Seasonal Flow Variability and Stage Dynamics of the Teesta River: Insights from 29 Years of Multi-Station Data

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Manuscript received: 08 December 2025; accepted for publication: 16 July 2026

ABSTRACT: This study examines the long-term seasonal flow variability and water level of the Teesta River between 1995 and 2023 across four main stations (Kaunia, Dalia, Doani, and Haripur), supporting a population of 11.5 million and approximately 14% of the agricultural land in Bangladesh. The results indicate that the maximum discharge has significantly decreased from 8577 m^3/s in 2004 to 1629 m^3/s in 2013 at Kaunia station. Additionally, the annual minimum discharge dropped to 1.47 m^3/s in 2012. Conversely, the water levels showed a rising pattern with the highest point at 30.23 mMSL at Kaunia and 52.91 mMSL at Dalia. The mean maximum and minimum discharges at Kaunia were 3171.75 m^3/s and 28.35 m^3/s respectively, indicating high intra-annual variability. The findings also indicate a decoupling of discharge and water level trends, indicating a decrease in channel conveyance capacity as a result of sedimentation and channel aggradation. These results reveal critical changes in the river dynamics and the need for combined transboundary water management and adaptive sediment control actions to secure long-term water security in the Teesta basin.

Keywords: Teesta River; Discharge Trend; Water Level Dynamics; Channel Aggradation; HILOW Framework; Seasonal Hydrological Variability

INTRODUCTION

The Teesta, the fourth-largest international river in Bangladesh, has emerged as a significant concern due to restricted water availability caused by diversion, alongside political challenges and climate change impacts. The Teesta River spans 12,159 km^2, of which 2,004 km^2 is situated within Bangladesh (Prasai & Surie, 2013). It crosses two distinct nations: India (83%) and Bangladesh (17%). The river originates at approximately 7200 meters in the Sikkim Himalayas at Chitamu Lake, proceeding to the Darjeeling plain in India, and ultimately arriving at the Duars valley in West Bengal. The Kharibari border in the Nilphamari district marks the entry point into Bangladesh. It is a perennial river sustained by rainfall and snowmelt (Mondal & Islam, 2017). During dry and wet seasons, the Teesta's water discharge changes dramatically. The Teesta River in Bangladesh has historically flowed at least 10,000 m^3/s at Dalia, which is located upstream of the Teesta Barrage and has an average maximum flow of 280,000 cusecs (Khalid, 2013). The river's dry flow is currently strictly regulated for hydroelectric and irrigation projects in Bangladesh and India. Bangladesh, the lower riparian state within the Ganges-Brahmaputra-Meghna (GBM) river system, has to deal with the issue of uncertainty over the amount of water that flows downstream from the upstream regions (Mondal & Islam, 2017). Most of Bangladesh's north Bengal region now receives less water since the Teesta's water flow is regulated by the building of barriers, canals, and additional irrigation infrastructure (Haque et al., 2017). As a result, the Teesta no longer exhibits the same flow characteristics or discharge volume. Furthermore, the Teesta is essential to irrigation, farming, agriculture, fishing, and navigation in the area and helps to wash out silt.

The Teesta basin in Bangladesh encompasses 35 upazilas and 5,427 villages, with an anticipated population of 11.5 million in 2022 (Sen et al., 2023). Only a few studies have been undertaken on the Teesta River flow in the past. Mullick et al., (2011) ascertained the water level properties and ambient discharge necessities for the Teesta River utilizing a few years of historical flow data. Afroz & Rahman, (2013) examined the transboundary river water flow rates of the Teesta and Ganges and identified a substantial decrease in discharge after the inauguration of the Gozoldoba Barrier in India and the Farakka Barrier in Bangladesh. Their analysis indicated that during the past decade, the bed level in the upstream cross-

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DOI: https://doi.org/10.3329/dujees.v15i1.92325

section had altered by 2.5 feet, while the downstream section and the Teesta Barrage impact zone had seen degradation (Khan & Hossain, 2001). Khan (2018) investigated the combined effects of climate change and upstream development on the Teesta water balance. Zannah et al., (2020) evaluated flow and water balance under climate change and upstream interventions, demonstrating significant alterations in hydrological regimes. Talukdar et al., (2020) applied flood susceptibility modeling, while Uddin et al., (2024) explored morphological changes using geospatial techniques. Saleh et al., (2024) used machine learning approaches for discharge prediction. Despite these contributions, previous studies have several research gaps: 1) They mainly focused on isolated aspects such as discharge trends, flood modeling, or morphological changes, lacking an integrated assessment of hydrological behavior; 2) Long-term variability of both highest and lowest discharges and water levels has not been comprehensively analyzed using multi-decadal datasets; 3) Comparative evaluation across multiple hydrological stations remains limited, restricting the understanding of spatial variability within the river system. These gaps have been addressed in the present study.

This study aims to i) examine the trends of highest and lowest flow (discharge and water level) in the Teesta River, ii) observe the variations in flow patterns resulting from water extraction and abrupt releases by India via the Gozoldoba Barrier and irregularities of flow during the construction and initial operation period of Teesta barrage, iii) evaluate the relationship between water discharge and water level, and to understand the chronological change, iv) introduce the HILOW (Highest and Lowest) framework as a new concept for evaluating river water justice in transboundary river management contexts.

This study is expected to reveal long-term hydrological changes in the Teesta River using integrated multi-station discharge and water level analysis. Compared to previous studies, it provides a more comprehensive evaluation of both temporal and spatial variability. The results will contribute to a better understanding of river system dynamics under changing conditions.

STUDY AREA

The Lower Teesta River basin, situated in the northern part of Bangladesh, has been selected as the primary research area for this investigation, lying between latitudes 25° 30′ 02″ N and 26° 18′ 37″ N, and longitudes 88° 52′ 58″ E and 89° 45′ 34″ E (Fig. 1). Dalia and Kaunia are the discharge stations whereas Dalia, Kaunia, Doani and Haripur are the water level stations of the research area (Table 1). The other important characteristics of the study area and the river are shown in Table 2. The Teesta River basin in Bangladesh is characterized by a subtropical monsoon climate, with a distinct wet and dry season. The majority of annual rainfall occurs during the monsoon period (June to September), often exceeding 2000 mm, while the dry season (November to March) experiences significantly reduced precipitation and flow conditions. The average temperature of the area is between 10°C in the winter and exceeding 30°C in the summer, which affects the evapotranspiration and hydrological processes (Haque et al., 2017; Das et al., 2022).

