



## Statistical Significance Assessment of Streamflow Elasticity of Major Rivers

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Received 27 January 2021; Revised 10 April 2021; Accepted 18 April 2021; Published 01 May 2021

### Abstract

Impacts of climate change on streamflow have long been an issue of concern for water experts. The main aim of this study is to assess the response of streamflow to precipitation and air temperature. In this study elasticity model was used to compute the precipitation and air temperature elasticity of 6 major rivers in Khyber-Pakhtunkhwa (KP) Province, Pakistan. In contrast to temperature elasticity estimator, box plots of precipitation elasticity estimator have low range and standard deviation leading to greater central affinity which produces valid, appropriate, and statistically significant elasticity results. Precipitation is positively correlated with streamflow while the air temperature is both positively and negatively linked with streamflow. 10% variation in precipitation and air temperature produces 12 to 20% and 8 to 18% change in streamflow, respectively. The sensitivity of streamflow to air temperature is higher as compared to precipitation. This research work shows that precipitation elasticity results are statistically valid and realistic as compared to temperature elasticity results. Moreover, it is suggested to support elasticity results by statistical correlation to avoid misleading and unrealistic results. Results of the current study can be used in formulating long term policies regarding streamflow sensitivity in the study region.

**Keywords:** Climate Change; Precipitation Elasticity; Streamflow; Temperature Elasticity; Water Management.

## 1. Introduction

Global warming cause variations in hydrologic cycle at global scale. In response, hydrologic systems will face variations in water quantity and extreme events [1]. These changes will affect hydropower sector, municipal and industrial demand, and public health. Impacts of climate on hydrologic systems vary in space [1-5]. Hydrologic systems are the backbone of any country as they greatly impact the economic development and environmental conditions of any region. Hydrologic cycle of any watershed is primarily affected by both climatic and non-climatic determinants. It is well-founded knowledge that climate change experts mainly considers evaporation, precipitation and air temperature [3, 6-10] as the fundamental environmental determinants responsible for variability in hydrologic systems.

Pakistan's economy and revenue are predominantly dependent on agriculture, which mainly depends on the water resources. Conversely, the water resources of the country are under threat and are highly stressed because of climate

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 <http://dx.doi.org/10.28991/cej-2021-03091698>



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change and human activities, therefore it is a big task for policymakers and water managers to cope with the situation and resolve the water related issues. Pakistan's water profile has changed from being a water-rich nation to one encountering water pressure. Today, the country is ranked among the most water-stressed countries. Pakistan ranks 7<sup>th</sup> as per 2018 global long-term climate risk index. The per capita water accessibility declined from 5000 cubic meters in 1947, to around 1000 cubic meters, and is expected to additionally diminish to 800 cubic meters per capita in 2025 [11]. This is shocking condition for the whole country owing to increase in water demand and decline in water storage. Therefore, informed and timely estimation of future water resources based on the prevalent and expected climate condition is important for any watershed management.

Lot of research work has been conducted on water resources of Pakistan [12-15]. Literature shows that majority of the studies focused on the water resources in Upper Indus Basin using hydrological models such as Snow Runoff Model (SRM), Soil and Water Assessment Tool (SWAT), Hydrologiska Byråns Vattenbalansavdelning (HBV), and Water And Energy Budget-based Distributed Hydrological Model with Snow (Web-DHM-S) model [16]. Yet, upon a thorough study of relevant literature, limited literature was found which assessed the impacts of climate change on water resources at provincial scale using the analytical models. Pakistan's water resources are primarily constructed for irrigation and hydropower generation. Although, globally precipitation elasticity, a renowned analytical model, has already been successfully implemented on large scale studies, yet no study has been witnessed using analytical model for water resources assessment of Pakistan.

The impacts of climatic determinants on streamflow has been studied by numerous researchers [17-21] in particular, variations in rainfall and potential evapotranspiration [22]. The larger part of these studies mainly focused on the estimation of the potential effects of environmental change on water assets and streamflow. Many hydrologists used hydrological models, where the models were calibrated using historical streamflow dataset under different climatic and land use scenarios and the results were compared with observed values to give an idea about the climatic and anthropogenic affects [3, 6-10, 16, 20, 23-25]. Streamflow sensitivity to climatic determinants is subjected to accurate hydrological model application and calibration. However, hydrological model selection and calibration criteria are subjective. Additionally, the areas having a diverse atmospheric and physical attribute may require distinctive models. The nonparametric estimator of climate elasticity introduced by Sankarasubramanian et al., (2001) assesses the response of streamflow to precipitation to long annual historical time series [17]. To date, researchers have assessed the general characteristics of elasticity and its instability consequences due to climatic and physiographic characteristics of watershed [25] forgetting the most important part that is statistical significance estimation of precipitation and temperature elasticity. The principal purpose which motivates the authors was to assess whether precipitation or temperature elasticity results are statistically superior.

Precipitation elasticity " $\epsilon_p$ " of streamflow, gauge the response of streamflow to variations in precipitation. The precipitation elasticity of streamflow ( $\epsilon_p$ ) is termed here as the corresponding change in mean yearly streamflow divided by the relative change in mean yearly rainfall [17]. An elasticity of 3.0 in this way demonstrates a unit percentage change in precipitation results 3% variations in streamflow. This technique is widely used for preliminary investigation at large scale [26]. The current study has three main objectives. Firstly, general attributes of precipitation and temperature elasticity of streamflow. Secondly, assessment of precipitation and temperature elasticity of streamflow, without aptly accounting for the precipitation-streamflow and temperature-streamflow relationship, yields misleading, improbable and unrealistic results. Thirdly, to check whether precipitation or temperature elasticity give statistically significant outcomes. The current study will provide a guideline for the application of elasticity approach to gauge the streamflow sensitivity to climate change. To achieve the objectives, 11 years (2005-2015) monthly discharge data were collected from the hydrology department for 16 monitoring sites located at 6 major rivers of Khyber-Pakhtunkhwa (KP) Province, Pakistan.

