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Rainfall and surface water resources of Rajasthan State, India

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Abstract

The water resources in Rajasthan State are facing a crucial stage even after average/good rainfall. Temporal distributions as well as the spatial variability of rainfall within the state were investigated by applying an analysis of variance (ANOVA) test. The effect of change in catchment characteristics and anthropogenic activities on overland flow are also investigated in this paper by applying a regression technique. Inflow to the surface water resources of the state is regularly decreasing. Time series analysis and sequential cluster analysis reveals that 1994 was the critical year, which divides the two consecutive non-overlapping epochs viz. pre-disturbance and post-disturbance. Due to increasing population and the subsequent increase in agriculture (specifically using groundwater sources) having increased catchment interceptions, there is a regular decreasing trend of surface runoff and surface water availability. The study highlights that, in spite of an increasing trend of rainfall witnessed during the last 100 years, inflow to the surface water resources of the state is decreasing at a fast pace owing to a decrease in the percentage area contributing to surface runoff.

Keywords: Catchment degradation; Critical year; Infiltration; Rainfall; Runoff; Surface water resources

1. Introduction

Rainfall is the ultimate source of water resources in Rajasthan State. Partitioning of precipitation into different hydrological processes at any place largely depends on precipitation intensity. Surface flow, or we can say the overland flow, depends upon rainfall pattern and catchment characteristics. The amount of falling rain that can be utilized depends greatly on the intensity, drop size, velocity of the rain, catchment roughness and other catchment characteristics. Infiltration results in recharge of the aquifer system and discharge as sub surface flow (Alfa *et al.*, 2011).

If rainfall intensity exceeds the infiltration capacity of the soil, rain will accumulate on the surface and, depending on the surface roughness, the gradient of the land surface, and the available depression storage, Hortonian Overland Flow (HOF) may occur, as according to Horton's Infiltration-excess Overland Flow (IOF) theory (Alfa *et al.*, 2011). Horton considered infiltration as central to the

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hydrological process on the land surface. Haan *et al.* (1994), as cited by Alfa *et al.* (2011), stated that different catchments respond differently to rainfall in terms of surface flow. The nature of the overlying soil and the type of bed rock determine the amount of runoff that will be generated and the path it will follow to reach a stream channel. Runoff generation and routing determine to a large extent how much water flows into streams within the period of the rainfall and after. Dunne (1978) as cited by Alfa *et al.* (2011) proposed Saturated-excess Overland Flow (SOF) and Subsurface Storm Flow (SSF) to complement the Horton theory. Generation of surface runoff is more likely in areas where the soils are either less permeable or the initial water content of the soils is very high. In Rajasthan State, rainfall data are mostly available as daily totals, which do not describe the precise temporal and spatial distribution of the rainfall; therefore the partitioning of rainfall into different hydrological processes may be misrepresented. Data which were collected for some critical events within the state show average intensities of 50 mm/h, and, in short time intervals, intensities up to 200 mm/h and above have also been recorded.

Rainfall data for 112 years (1901–2012) for 33 districts of the Rajasthan State were collected and an analysis of variance (ANOVA) test was conducted and analyzed. It was found that high variation exists between the groups, i.e. districts, and also within the same district over the years. Computed F-values (7.705 and 95.136) of the ANOVA are very high in comparison to the permissible value. Therefore, we can say that temporal and spatial variation of rainfall within the state is likely. The population of the state increased from 10.3 million in 1911 to 68.5 million in 2011. Decadal growth rate of the population also increased from 7% during 1911–1921 to 33% during 1971–1981; thereafter it reduced to 21% during 2001–2011. Catchment characteristics have also changed due to change in land use/cover pattern. The irrigation area has increased from 21,000 km^2 (1968) to 78,000 km^2 (2006). The major component of irrigation sources always remains as groundwater sources, ranging from 50 to 75% of the total area irrigated. This has led to more and more ploughed land instead of barren land and also to the lowering of the groundwater table, leading to a declining trend of surface runoff and reducing water inflow to the dams.

