RAINFALL TREND ANALYSIS AND RELATIONSHIP WITH FLUVIAL DISCHARGE AND SUSPENDED SEDIMENT TRANSPORT IN KALI GANDAKI RIVER BASIN, HIMALAYA, NEPAL

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ABSTRACT

The complex process of weathering, land sliding, glacial and fluvial erosion yields the sediment from a catchment which depends on the catchment area, topography, slope of catchment, amount of rainfall, temperature and soil characteristics. Stream flow with suspended sediment (SS) transport rate variation is one of the most remarkable effects of rainfall changing patterns in Himalayas, Nepal. This study analyzed relationship between specific discharge and rainfall together with SS transport from Kali Gandaki (KG) River basin area of 7060 km^2 at hydropower reservoir. Mann-Kendall trend (MKT) test along with Sen's slope for 20 homogenized meteorological stations situated between the elevations ranges 700 to 2744 m MSL were used to evaluate monthly, seasonal and annual time series rainfall data over the period 1957-2017. Among 20 homogenized stations, MKT statistics showed that the rainfall in 9 stations exhibited increasing and remaining 11 stations showed decreasing trends. Statistically, four stations showed decreasing trend during winter (December-February), three stations showed increasing trend during pre-monsoon (March-May), one station showed decreasing and one station showed increasing trend during monsoon (June-September) and only one station showed significantly decreasing trend in 95% confidence interval during post monsoon (October-November). The increasing trend of rainfall during monsoon increased the discharge of KG River which transported an average of 40.90±12.45 Megatons (Mt) of suspended sediment annually in to hill-side reservoir dam.

Keywords: Suspended sediment, Himalayas, Kali Gandaki River basin, Mann- Kendall trend test

1. INTRODUCTION

The sediment yield from a catchment depends on the catchment area, topography, slope of catchment, amount of rainfall, temperature and soil characteristics. Climate change is a remarkable global issue from past few decades, had a significant impact on higher mountains in the form of extreme weather conditions such as rising temperature, changing of precipitation patterns, decrease of snowfall and decreasing the glaciers numbers. An alteration in regional hydrological cycles and changes in river flow such as flood or low flow are the significant potential consequences of climate change (Zhang et al., 2008). The global monsoon precipitation trend had a tendency to increase from 1901 to 1955 and decreasing trend since the 1950s up to

2001 (Zhang and Zhou, 2011). Studies between 1951−1999 (Min et al., 2009) and between 1900–2009 (Westra et al., 2013) showed about two-thirds of rainfall stations globally exhibited increasing trends.

Climate change is threatening Nepal's as well as worldwide food security, water resources, human habitats and tourism sectors seriously (Karki et al., 2009; Langat et al., 2017). The Himalaya regions are more vulnerable, changing of altitudes within a short distance and extreme weather events are associated with heavy rainfall which are principal drivers of landslides, debris flows and flood disasters, resulting casualties and loss of properties (Talchabhadel et al., 2018). The increasing temperature and shifting of rainfall patterns affected the livelihoods of people in the KG basin (Dandekhya et al., 2017) where springs are a major source of water and depend on annual rainfall to recharge the aquifers that fed them (Andermann et al., 2012). The availability of water in KG basin is of major importance for hydropower as well as the small farmer managed irrigation scheme along the river and water transportation on hydropower reservoir. Because of less data availability and limited numbers of meteorological stations in Himalayan region, Nepal, only few researches of climate change and its impacts were conducted (Shrestha et al., 2019). The effects of climate changes in Nepal have been documented by different researchers in context of temperature and precipitation scenario (Duncan et al., 2013; Karki et al., 2017; Shrestha et al., 2017).

The main drivers of streamflow trends are climatic variability and changes, and the streamflow trend identification in a catchment is important for understanding the impact of climatic variability and changes in the region (Gautam and Acharya, 2012). The suspended sediment transport rate varied with streamflow, which is one of the noticeable effects of rainfall change patterns in Himalayas mountain catchment of KG River. It is paramount importance to conduct this study in KG River catchment at hydropower station, as this river originates from Himalayas and there are only limited studies about rainfall trend analysis and relationship with fluvial discharge and sediment discharge into the hydropower reservoir, which could be valuable in hydropower reservoir management.

