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Research Paper

Trend analysis of hydrometeorological parameters and reservoir level of Tarbela reservoir, Pakistan

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ABSTRACT

This study identified the trends in monthly temperature, precipitation, and evaporation for Astore, Darosh, Gilgit, Gupis and Skardu and trends in inflow, outflow and reservoir level for Tarbela reservoir. Two non-parametric tests i.e. Man-Kendall and Sen's Slope and Innovative Trend Analysis (ITA) were used to determine the trend. The first Mann-Kendall test with a significance level 5% was applied to 33-year data of five selected areas from 1990-2022. The results showed an increasing trend in temperature in March for all selected areas. No significant trend was observed in precipitation except negative trends for Darosh in March, May and December and positive trend for Gilgit in January and September. It has been observed that the trend direction given by ITA and Mann-Kendall is similar. Inflows to reservoir were found directly related to the temperature because of glacier melt in rising temperature, thus increasing the inflow, although the precipitation was found decreasing with increase in temperature. Altered snowmelt patterns can influence weather systems, potentially contributing to more extreme weather events.

Keywords: Global warming, Mann-Kendall test, Sen's Slope Test, Innovative Trend Analysis, Snowmelt

A dam is any structure built to store water for later release or increasing water's surface elevation. The stored body of water is called reservoir. Reservoir level forecasting is a crucial aspect of water resource management, particularly in areas with reservoirs used for various purposes, such as hydroelectric power generation, irrigation, and water supply (Allawi *et al.,* 2019). Because of complex engineering conditions and natural environment are intertwined in the reservoir's operations and functions, reservoir release decisions are affected by many hydrological factors, such as the reservoir storage and inflow. In recent years, climate change and hydrological intensification have resulted in more frequent and intensive natural hazards, such as heavy rainfall, severe flooding, and extreme heat (Bolan *et al.,* 2024). Large-scale reservoirs play an essential role in water resource management for agricultural irrigation, water supply, and flood control. However, there is a need of robust reservoir operation system under both normal flow and extreme flow conditions (Yang *et al.,* 2019). Assessing trends of hydrologic variables related to both hydrologic processes facilitates accurate water resources forecasting, especially in arid and semiarid regions with high evaporation and low rainfall volume (Forootan, 2019). An important condition changing in the whole world is the climate condition. Today, all creatures on the Earth are under the threat of global warming and climate change, because excessive and unplanned use of the resources have led to global warming, and this, in return, has led to climate change. Depending on climate change, the temperature has increased throughout the world and precipitation regimes have changed greatly (Trenberth, 2011). Drought is a prolonged period of dry conditions that can occur globally as part of the natural climatic cycle. This slow-onset catastrophe is marked by a lack of precipitation, leading to a deficit in water availability (Singh *et al.,* 2021). The water security of Pakistan is likely to be impacted due to changes in the temporal and spatial distribution of water (Ahmad *et al.,* 2023). The erratic and uncertain pattern of water availability is likely to impact crop yields due to changes in the dynamics of the hydrological cycle (Kang *et al.,* 2009). Reservoir release decisions are influenced by a variety of factors, categorized into static, decision-related, and dynamic elements. Static factors, like reservoir functionalities, remain constant (Geressu and Harou,

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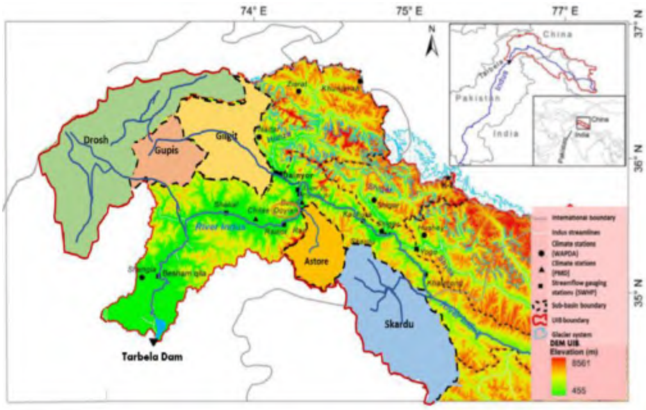