2. Study area

Rajasthan State is located within latitude 23°3′N-30°12′N and longitude 69°30′E-78°17′E in the western part of the Indian subcontinent. Rajasthan State encompasses an area of about 343×10^3 km^2, the largest state by geographical area in the country. There are 15 river basins and 33 administrative districts in the state. Most of the state belongs to the Ganga basin. The 15 river basins of the state are: Shekhawati river basin, Ruparail river basin, Banganga river basin, Gambhir river basin, Parbati river basin, Sabi river basin, Banas river basin, Chambal river basin, Mahi river basin, Sabarmati river basin, Luni river basin, West Banas river basin, Sukli river basin, Other Nallah river basin, and Outside river basin (Figure 1). Salient features of Rajasthan State are shown in Table 1.

The state is located in a tropical region, which is characterized by mean annual temperature of about 20°C. The months of May and June are the hottest periods, with an average temperature of about 40°C. December is the coolest month, with an average temperature of about 10°C. The state exhibits large variations in rainfall amount and intensity, both in space and time. Rainfall occurs mainly in the monsoon season during July to September, and is erratic in its occurrence.

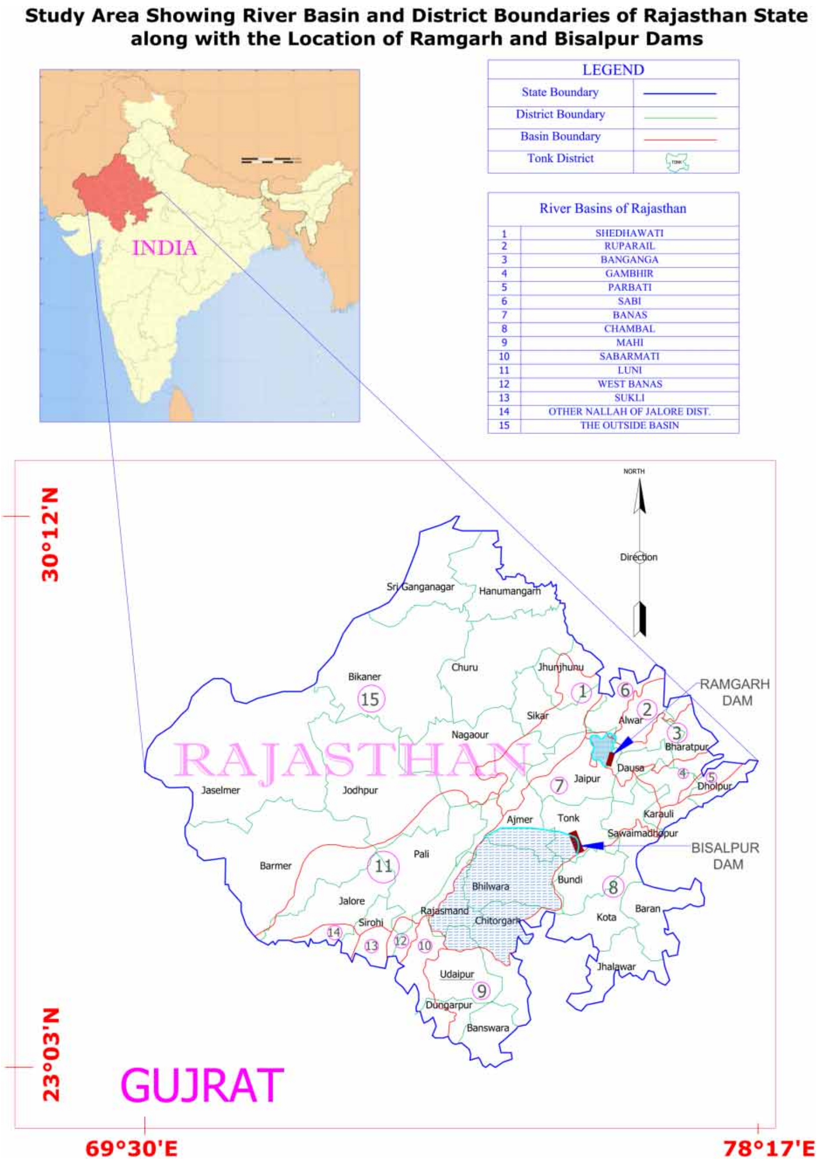

Fig. 1. Hydrological map of Rajasthan State.