2. MATERIALS AND METHOD

2.1 Study site description

The KG River is a glacier-fed river which flows from north, higher Himalayan region to south in the Terai plains of Nepal and ultimately merge with the Ganges River in India. The catchment has 7060 Km^2 area having complex geomorphology with rapid changes in elevations. The catchment area consists of elevation less than 2000 m MSL with no snow cover (19% coverage area), 2000 ~ 4700 m MSL with seasonal snow (48% coverage area), 4700 ~ 5200 m MSL with completely snow except 1 or 2 month (10% coverage area) and elevation greater than 5200 m MSL with permanent snow (23% coverage area). Figure 1(a) shows the catchment coverage area (Baniya et al., 2019) showing river networks with locations of meteorological stations created in ArGIS10.3.1(ERSI Inc., USA) software. The bed elevation of river within 210 km, decreases from 5039 m MSL in higher Himalaya to 529 m MSL at Setibeni, which is 5 km upstream from hydropower dam (Figure 1b). A wide variation in average rainfall ranging minimum 270 mm/year in Tibetan Plateau and maximum 5376 mm/year in the monsoon-dominated Himalayas.

2.2 Data collection and acquisition

Department of Hydrology and Meteorology (DHM), Nepal sets different hydrometric stations (www.dhm.gov.np) and the station no. 410 (~5 km upstream from dam) was operated up to 1995 and now it is not operated after dam construction. The bed level of dam was increasing yearly due to trapping of bedload as well as suspended sediment load by dam, which curtail sediment load in to the downstream (Asaeda et al., 2011). The sedimentation in the hydropower reservoir lowers the reservoir capacity of dam annually. Monthly rainfall time series data from 1957 to 2017 (available maximum duration) were obtained by summing the daily rainfall data measured in the 20 homogenized rainfall stations installed by DHM.

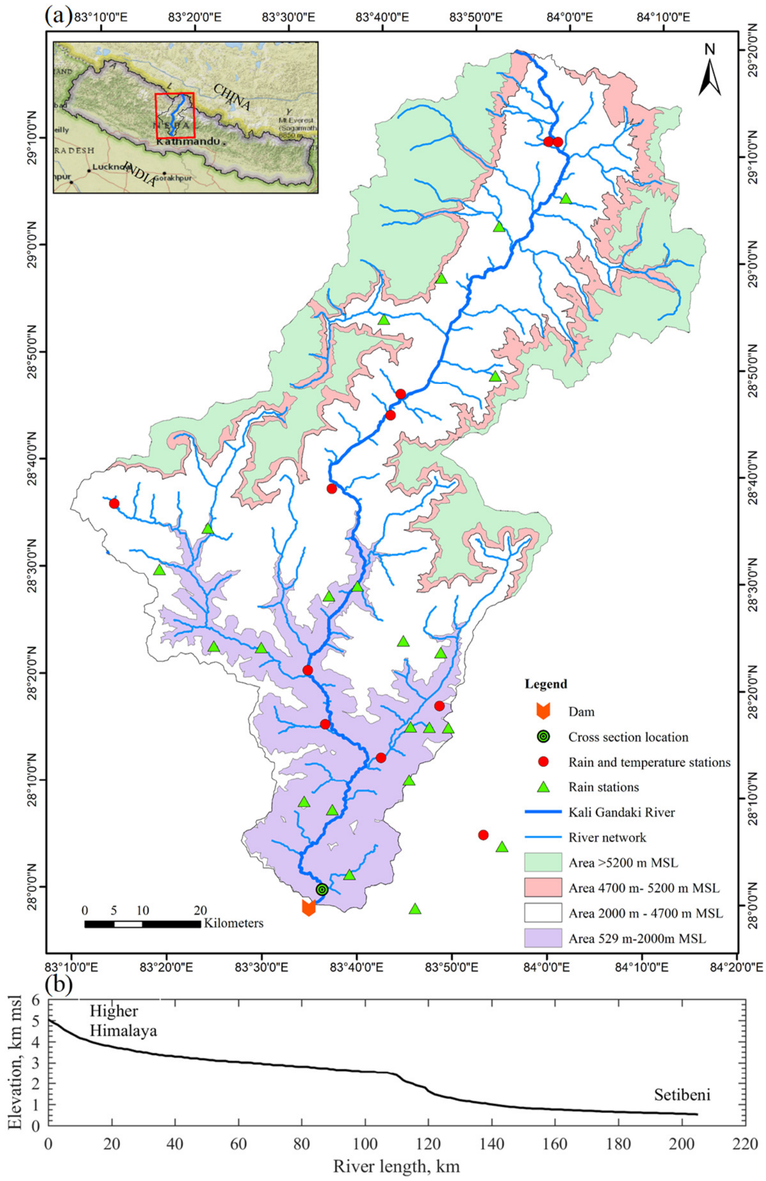

Figure 1. (a) Catchment area of KG River (b) Longitudinal profile of KG River.

