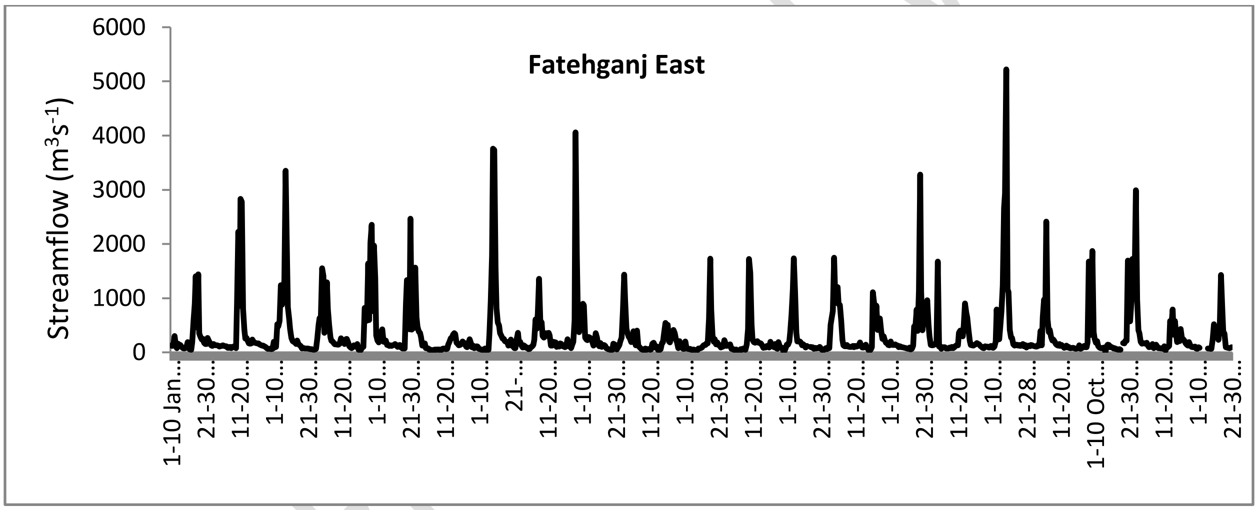
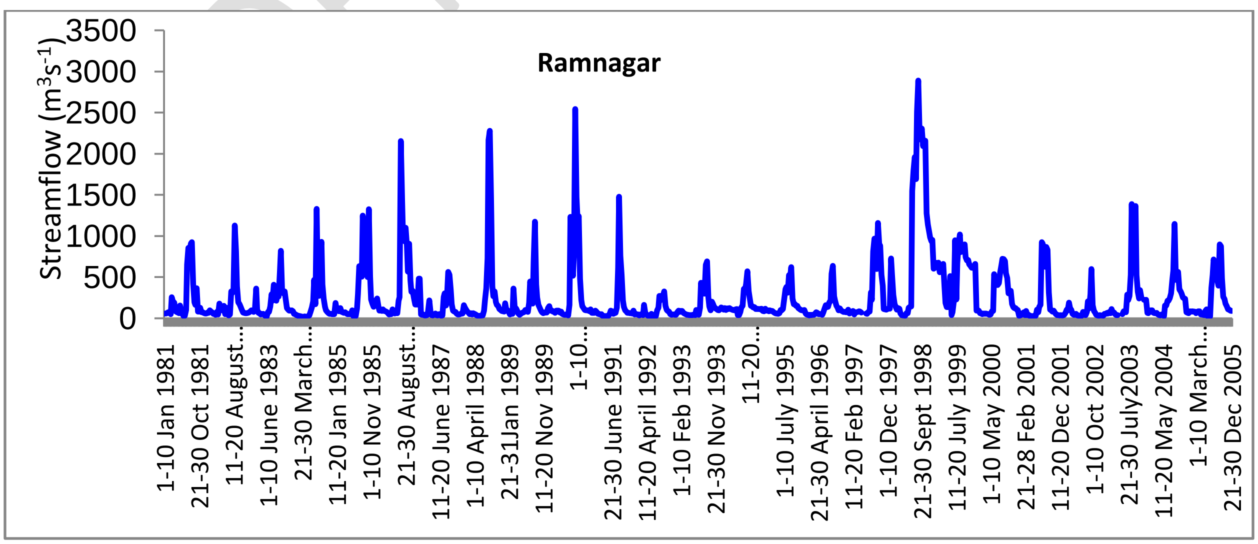
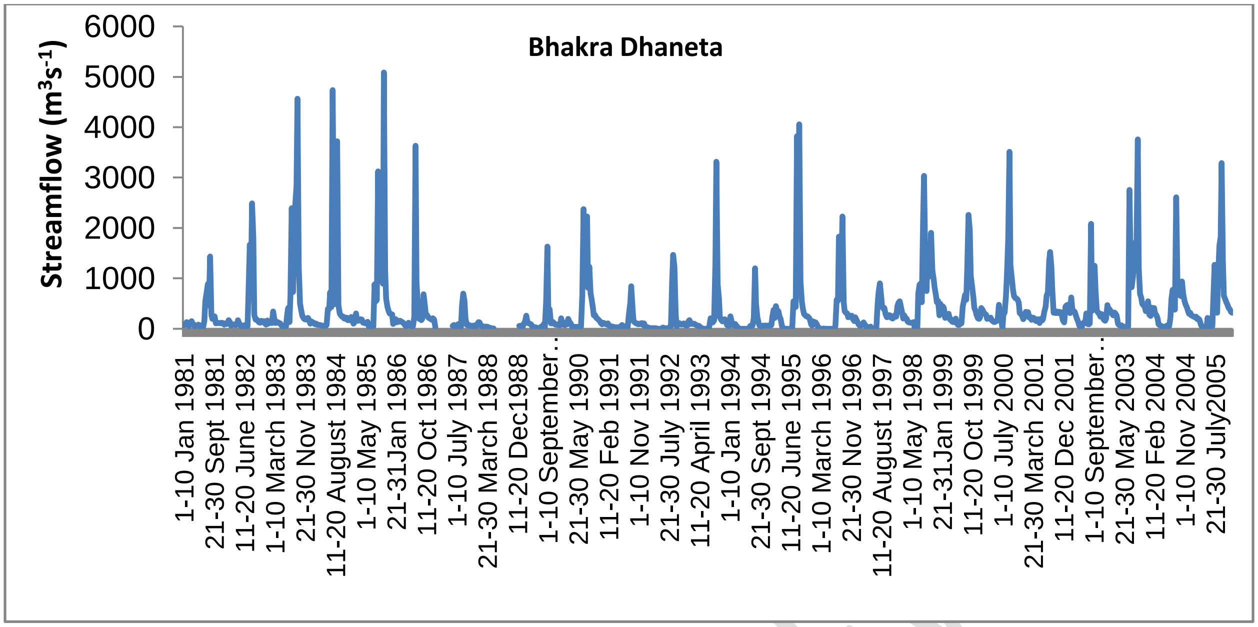