Fig. 1: Hydrometeorological stations of Tarbela reservoir

Table 1: Details of climatic station for Tarbela reservoir

ID	Stations	Lat (°N)	Long (°E)	Elevation (m.a.s.l.)
1	Gilgit	35.91	74.33	1460
2	Skardu	35.30	75.68	2210
3	Gupis	36.01	73.40	2156
4	Darosh	35.56	71.78	1465
5	Astore	35.33	74.90	2394

2019). Decision-related factors, such as upstream operations, involve choices made during decision-making processes. Dynamic factors, including inflow, storage, and meteorological forcing, vary over time and are observed through time series data. The complex interplay of these factors guides the decision-making process for reservoir releases (Meydani *et al.,* 2022). From the viewpoints of socioeconomic development and climate change, long-term trend analysis is crucial as changes in the rainfall patterns and temperature variation both seasonally and annually may have a massive impact on the quantitative water available in a reservoir (Asfaw *et al.,* 2018). Daily rainfall data from 1971 to 2011 and temperature data during the period of 1971-2007 were analyzed. Sen's Slope Estimator and Mann-Kendall Test were implemented for monthly variability concerning the magnitude of the trend. Variations occur in the months, but there is no overall change with statistical significance (Yadav *et al.,* 2014). So, it is essential to examine the temporal variations in temperature, precipitation, evaporation in the catchment area of reservoir and also inflow & outflow to & from reservoir. The aim of the study was to evaluate the long-term historical (1990-2022) temporal trends in mean monthly temperature, precipitation, and evaporation in the catchment area of the reservoir and also variation in Inflow & outflow from reservoir, and finally the impact of all these selected parameters on the reservoir level was assessed. For this study trend analysis were carried out using three non-parametric tests Mann-Kendell, Sen's Slope test, and Innovative Trend Analysis (ITA). These methods demonstrated these parameters monthly & seasonal increasing and decreasing patterns. Trend analysis of climate variables such as inflow, outflow, precipitation, temperature and evaporation provided useful information for understanding the hydrological changes associated with reservoir level. The study will be a considerable addition to the knowledge of related areas. It will help the policy maker in the water resource management of the region considering the impact of hydrometeorological parameters on reservoir level.

MATERIALS AND METHODS

Study area and data

The Tarbela Reservoir, situated in the Upper Indus River basin (UIB), stands as a monumental tribute to water resource management in Pakistan, located in the Haripur District of Khyber Pakhtunkhwa province (Rafique *et al.,* 2020). The dam was completed in the early 1970s and has since played a pivotal role in mitigating water scarcity, supporting agriculture, and generating hydroelectric power for the region. As the region grapples with evolving environmental and climate patterns, understanding the complexities of the Tarbela Reservoir becomes essential for sustainable water resource management and ensuring the well-being of communities dependent on its waters.

Hydrometeorological station distribution network for Tarbela Reservoir which was established by WAPDA Pakistan is shown in the Fig.1 and area of study taken for this research is shown with solid colors. i.e. Astore, Darosh, Gilgit, Gupis & Skardu. Mean monthly data (1990-2022) of precipitation and temperature have been collected from the Pakistan Meteorological Department (PMD). Mean monthly (1990-2022) inflow, outflow and Reservoir levels data have been collected form Water and Power Development Authority (WAPDA) Pakistan. Details of meteorological station for Tarbela Reservoir are given in Table 1.

Mann-Kendall trend test

The Mann-Kendall (MK) test is a statistical test commonly employed for detecting trends in hydro meteorological data (Sudarsan and Lasitha, 2023). The test involves the calculation of the S statistic and the sign function based on the following equations:

$$S = Sgn\sum_{k=1}^{n-1}\sum_{m=k+1}^{n}(x_m - x_k) \quad (1)$$

where x_k indicates the time series; k is the rank of the time series from 1 up to n, and x_m represents the ranking of data points in a series of m = k + 1, k + 2, k +3, … n

x_k are the data points treated as a reference and then compared with the rest of the data points x_m to fulfil the following condition

$$Sgn(x_m - x_k) = \begin{cases} +1 & if\ x_m - x_k > 0 \quad increasing\ trend \\ 0 & if\ x_m - x_k = 0 \quad no\ trend \\ -1 & if\ x_m - x_k < 0 \quad decreasing\ trend \end{cases} \quad (2)$$