2.3 Rainfall trend analysis

The monotonic trend of rainfall time series was performed using the Mann- Kendall trend (MKT) test (Mann, 1945). The MKT test assumes of uncorrelated data. Before assessing MKT test, lag1 autocorrelation for all the time series were checked using autocorrelation function (ACF) in Matlab R2016a software. If any serial correlation exists, the Modified Mann- Kendall (MMK) test should be applied (Hamed and Rao, 1998; Bari et al., 2016). However, there were no times series was significantly serially correlated in 95% confidence limit.

The Mann- Kendall statistics S is given by (Sonali and Kumar, 2013; Bari et al., 2016)

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{1}$$

where "sgn" is the sign function, and n is the number of observations in the data sets.

$$sgn(x) = \begin{cases} 1 \; if \; x > 0 \\ 0 \; if \; x = 0 \\ -1 \; if \; x < 0 \end{cases} \tag{2}$$

where x_j are the sequential data values, n is the length of the data set.

The variance σ^2 is

$$\sigma^2 = \left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j \left(t_j - 1\right)\left(2t_j + 5\right) \right\} / 18 \tag{3}$$

where p is the number of the tied groups in the data set and t_j is the number of data points in the j^{th} tied groups. The statistic S is approximately normal distributed provided that the following Z- transformation is employed.

$$Z = \begin{cases} \frac{S-1}{\sigma} \; if \; S > 0 \\ 0 \; if \; S = 0 \\ \frac{S+1}{\sigma} \; if \; S < 0 \end{cases} \quad (4)$$

The significance level of α =0.05 was used in this study. A positive value of Z indicates an increasing trend, whereas negative indicates decreasing trend. If the computed value of |Z|>Zα/2, the null hypothesis is rejected at the α level of significance in a two- sided test.

3. RESULTS AND DISCUSSION

3.1 Monthly, seasonal and annual trend analysis

The MKT test was applied in order to study monthly, seasonal and annual rainfall trends of 20 homogenized meteorological stations inside the KG catchment. The results of monthly MKT test (Figure 2) showed decreasing trend in most of the stations with some exceptions showing no trends at all. Out of 20 stations, 14 stations during pre-monsoon (Mar-May) and 11 stations during monsoon (Jun-Sep) showed increasing trend. In the basin, 80% stations showed decreasing trends during winter and 75% stations showed decreasing trends during post-monsoon. In contrast, 70% stations showed increasing trends during pre-monsoon and 55% stations showed increasing trends during monsoon. Only 2 stations of the catchment followed no trends during post-monsoon season. Subjected to annual total rainfall series, 45% stations showed increasing and remaining 55% stations showed decreasing trends. This showed that the pre-monsoon and monsoon rainfall in KG basin was followed increasing trend.