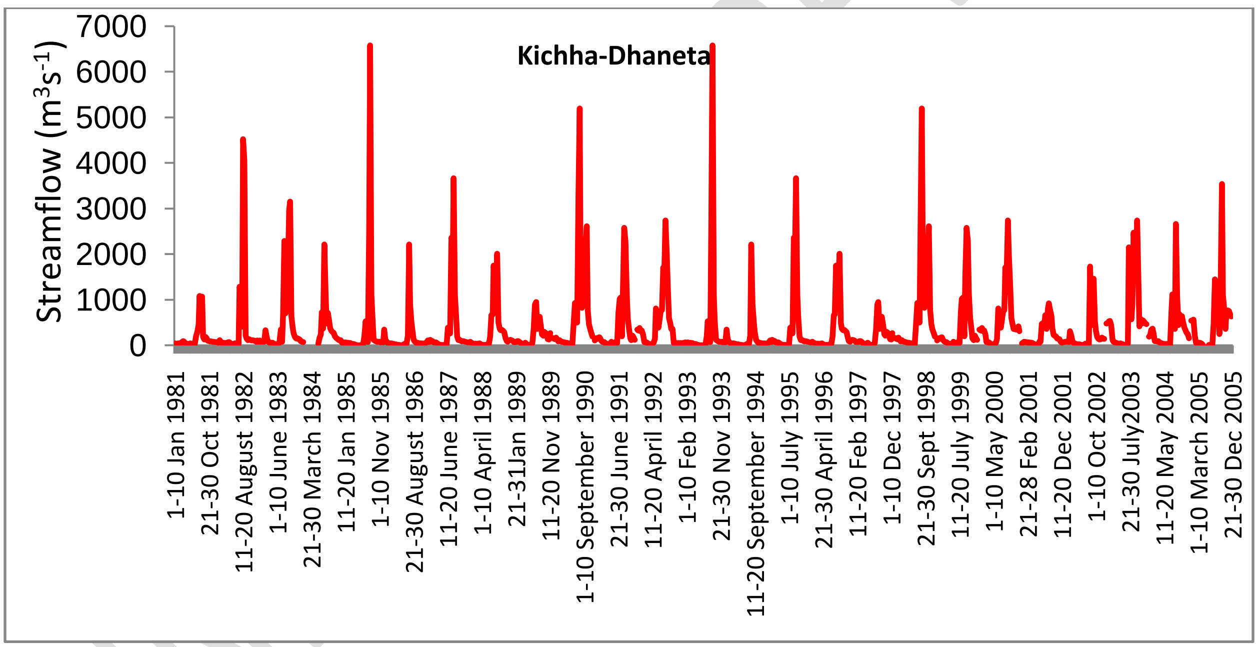
Figure 2. Delineated catchments of a) Moradabad, b) Rampur, c) Bareilly, d) Fatehgunj, and e) Dabri in Ramganga River basin


Moradabad
Streamflow (m3s-1)
1600
1400
1200
1000
800
600
400
200
0
1-10 Jan 1981
21-30 Dec 1981
11-20 Dec1982
1-10 Dec 1983
21-30 Nov 1984
11-20 Nov 1985
1-10 Nov 1986
21-30 Oct 1987
11-20 Oct 1988
1-10 Oct 1989
21-30 Sept 1990
11-20 September 1991
1-10 September 1992
21-30 August 1993
11-20 August 1994
1-10 August 1995
21-30 July 1996
11-20 July 1997
1-10 July 1998
21-30 June 1999
11-20 June 2000
1-10 June 2001
21-30 May 2002
11-20 May 2003
1-10 May 2004
21-30 April 2005
11-20 April 2006
1-10 April 2007
21-30 March 2008
11-20 March 2009
1-10 March 2010
21-28 Feb 2011
11-20 Feb 2012


Fatehganj East
Streamflow (m3s-1)
6000
5000
4000
3000
2000
1000
0
1-10 Jan...
1-10 Oct...


Ramnagar
Streamflow (m3s-1)
3500
3000
2500
2000
1500
1000
500
0
1-10 Jan 1981
21-30 Oct 1981
11-20 August...
1-10 June 1983
21-30 March...
11-20 Jan 1985
1-10 Nov 1985
21-30 August...
11-20 June 1987
1-10 April 1988
21-31Jan 1989
11-20 Nov 1989
1-10...
21-30 June 1991
11-20 April 1992
1-10 Feb 1993
21-30 Nov 1993
11-20...
1-10 July 1995
21-30 April 1996
11-20 Feb 1997
1-10 Dec 1997
21-30 Sept 1998
11-20 July 1999
1-10 May 2000
21-28 Feb 2001
11-20 Dec 2001
1-10 Oct 2002
21-30 July2003
11-20 May 2004
1-10 March...
21-30 Dec 2005


Bhakra Dhaneta
Streamflow (m³s⁻¹)
6000
5000
4000
3000
2000
1000
0
1-10 Jan 1981
21-30 Sept 1981
11-20 June 1982
1-10 March 1983
21-30 Nov 1983
11-20 August 1984
1-10 May 1985
21-31Jan 1986
11-20 Oct 1986
1-10 July 1987
21-30 March 1988
11-20 Dec1988
1-10 September…
21-30 May 1990
11-20 Feb 1991
1-10 Nov 1991
21-30 July 1992
11-20 April 1993
1-10 Jan 1994
21-30 Sept 1994
11-20 June 1995
1-10 March 1996
21-30 Nov 1996
11-20 August 1997
1-10 May 1998
21-31Jan 1999
11-20 Oct 1999
1-10 July 2000
21-30 March 2001
11-20 Dec 2001
1-10 September…
21-30 May 2003
11-20 Feb 2004
1-10 Nov 2004
21-30 July2005