Geomorphologically, the Teesta River flows through an alluvial floodplain dominated by unconsolidated sediments, making it highly dynamic and prone to channel shifting, bank erosion, and sandbar (char) formation. The river carries a substantial sediment load from the Himalayan upstream region, contributing to aggradation and morphological instability in the downstream reaches of Bangladesh (Haque et al., 2017; Uddin et al., 2024). These characteristics play a significant role in controlling flow variability and water level fluctuations observed in the basin.

DATA AND METHODOLOGY

The Bangladesh Water Development Board (BWDB) provided primary hydrological data (daily discharge and water level 1995-2023). Discharge data were obtained for the Dalia and Kaunia stations, while water level data were collected for Dalia, Kaunia, Doani, and Haripur stations, representing different segments of the Teesta River basin. This location map was created based on the Shuttle Radar Topography Mission (SRTM) Level-1 data, which gave high-resolution elevation data to replicate the terrain accurately. Additionally, Landsat 8 satellite imagery was incorporated to enhance the visualization of land surface features. Then the location map was drawn using the ArcGIS 10.8 software. The collected datasets were checked for consistency, missing values, and outliers, and any incomplete or erroneous records were excluded where necessary. Daily observations were processed to derive monthly maximum and minimum discharge and water level values, which were used to assess temporal variability. Temporal trends and seasonal variations were analyzed using graphical techniques such as line plots and bar charts, and linear trendlines were fitted to evaluate the direction and magnitude of changes over the study period. All data processing, statistical analysis, and visualization were performed using Microsoft Excel. To quantify temporal trends in discharge and water level, linear regression analysis was applied to the annual maximum and minimum time series for each station. The slope of the regression line was used to determine the direction and magnitude of hydrological change over the study period. Seasonal variability was assessed by analyzing monthly maximum and minimum values, allowing identification of intra-annual flow patterns and monsoon-dominated discharge behavior. A comparative analysis among multiple hydrological stations (Kaunia, Dalia, Doani, and Haripur) was conducted to evaluate spatial variability and consistency of hydrological trends across the basin.

There are limited historical records of Bangladesh's river phases and discharges. The Teesta River's flow parameters were examined by computing the monthly highest and lowest discharges and water levels from 1995 to 2023 at several stations (Table 1). The BWDB provided the historical hydrological discharge data for the Dalia and Kaunia stations and water level data for the Kaunia, Dalia, Doani, and Haripur stations (Table 1). Following chronological data, several graphs were created using the Microsoft Excel 2019 to analyze and compare the data, and to visualize the seasonal variations in monthly highest and lowest flow and water levels.

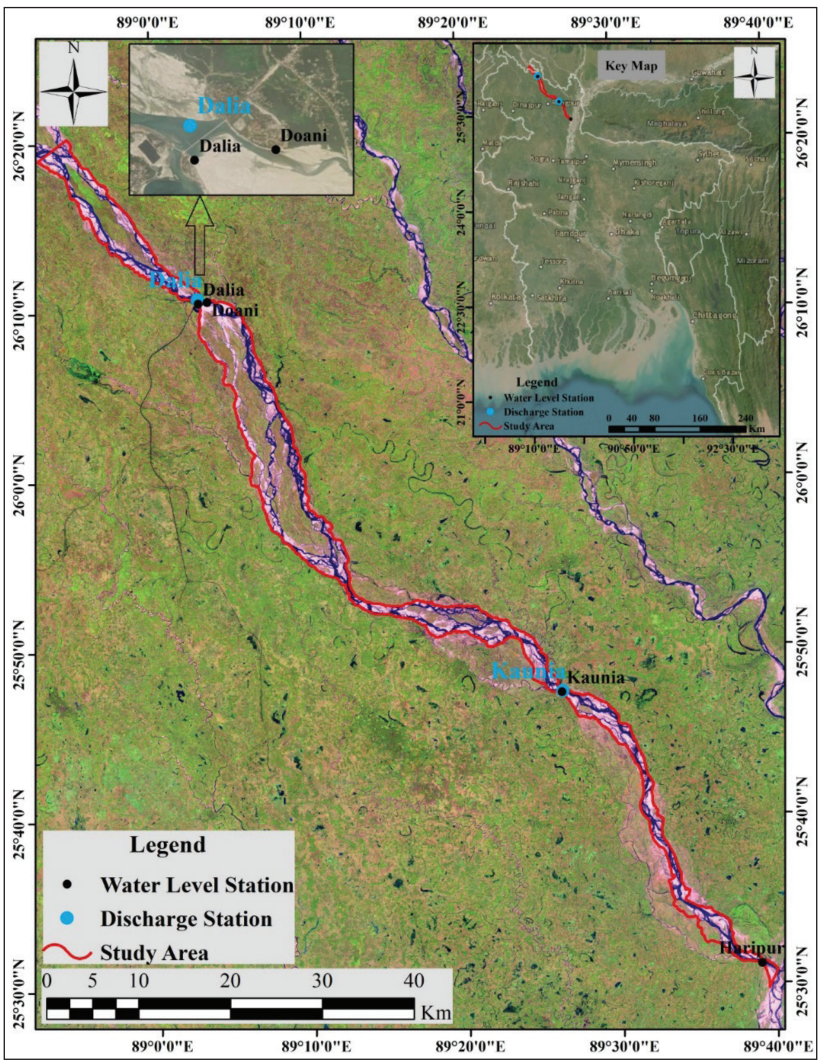


Figure 1: Study Area of the Teesta River and the Hydrological Stations of this Study

Table 1: Details of the Stations

Station	Station ID	Location	District	Danger level (mMSL)
Dalia	SW291.5 R	26° 07' 30.99" N, 89° 4' 25.42" E	Nilphamari	52.6
Kaunia	SW294	25° 47' 16.31" N, 89° 26' 14.30" E	Rangpur	29.2
Doani	SW291.5L	25° 47' 19.68" N, 89° 26' 19.86" E	Lalmonirhat	52.25
Haripur	SW294.5	25° 31' 9.01" N, 89° 39' 1.99" E	Gaibandha	-

Table 2: Prominent Characteristics of the Teesta River Basin (Das et al., 2022)

Region	Country	State/Division (District)	Basin Area (km²)	Proportion of Water (%)
Northern	India	Sikkim (East, West, North, and South Sikkim)	7039	57
Central	India	West Bengal (Darjeeling, Jalpaiguri, Cooch Behar)	3294	26
Southern	Bangladesh	Rangpur (Gaibandha, Kurigram, Lalmonirhat, Nil-phamari, and Rangpur)	2037	17
Entire	India, Bangladesh	-	12,370	100

RESULTS

Variation of Discharge

An analysis was conducted on the historic monthly highest and lowest discharge of the Teesta River for two stations from 1995 to 2023 to comprehend seasonal fluctuations in flow on a monthly and annual basis.