Monsoon rainfall is above 90% of the annual rainfall. The meteorological statistics show that, on average, about 10% of the rainy days produce 50% of the total monsoon rainfall. The total monsoon rainfall of the western desert averages about 100–150 mm and approaches 1,000–1,100 mm in the eastern and southern part of the state. There is occasional rainfall in the dry season (October to June). This occasional rainfall locally known as Mawath occurs mainly during January, and rarely exceeds 50 mm except in June during which rainfall up to 100 mm has been recorded.

Table 1. Salient features for Rajasthan State.

Parameter	Country (India)	State (Rajasthan)	Percentage (%)
Area (km^2)	3,287,300	343,000	10.40
Population 2011 (million)	1,210	68.50	5.66
Live Stock (million)	292	54.7	18.70
Cultivable Area (km^2)	1,843,700	257,000	13.90
Food Production (MT)	211	13.82	6.50
Average Rainfall (mm)	1,170	575	49.15
Per Capita Water Availability (m^3)	1,760	740	42.05
Total Precipitation (BCM)	4,000	197	4.90
Water Availability (BCM)	1,869	21.71	1.16
Utilizable Water Availability (BCM)	1,121	16.05	1.43
Surface Water Utilization (BCM)	690	12.55	1.82
Replenishable Groundwater (BCM)	431	8.13	1.89
Over Exploited Blocks as in 2009 (nos)	802	166	20.70
Desert Blocks	142	85	60

BCM = Billion (10^9) cubic meters.

3. Objective of the study

The objective of the study was to analyze rainfall pattern and change in catchment characteristics, and their influence on the availability of surface water resources within the state. The specific objectives of the research included the following:

- to check the hypothesis that temporal and spatial distributions of the rainfall pattern exists;
- to analyze the trend of inflow to surface water resources;
- to analyze the irrigation pattern leading to change in land use/cover and lowering of the water table;
- to analyze the increasing trend of population of the state and its impact on surface runoff; and
- to determine the critical year and find the principal component affecting inflow to the dams.

4. Methodology adopted

Various actual data, e.g. rainfall for 33 districts of the state, irrigation area by various sources, population, groundwater, climatic parameters, and land use data were collected. An ANOVA test was conducted to draw inference about temporal and spatial distribution of rainfall. Trends of the various parameters over the years were plotted, analyzed and discussed. Correlation analyses between various parameters were computed. Time series analysis and sequential cluster analysis were employed to find the critical year.

5. Collection and analyses of data

Various data related to the study like rainfall data for 33 districts over 112 year span (1901–2012), population data, decadal growth rate, surface water availability, water received in the dams during many previous years, per capita water availability (Table 2), irrigation area along with its source and variation over years were collected (Water Resources Department and Directorate of Economics and Statistics; see: www.waterresources.rajasthan.gov.in; DES, 1993, 1996, 2000, 2002, 2003, 2005, 2006, 2008, 2009, 2010, 2012).

Time series analysis was employed for determination of possible critical years (marked *** in Table 3), and sequential cluster analysis (Table 4) was undertaken to determine the critical year. The minimum sum of squared deviations of hydrological series before and after the possible critical year corresponds to 1994 as shown in Table 4. This shows that some disturbances have taken place after 1994 which are attributed to low inflow to the dams.