Kichha-Dhaneta
Streamflow (m³s⁻¹)
7000
6000
5000
4000
3000
2000
1000
0
1-10 Jan 1981
21-30 Oct 1981
11-20 August 1982
1-10 June 1983
21-30 March 1984
11-20 Jan 1985
1-10 Nov 1985
21-30 August 1986
11-20 June 1987
1-10 April 1988
21-31Jan 1989
11-20 Nov 1989
1-10 September 1990
21-30 June 1991
11-20 April 1992
1-10 Feb 1993
21-30 Nov 1993
11-20 September 1994
1-10 July 1995
21-30 April 1996
11-20 Feb 1997
1-10 Dec 1997
21-30 Sept 1998
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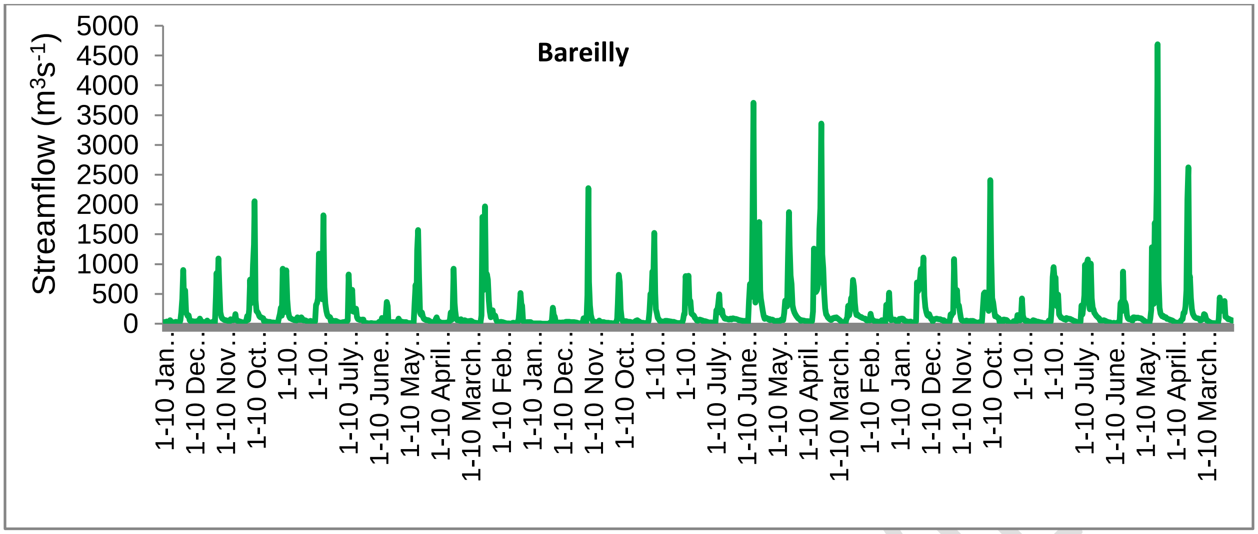
1-10 March 2005
21-30 Dec 2005



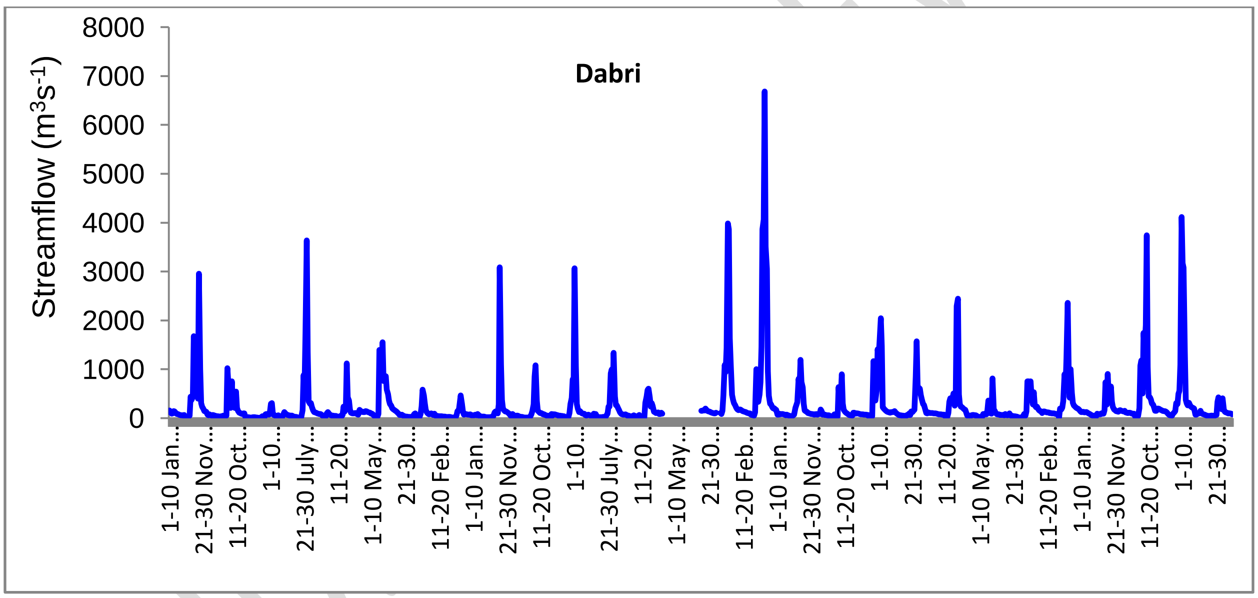


Figure 3.Decadal average streamflow at gauging station (a) Moradabad (b) Fatehgunj (c)Ramnagar (d) B-Dhaneta (e) K- Dhaneta (f) Bareilly and (g) Dabri over the available data period