Monthly highest and lowest discharge of Kaunia station

According to the monthly maximum discharge analysis for Kaunia Station, the volume increased after February (232.00 m³/s, 19/02/1995) and peaked in April (8577.00 m³/s, 21/04/2004). After that, the water started to recede until June (3310 m³/s, 14/06/1998).

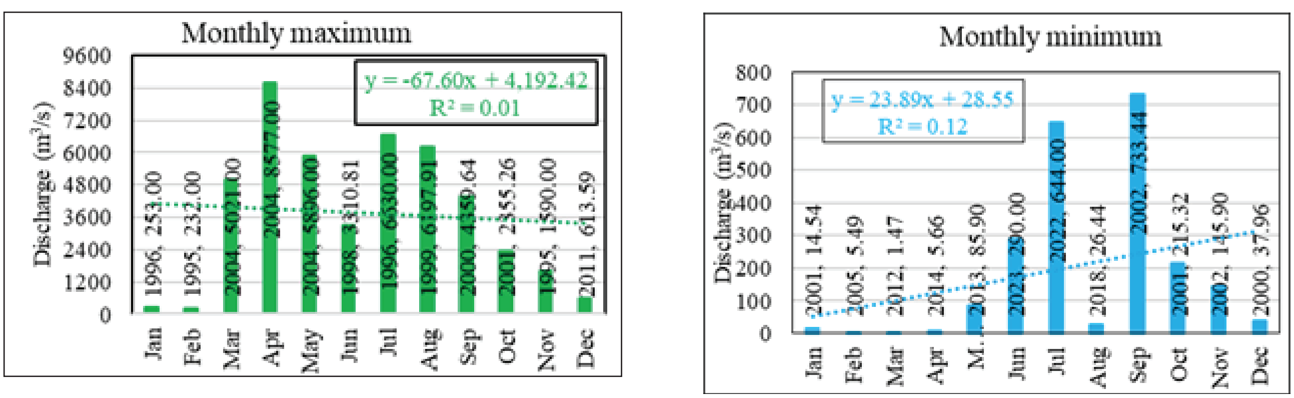


Figure 2: Monthly Maximum and Minimum Discharge of Kaunia Station

Yet again, the water output spiked to its second highest peak (6630.00 m³/s, 14/07/1996), and then started to decline again, reaching its lowest flow in February where the average, median, and standard deviation were 3753.02 m³/s, 3835.23 m³/s and 2786.74 m³/s. The volume for the monthly minimum discharge increases after March (1.47 m³/s, 06/03/2012) and peaks again in July (644.00 m³/s, 18/07/2022), which is the second highest monthly. After that, the water started to decline until August (26.44 m³/s, 28/08/2018). The water discharge surged again that peaked in September 2002 (733.44 m³/s), and then it started to recede again until reaching its lowest discharge in March where average, median, and standard deviation were 183.84 m³/s, 61.93 m³/s, and 253.81 m³/s. For the past 29 years, Kaunia Station's minimum discharge has been gradually rising while the maximum trend line is sharply declining (Fig. 2).

Annual Maximum Discharge of Kaunia Station

The outcome based on the annual maximum discharge is displayed in Figure 3. Peak flow values ranged from 1628.92 m^3/s on 9/07/2013, to 8577 m^3/s on 03/04/2004. The flow was highly erratic from 1995 to 2004 during the construction and early operational age of the Teesta Barrage. After that, it stabilized until 2020, at which point it repeatedly became unstable and stayed that way. The trend was downhill with a bigger negative slope, which is a concerning development and a trend indicating significant hydrological alteration. The average, median, and standard deviation for the research periods were, respectively, 3171.75, 2414.48, and 1753.83 m^3/s. Except for 1996 (6630 m^3/s, 14/07/1996), 1999 (6197.91 m^3/s, 27/08/1999), and 2004 (8577 m^3/s, 03/04/2004), the majority of the peak discharge stayed between 6000 and 1700 m^3/s. In contrast, 2006 (1684 m^3/s, 25/09/2006), 2013 (1628.92 m^3/s, 07/09/2013), and 2015 (1680.37 m^3/s, 09/01/2015) remained below 1700 m^3/s.