After computing the S statistic, the variance of S and the Z test statistic are determined using the following equations:

The variance is given as

$$Var(s) = \frac{m(m-1)(2m+5) - \sum_{k=1}^{m} T_k(T_k - 1)(2T_k + 5)}{18} \quad (3)$$

T_k is known as the number of ties up to sample k and the test statistics Z_s may be expressed as:

$$Z_s = \begin{cases} \frac{S-1}{\sqrt{Var(s)}} & for\ S > 0 \\ \frac{S+1}{\sqrt{Var(s)}} & for\ S < 0 \end{cases} \quad (4)$$

For current study the Significance Level is taken 5% for Mann-Kendall test, if the value of the Z test statistic is greater than a critical value (1.96), the null hypothesis is rejected, suggesting the presence of a positive trend and if in the time series Z test statistic is lower than a critical value (-1.96) showing the negative trend.

Null Hypothesis (**H_0**): No trend exists in the time series

Sen's Slope estimation test

The Sen's slope estimator, introduced by Sen (1968), is a method used to assess the extent of a trend in time series data. This technique is particularly useful for calculating the slope of the trend without assuming any specific distribution for the data (Aswad *et al.,* 2020).

The expression used to find the slope (T_c) for the data pairs in Sen's method is given by:

$$T_c = \frac{x_r - x_p}{r - p} \quad for\ c = 1,2,3, \ldots .n \quad (5)$$

where x_r and x_p are the data values at points of time, r and p (r > p) are taken equally.

Using these n values of Tc, Sen's estimator of the slope is determined as follows

Take the median of all the values will give the slope.

Innovative trend analysis (ITA)

ITA was proposed by Şen (2012). The series of data of a hydrological variable is arranged in order from the starting date of observations to the ending date. Next, the series is divided into two equal parts, each arranged from low to high values. The first part of the series of data, Y_1, is plotted by the X-axis, and the second part, Y_2, is plotted by the Y-axis (Ali *et al.,* 2019). In the ITA method, the trends indicator, D, is obtained as a difference between values Y_2 and Y_1 for a point, showing the distance towards the 1:1 line. The formula to compute D is the following:

$$\boldsymbol{D = \frac{2 * (\overline{y_1} - \overline{y_2})}{n}} \quad (5)$$

$\overline{y_1}$ is the average of the 1st part

$\overline{y_2}$ is the average of the 2nd part

n is the total number of data points

RESULTS AND DISCUSSION

Precipitation, temperature and reservoir inflow

The mean monthly precipitation, temperature and reservoir inflow of Tarbela Reservoir are presented in Fig. 2. It is seen that an increase in temperature increases the inflow into the reservoir. The maximum inflow was observed in the summer season with low precipitation (Fig. 2). It's because glaciers are melting due to increasing temperatures. Many researches showed that water in river comes from Glaciers melting in the Hindukush-Karakoram-Himalayas (HKH). Similarly, 80% of the water come to Upper Indus Basin (UIB) from snow and glaciers melting.