## 2. Materials and Methods

### 2.1. Study area

This study is conducted at provincial scale covering major rivers of KP Province. The current research work is based on 16 monitoring sites located at 6 large rivers i.e. Swat River (4 monitoring sites), Pajkora River (1 monitoring sites), Bara River (2 monitoring sites), Jindi River (1 monitoring sites), Kurram River (1 monitoring sites) and Kabul River (7 monitoring sites) as obvious from Figure 1. The Swat River is perennial which is widespread in Northern region of KP Province. The length and catchment area of Swat River is 240 km and 14000 km<sup>2</sup> respectively. The peak flow of Swat River is 25,301 cusecs. The river originates from Kalam having two main tributaries i.e., Ushu and Utror which runs downstream across the valley of Maidan up to 160 kilometers to Chakdara. The snow melting of Hindukush Mountains are the main source of Swat River. It joins Panjkora and Kabul River at Qalangi and Charsadda respectively. The Swat Canal flows through Benton Tunnel in Malakand. After passing Dargai, the upper canal is distributed in two branches which supply water to Charsadda, Swabi, and Mardan. Hydropower is also generated at Jabban and Dargai. Panjkora River flows in the North-West region of KP Province. It is mainly located in Chakdara.

Glaciers of the Hindukush Mountains are the main source of river flow. It passes through the Upper and Lower Dir Districts. It forms a junction with the Swat River near Totakan in the Malakand District. It lies at an elevation of 3600 m and comprises a length of 220 km. Bara River is located in the North-West of KP Province. This river originates from the Tirah Valley of Tehsil Bara which is located in Khyber Agency. Bara River joins Kabul River (Akbarpura) before entering the Peshawar region. In the North-East direction, Bara River enters the Nowshera District. Bara River is located at high elevation (293 m from the mean sea level) so very limited areas flow into it through gravity. The Jindi River (also called Kot and Manzari Baba) originates from the hills of Malakand Agency, in the Northern part of Charsadda district, KP Province. River flow is higher in summer as compared to winter. Irrigation for crop production is mainly dependent on rains in winter due to low river flow. In summer, people irrigate their crops using small dams water constructed on Jindi River. Kabul and Jindi rivers irrigate the largest portion of KP Province. The population is rapidly increasing in the area. River flow is decreasing day by day due to climatic and non-climatic factors. In the south of Charsadda, it joins the Swat River. Kurram River originates from the Khost and Paktia Provinces of Afghanistan, and Kurram Agency, North Waziristan KP Province, Pakistan. The length of the Kurram River is 320 km. It is in the South-East at a distance of 20 km from Gardez and Paktia. This river is a tributary of river Indus. The Kabul River ranks one of the significant and major rivers of KP Province. It originates from Maidan Wardak Province in the Sanglakh Range of the Hindukush mountains in Afghanistan. The length and catchment of this river are 700 km and 66,000 km<sup>2</sup>. Kabul River joins the Indus River near Attock, Pakistan. This river is also the main river of eastern Afghanistan. The Kabul River flows through various cities such as Surobi, Kabul, and Jalalabad in Afghanistan before entering the KP Province, Pakistan. Kabul River flows through the cities of Peshawar, Charsadda, and Nowshera. The peak discharge of Kabul River is 75,700 cusecs at Nowshera.

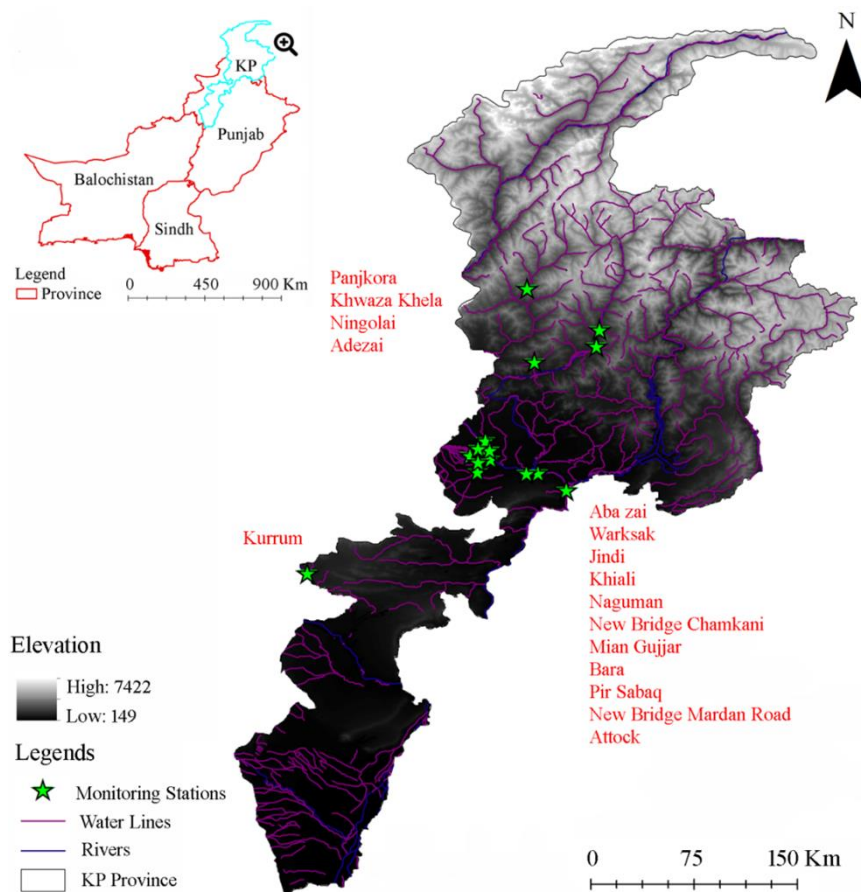


Figure 1. Hydrological monitoring stations located at major rivers of KP Province

## 2.2. Hydro-meteorological Data

Pakistan is a data scarce country. 11 years' (2005-2015) monthly discharge data were collected from the hydrology department for 16 monitoring sites located at 6 major rivers of KP Province. Mean monthly precipitation (P, mm) and air temperature (T, °C) dataset were extracted from reconstructed 0.5° × 0.5° latitude/longitude global grids [23]. The above-stated variables data were downloaded from National Oceanic and Atmospheric Administration (NOAA) [29]. For the current study, climatic variables data for the selected hydrological monitoring points was mined via multidimensional tool of geographic information system (GIS) [30].