5.1. Rainfall data

Figure 2(a) shows a slightly increasing trend of rainfall. Maximum rainfall was recorded in the year 1917 at 1,079.5 mm while minimum rainfall recorded was in the year 1918 at the level of 205 mm. Monthly rainfall data plotted in Figure 2(b) shows that 90% of the rainfall occurs during the monsoon period, i.e. June to September and in the remaining months rainfall occurrence is negligible. There is an average of 30 rainy days in a year. High intensity rainfall occurs during July and August, which yields an average 200 mm rainfall in a month during these two months. District wise average rainfall has been plotted in Figure 3(a), and shows a wide spatial variation of rainfall within the state ranging from an average yearly rainfall of 194 mm in Jaisalmer to 1,000 mm in Jhalawar and Banswara districts. This type of rainfall distribution leads to a wide diversity in the state with respect to surface water availability. Frequency distribution of rainfall has been plotted in Figure 3(b), and shows a nearly normal distribution with mean 574 mm, median 563 mm and mode 550 mm.

We proposed a one way ANOVA to study the impact of districts and year on the annual rainfall. Table 5 shows that the impact of year on annual rainfall was highly significant (P value < 0.01), calculated value of $F = 7.705 > F$ (tabulated) at degree of freedom (df) = 111, 3341 at 1% level of

Table 2. Rainfall and surface water availability.

	Population		Decadal average		
Year	Millions	Increase (%)	Surface water availability (BCM)	Per capita availability (m^3)	Rainfall (mm)
1911	10.3				512
1921	11.0	7	22.86	2,081	553
1931	11.7	7	22.80	1,940	553
1941	13.9	18	22.29	1,608	518
1951	16.0	15	35.31	2,211	643
1961	20.2	26	28.99	1,438	638
1971	25.8	28	22.96	891	537
1981	34.3	33	34.57	1,009	631
1991	44.0	28	23.05	524	535
2001	56.5	28	29.34	519	609
2011	68.5	21	22.23	325	555

Table 3. Time series analysis for inflow to the dams of Rajasthan State.

Year	Inflow (%) U_i	T	$t*U_i$	$t*t$	Trend	Elimination of trend	Possible critical years
1990	71.01	−11	−781.11	121	67.72	3.28	
1991	78.53	−10	−785.3	100	67.45	11.07	
1992	66.16	−9	−595.44	81	67.18	−1.02	***
1993	62.6	−8	−500.8	64	66.91	−4.31	
1994	85.76	−7	−600.32	49	66.65	19.1	***
1995	77.6	−6	−465.6	36	66.38	11.21	
1996	76.7	−5	−383.5	25	66.11	10.58	
1997	71.09	−4	−284.36	16	65.84	5.24	
1998	57.78	−3	−173.34	9	65.57	−7.79	
1999	43.58	−2	−87.16	4	65.3	−21.72	
2000	42.03	−1	−42.03	1	65.04	−23.01	
2001	58.4	0	0	0	64.77	−6.37	***
2002	30.87	1	30.87	1	64.5	−33.63	
2003	58.08	2	116.16	4	64.23	−6.15	***
2004	71.01	3	213.03	9	63.96	7.04	
2005	71	4	284	16	63.69	7.3	
2006	83.58	5	417.9	25	63.43	20.14	
2007	69.72	6	418.32	36	63.16	6.55	***
2008	56.2	7	393.4	49	62.89	−6.69	
2009	41.27	8	330.16	64	62.62	−21.35	***
2010	51.52	9	463.68	81	62.35	−10.83	
2011	73.35	10	733.5	100	62.09	11.25	
2012	76.78	11	844.58	121	61.82	14.95	
2013	76.71	12	920.52	144	61.55	15.15	
Sum	1,551.33	12	467.16	1,156	1,551.33		

significance. Table 6 shows that the impact of districts on annual rainfall was also significant (P value <0.01) and calculated a value of F = 95.136 > F (tabulated) at df = 32, 3420 at 1% level of significance.

5.2. Population growth

Population increase and its growth rate have been plotted in Figure 4, and show the regularly increasing population with increasing growth rate. It is good to observe that the growth rate of the population has shown a decreasing trend since 1981 and was 21% during 2001–2011.