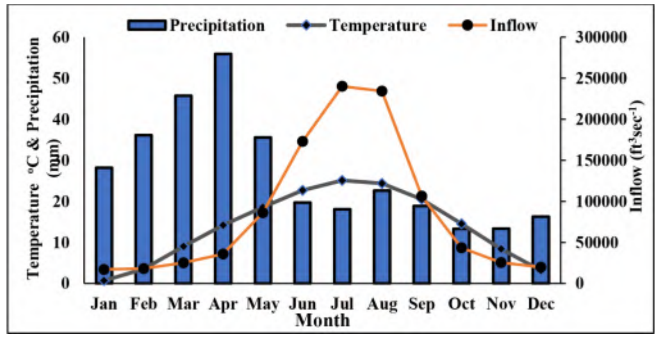

Fig. 2: Relation between temperature, precipitation and reservoir inflow

Mann-Kendall trend test

From Fig. 3(a), it has been concluded that the temperature of each selected region was increasing in March. If we look at trends, most of the values of Z_s are greater than zero, representing the increasing temperature pattern and longer summer and shorter winter in the Upper Indus Basin. The temperatures in Darosh and Skardu are going to decrease in September. But overall, the temperature has an increasing trend. The precipitation (Fig. 3b) has no specific trend, but if we look at the trend direction, it somehow has a reverse relation with temperature. As temperature in March has the increasing direction but the precipitation has the decreasing direction. If we look at Darosh and Skardu, which have a decreasing trend in September, here the precipitation is increasing. If we look at the Fig. 3(b), most of the values are negative, representing the drought condition in the near future for the Upper Indus Basin. A drought is a spell of abnormally dry weather that begins with a drop in precipitation and has adverse effects on agriculture, the hydrological balance, and the water budget (Alkan, 2024). The overall trend is decreasing. From Fig. 3(c), it has been concluded that inflow is going to increase from March to June, with increasing inflow in August representing glacier melting and a very high trend in October and the lowest in September. The reservoir level was observed increasing from January to April and then decreasing towards August. Outflow from the reservoir was increasing from February to June and then decreasing towards October. The precipitation in spring was decreasing while increasing in the summer and autumn seasons, and the temperature was increasing in spring and decreasing in summer and autumn. From seasonal trends, it is also clear that in the Upper Indus Basin, precipitation and temperature have a reverse relationship. Also, maximum inflow, outflow, and reservoir level were observed in the spring season as compared to other seasons.

Sen's Slope estimator test

From Fig. 4(a) it has been concluded that change in temperature was observed using Sens slope estimation test.