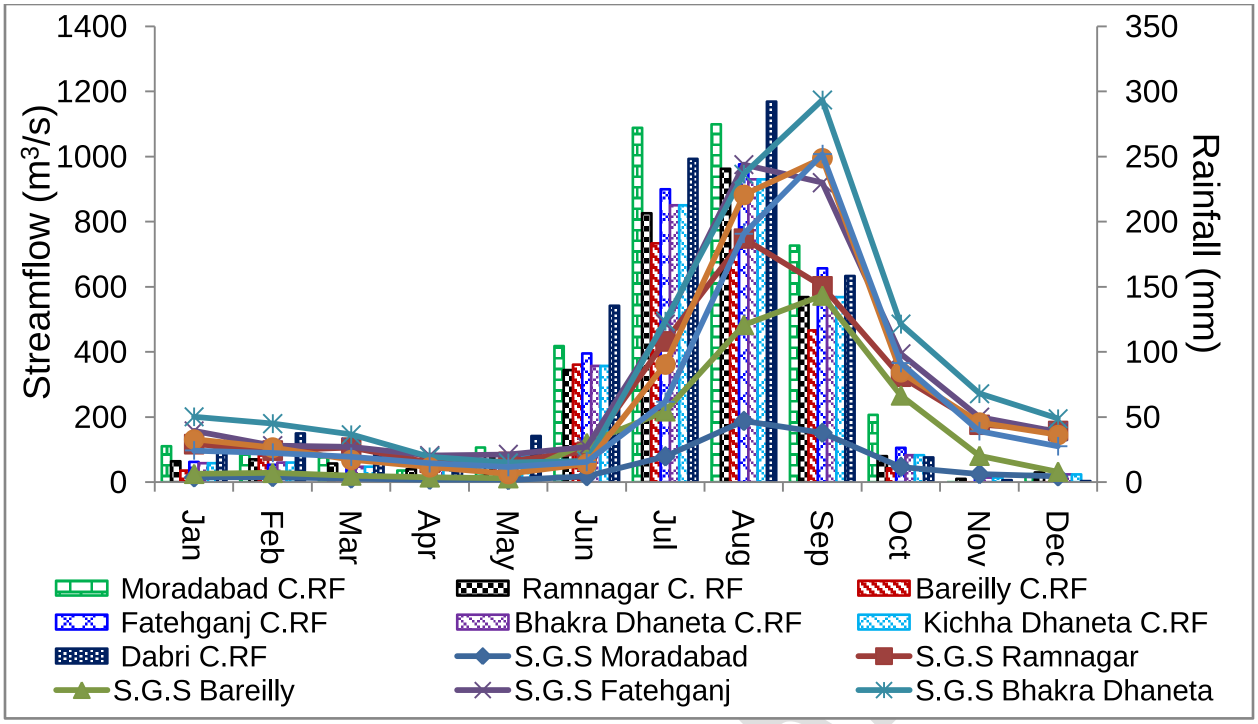


Figure 4. Mean monthly streamflow and mean monthly rainfall (1981 to 2005) of different catchment of Ramganga River basin

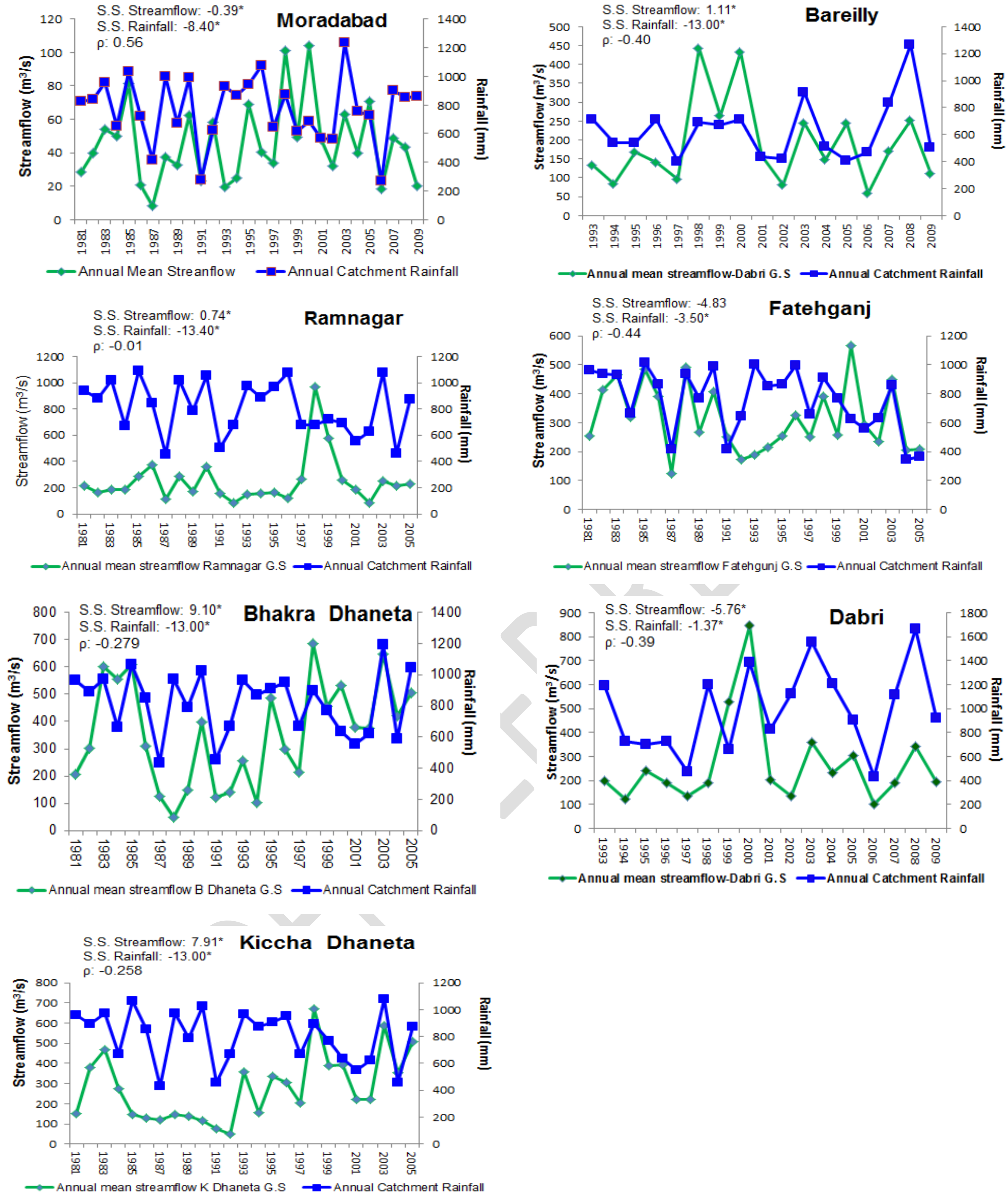


Figure 5.Spatial distribution of annual mean streamflow and annual rainfall and their correlations for (a) Moradabad, (b)Ramnagar, (c) Bhakra Dhaneta (d) Kiccha Dhaneta (e) Bareilly, (f) Fatehganj, (c) Dabri