### 3. Elasticity Approach

Sensitivity measure of streamflow response to precipitation separately from air temperature, is based on elasticity concept initiated from economics and aftermath developed in hydrology and environmental sciences [17, 21, 29-32]. The research methodology is demonstrated by flowchart as obvious from Figure 2. Precipitation elasticity and temperature elasticity are demonstrated by Equations 1 and 2.

$$\varepsilon_p = \text{median} \left( \frac{Q_t - \bar{Q}}{P_t - \bar{P}} \frac{\bar{P}}{\bar{Q}} \right) \quad (1)$$

$$\varepsilon_T = \text{median} \left( \frac{Q_t - \bar{Q}}{T_t - \bar{T}} \frac{\bar{T}}{\bar{Q}} \right) \quad (2)$$

Where  $\bar{Q}$  = mean monthly river discharge,  $\bar{T}$  = mean monthly air temperature while  $\bar{P}$  = mean monthly precipitation. Similarly,  $Q_t$ ,  $T_t$ , and  $P_t$  denotes river discharge, air temperature and precipitation at any given time  $t$ . The values demonstrated above in Equations 1 and 2 is identified here as the percentage change-based elasticity estimator.

The value  $\frac{Q_t - \bar{Q}}{T_t - \bar{T}} \frac{\bar{T}}{\bar{Q}}$  is calculated per set of ( $Q_t$  and  $T_t$ ) utilizing time series data set for each month.

The nonparametric precipitation and temperature elasticity estimator can be obtained by considering median values of Equations 1 and 2. Elasticity technique quantifies the response of streamflow to precipitation and air temperature. Elasticity technique overweighs hydrological modelling techniques e.g. firstly elasticity approach is unitless (simplifies data analysis). Secondly, the entire function of elasticity is based on a median value which reduces the effects of outliers (extreme events) i.e. floods and droughts. Thirdly, this approach is appropriate for large scale studies because it needs a small set of input variables as compared to other hydrological approaches. Moreover, elasticity does not demonstrate causal associations between discharge and climatic variables. Elasticity is important when the concerned variables are physically tied. Elasticity approach is based on mean monthly values; it gauges the response of mean monthly discharge to mean monthly precipitation and temperature, ignoring the rest socioeconomic, environmental, and topographic factors. It considers the remaining determinants constant which is practically impossible. Elasticity technique ignores all the intermediate processes.

#### 3.1. Statistical Significance Estimation of Precipitation and Temperature Elasticity

The non-parametric estimator of elasticity is gauged by its median value. Scattered distribution, high range and standard deviation, of elasticity estimators gives less significant elasticity results owing to outliers and lower central tendency. Box plots analysis was conducted to assess the precipitation and temperature elasticity estimator's distribution pattern. Box plot measure the central affinity of precipitation and air temperature elasticity estimators about the median value. Indices having high central affinity produce statistically significant results since all values fall close to the center having minimum outliers [28].

#### 3.2. Comparison of the Precipitation and Temperature Elasticity with a Correlation Coefficient

Apart the elasticity procedure, Pearson's rank correlation coefficient [30] is likewise utilized to assess the connection between climate drivers and streamflow. Elasticity, like correlation, is certainly not an adequate index which unveils the cause-and-effect relation between climatic determinants and streamflow. In this manner, elasticity is just important when the two variables under our concern are physically connected. Prior knowledge of causal linkage can strengthen the elasticity results. Computing precipitation and temperature elasticity of streamflow without first gauging the strength of the precipitation-streamflow and temperature-streamflow connections can deliver deceiving and implausible outcomes [16].