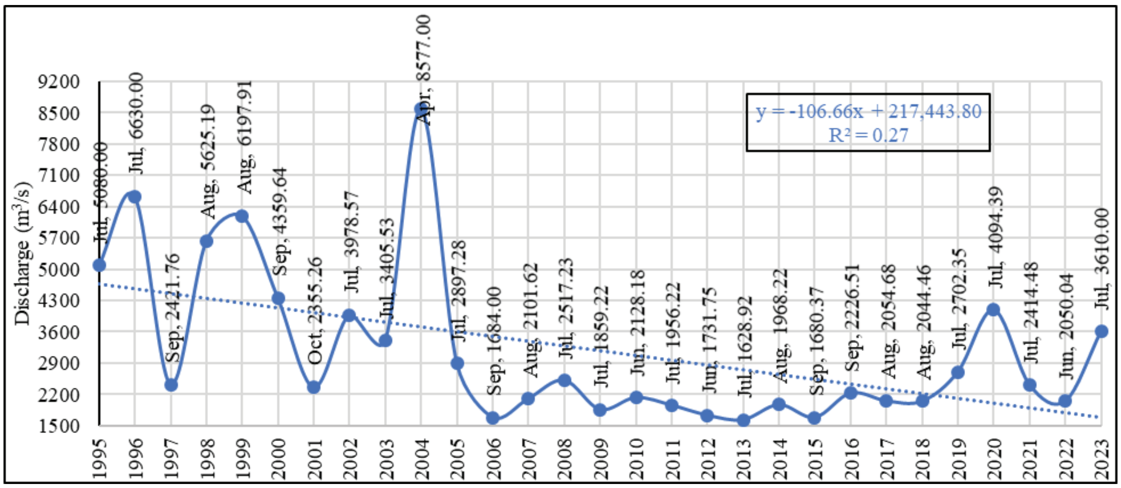


Figure 3: Annual Maximum Discharge of Kaunia Station

Annual Minimum Discharge of Kaunia Station

During the research period from 1995 to 2023, the annual minimum discharge was declining (Fig. 4), with a considerably negative slope. Before 1997, the discharge was dynamic and irregular; following that, it stabilized, albeit not significantly; as a result, the mean, median, and standard deviation were 28.35 m^3/s, 24.00 m^3/s, and 25.52 m^3/s. The highest discharge was 106.00 m^3/s (24/04/1996) and the lowest was 1.47 m^3/s (06/03/2012). Except for 1995 (91.20 m^3/s on 02/07/1995), 1996 (106.00 m^3/s on 24/04/1996), and 1997 (74.74 m^3/s on 28/12/1997), every annual minimum discharge stayed below 50.00 m^3/s.

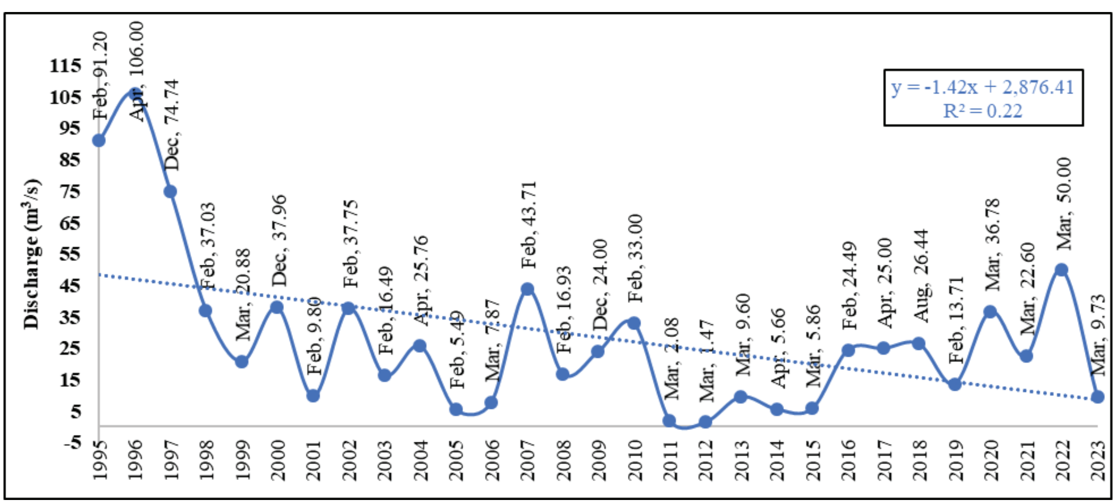
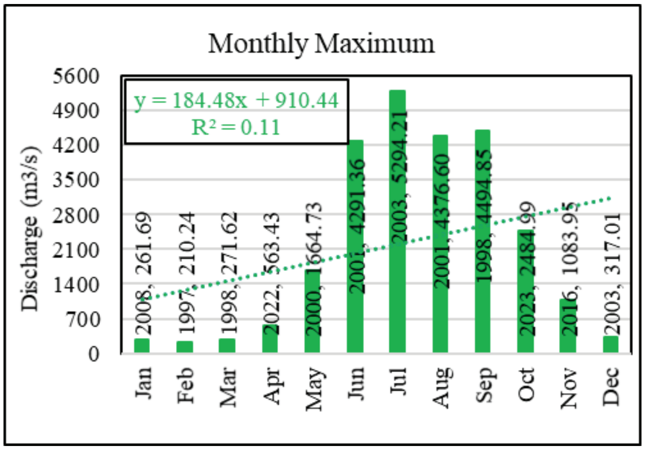


Figure 4: Annual Minimum Discharge of Kaunia Station

Monthly highest and lowest discharge of Dalia station

The maximum monthly discharge for Dalia Station increased starting (Fig. 5) in February (210.24 m^3/s, 24/02/1997), peaking in July (5294.21 m^3/s,10/07/2003) and again fell in August (4376.60 m^3/s, 23/08/2001). Once more, the discharge increased to its second-highest peak in September (4494.85 m^3/s, 03/09/1998), after which it started to decline and reached its lowest flow until February.



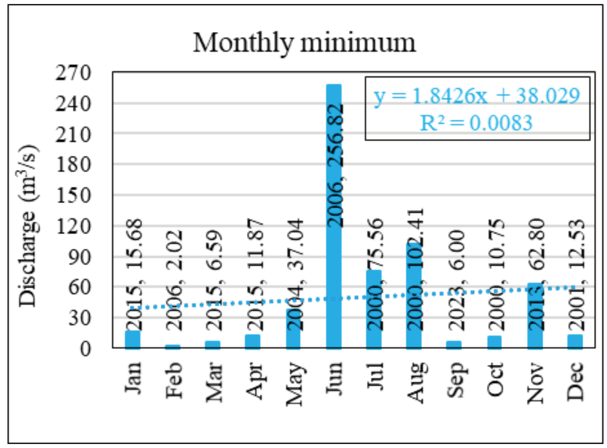


Figure 5: Monthly Maximum and Minimum Discharge of Dalia Station

The monthly maximum average, median, and standard deviation were 2109.56 m^3/s, 1374.34 m^3/s, and 1980.03 m^3/s. The largest flow of monthly maximum was 5294.21 m^3/s on 10/07/2003, and the lowest was 210.24 m^3/s on 24/02/1997.

For monthly minimum discharge, frequent irregularities were found, the volume climbed after February (2.02 m^3/s, 12/02/2006) and reached its highest peak in June (256.82 m^3/s, 21/06/2006) then recede until July (75.56 m^3/s, 27/07/2000).