(Where: S.S. Sen's Slope; ρ: Correlation coefficient, single asterisk designates significance at 0.05 level)

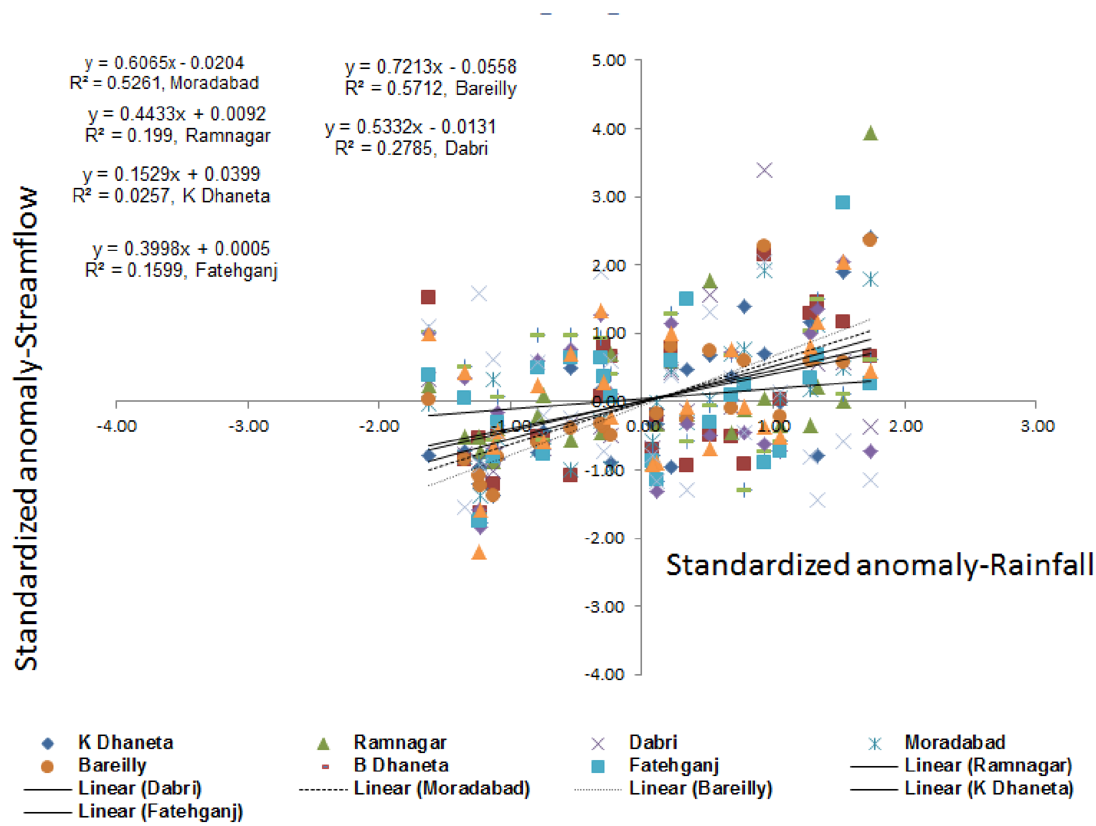


Figure 6. Standardized anomaly of annual streamflow vs rainfall of different catchments of Ramganga River basin

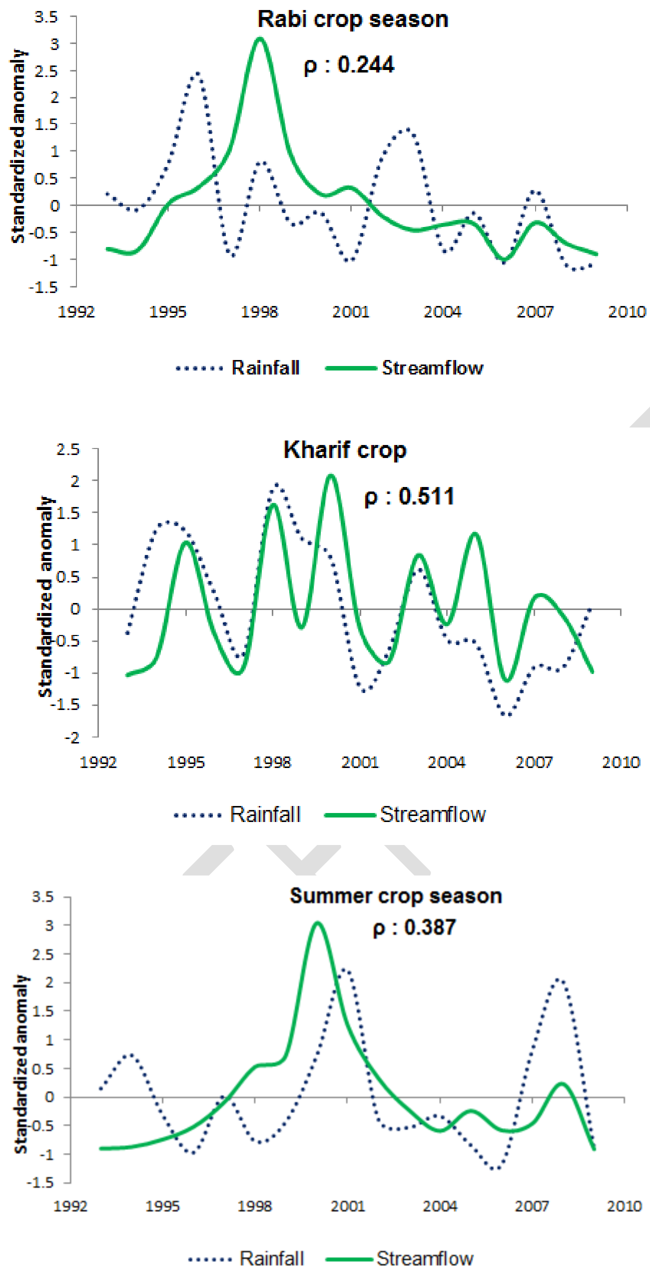


Figure 7.Temporal distribution of standardized anomaly of streamflow and rainfall in different crop season of upstream region of Ramganga River basin