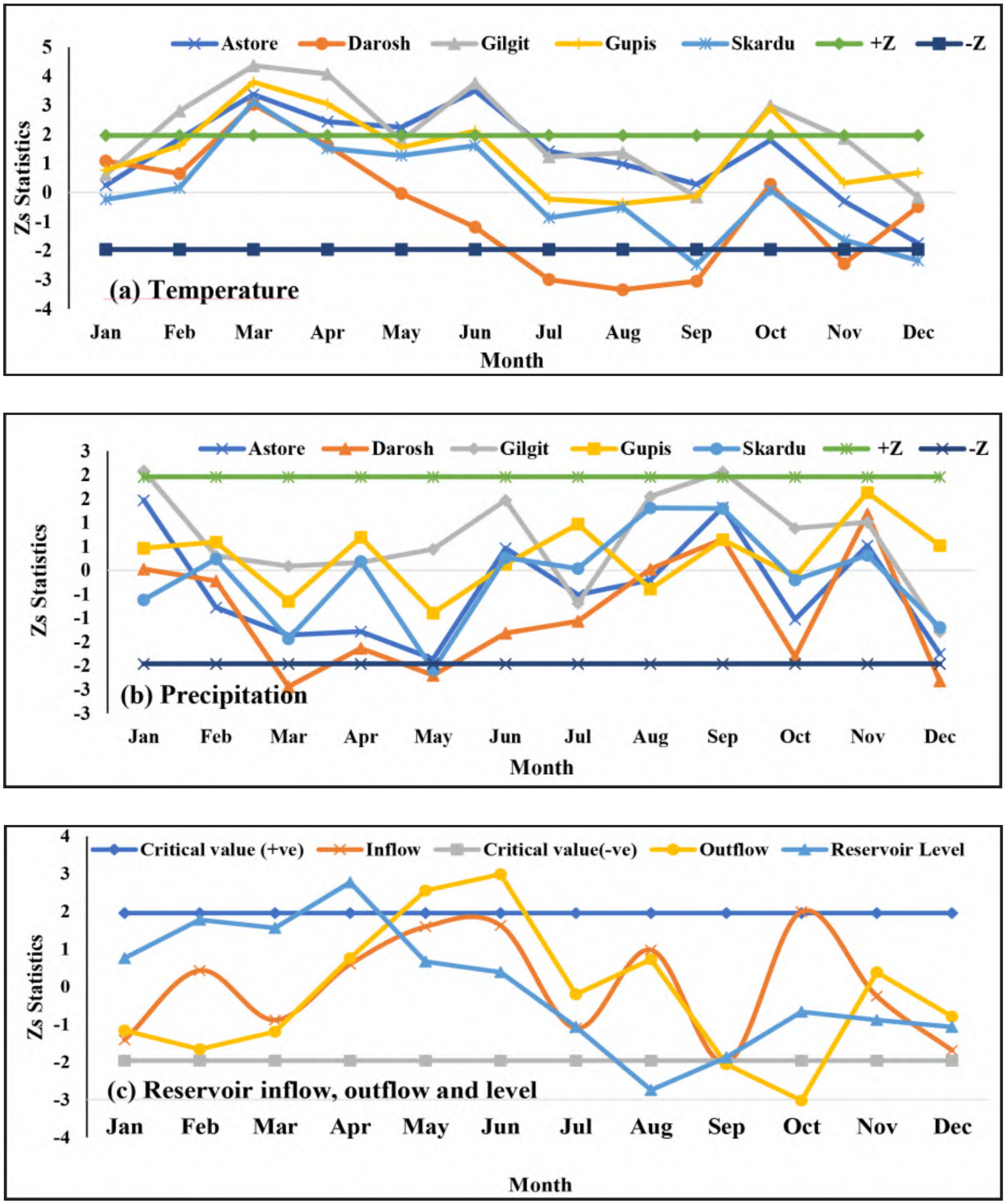

Fig. 3: M-K trend analysis of (a) Temperature (b) Precipitation (c) Inflow, outflow and reservoir level

Maximum magnitude in Gupis was 0.122 ^{o}C in March and lowest magnitude was -0.88 ^{o}C in August for Darosh. From Fig. 4(b) it has been concluded that change in precipitation was observed. Maximum magnitude was 0.38 mm in November and lowest was -2.02 mm in March for Darosh. From Fig. 4(c) it has been concluded that maximum magnitude in inflow was observed in June (1189 ft^{3}sec^{-1}) and minimum magnitude was in July (-967 ft^{3}sec^{-1}). For outflow, the maximum magnitude was in June (1940 ft^{3}sec^{-1}) and minimum was in October (-463 ft^{3}sec^{-1}) and for reservoir level, the maximum magnitude was in April (2.357 ft) and minimum was in December (-0.618ft).

Innovative trend analysis (ITA)

From Fig. 5(a) it has been concluded that change in temperature was observed using innovative trend analysis (ITA). The maximum magnitude in Gupis was 0.14 ^{o}C in March and lowest magnitude was -0.1 ^{o}C in September for Darosh. From Fig. 5(b) it has been concluded that change in precipitation was observed. The

