Civil Engineering

Sensitivity of Annual Runoff to Precipitation in Madhya Pradesh, India

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Abstract

Assessing the sensitiveness of hydrological responses to changing climate is an important topic in the field of hydrology. Any substantial changes in the available water yield or runoff put the human society in danger. Thus, predicting the fluctuations in runoff generations is a key for proper implementation of water management plans. The present study is conducted to evaluate the sensitivity of water yield to variations in the annual precipitation by quantifying precipitation elasticity of runoff in the state of Madhya Pradesh. Budyko based climate elasticity method is adopted with a parametric Budyko equation to incorporate the inherent surface characteristics in the analysis. Pixel-scale calculations are carried out to implement the heterogeneity of hydro-climatological parameter into elasticity. The precipitation elasticity values are presented as spatial mean values. It is observed that elasticity value ranged between 1.254 and 1.505 with a mean value of 1.334 for the 39 watersheds, considered in the study. It means that a 10 % change in the mean annual precipitation would result in 12.54 % to 15.05 % change in runoff generation. The values of elasticity are further presented for 5 major river basins (ranged between 1.304 and 1.401) and the 51 districts (ranged between 1.254 and 1.445) covered by the state. A significant inverse exponential relationship is observed between gridded precipitation elasticity of runoff to runoff ratio ($R^2 = 0.876$, $P < 0.01$) and mean annual runoff ($R^2 = 0.420$, $p < 0.01$). In addition, it is observed that runoff is more sensitive to variation in annual precipitation in the arid regions of the state compared to the humid regions. Quantification of runoff elasticity to precipitation is an effective approach to evaluate the influence of climatic variability on the catchment hydrology.

Keywords: *Budyko hypothesis**,** climate elasticity, Madhya Pradesh, precipitation, runoff*

Introduction

Runoff alterations under changing climate has been a global concern since late 20^{th} century (Arnell, 1999; Liu, Liu, Luo, Zhang, & Xia, 2012; Wu, Miao, Wang, Duan, & Zhang, 2017). In recent times, intensification of hydrological cycle due to climate change has transported both spatial and temporal variability in precipitation globally (Easterling et al., 2000). The hydrological cycle is a multipart process that is very sensitive to climatic variables (Chahine T., 1992). Any variability in climatic variables brings unpredictability in the hydrological responses (Allen & Ingram, 2002; Miao, Kong, Wu, & Duan, 2016). Numerous researches have been carried out to evaluate the influences of unevenness in the climate on the hydrological processes (Singh & Kumar, 2015; Tan et al., 2015; Zhan et al., 2014). The commonly used methods incorporated to check the sensitivity of the runoff can be characterised into 3 categories namely statistical methods using long climate datasets (Xu, 2011), hydrological modelling (Babar & Ramesh, 2015; Gosain, Rao, & Basuray, 2006; Li, Liu, Zhang, & Zheng, 2009) and elasticity based methods (Wu et al., 2017; Zhan et al., 2014). The elasticity based methods using Budyko framework are simple that employ modest physical operations and require less datasets compared to huge observed input data, required in hydrological models (Nash & Gleick, 1991). The budyko framework explains the mean annual water and energy balance at catchment scale. In addition, there is a need to perceive the idea of the influence of heterogeneity in the climatic and catchment properties on the water yield process. To address the issue, a study is carried out using pixel-scale evaluation of the precipitation elasticity of runoff in the state Madhya Pradesh of India. The study also considered 39 catchments across the 5 major river basins, covered by the state with their gauging stations given by Central Water Commission (CWC), India (Government of India, 2012). The elasticity results are averaged at the watershed and river basin scale as per the hypothesis of the Budyko framework. In addition, the elasticity values are also averaged to districts to obtain a vague idea of potentiality in runoff generation at district scale.