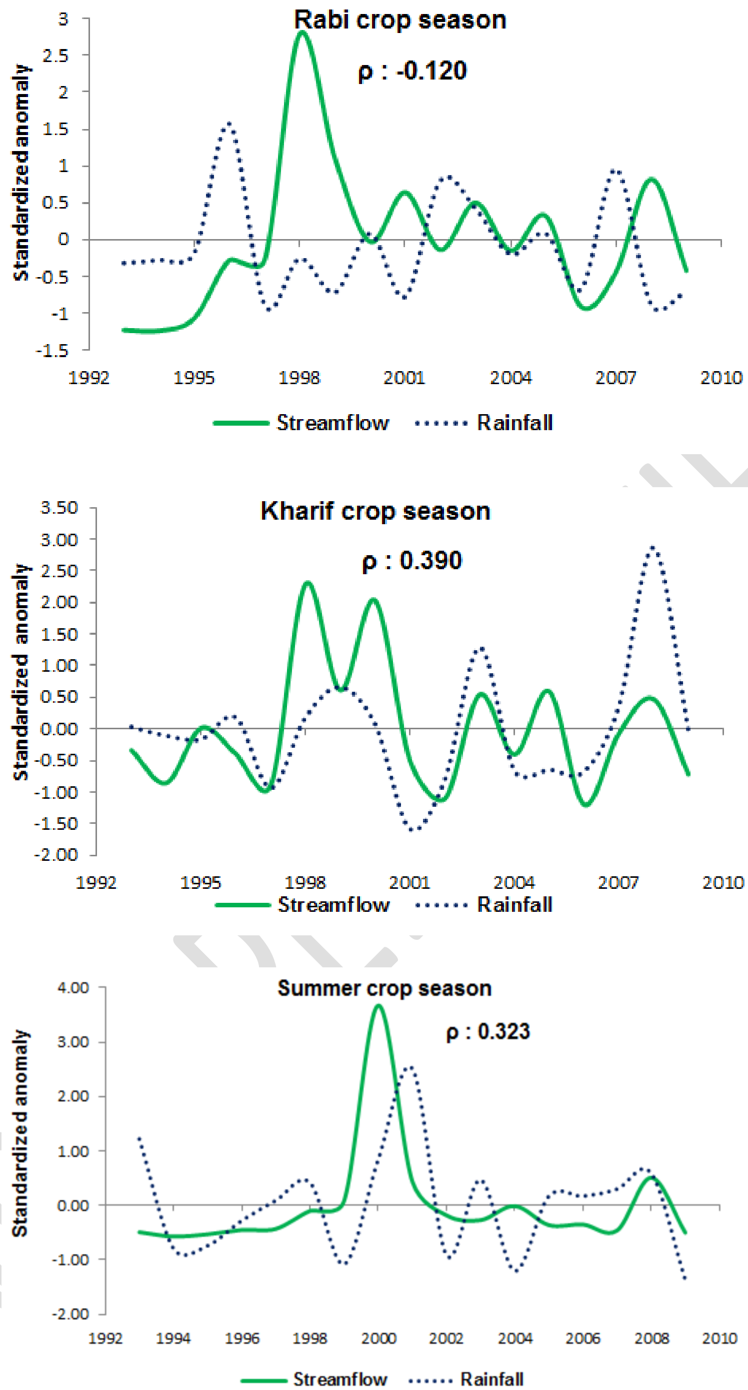


Figure 8.Temporal distribution of standardized anomaly of streamflow and rainfall in different crop season of mid-stream region of RamgangaRiver basin