The water release surge reached its 2nd highest peak in August (102.41 m^3/s, 10/08/2000) after that again receded till September (6 m^3/s, 17/09/2023). From September, the discharge rose to its 3rd highest peak in November (62.8 m^3/s, 06/11/2013) and continued to decline till December (12.53 m^3/s, 31/12/2001) and meets with January (15.68 m^3/s, 22/01/2015) with 4th highest peak and fall the lowest flow on February. The lowest monthly minimum was 2.02 m^3/s (12/02/2006), and highest was 256.82 m^3/s (21/06/2006) while the average, median, and standard deviation were 50.01 m^3/s, 14.11 m^3/s, and 72.94 m^3/s.

Annual Maximum Discharge of Dalia Station

The annual peak discharge was extensively dynamic from 1997 to 2003 (Fig. 6) then it became stable till 2019 again showed its turbulent behavior.

For the study period, the highest discharge was 5294.21 m^3/s (07/10/2003) while average, median, and standard deviation were 2724.76 m^3/s, 2298.24 m^3/s and 965.65 m^3/s. Annual peak discharge of Dalia point was decreasing and most of the discharge was between 4000 m^3/s, and 1800 m^3/s except in 1998 (4494.85 m^3/s, 03/09/1998), 2001 (4376.60 m^3/s, 23/08/2001) and 2003 (5294.21 m^3/s, 10/07/2003) while the discharge was too high.

Annual Minimum Discharge of Dalia Station

The average annual least discharge was 25.77 m^3/s while the median and standard deviation were 24.53 m^3/s and 15.71 m^3/s (Fig. 7). Among the discharge graphs, the annual minimum discharge of Dalia station didn't follow any sequence hence it was irregular for the whole study period. On the contrary while other annual discharges were decreasing here it was increasing but the increasing trend wasn't so significant. The highest discharge was 55.75 m^3/s (22/12/2022) and the lowest was 2.02 m^3/s (12/02/2006). Most of the year discharge was below 45 m^3/s except in 2010 (47.57 m^3/s, 14/02/2010), 2020 (48.90 m^3/s, 05/03/2020), and 2022 (55.75 m^3/s, 22/12/2022) when it was excessively high.

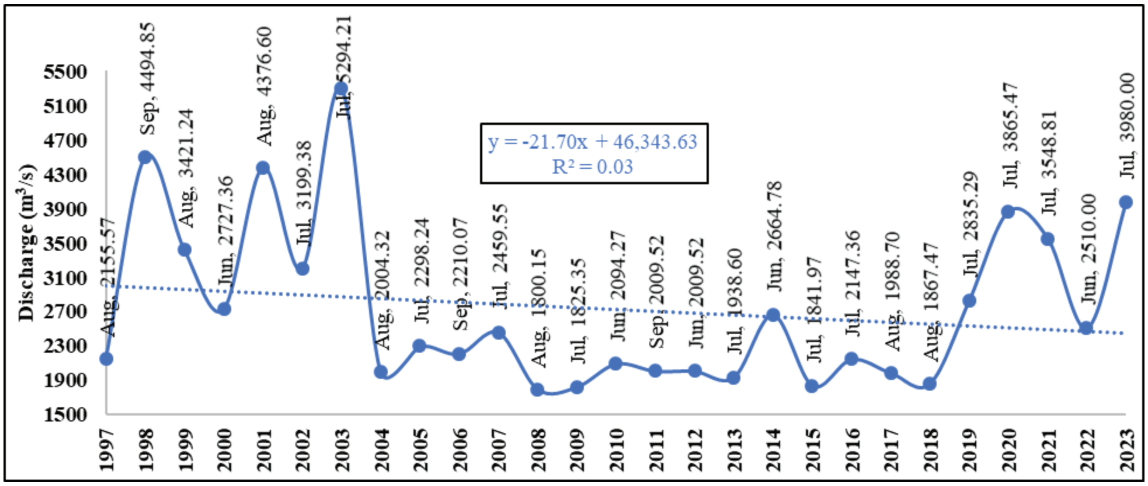


Figure 6: Annual Maximum Discharge of Dalia Station

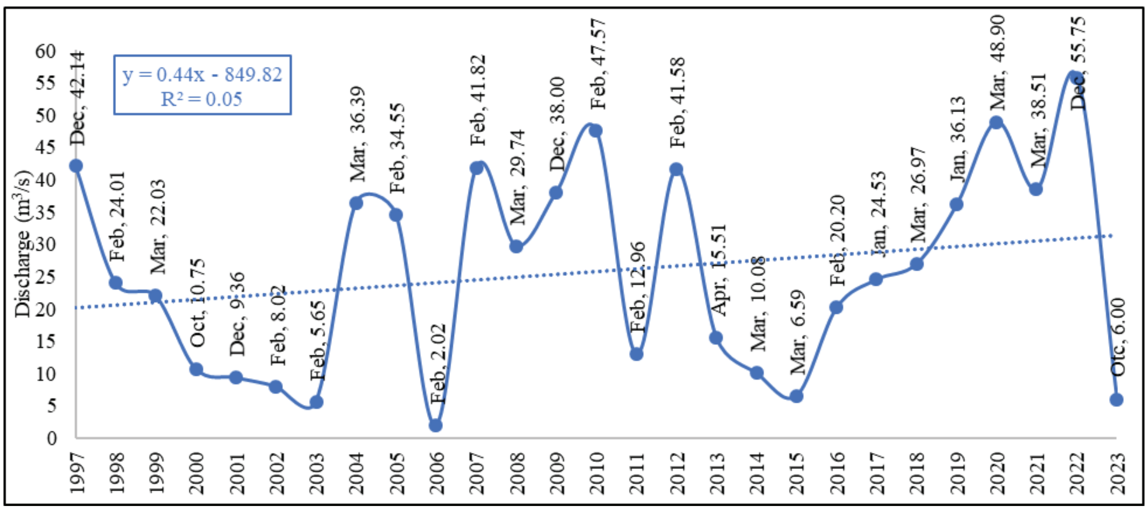


Figure 7: Annual Minimum Discharge of Dalia Station

Variation of Water Level

Water levels are predicted to climb as rivers release more water. However, due to variables including stream breadth, depth, terrain, flow rate, and sedimentation pattern, the peak discharge and the greatest water level may not always occur at the same time. Nonetheless, there is a clear correlation between the general trend of rising and falling water levels and outputs. This summary of the varying water levels over several years is given in the following article.