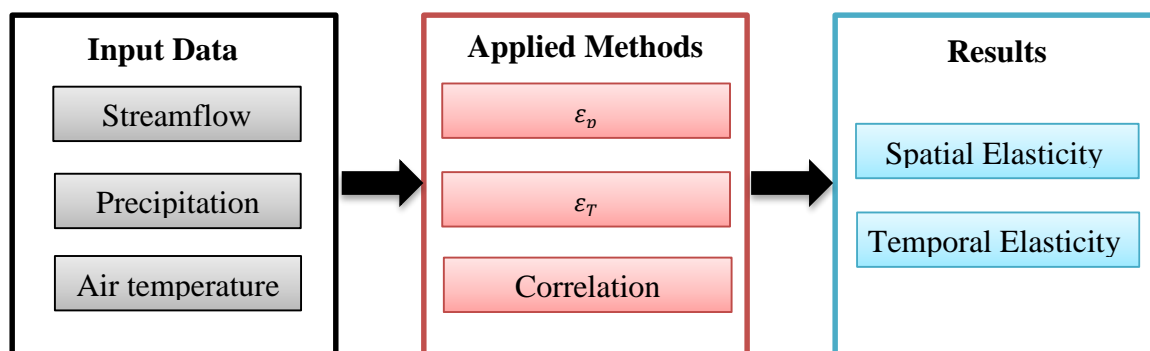


Figure 2. Flowchart demonstrating the research methodology

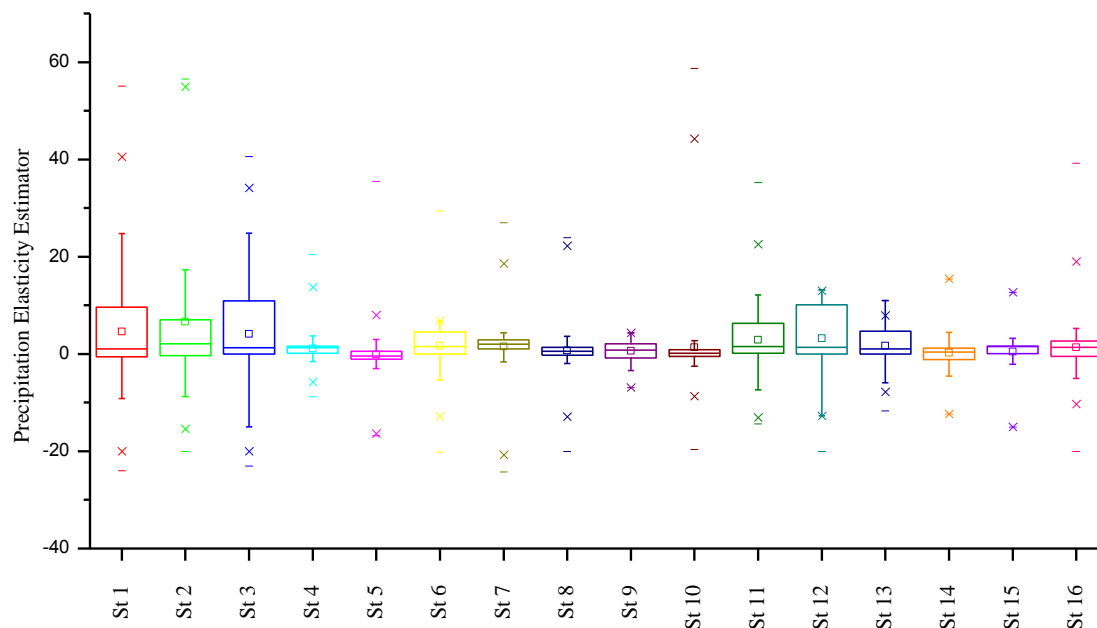
## 4. Results and Discussion

### 4.1. Comparison of Elasticity and Distribution Characteristics of Elasticity Estimators

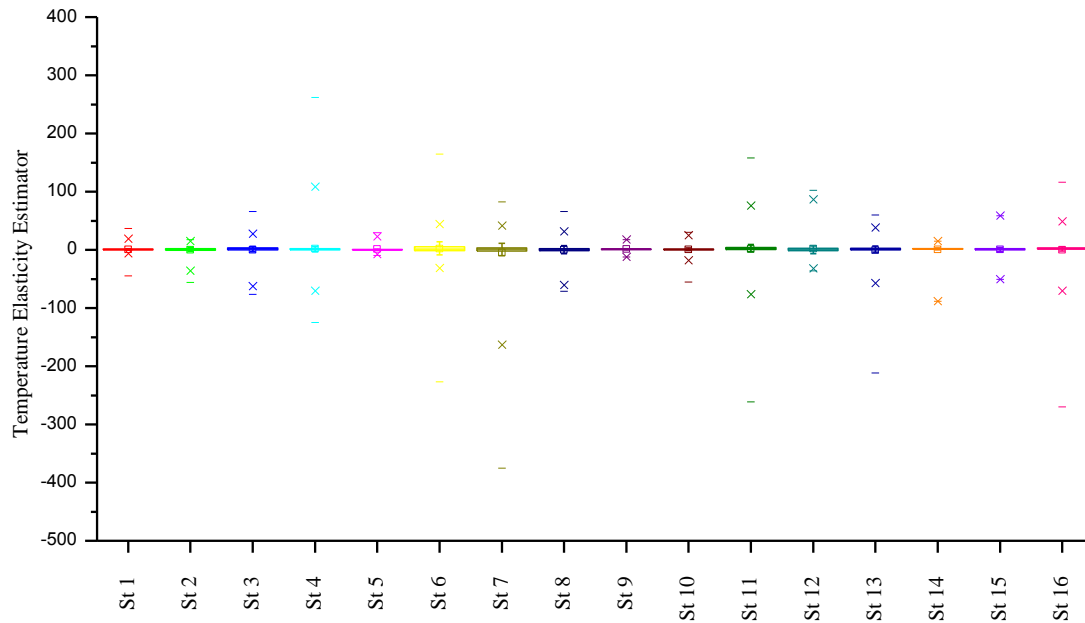
Figure 3 and Table 1 demonstrate that precipitation elasticity estimators have lower range and high standard deviation in contrast to temperature elasticity estimators for majority hydrological monitoring stations of KP Rivers. The results of the precipitation elasticity estimators are compact as opposed to the temperature elasticity estimators which demonstrate its higher central tendency. Lower range and standard deviation of the elasticity estimator gives a statistically significant result owing to high central tendency. Disperse elasticity estimators produce misleading and unrealistic precipitation and temperature elasticity [29]. Precipitation elasticity estimators have lower range and standard deviation at majority hydrological monitoring stations which demonstrate its high central affinity. On the other hand, temperature elasticity estimators at all monitoring sites have a lower central tendency due to higher range and standard deviation which produces less significant, unrealistic, and misleading results. The above discussion shows that temperature elasticity results are statistically less significant in contrast to precipitation elasticity because precipitation elasticity estimators' values cluster in the center approximately at all hydrological monitoring stations. The higher central tendency of precipitation elasticity estimators produces statistically significant precipitation elasticity results. This effect may be due to the dependency of majority rivers flow on rainfall in the understudy province.

**Table 1. Statistical characteristics of precipitation and temperature elasticity estimators**

Monitoring sites	Precipitation elasticity estimators				Temperature elasticity estimators			
	Minimum value	Maximum value	Range	Standard deviation	Minimum value	Maximum value	Range	Standard deviation
St 1	-10.4	15.7	5.2	6.7	-44.1	37.2	-6.9	5.7
St 2	-10.0	17.3	7.3	6.5	-55.3	17.9	-37.4	6.9
St 3	-13.1	17.8	4.7	7.0	-76.5	65.9	-10.5	13.7
St 4	-8.8	15.1	6.3	2.4	-124.7	262.4	137.6	28.0
St 5	-10.5	14.8	4.3	2.6	-9.0	29.5	20.5	4.2
St 6	-12.8	14.1	1.3	3.6	-226.8	165.1	-61.7	25.4
St 7	-13.1	18.6	5.5	3.9	-374.7	83.1	-291.6	39.8
St 8	-12.9	12.9	0.0	2.9	-70.6	66.5	-4.0	13.1
St 9	-6.9	4.4	-2.5	2.1	-12.0	17.6	5.6	3.1
St 10	-11.8	15.8	4.0	3.6	-54.7	30.8	-24.0	6.5
St 11	-13.0	15.2	2.2	4.4	-261.1	158.2	-102.9	29.7
St 12	-13.1	13.2	0.1	5.9	-35.7	102.8	67.1	15.3
St 13	-11.6	11.0	-0.7	3.2	-211.0	60.5	-150.5	21.6
St 14	-12.3	15.4	3.2	4.1	-88.2	15.3	-72.9	11.7
St 15	-12.1	12.7	0.6	3.0	-50.3	58.7	8.4	8.8
St 16	-11.2	16.8	5.6	3.6	-269.5	116.5	-153.0	27.4







**Figure 3. Precipitation elasticity estimator and temperature elasticity estimators at various monitoring stations in KP Province**

#### 4.2. Checking Elasticity Values

It is clear from Figure 4 that the coefficient of determination between precipitation and streamflow is positive at all monitoring stations which show that rainfall is the main cause of streamflow. Strong relationships were observed between precipitation and streamflow during January, March, April, May, Jun, August and October. In contrast, air temperature and streamflow are positively and negatively correlated which may due to two reasons; firstly, high air temperature favors the melting of glaciers which enhance streamflow. Secondly, high air temperature speeds up evapotranspiration losses which reduce streamflow. Spatially, both precipitation and temperature are positively correlated with streamflow which shows that both climatic factors are contributing to streamflow in the study area.