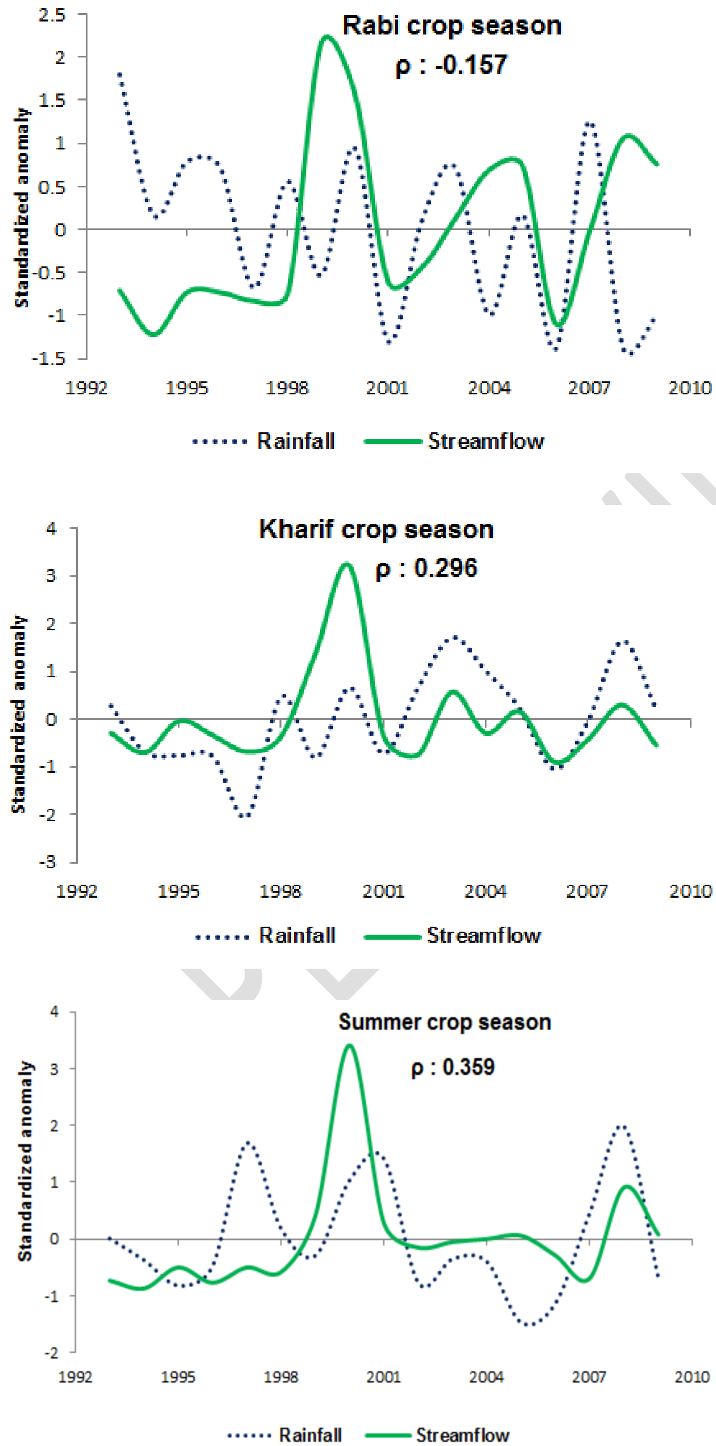


Figure 9. Temporal distribution of standardized anomaly of streamflow and rainfall in different crop season of downstream region of Ramganga basin

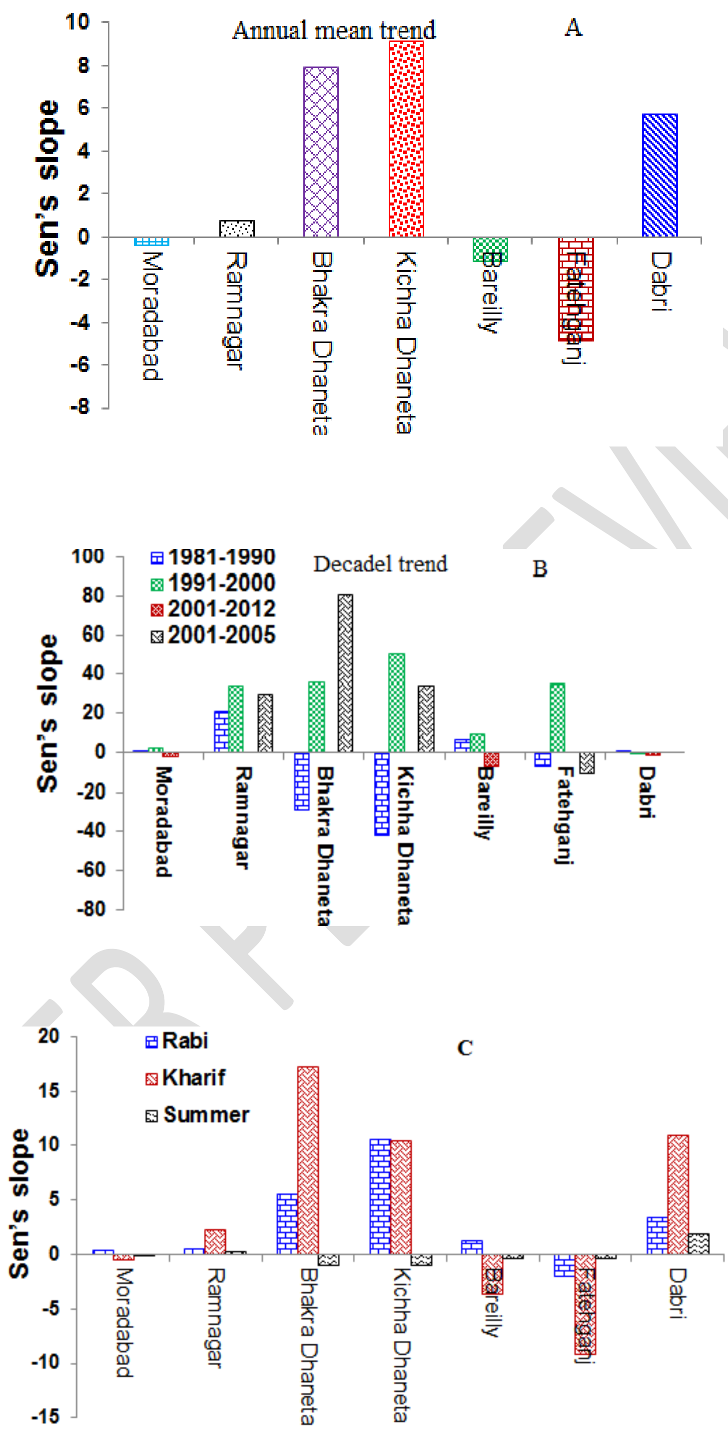


Figure 10. Statistical Mann–Kendall trend test with Sen's slope estimator for annual mean trend, decadal period and crop seasonal mean streamflow (m^3/s/year) for different catchment in Ramganga basin ((-) shows decreasing trend and (+) shows increasing trend)

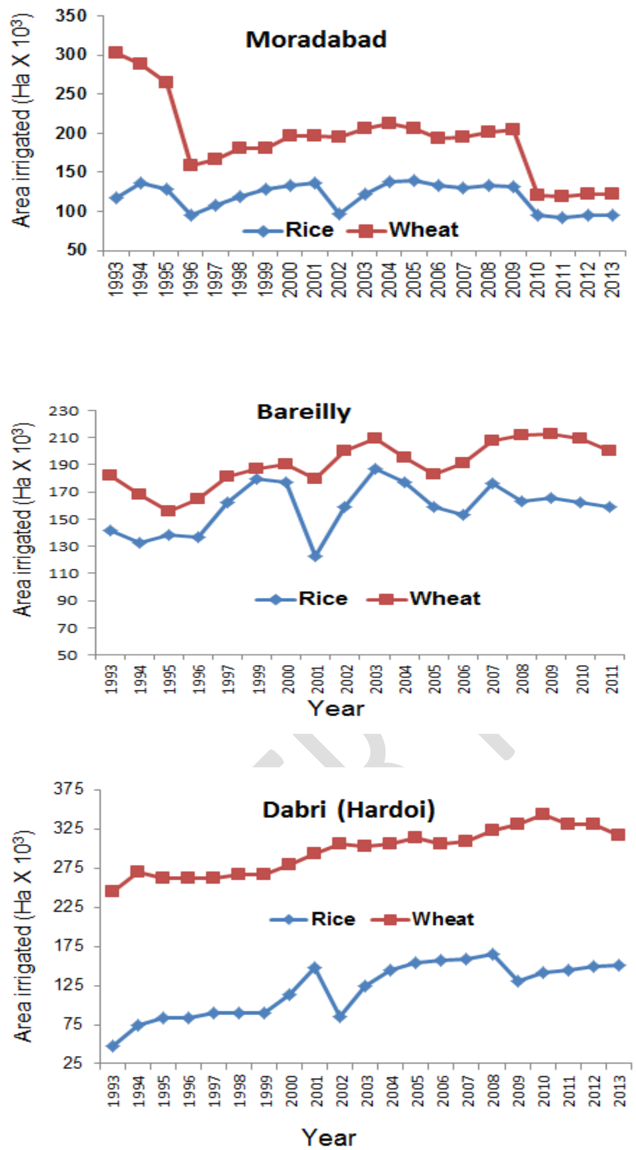


Figure 11.Variation of total area irrigated under Rice and Wheat in major districts of Ramganga river basin from 1993-94 to 2013-14