5.3. Irrigation development

With the rapidly increasing population, irrigation area is also increasing to cater for the population. Irrigation area increased from 21,000 km^2 in year 1968 to 78,000 km^2 in year 2006. Irrigation from underground water sources increased from 11,000 km^2 to 54,000 km^2 during this period (Figure 5). This reveals ploughing of more and more land and an over exploitation of underground water to harvest more and more crops to cater for the increasing population. It is important to note that after 1990 there was a rapid increase in irrigation by wells, dug wells and tube wells which contribute significantly to irrigation, i.e. approximately 70% is

Table 4. Sequential cluster analysis for inflow to the dams of Rajasthan State.

			Sequential cluster analysis					
S.N.	Year	Inflow (%)	1992	1994	2001	2003	2007	2008
1	1990	71.0	0.8	3.2	26.1	65.7	32.6	38.5
2	1991	78.5	44.0	32.9	159.6	244.4	175.1	188.6
3	1992	66.2	32.9	44.1	0.1	10.6	0.7	1.8
4	1993	62.6	1.0	104.0	10.9	0.1	7.3	4.8
5	1994	85.8	491.1	168.0	394.5	522.7	418.7	439.4
6	1995	77.6	195.9	227.9	136.8	216.0	151.2	163.7
7	1996	76.7	171.5	201.6	116.6	190.4	129.9	141.6
8	1997	71.1	56.1	73.8	26.9	67.1	33.5	39.6
9	1998	57.8	33.9	22.3	66.0	26.2	56.6	49.3
10	1999	43.6	400.8	357.9	498.1	373.2	471.7	450.3
11	2000	42.0	465.4	419.1	569.9	435.7	541.6	518.6
12	2001	58.4	27.0	16.8	56.2	20.2	47.6	40.9
13	2002	30.9	1,071	1,000.3	1,051.5	1,025.8	1,185.3	1,151.1
14	2003	58.1	30.5	19.6	27.3	23.3	52.2	45.2
15	2004	71.0	54.9	72.4	59.4	15.3	32.6	38.6
16	2005	71.0	54.7	72.2	59.3	15.2	32.5	38.4
17	2006	83.6	399.4	444.5	411.4	271.7	334.3	352.8
18	2007	69.7	37.5	52.1	41.2	6.9	50.7	24.2
19	2008	56.2	54.7	39.7	50.4	118.7	40.9	73.9
20	2009	41.3	498.8	450.9	485.5	667.4	455.2	512.3
21	2010	51.5	145.9	120.6	138.8	242.7	122.8	153.3
22	2011	73.3	95.0	117.6	100.9	39.0	115.5	89.2
23	2012	76.8	173.6	203.8	181.6	93.6	201.0	165.8
24	2013	76.7	171.7	201.8	179.7	92.3	199.0	164.0
		Sum	4,708	4,467	4,849	4,784	4,888	4,886

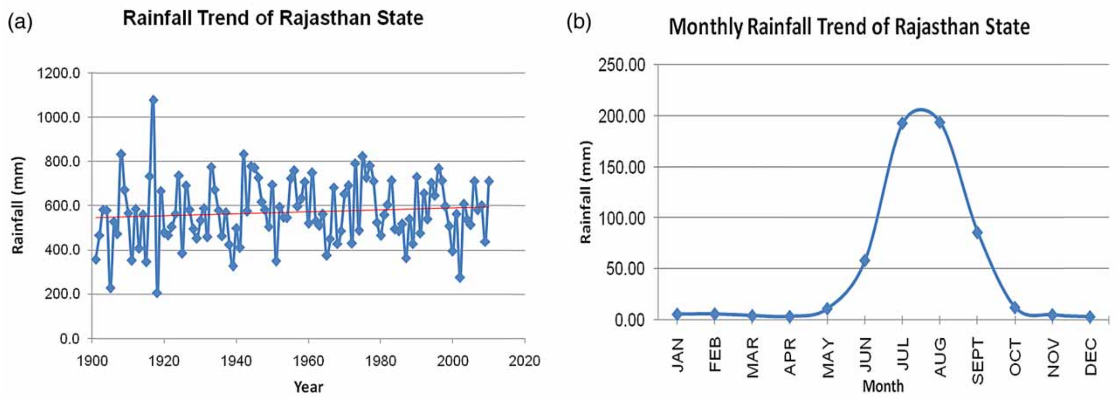

Fig. 2. (a) Yearly rainfall trend and (b) monthly rainfall trend.