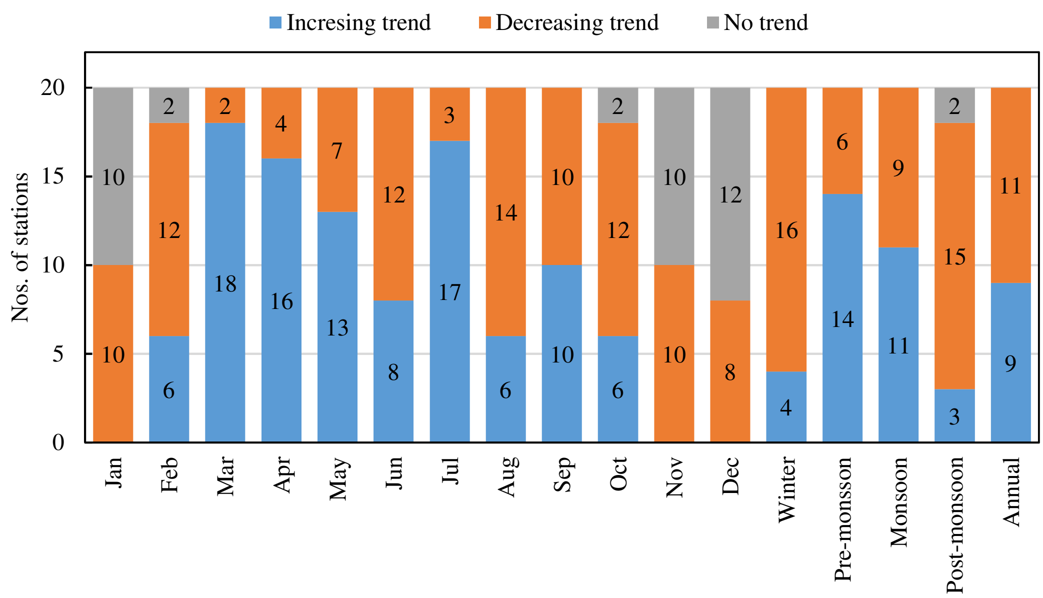

Figure 2. Overall trends of rainfall stations.

Figure 3(a) shows elevation (Elv.) wise average annual rainfall in different meteorological stations located inside the KG basin and Figure 3(b) shows elevation wise Sen's slope magnitude of meteorological stations located inside the KG basin. The annual Sen's slope magnitude for stations situated at Elv. 1000 m to 1432 m showed highest decreasing trend magnitudes, whereas stations having Elv. 1960 m and 2330 m showed higher increasing trend magnitudes. The highest rainfall station Lumle (Elv. 1740 m MSL avg. total rainfall 5377 mm/year) showed the increasing trend of magnitude +2.27 mm/year and the station Ghandruk (Elv. 1960 m MSL, avg. total rainfall 3589 mm/year) showed highest increasing trend of +25.51 mm/year. In contrast, the station Pamdur (Elv. 1160 m MSL, avg. total rainfall 4941 mm/year) showed overall highest decreasing trend of magnitude -30.02 mm/year.

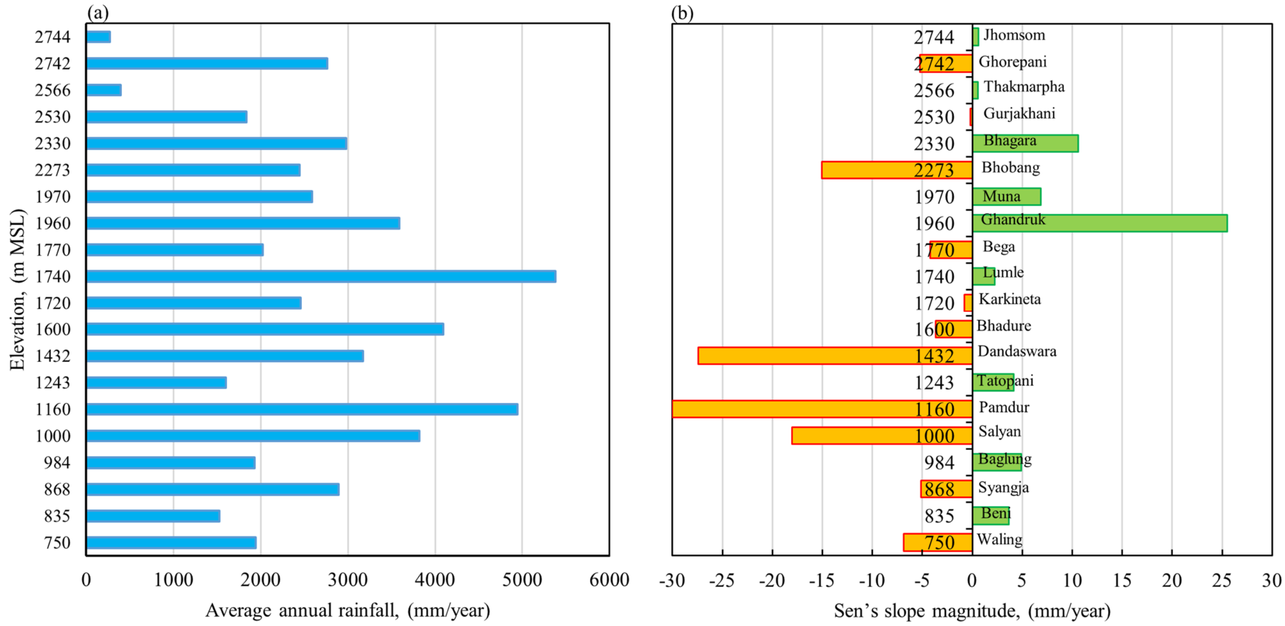

Figure 3. Annual (a) average total rainfall (b) Sen's slope magnitude with elevation of stations.