Table 1. Characteristics of Streamflow of Ramganga River basin

Name of the Gauging Station	Latitude	Longitude	Catchment area (km^2)	Streamflow (m^3/s)	Period of records
Moradabad	28.83	78.78	6807	10 day average	1981–2012(31 ys)
Bareilly	28.36	79.41	18340	10 day average	1981–2012 (31 ys)
Ramnagar	28.80	79.00	7164	10 day average	1981-2005 (25 ys)
Fatehganj	28.46	79.30	2639	10 day average	1981-2005 (25 ys)
Dabri	29.49	78.40	23919	10 day average	1985–2012 (27 ys)

Table 2. Summarized results of Mann-Kendall test with Sen's slope estimator for interannual monthly mean streamflow (m3s-1year-1) and monthly rainfall (mm year-1) for different catchment

Month / station	Moradabad		Ramnagar		Bhakra Dhaneta		Kiccha Dhaneta		Bareilly		Fatehganj East		Dabri	
	SF	**RF**	**SF**	**RF**	**SF**	**RF**	**SF**	**RF**	**SF**	**RF**	**SF**	**RF**	**SF**	**RF**
Jan	0.19	-0.02	-0.89	0.19	12.58	-0.21	4.34	-0.11	-1.18	-0.11	-2.19	0.15	2.42	-0.04
Feb	0.34	0.07	0.56	0.18	8.60	0.19	2.80	0.15	-1.45	0.15	-1.14	0.27	3.11	0.05
Mar	-0.21	0.02	0.79	-0.17	6.35	-0.21	-0.24	-0.16	-1.03	-0.16	-0.84	-0.08	2.36	-0.11
Apr	-0.09	-0.65	-0.30	-0.49	0.25	-0.69	-1.41	-0.37	0.41	-0.37	-0.65	-0.29	1.99	-0.21
May	-0.06	-0.50	0.31	-1.28	0.00	-0.55	-0.02	-0.76	0.01	-0.76	-0.50	-0.64	1.56	-0.39
Jun	-0.37	1.20	0.45	-2.58	-1.59	-0.58	-1.64	-0.58	0.34	-0.58	-0.07	1.21	1.17	-1.21
Jul	0.45	-3.55	0.94	-3.94	-9.65	-2.69	4.32	-3.69	0.58	-3.69	-2.60	1.51	2.10	1.59
Aug	-0.38	-3.70	6.47	-6.89	-2.90	-5.84	22.45	-5.82	0.14	-5.82	-10.44	-2.22	14.53	-0.23
Sep	0.85	1.34	1.96	1.49	-7.42	0.91	26.22	0.91	6.59	0.91	-9.02	4.11	20.73	0.77
Oct	0.62	-0.04	1.87	-0.06	18.35	-0.26	14.63	-0.21	4.79	-0.21	0.56	-0.26	8.61	-0.18
Nov	0.33	0.00	3.26	0.00	14.43	0.01	9.21	0.00	1.26	0.00	-4.23	0.00	5.29	0.00
Dec	0.24	-3.62	0.47	-3.28	8.54	-0.39	5.05	-0.35	1.19	-0.35	-2.84	-0.23	2.99	-0.26

Where SF: Streamflow; RF: Rainfall

Table 3. Summarized results of Mann-Kendall test with Sen's slope estimator ($^{o}C\ year^{-1}$) of mean temperature of different catchments of Ramganga River basin (1981-2005)

Catchment	Mean annual	Mean Kharif	Mean Rabi	Maximum annual mean	Minimum annual mean
Moradabad	0.014*	0.014*	0.010*	-0.001	0.035*
Ramnagar	0.012*	0.013*	0.010*	-0.001*	0.031
Bhakra Dhaneta	0.011*	0.012*	0.012*	-0.000*	0.027*
Kiccha Dhaneta	0.011*	0.012*	0.012*	-0.000	0.027*
Bareilly	0.011*	0.012*	0.012*	-0.000*	0.027

Fatehganj	0.013*	0.014*	0.01*	-0.001*	0.021*
Dabri	0.013*	0.012*	0.01	-0.002	0.025*

*0.05 (significance level based on MK test)

Table 4.Population of different districts of Ramganga river basin in 1991 and 2011

District	Area (km^2)	Population 3/1/1991 Census	Population 3/1/2011 Census	% change in Population
Chamoli	8,030	391,605	370,359	-5.74
Pauri Garhwal	5,329	687,271	697,078	1.41
Almora	3,144	630,567	622,506	-1.29
Bijnor	4,561	3,131,619	3,682,713	14.96
Champawat	1,766	224,542	259,648	13.52
Jyotiba Phule Nagar	2,249	1,499,068	1,840,221	18.54
Udham Singh Nagar	2,542	1,234,614	1,648,902	25.06
Moradabad	3,718	2,467,960	3,126,507	37.86
Rampur	2,367	1,923,739	2,335,819	35.69
Bareilly	4,120	3,618,589	4,448,359	36.28
Pilibhit	3,686	1,283,103	2,031,007	36.82
Budaun	5,168	2,630,710	3,127,621	15.89
Shahjahanpur	4,368	1,987,395	3,006,538	35.95
Etah	2,431	1,561,705	1,774,480	11.99
Hardoi	5,986	3,398,306	34,710,102	32.88
Total for the basin	59,845	26,263,890	34,710,102	20.65

Source: The Office of Registrar General & Census Commissioner of India. http://www.geohive.com/cntry/in-09.aspx