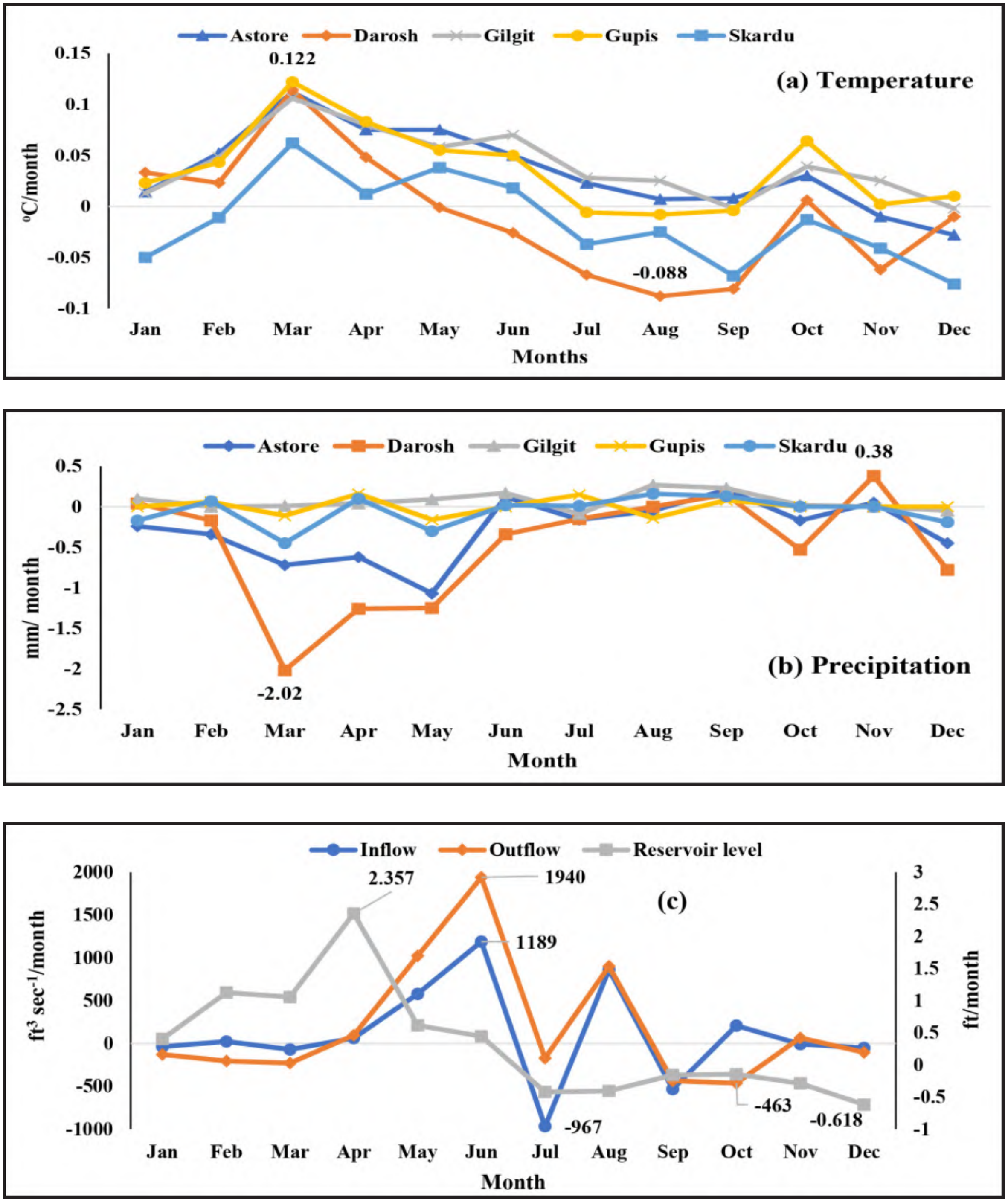

Fig. 4: Sen's Slope trends for (a) Temperature (b) Precipitation (c) Inflow, outflow and reservoir level

maximum magnitude was 0.34 mm in November and lowest was -2.97 mm in March for Darosh. From Fig. 5(c) it has been concluded that maximum magnitude in inflow was observed in July (1155 ft^3sec^{-1}) and minimum magnitude was in August (-1901 ft^3 sec^{-1}). For outflow, the maximum magnitude was in August (1431 ft^3sec^{-1}) and minimum was in October (-364 ft^3sec^{-1}) and for reservoir level, the maximum magnitude was in April (1.44 ft) and minimum was in August (-0.11ft).

CONCLUSION

The results revealed that for temperature, most of the values in the Mann-Kendall test were positive, representing a longer summer and a shorter winter in the near future. For precipitation, most of the values in the Mann-Kendall test were negative, representing the drought condition in the near future. The temperature in March was increasing while precipitation was decreasing. Overall, the temperature of UIB was increasing and