3.2 Seasonal fluvial discharge

The hydrology of snow-fed river systems is distinctive during snow melting season. The snow and glacier melts during snow melting season have significant effect on the hydrology of the river systems in Nepal (Water and Energy Commission Secretariat Nepal, 2011). Figure 4(a) shows the historical seasonal and annual average discharge of KG River at different years. The winter and pre-monsoon average discharge was followed the same trends. The monsoon discharge from 1964 seems increasing trends up to 2013, whereas the post-monsoon seems nearly consistent. Figure 4(b) shows the average monthly discharge. Particularly, the discharge increases from April and May due to melting of snow and glaciers of Himalayas. In addition, the increasing rainfall during monsoon increased the discharge of KG River. However, the wet season has an apparently flow increasing trend in basin. The hydrometric station was not working during dam construction period (1997-2002).

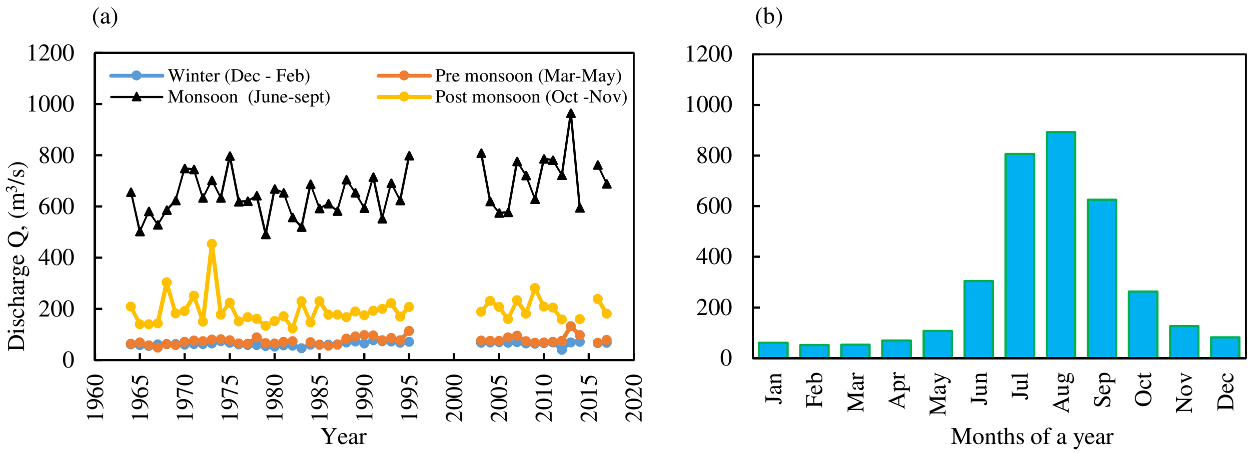

Figure 4. (a) Historical seasonal discharge of KG River (b) Average monthly discharge of KG River.

3.3 Specific discharge and rainfall relationship

Figure 5 shows daily specific discharge and daily rainfall relationship for KG River catchment at hydropower station (tail of river). The discharge was increased with increasing rainfall from pre-monsoon to the monsoon and decreasing during post-monsoon. The specific discharge (Q/A) calculated from observed discharge data and catchment area followed an anticlockwise hysteresis loop with rainfall data showing higher discharge during post-monsoon compared with the pre-monsoon for a given rainfall rate. This pattern illustrated that part of the rainfall was temporarily reserved within the catchment. The whole rainfall inside the catchment was not transferred directly to the river during the pre-monsoon and the monsoon seasons, whereas the storage portion was drained during the post-monsoon season. The same patterns were observed in Karnali, Narayani and Sapta Koshi basins of Nepal (Andermann et al., 2012).