It is obvious from the above discussions that both precipitation and temperature contribute to streamflow in the study area. In case where correlation is weak enhancement in precipitation decreases streamflow and vice versa. This primarily happens because of two underlying reasons: a small precipitation increase combined with a large temperature increase and a small precipitation decrease combined with a large temperature decrease. Bivariate elasticity could not give a clear picture of precipitation-streamflow and temperature-streamflow relationships. Therefore, it is suggested to use a multivariate elasticity approach (nonparametric, double-logarithm, and variable transformation) to show the impacts of climatic factors (precipitation, air temperature etc.) and non-climatic determinants (land use land cover, soil etc.) on streamflow simultaneously which will give the clear picture of all factors contributing to streamflow [21]. Precise research results will help the watershed managers in the application of elasticity methods to measure hydrological response to climate change which will be helpful in the formulation of water management strategies.

#### 4.3. Precipitation-streamflow and Temperature-streamflow Relationship and Elasticity

The accuracy of the precipitation and temperature elasticity results depends on the strength of the relationships of precipitation-streamflow and temperature-streamflow, respectively. Weak precipitation-streamflow and temperature-streamflow relationships lead to misleading and unrealistic results. Time series having strong precipitation-streamflow and temperature-streamflow linkages, having a high coefficient of determination, can produce valid, statistically significant, elasticity results [16]. Based on the above discussions, the spatial precipitation elasticity values of streamflow are 1.2, 2, 1.5 and 1.3 at St 4, St 7, St 15, and St 16 respectively which are more valid owing to strong precipitation-streamflow relationships (high coefficient of determination) as demonstrated by Table 2. The results imply that a 10% change in precipitation can cause 12, 20, 15, and 13% change in streamflow at the above mentioned four monitoring stations, respectively. It shows that rainfall enhances streamflow. Similarly, the spatial temperature elasticity values of streamflow are 0.8, 0.8, 1.7, 1.3, 1.7, 1.2, and 1.8 at St 9, St 10, St 11, St 13, St 14, St 15, and St 16 respectively which are statistically significant owing to strong temperature-streamflow relationships (high coefficient of determination). 10% change in air temperature would result in 8, 8, 17, 13, 17, 12 and 18% change of streamflow for the above stated five monitoring stations, respectively. The increase and decrease in streamflow may be due to the melting of glaciers and evapotranspiration losses caused by a rise in air temperature [33-35]. Pakistan lies in the

temperate climate zone (generally arid) which is characterized by cold winters and hot summers. Results of the current study are supported by Chiew et al., (2006) research work where precipitation elasticity falls in the range of (0.5-2.5) for Warm Arid (BWh) Koppen climate class [16, 37].