Study area details, methods and data used

Study area

The study is carried out in the state Madhya Pradesh of India. Further, results are discussed for 51 districts, 5 major river basins and 39 sub-watersheds within the basins as shown in Fig. 1. The state covers portion of the major river basins namely Ganga, Mahi, Narmada, Tapi and Godavari. The watersheds are delineated in ArcMap using 30m SRTM Digital elevation model (DEM) datasets with their gauging stations obtained from CWC (Government of India, 2012).

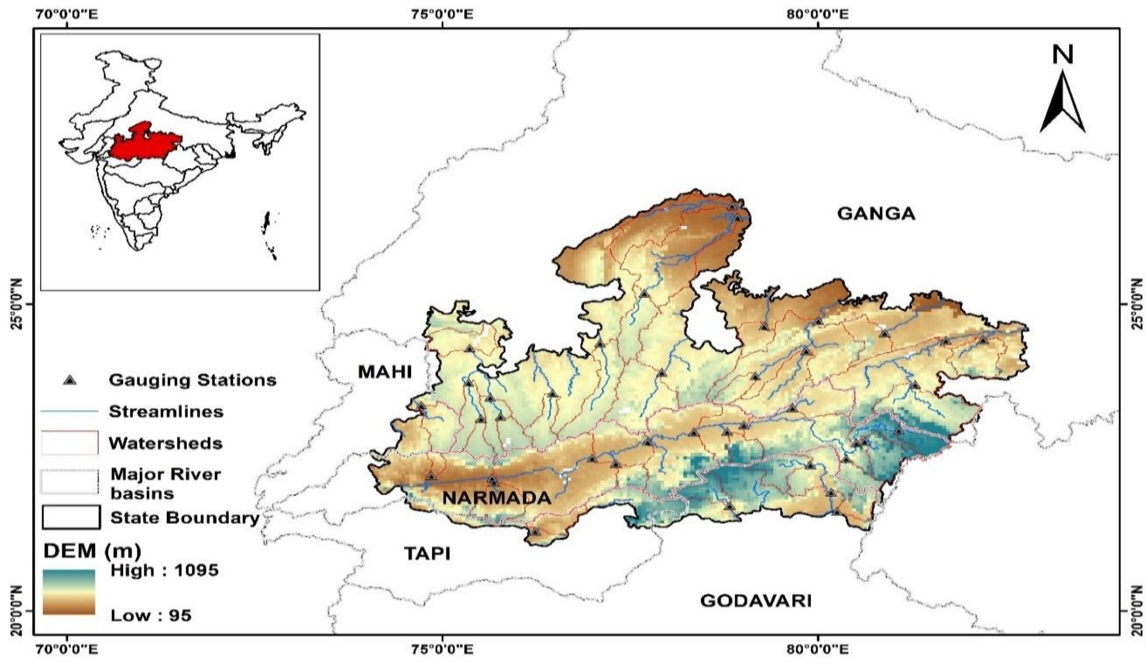

Fig 1: Map of state Madhya Pradesh with 39 sub-watersheds and their gauging stations (GD, GDSQ; CWC). The state covers small portions of five major river basins.

The watersheds cover approximately 60% of total expanse of the state. The elevation of the state varies from 95 m to 1095 m above mean sea level. India has a tropical climate that is dominated by monsoons (southwest and northeast monsoon). The orographic features are the key reasons for the spatial variability of rainfall and temperature in the country (Revadekar, Tiwari, & Kumar, 2012), which is also observed in the state i: e higher precipitation occurred at high elevated regions of Madhya Pradesh. Precipitation varied from 454.259 mm to 1414.520 mm for the state during the study period. Since the present study is carried out pixel wise, there is no actual purpose of displaying mean meteorological values for the watersheds. Therefore, only spatial locations of the gauging stations are shown in table 1.