Monthly Documented Highest and Lowest Water Levels at Kaunia Station

Figure 8 shows that the monthly highest and lowest water levels at Kaunia station, from November to May (1995-2023) continuously stayed below the danger limit. In contrast, it was above the danger limit in June (29.92 mMSL, 30/06/1999), July (30.23 mMSL, 14/07/1996), August (30.06 mMSL, 13/08/2017), September (29.82 mMSL, 03/09/1998), and October (29.65 mMSL, 21/10/2021). The monthly highest level revealed that starting in January, the water level gradually increased until it reached the risk level between May and October. Since 1995, the water level at Kaunia Point has risen above the danger limit twenty times. In July, the stage reaches its maximum level (30.23 mMSL, July 14, 1996). The monthly minimum water level has consistently been below the risk threshold. On March 19, 2019, the lowest minimum was measured at 25.21 mMSL, while on July 6, 2018, the highest recorded minimum was measured at 27.63 mMSL. Both the maximum and minimum water levels during the research period were rising as predicted.

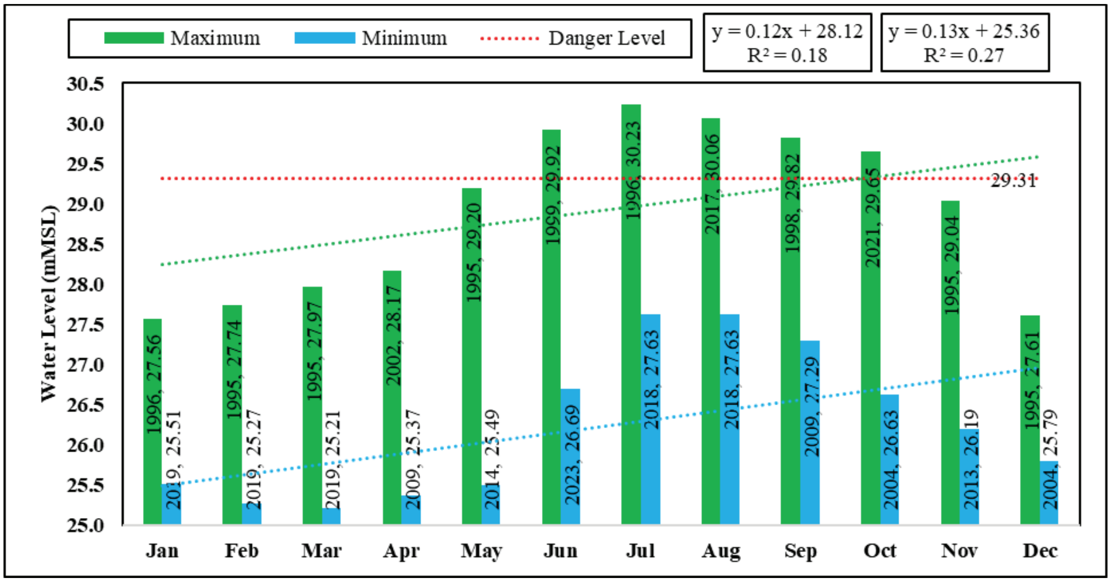


Figure 8: Monthly Highest and Lowest Water Level of Kaunia Station

Annually Documented Highest and Lowest Water Levels at Kaunia Station

The highest-level plot line for the data was gathered from 1995 to 2023 which showed an irregular dynamic shifting tendency (Fig. 9 and Fig. 10). The lowest water level consistently stayed below the danger threshold, whereas the maximum water level typically stayed beyond it. The fact that the water level was dropping significantly at the annual low and maximum was the most startling finding. The annual maximum water level was measured with the following values: 29.47 mMSL, 29.46 mMSL, 0.41 mMSL, 28.61mMSL (18/06/2018), and 30.23 mMSL (14/07/1996) as the average, median, standard deviation, minimum and maximum for annual minimum water level was measured with the following values: 25.96 mMSL, 25.79 mMSL, 0.54 mMSL, 25.21mMSL (19/03/2019), and 27.28 (06/02/1995) mMSL of same variables.