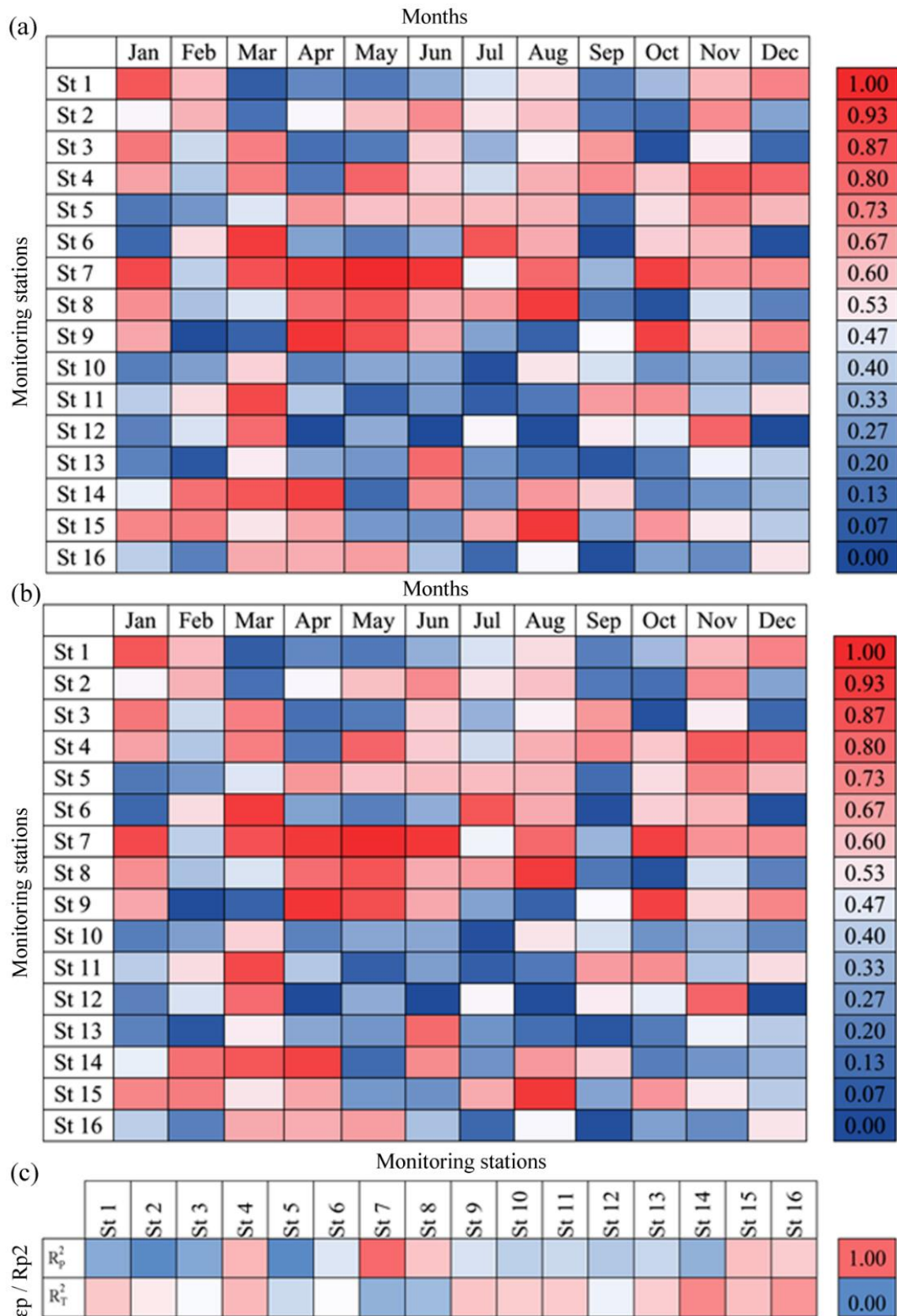
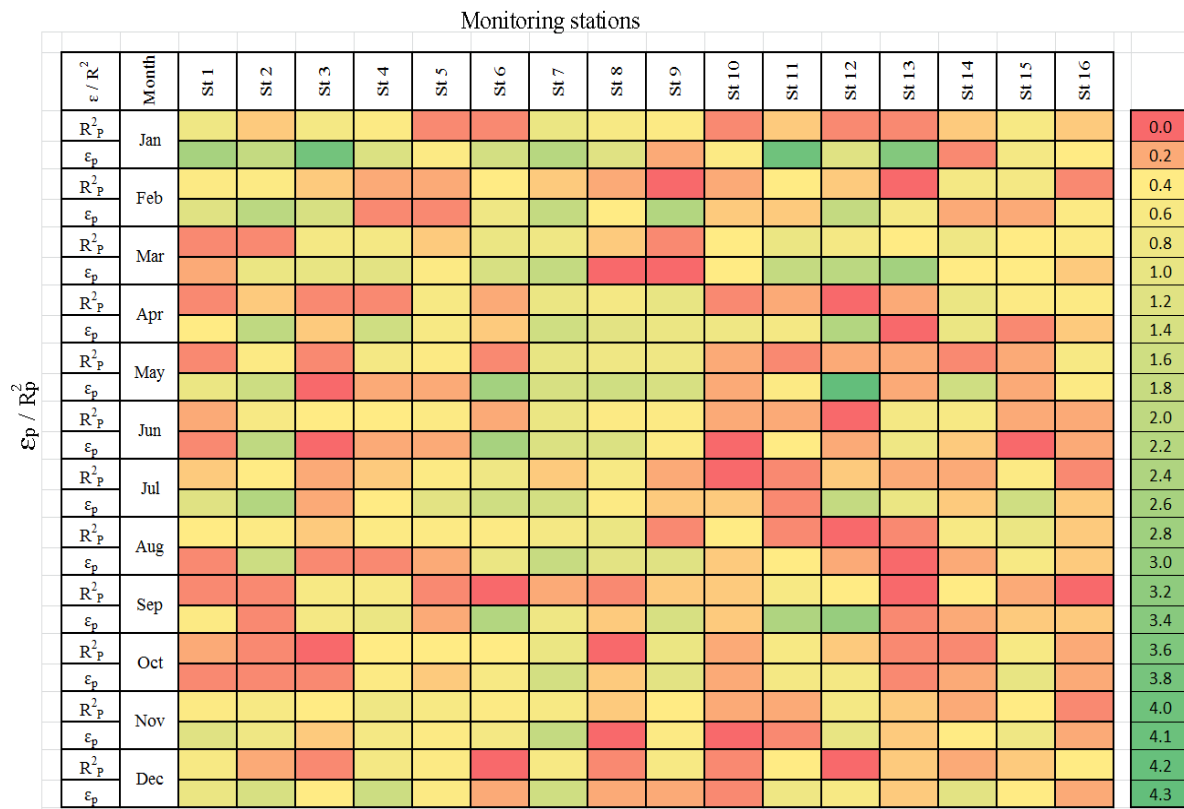


Figure 4. a) Precipitation-streamflow; b) Temperature-streamflow; c) Temporal correlogram, and spatial correlogram for the KP Province

**Table 2. The coefficient of determinations, precipitation, and temperature elasticity of streamflow for the KP Province**

Monitoring sites	$R^2_P$	$\varepsilon_p$	$R^2_T$	$\varepsilon_T$
St 1	0.2	1.0	0.6	0.5
St 2	0.1	2.1	0.5	0.6
St 3	0.2	1.3	0.4	1.7
St 4	0.6	1.2	0.6	1.2
St 5	0.1	0.4	0.3	0.3
St 6	0.3	1.5	0.4	1.4
St 7	0.9	2.0	0.2	1.3
St 8	0.6	0.5	0.2	0.1
St 9	0.3	1.9	0.6	0.8
St 10	0.3	0.4	0.6	0.8
St 11	0.3	1.5	0.6	1.7
St 12	0.3	1.3	0.4	1.5
St 13	0.3	1.1	0.6	1.3
St 14	0.2	0.4	0.8	1.7
St 15	0.6	1.5	0.6	1.2
St 16	0.6	1.3	0.7	1.8

Temporal precipitation and temperature elasticity results are given in Figures 5 and 6. Coefficient of determination support precipitation elasticity values throughout the year except for February. Majority precipitation elasticity results are reinforced by the coefficients of determination during the months of January, March, May, and October. The aforementioned month's results are more appropriate owing to the strong precipitation-streamflow linkage. On the other hand, the coefficient of determination and temperature elasticity results were found parallel throughout the year.