fed by underground water. Besides this, anthropogenic activities like townships, industries, recreational activities and various institutional demands are also being catered for by groundwater exploitation. The

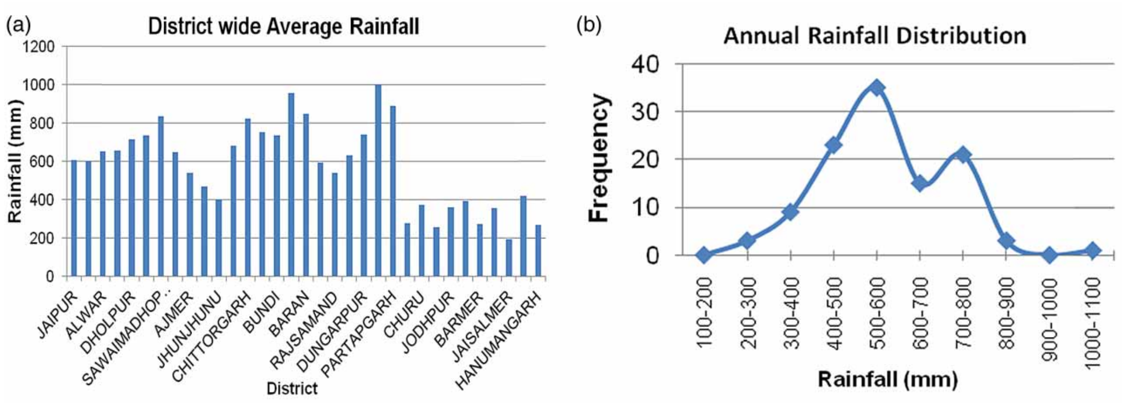

Fig. 3. (a) District wide average rainfall and (b) frequency distribution of rainfall.

Table 5. One way ANOVA using year as factor.

	Sum of squares	*df*	Mean square	*F*	Sig.
Between Groups	68,690,485	111	618,833.198	7.705	0.000
Within Groups	2.68×10^8	3,341	80,314.481		
Total	3.37×10^8	3,452			

Table 6. One way ANOVA using district as factor.

	Sum of squares	*df*	Mean square	*F*	Sig.
Between Groups	1.59×10^8	32	4,959,945.535	95.136	0.000
Within Groups	1.78×10^8	3,420	52,135.353		
Total	3.37×10^8	3,452			

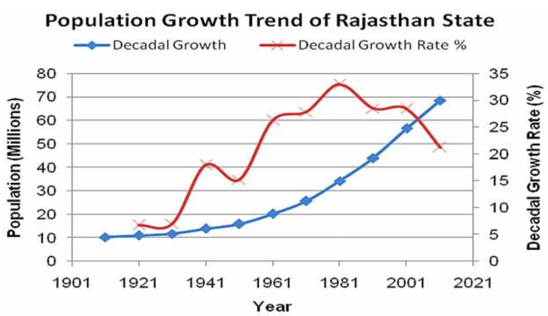

Fig. 4. Population growth and decadal growth rate.

depleting water table has converted safe areas into dark zones and presently 172 blocks have been declared dark zones out of a total of 243 blocks. These anthropogenic activities change the land use/cover and

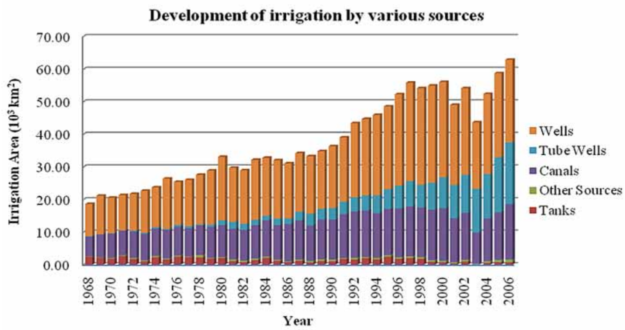

Fig. 5. Development of irrigation by various sources.