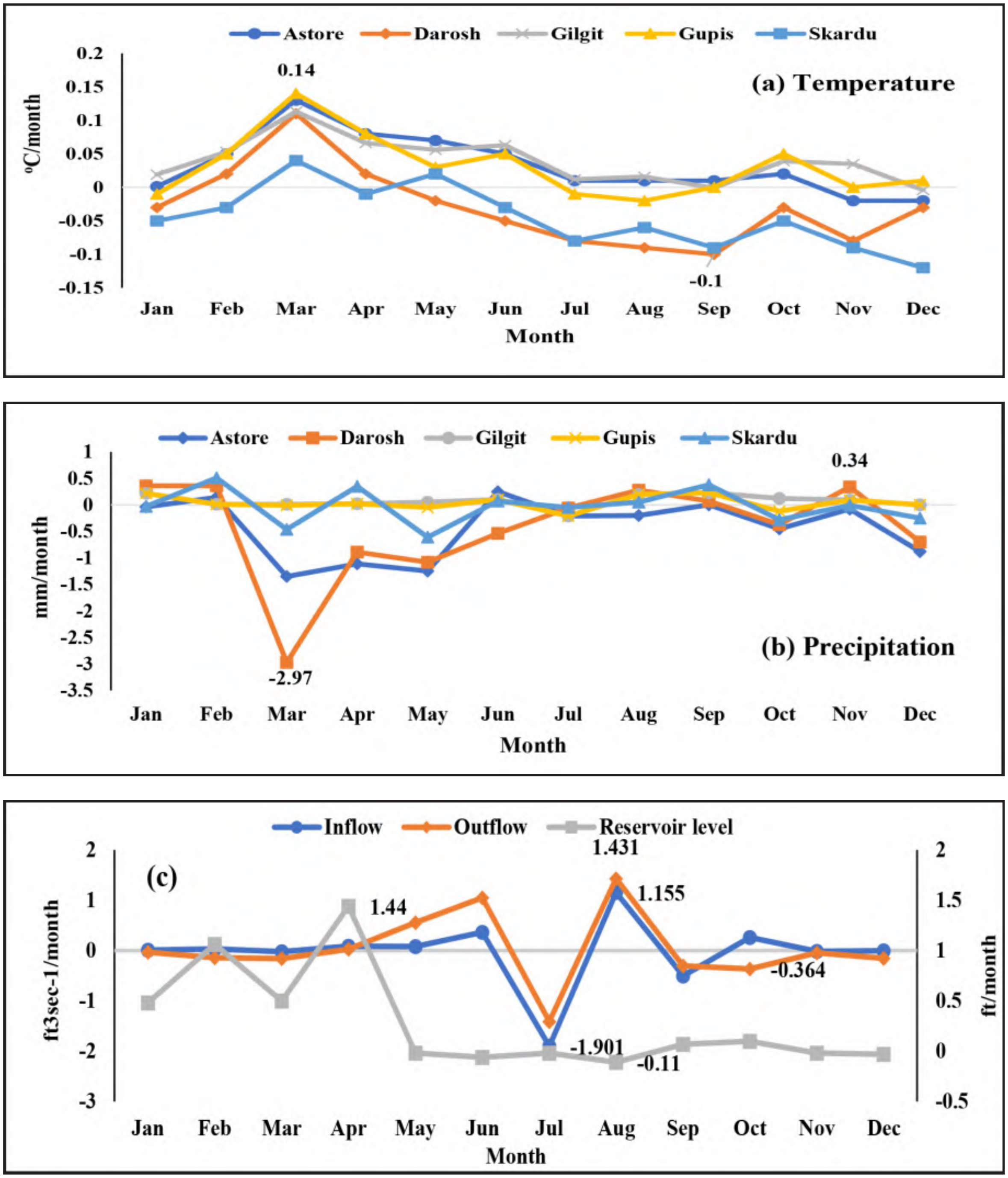

Fig. 5: Innovative trend analysis of (a) Temperature (b) Precipitation (c) Inflow, outflow and reservoir level

precipitation was decreasing. Temperature and inflow follow the same pattern because of glacier melting. Increasing temperatures and reservoir levels and decreasing precipitation were observed for the spring season.

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Author contributions: **A. A. Khan:** Methodology & Conceptualization. **A. Rauf:** Methodology and analytical

framework. **A. Noreen**: Data preparation, Tables and figures. **S.Jan, U.Khan & H.A. Jan:** Paper writing & drafting.

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