**Figure 5. Temporal precipitation elasticity of streamflow and coefficient of determinations of KP Rivers**



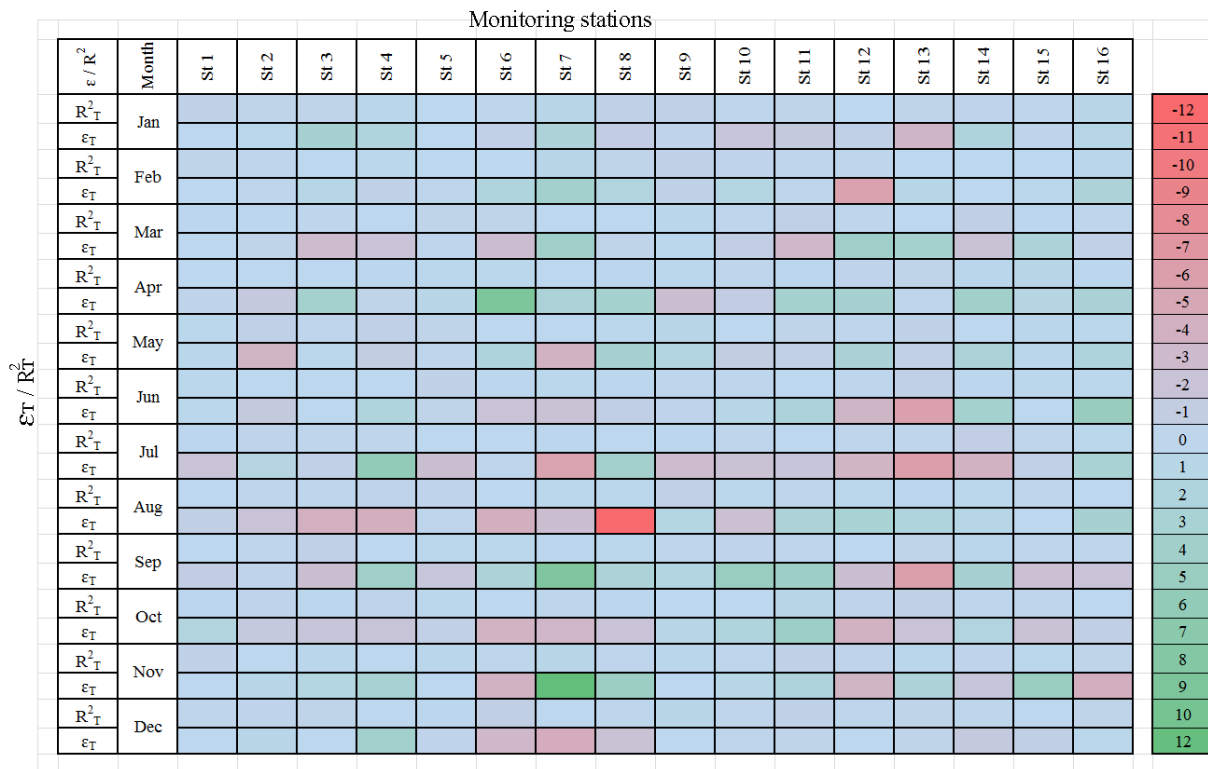
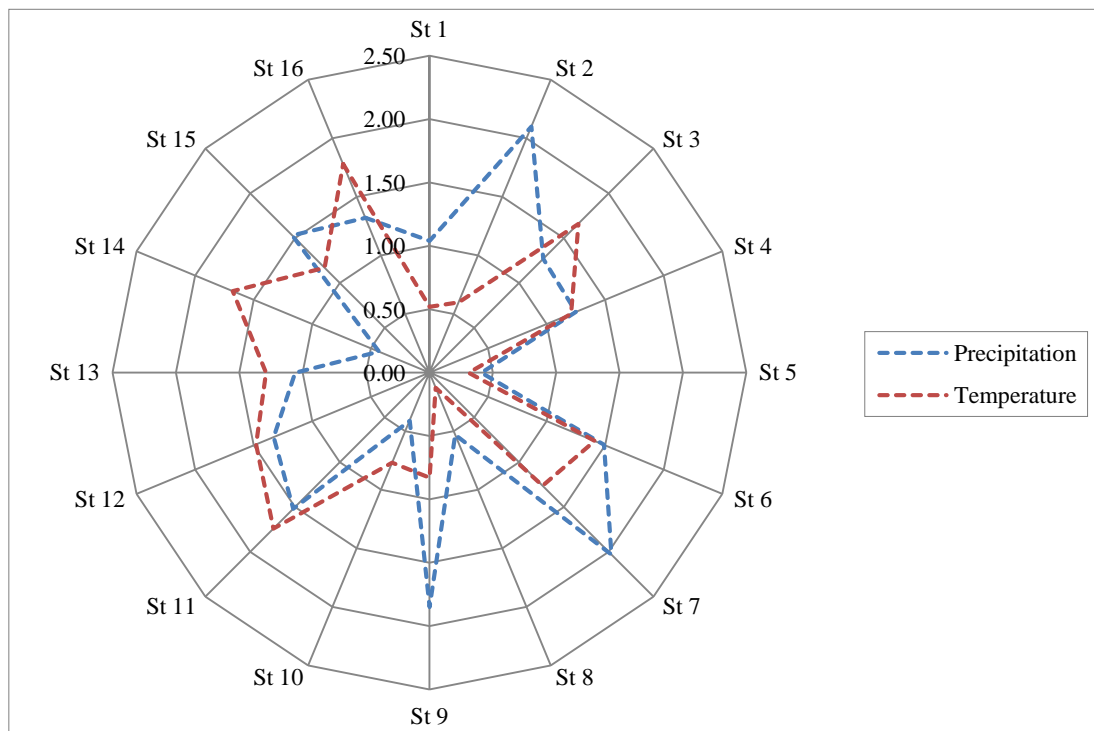
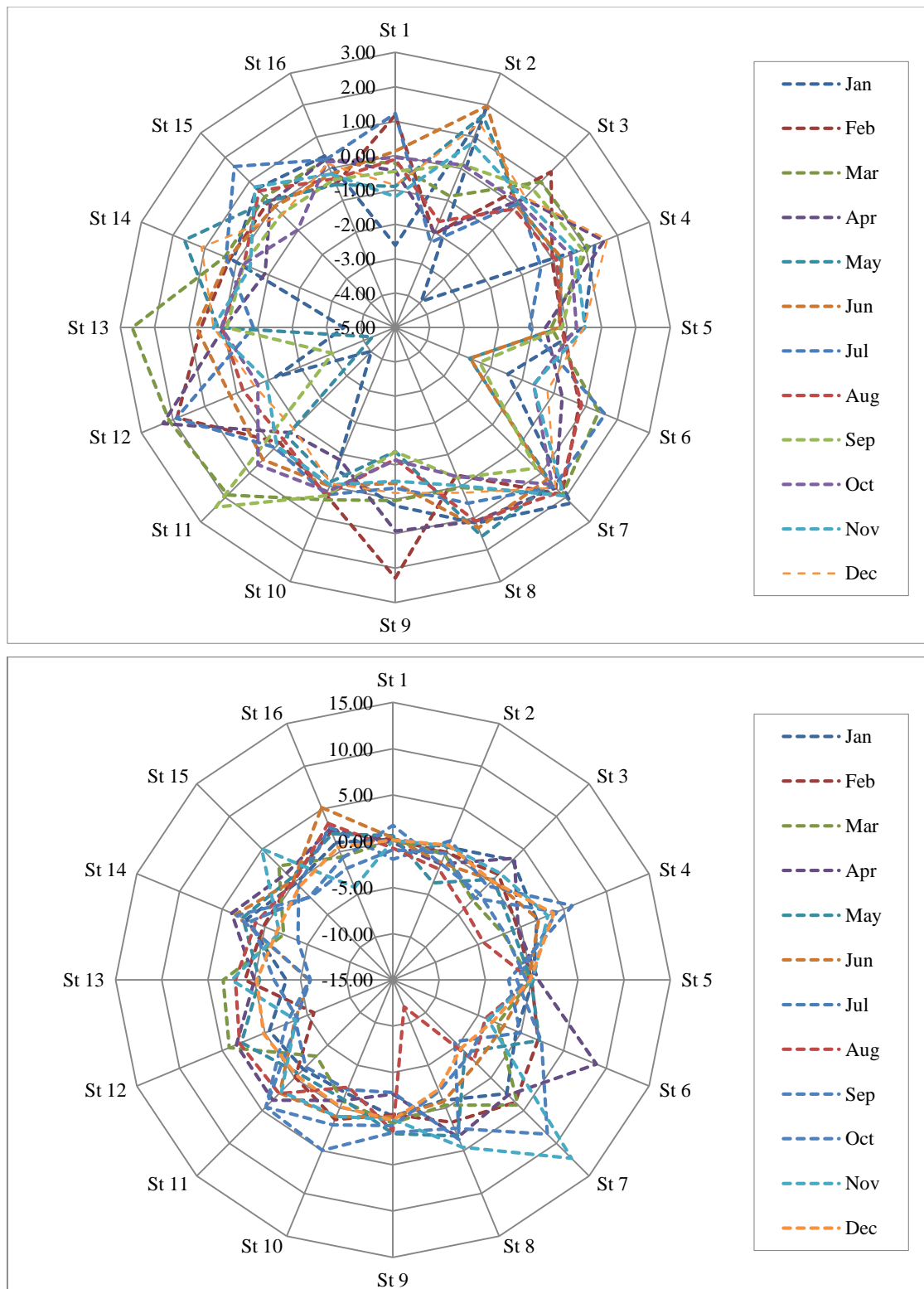