Table 1: Geographical locations of the gauging stations in Madhya Pradesh, considered for the study

Gauging Stations	**Lat**	**Long**	**Gauging Stations**	**Lat**	**Long**	**Gauging Stations**	**Lat**	**Long**
Bhind	26.608	78.857	Patan	23.311	79.662	Manot	22.736	80.513
Seondha	26.418	78.930	A.B.Road Crossing	24.366	77.099	Mohgaoan	22.766	80.623
Garrauli	24.641	79.283	Mahidpur	23.481	75.636	Handia	22.492	76.994
Pachauli	25.179	77.687	Dhareri	23.133	75.515	Chhidgaon	22.406	77.308
Satna	24.533	80.888	Ujjain	23.168	75.771	Bamni	22.484	80.378
Madla	24.733	80.007	Basoda	23.887	77.920	Keolari	22.382	79.900
Nahargarh	24.283	75.361	Mataji	23.350	74.718	Mandleshwar	22.168	75.661
Kuldah Bridge	24.413	81.704	Sarangpur	23.550	76.467	Dhulsar	22.206	74.852
Jhukoo	24.425	82.201	Barmanghat	23.031	79.016	Kogaon	22.101	75.684
Garhakota	23.829	79.167	Sandia	22.916	78.348	Kumhari	21.934	80.175
Tal	23.723	75.347	Gadarwara	22.923	78.791	Ramakona	21.719	78.824
Goverdhey Ghat	23.690	81.296	Dindori	22.948	81.076	Rajegaon	21.626	80.254
Gaisabad	24.243	79.844	Hoshangabad	22.756	77.733	Burhanpur	21.299	76.235

Methods

The runoff generated at each pixel is quantified using the mean annual water balance equation given as:

$$Q_x = P_x - AET_x \tag{1}$$

where, Q is runoff, P is precipitation and AET is actual evapotranspiration. All the parameters are in mean annual scale. The pixels are indexed using the subscript ‘x’. While implementing budyko hypothesis, the change in water storage is considered to be negligible (ΔS = 0).

For the calculation of catchment characteristics that define the landscape properties, budyko-based equation given by Fu, (1981) is implemented and is given by:

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - \left(1 + \left(\frac{PET_x}{P_x}\right)^{\omega_x}\right)^{\frac{1}{\omega_x}} \tag{2}$$

where, PET is mean annual potential evapotranspiration. The ratio of PET to P is termed as dryness index (φ) whereas, the ratio of actual evapotranspiration to precipitation is termed as evaporative index. The catchment parameter ω is calculated at each pixel and is further used for the evaluation of precipitation elasticity of runoff (ε_P).

The analytical derivation of the elasticity of runoff to precipitation using the multi-year water balance is presented by Arora, (2002) and it is further implemented as:

$$\varepsilon_{P_x} = 1 + \frac{\emptyset_x f'(\emptyset_x)}{1 - f(\emptyset_x)} \tag{3}$$

Here, f(φ) is nothing but the mathematical expression of the budyko based hypothesis stated in eq. 2 that equals to the evaporative index (EI).

The precipitation elasticity explains the sensitivity of runoff to changes in the precipitation. It can further be interpreted as the ratio of relative change in discharge to relative change in precipitation, defined by:

$$\varepsilon_{P_x} = \frac{dQ_x/Q_x}{dP_x/P_x} = \frac{dQ_x}{dP_x}\frac{P_x}{Q_x} \tag{4}$$

Data used

Annual precipitation data are obtained from India meteorological department. The point dataset was available for the study period of 2000 to 2014 at a spatial resolution of 0.25° × 0.25° (Pai et al., 2014). Actual and potential Evapotranspiration data are obtained from the global MOD16A2 product from the NASA Earth Observation System (EOS) program. The datasets are available at a spatial resolution of 0.05^0 × 0.05° (available from http://www.ntsg.umt.edu/project/modis/). The precipitation data is converted to the same spatial resolution as that of evapotranspiration data.