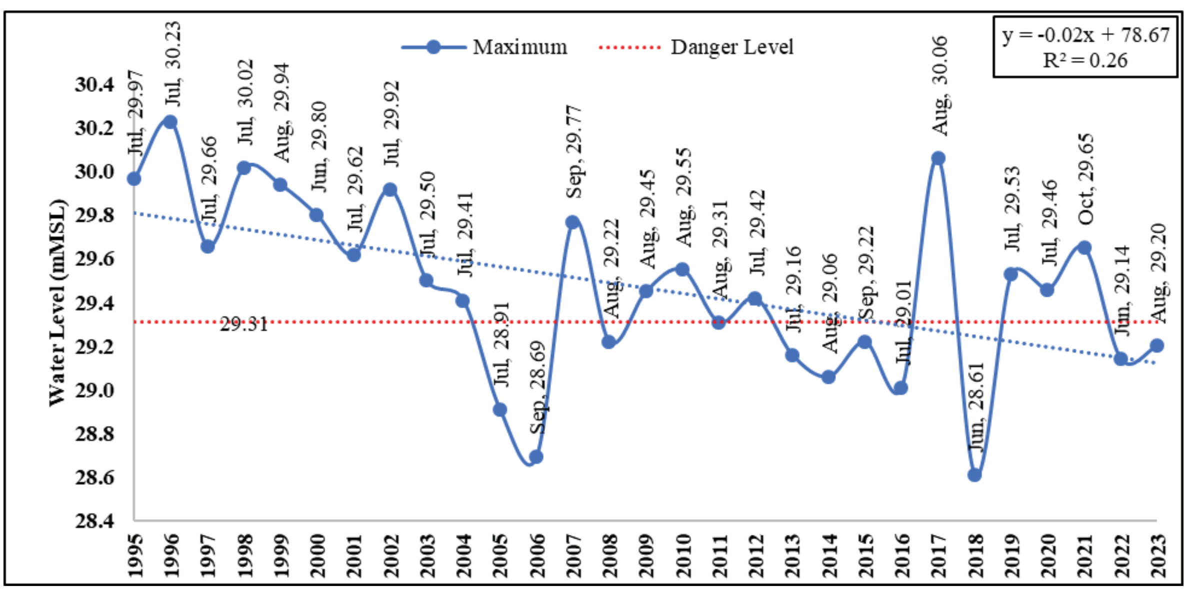


Figure 9: Annual Maximum Water Level of Kaunia Station

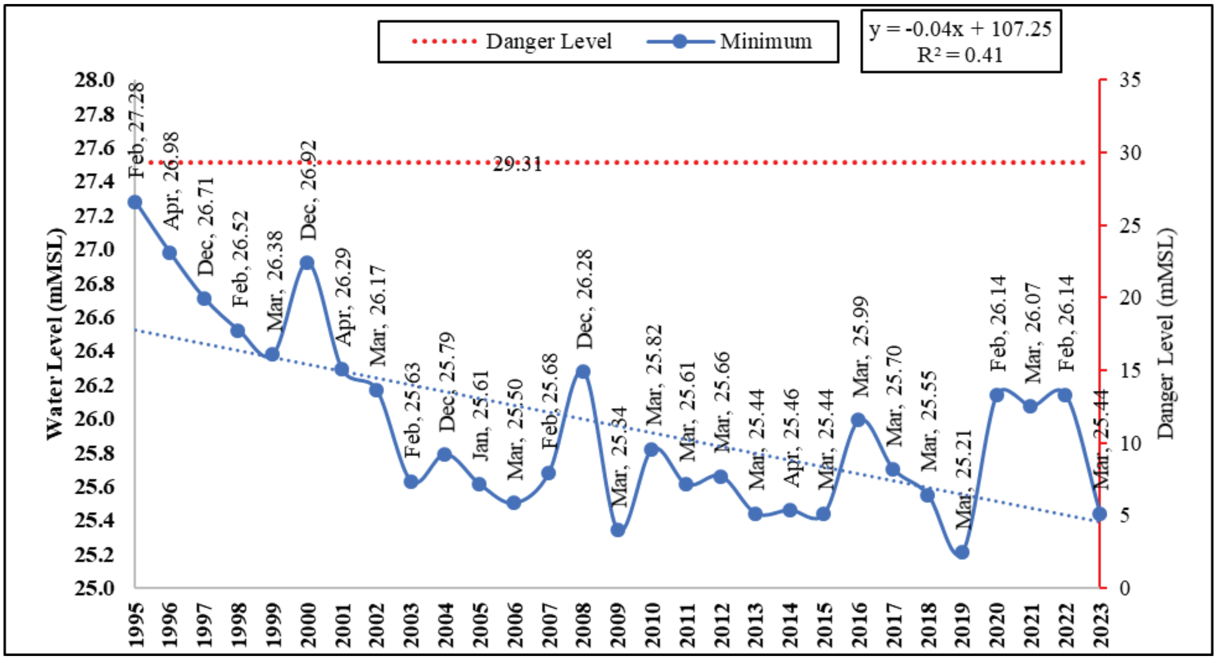


Figure 10: Annual Minimum Water Level of Kaunia Station

Monthly Documented Highest and Lowest Water Levels at Dalia Station

The water level of the monthly maximum at Dalia Point rose from February (50.62mMSL, 05/02/2022) to June (52.91 mMSL, 20/06/2022) and decreased in July (52.72mMSL, 13/07/2020) but increased in August (52.82mMSL, 01/08/2022), subsequently declined in September (52.80 mMSL, 01/09/2022) and reached in October (52.90 mMSL, 20/10/2021) after that water level continue to decline and reach February as illustrated in Fig. 11. Most of the highest peaks both monthly maximum and minimum are below the danger level Except the June to October monthly maximum. There were also irregularities in the monthly minimum water level but in most cases, wet seasons gained high levels. Both monthly maximum and minimum were in increasing trend as usual.

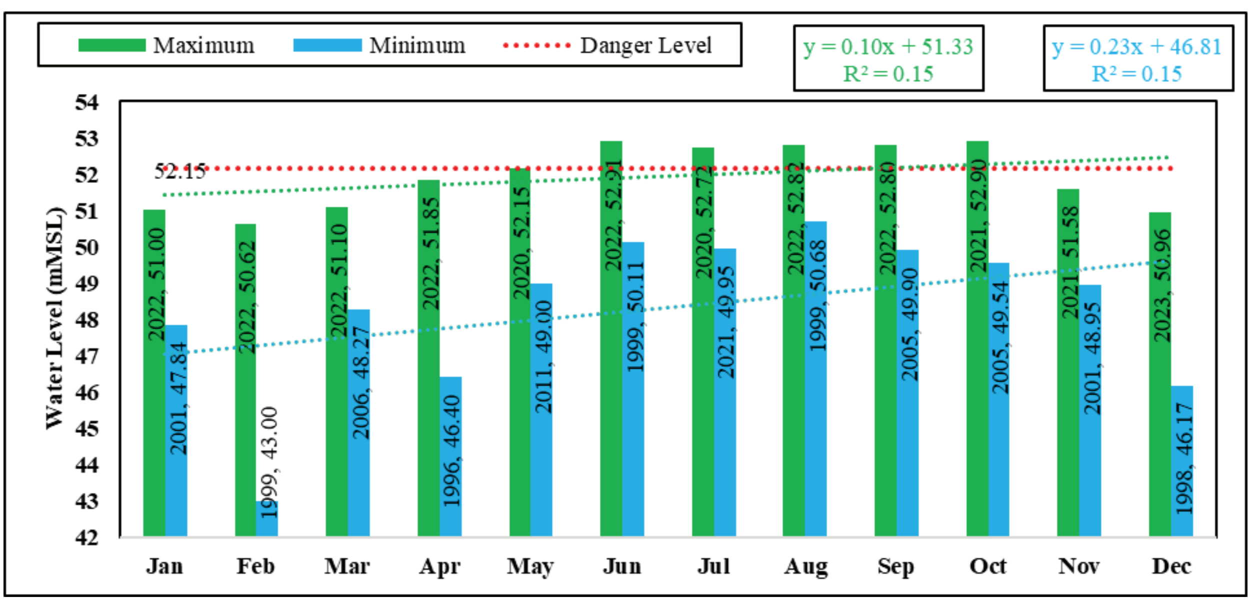


Figure 11: Monthly Highest and Lowest Water Level of Dalia Station

The monthly minimum water level increased after February (43 mMSL, 15/02/1999) and reached 48.27 mMSL on 01/03/2006 again falling in April at 46.40 mMSL (16/04/1996) and continued rising till June at 50.11 in 09/06/1999 and again fall at July 49.95 mMSL (02/07/2021) reached in August at 50.68 mMSL (04/08/1999) again fall till December at 46.17 mMSL (31/12/1998) and reached in January at 47.84 mMSL (24/01/2001) then meets February by decreasing (Fig. 11).