Figure 6. Temporal temperature elasticity of streamflow and coefficient of determinations of KP Rivers

#### 4.4. Spatial Behavior of Precipitation and Temperature Elasticity

Precipitation and temperature elasticity values range between 0.41 and 2, and 0.2 and 1.8 respectively at all hydrological monitoring sites as demonstrated by Figure 7. The precipitation elasticity results demonstrate that a 1% increase in precipitation can cause a maximum 2% increase in streamflow while a 1% increase in air temperature can cause a maximum 1.2% increase in streamflow. Results of the current study are supported by Chiew et al., (2006) research work where precipitation elasticity falls in the range of (0.5-2.5) for Warm Arid (BWh) Koppen climate class [37]. The results also show that the sensitivity of streamflow to precipitation is higher as compared to air temperature. The results also depicted that both precipitation and air temperature contribute to streamflow. Precipitation and air temperature fuels streamflow via surface runoff and glaciers melting in the understudy rivers [33-36].





**Figure 7. Spatial behavior of temperature and precipitation elasticity; Temporal behavior of precipitation elasticity; Temporal behavior of temperature elasticity**

#### 4.5. Temporal Behavior of Precipitation and Temperature Elasticity

Precipitation and temperature elasticity values range between -5 and 2, and -15 and 15 respectively at all hydrological monitoring sites as demonstrated by Figure 7. The precipitation elasticity results demonstrated that a 1% increase in precipitation can cause a maximum 5% increase in streamflow while a 1% increase in air temperature can cause a maximum 15% increase in streamflow. The results of precipitation elasticity are reasonable while results of temperature elasticity are not practically possible.

## 5. Conclusion

The current research work presents the estimates of precipitation and temperature elasticity of streamflow in 6 major rivers of KP Province across Pakistan, using a nonparametric estimator of elasticity. Spatially Precipitation and temperature elasticity values range between 0.41 and 2, and 0.2 and 1.8 respectively. 1% change in precipitation and temperature produce 2 and 1.8% change in streamflow, respectively. On the other hand, temporally precipitation and temperature elasticity values range between -5 and 2, and -15 and 15 respectively. The precipitation elasticity results demonstrated that a 1% increase in precipitation can cause a maximum 5% increase in streamflow while a 1% increase in air temperature can cause a maximum 15% increase in streamflow. The results of precipitation elasticity are reasonable while results of temperature elasticity are not practically possible. This research work seeks to improve our ability to quantify the impacts of precipitation and temperature on streamflow. The results of the current study indicate that precipitation elasticity is more reliable, consistent and precise in comparison to temperature elasticity. The response of streamflow to precipitation is lower as compared to air temperature. Precipitation elasticity results are valid due to higher central affinity (low range and standard deviation) of its corresponding estimators. A more reliable elasticity value estimate is produced by inducing a time series with the strongest relationship of precipitation-streamflow and temperature-streamflow. Spatial precipitation and temperature elasticity results are reasonable as compared to temporal precipitation and temperature elasticity results. The results of the current study can be utilized in formulating water management strategies in KP Province in term of streamflow response to climate change. The sensitivity of streamflow to precipitation and air temperature can be modulated using best management practices and nature-based solutions.

## 6. Declarations

### 6.1. Author Contributions

L.A.S. analyzed the data under the supervision of A.U.K. and F.A.K. and A.R. helped in data collection and results interpretation. S.U.R., M.J.I., I.A., A.A. and Z.K. writing—review and editing. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 6.4. Acknowledgements

Authors are thankful to the Hydrology Department, Peshawar, Pakistan, and the staff of the Irrigation Division Peshawar for their assistance in organizing the necessary information and data which truly helped in the fulfillment of this study.

### 6.5. Conflicts of Interest

The authors declare no conflict of interest.

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