Results and Discussions

With the raster datasets of mean annual precipitation and actual evapotranspiration, runoff is calculated at each pixel using water balance equation, considering the assumption of negligible water storage (Δs = 0). Having all the datasets, aridity index (φ = PET/P), evaporative index (EI = AET/P) and runoff ratio (Q/P) are quantified at each grid and their spatial dispersals are displayed in Fig. 2 (a-c) respectively. It is clearly visible that the eastern and central part of Madhya Pradesh are comparatively less dry (lower values of φ) than western and northern parts of the state (Fig. 2(a)). Evaporative index is observed to be higher in the periphery of the state, but most prominent in the extreme northern and south-western parts. Runoff ratio i: e. the ratio of mean annual runoff (Q) to mean annual precipitation (P) is higher in the central portion of Madhya Pradesh. It is noticeable that the spatial trends of runoff ratio and evaporative index is opposite in nature. This is evident from the fact that as AET increases, lower portions of precipitation are partitioned to runoff generation. Moreover, conflicting trends in φ and runoff ratio also indicate the condition of lower evaporative demand of the atmosphere, which is independent of crop type, that in turn increases greater chances of increased runoff generation (also seen in Sankarasubramanian & Vogel, (2003)).

Adopting the Budyko equation ((B. Fu, 1981)), the catchment parameter (ω) is computed for each pixel and the distribution is shown in the Fig. 2(d). The catchment parameter represents the catchment properties like vegetation cover, land use characteristics, soil properties etc. It introduces the impressions of inherent catchment attributes in the quantification of climate elasticity of runoff. It is seen that ω is higher in extreme northern, extreme south eastern and western parts of Madhya Pradesh. Interestingly, a similar spatial trend is observed between evaporative index (EI) and ω. Although ω was computed using budyko hypothesis, catchment attributes are solely due to surface properties and are independent of climatic influences. This indicates a need of further research to explain this phenomenon.