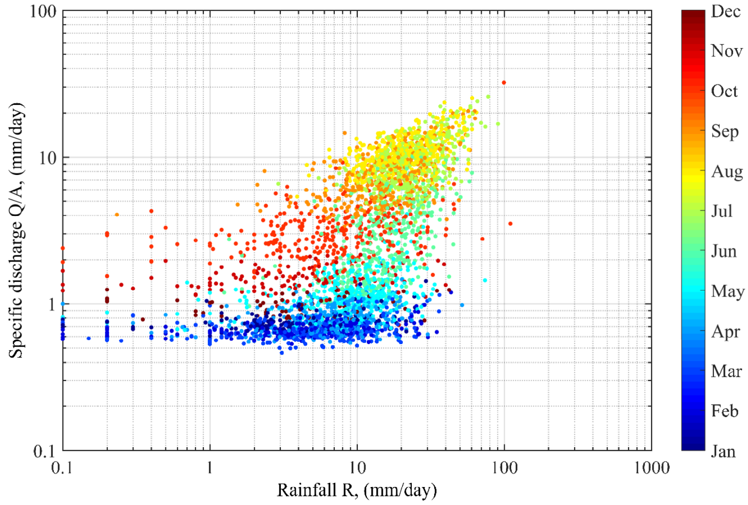

Figure 5. Specific discharge vs. mean daily Rainfall for Kali Gandaki River basin at Seti Beni.

3.4 Suspended sediment and fluvial discharge relationship

The suspended sediment discharge and fluvial discharge relationship with different rainfall classes for KG River basin (2006-2011) is expressed in sediment rating curve shown in Figure 6(a). Higher the fluvial discharges, higher suspended sediment was transported from Himalayas to hydropower reservoir. The suspended sediment discharge directly depends on fluvial discharge. The fluvial discharge value corresponding to 20 mm/day or greater rainfall value was estimated as 400 m^3/s or higher discharge value, which transported suspended sediment at the rate of 1,000 kg/s or higher rate (Figure 6a). Figure 6(b) shows the annual average rainfall occurred inside the KG basin and average suspended sediment transport from Himalayas to hydropower reservoir. The basin received average total annual rainfall ranges from 270 to 5376 mm/year, and fluvial discharge of KG River transported 27.071 to 58.426 Mega ton (Mt) suspended sediment annually.

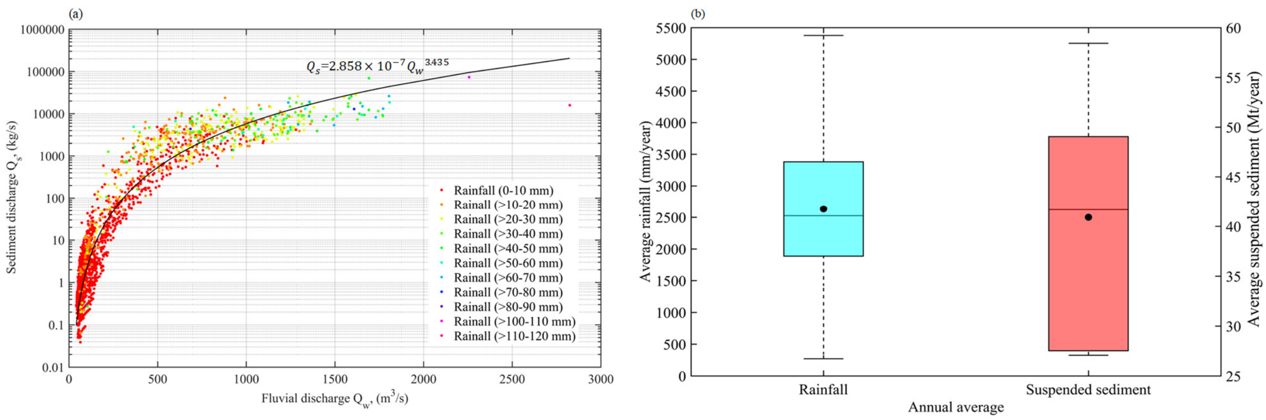

Figure 6. (a) Sediment discharge and fluvial discharge with different rainfall classes (b) Total suspended sediment transport for KG River basin (2006-2011). Central lines indicate the median and bottom and top edges of the box indicate the 25th and 75th percentiles respectively. The whiskers extend to the most extreme data points.

4. CONCLUSIONS

In this study, the rainfall trends of KG basin over the period 1957- 2017 were examined using MKT test with Sen’s slope estimator, showed that 70% stations showed increasing trend during pre-monsoon whereas 55% stations showed increasing trend during monsoon season. Also, the station Ghandruk (Elv. 1960 m MSL) performed highest increasing trend (+25.5 mm/year) whereas station Pamdur (Elv.1160 m MSL) performed highest decreasing trend (-30.0 mm/year). The fluvial discharge transports an average 40.90±12.45 Mt suspended sediment annually from Himalayas into the hydropower reservoir. The study could be useful in the context of hydropower reservoir management.

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