catchment characteristics resulting in reduced surface runoff, and the solution lies with water sharing, watershed planning, groundwater banking and water privatization (Frevert *et al.*, 2006; Walker, 2006; Draper, 2007, 2008; Wang *et al.*, 2008; Karamouz *et al.*, 2010; Petrov & Normatov, 2010; Kar, 2011; Solis *et al.*, 2011; Takayanagi *et al.*, 2011; Teasley & Mckinney, 2011; Kim *et al.*, 2012; Saito *et al.*, 2012).

5.4. Water inflow to the dams

We have the water level gauges of dams of the Rajasthan State and considered the rainy season from 15th June to 30th September every year. We also have the capacity table of the dams showing the surface water available in the dam at any particular gauge. Accordingly the water inflow in the dams has been computed from the dam gauges on 15th June and 30th September every year. Water received in the dams against their design capacity gives us percentage inflow to the dams. This temporal variation of water inflow has been plotted in Figure 6, showing a declining trend over the years.

5.5. Surface water availability

Surface water availability in the state has been plotted in Figure 7, and shows a nearly constant trend even after a slightly increasing trend of annual rainfall and tremendous water resources development. Inflow percentage to the design capacity of the dams has reduced from 71.1 to 51.5% from the year

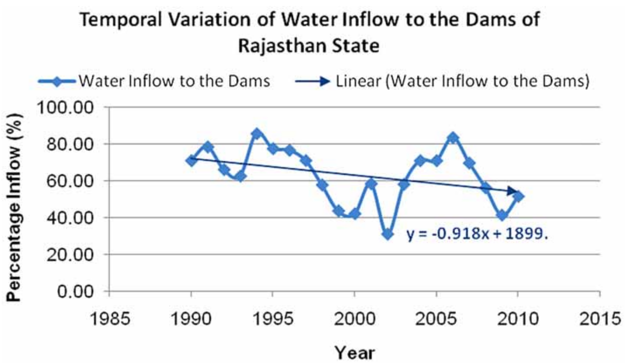

Fig. 6. Temporal variation of water inflow to the dams.

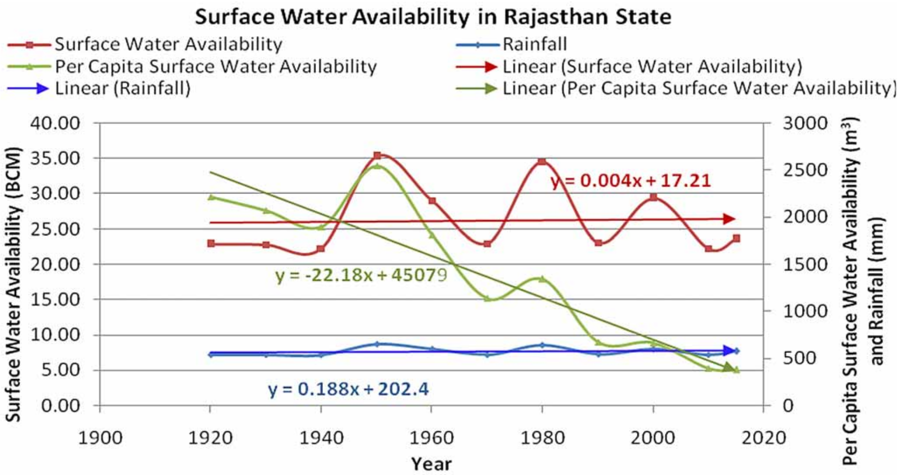

Fig. 7. Surface water availability, per capita surface water availability and rainfall trend.

1990 to 2010. The situation is worsening because of the increasing trend of population (Figure 4). Because of all these factors, per capita surface water availability is reducing drastically. Per capita total water availability was 2,221 m^3 in the year 1911, but has reduced to the level of 621 m^3 in the year 2011, below the international level of water scarcity, i.e. 1,000 m^3 per capita per year. Surface water availability in the state is only 393 m^3 per capita per year. If these conditions prevail, per capita water availability is projected to decrease below the absolute scarcity level of 500 m^3 by the year 2026.