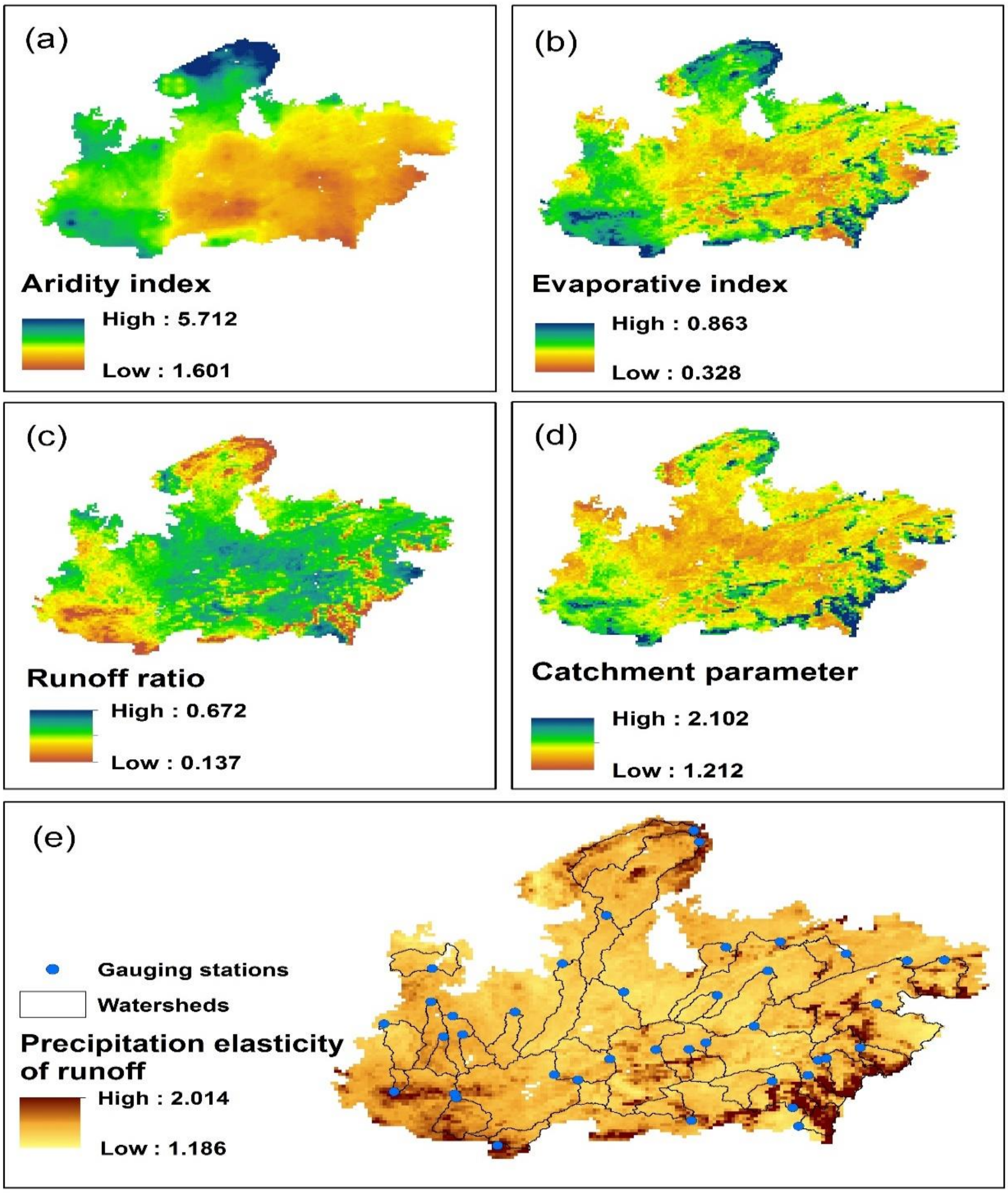

Fig 2: Spatial variations of hydro-climatological attributes, calculated at each pixel. (a) Aridity index (PET/P). (b) Evaporative index (AET/P). (c) Runoff ratio (Q/P). (d) Catchment parameter (ω) obtained from implementing Budyko based equation (Fu et al., 2007). (e) Runoff elasticity to precipitation (ε_P) along with watersheds and their respective outlets given by CWC

Precipitation elasticity of runoff (ε_P) is quantified using equation 3 and the spatial variation is shown in Fig. 2(e). It varied between 1.186 and 2.014 with a mean value of 1.326 in the state. Higher values of ε_P are detected at pixels near to the boundary of the state (significantly at northern, eastern and southern boundaries). No noteworthy pattern is observed within the watersheds, shown along with the gauging stations in the figure. Table 2 shows the spatial mean values of precipitation elasticity for all the districts, major river basins and the watersheds. Values of ε_P ranged between 1.254 (Anuppur) to 1.445 (Burhanpur) for the 51 districts considered in the study. In the case of major river basins, Tapi has shown the highest ε_P value (1.401) with lowest value in Mahi (1.304). Within the 39 delineated watersheds, the ε_P value ranged between 1.254 (Garhakota) to 1.505 (Rajegaon) with a mean value of 1.334. From hydrological point of view, the elasticity values are more important for watersheds. Thus the results indicate that with a 10 % change in the precipitation, the watersheds would experience percentage changes in runoff generation, ranging from 15.05 % to 12.54 %.

The pixel values of Precipitation elasticity to runoff is further investigated to observe any relationship with surface and hydro-meteorological characteristics (Fig. 3). Note that the blue circular markers represent the 27636 pixels that are analysed separately. No relationship is observed between DEM and the elasticity values of the pixels (Fig. 3(a)). This may be the reason of absence of any spatial trends of elasticity values within the watersheds (Fig. 2(e)).