6. Results and discussion

6.1. Overall analysis

Rainfall and water inflow to surface water resources were plotted to get the regression equation over the years. Surface water availability, rainfall and per capita availability were drawn against the successive years and respective regression equations have also been shown in Figures 6 and 7. Exceptional periods were determined by employing time series analysis and the critical year was determined by sequential cluster analysis. An ANOVA test was applied on the 112 years' rainfall data. Trends of population growth, decadal growth, irrigation development and their sources have been plotted and analyzed in this paper.

6.2. Result

The rainfall trend over the years is increasing. Results of the ANOVA test infer that temporal and spatial distribution of rainfall exists over the state. There exists temporal variation of inflow to the surface water resources. Inflow percentage has reduced from 71.1 to 51.5% from the year 1990 to 2010. Per capita water availability has decreased to 621 m^3 and per capita surface water availability has reached the level of 393 m^3, which is below the absolute scarcity level. Time series analysis and sequential cluster analysis show that 1994 may be considered as the critical year. The reasons for this may be attributed to the change in land use/cover pattern (sub-section 5.3). Irrigation area has increased by three to five times from 1968 to 2006. A major part of this increased agriculture is being fed through groundwater sources, lowering the groundwater table. The population of the state is continuously increasing.

6.3. Conclusion

There exists a declining trend of inflow to surface water resources in spite of an increasing trend of rainfall. Average annual rainfall for the state is 574 mm and the trend is slightly increasing. The land use/cover pattern is continuously changing. Due to the regular increase in population, agricultural activities are also increasing during the rainy season. Housing clusters, industries, mines, watershed activities, road networks, etc. are increasing day by day, resulting in a deteriorated catchment for surface runoff. Surface roughness has been increasing due to all these activities. The year 1994 is the critical year, which divides the pre-disturbance and post-disturbance epochs. Due to increased demand, groundwater is being exploited at a higher rate, resulting in the lowering of the groundwater table and an increase in the number of dark zones. It was observed that for the same soil parameters and with the normal daily rainfall, a relatively very high percentage of rainfall infiltrated the soil even though not all the infiltrated rainfall reached the aquifer system. A major part of it is infiltrated in the vadose zone, not combining with the groundwater table. This water from the vadose zone gets evaporated repeatedly in a rainy season. Surface water is also not getting a contribution from sub base flow due to regular lowering of the groundwater table. Since rainfall intensity is a very important parameter in determining the partitioning of rainfall into the different hydrological processes, it is not surprising to observe that overland flow generation was minimal with normal or even above normal daily rainfall events.

The practical optimal temporal resolution of rainfall data for water balance computation and description of hydrological processes is hourly data. It is expected that a much finer temporal resolution of rainfall data (by the minute) could produce an even more accurate description of hydrological processes, but this has practical limitations since it is time consuming and requires longer computation time as well as larger computer storage space. If detailed hydrological processes are to be adequately described, hourly rainfall data are by far the most appropriate. Rainfall intensity has a significant effect on the partitioning of rainfall into overland flow and infiltration. If all factors remain constant, rain falling with high intensity will favour the processes of overland flow, whereas lower intensity rainfall contributes more to infiltration (Alfa *et al*., 2011).

Rainfall intensities below 10 mm/h replenish soil moisture except when they occur in large amounts, between 10 to 70 mm/h rainfall intensity contributes to groundwater recharge, and above 70 mm/h rainfall intensity will generate Hortonian overland flow. About 70% of rainfall in the basin is lost through evapotranspiration. The amount of rainfall occuring at intensities between 10 mm/h and 100 mm/h is considered to be the domain in which all the processes such as infiltration, overland flow, and groundwater recharge take place. The available daily rainfall data in the basin can be used as hourly rainfall data spread over 5 h per day (Alfa *et al*., 2011).

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