Figure 3(b, c) shows the relationship of runoff ratio (Q/P) and runoff to precipitation elasticity values respectively. A very strong and significant exponential relationship is observed between runoff ratio and ε_P ($R^2 = 0.876$, $p < 0.01$). The plot justifies the inverse relationship of runoff ratio to precipitation elasticity which can also be observed from equation 4. The curve explains the non-linearity characteristic of the precipitation-runoff processes. Similar explanation holds for the significant inverse relationship between mean annual runoff and ε_P ($R^2 = 0.420$, $p < 0.01$). Surface properties like soil moisture tends to buffer the impacts of climate change on the hydrology at catchment scale. If we consider a humid or semi-humid catchment with the condition of negligible inter-annual variation in water storage that leads to higher generation of surface runoff (higher partitioning of precipitation to runoff), the sensitivity of runoff to variability in precipitation tends to reduce. This highlights the fact that arid and semi-arid regions of Madhya Pradesh have shown higher ε_P values compared to the humid regions. Similar results have been observed in previous studies (Sankarasubramanian & Vogel, 2003). In addition, a significant positive linear relationship is observed between catchment characteristics (ω) and ε_P. The trend-line almost resembled the 1:1 line in this case. It has been observed in previous studies that increased partitioning of precipitation to evapotranspiration (thus low runoff generation) is explained by higher magnitudes of catchment parameter (B. Fu, 1981; Yang et al., 2007). This explains the strong relationship which suggests that with increase in ω, the sensitivity of runoff to variability in precipitation increases.

Table 2: Mean precipitation elasticity of runoff (ε_P) for districts, Major river basins and sub-watersheds in Madhya Pradesh

DISTRICTS					
Districts	ε_P	**Districts**	ε_P	**Districts**	ε_P
Agar Malwa	1.285	East Nimar	1.327	Ratlam	1.319
Alirajpur	1.365	Guna	1.278	Rewa	1.303
Anuppur	1.254	Gwalior	1.339	Sagar	1.268
Ashoknagar	1.287	Harda	1.320	Satna	1.331
Balaghat	1.429	Hoshangabad	1.339	Sehore	1.275
Barwani	1.400	Indore	1.335	Seoni	1.327
Betul	1.338	Jabalpur	1.277	Shahdol	1.301
Bhind	1.417	Jhabua	1.298	Shajapur	1.288
Bhopal	1.269	Katni	1.318	Sheopur	1.317
Burhanpur	1.445	Mandla	1.342	Shivpuri	1.316
Chhatarpur	1.311	Mandsaur	1.315	Sidhi	1.337
Chhindwara	1.318	Morena	1.361	Singrauli	1.338
Damoh	1.271	Narsimhapur	1.314	Tikamgarh	1.329
Datia	1.404	Neemuch	1.271	Ujjain	1.331
Dewas	1.307	Panna	1.301	Umaria	1.372
Dhar	1.384	Raisen	1.289	Vidisha	1.264
Dindori	1.418	Rajgarh	1.276	West Nimar	1.397

RIVER BASINS	
River Basins	ε_P
Mahi Basin	1.304
Narmada Basin	1.343
Tapi Basin	1.401
Ganga Basin	1.310
Godavari Basin	1.360

GAUGING STATIONS					
Gauging stations	ε_P	**Gauging stations**	ε_P	**Gauging stations**	ε_P
Bhind	1.363	Patan	1.316	Manot	1.350
Seondha	1.336	A.B.Road Crossing	1.271	Mohgaon	1.447
Garrauli	1.312	Mahidpur	1.337	Handia	1.296
Pachauli	1.292	Dhareri	1.360	Chhidgaon	1.282
Satna	1.328	Ujjain	1.335	Bamni	1.428
Madla	1.289	Basoda	1.274	Keolari	1.282
Nahargarh	1.292	Mataji	1.301	Mandleshwar	1.331
Kuldah Bridge	1.317	Sarangpur	1.302	Dhulsar	1.389
Jhukoo	1.353	Barmanghat	1.297	Kogaon	1.401
Garhakota	1.254	Sandia	1.312	Kumhari	1.384
Tal	1.356	Gadarwara	1.321	Ramakona	1.332
Goverdhey Ghat	1.317	Dindori	1.401	Rajegaon	1.505
Gaisabad	1.266	Hoshangabad	1.325	Burhanpur	1.381

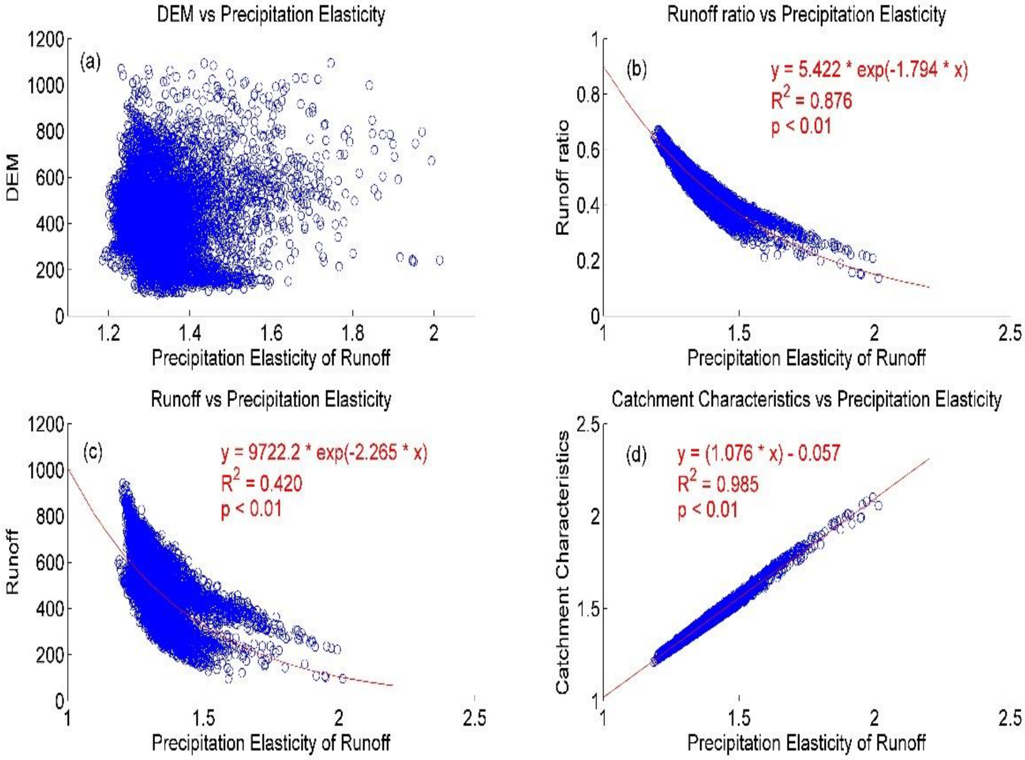

Fig 3: Attributes of Precipitation elasticity calculated for each pixel covering Madhya Pradesh. (a) Relationship between DEM and precipitation elasticity. (b) Relationship between runoff ratio and precipitation elasticity. (c) Relationship between runoff and precipitation elasticity. (d) Relationship between catchment parameter (ω) and precipitation elasticity

Conclusion

Human civilisation has always been dependent on available water resources and it is vital to design management policies and implement laws that ensures its accessibility (Creed et al., 2014). Thus, it is necessary to predict changes in streamflow following variability in the climatic parameters. The present study attempted to explain the sensitivity of runoff to variance in precipitation in the state Madhya Pradesh. It is found that the precipitation elasticity varied between 1.254 and 1.505 for the 39 watersheds considered in the state. The study implies that larger changes in runoff generation would occur compared to changes in the annual precipitation. Very strong and significant inverse correlations are obtained between gridded values of precipitation elasticity, runoff and runoff ratio that strengthens the non-linearity functioning of the hydrological processes. The study is carried out using pixel-scale calculations to analyse the heterogeneity of hydro-climatic parameters and catchment attributes on the sensitiveness of runoff to precipitation. A strong and significant linear relationship is seen between catchment attributes and gridded elasticity values. Further detailed and comprehensive study could be performed to observe the role of more intrinsic surface properties on the climatic elasticity of annual runoff.

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