Annually Documented Highest and Lowest Water Levels at Dalia Station

Since 1996, the water level has climbed above the danger threshold eighteen times at Dalia point. Except for the early years of our research period, both the yearly maximum and minimum followed an increasing tendency consistently compared to the other stations, that phenomenon was unique. The annual minimum was consistently below the danger level, but the annual maximum grew significantly in recent years, crossing the danger level in 2017 and continuing from 2019 until 2023 (Fig. 12 and Fig. 13).

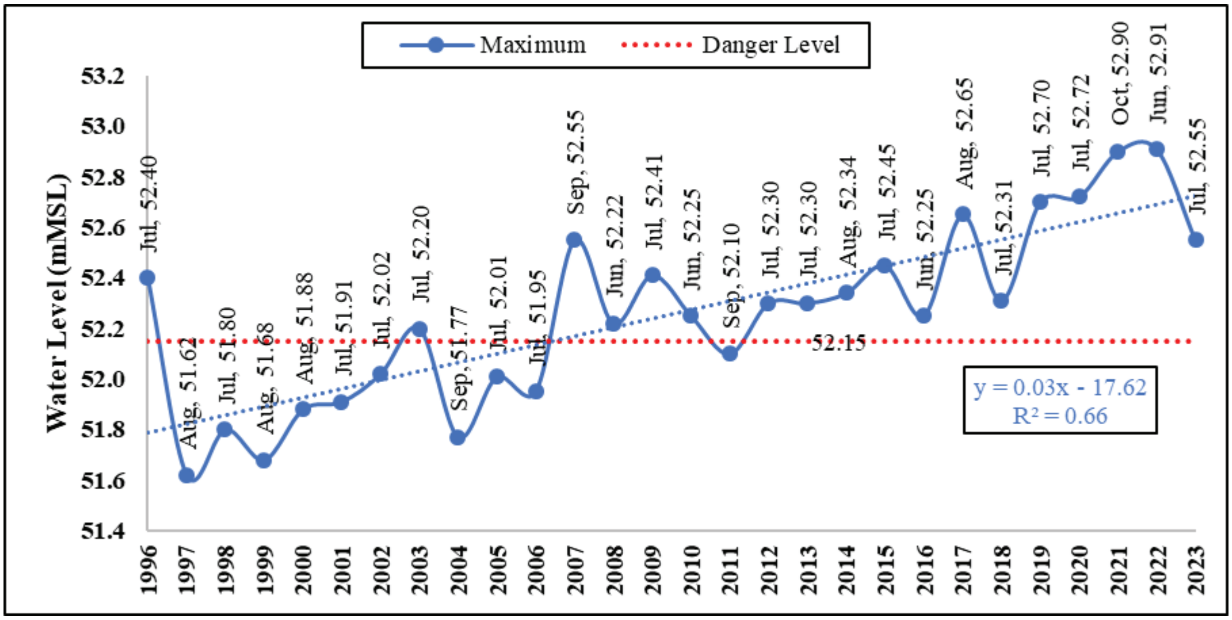


Figure 12: Annual Maximum Water Level of Dalia Station

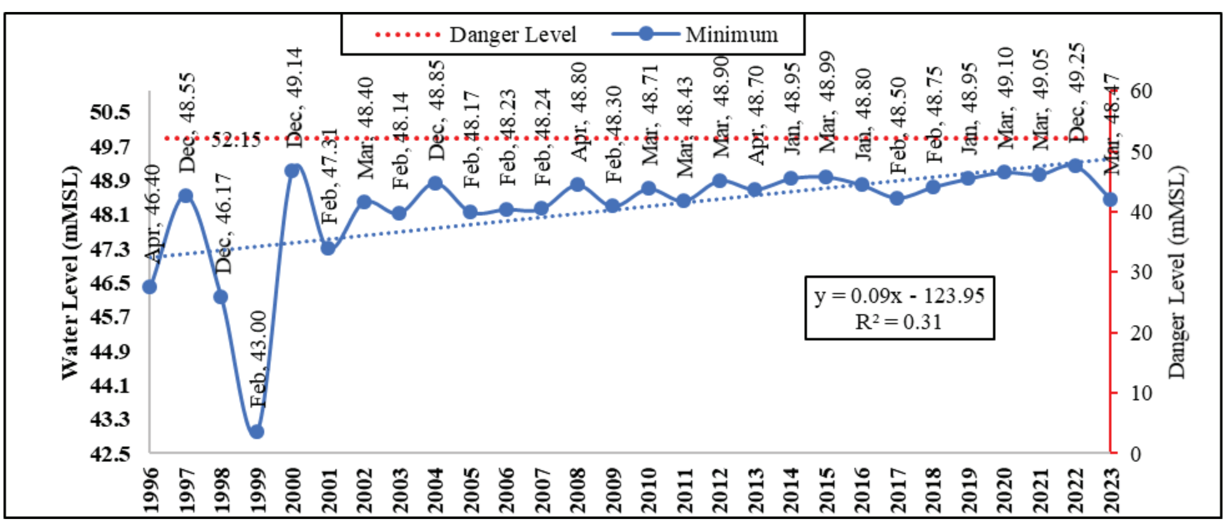


Figure 13: Annual Minimum Water Level of Dalia Station

The yearly maximum water level was 52.91 mMSL (20/06/2022), 51.62 mMSL (10/08/1997), 52.26 mMSL, 0.35 mMSL, and 52.28 mMSL at its maximum, minimum, average, standard deviation, and median. In contrast, the yearly minimum was 49.25 mMSL on December 31, 2022, 43.00 mMSL on May 16, 1999, 48.26 mMSL, 1.26 mMSL, and 48.63 mMSL of the same variables.

Monthly Documented the Highest and Lowest Water Levels at Doani Station

The monthly maximum water levels at Doani Station exceeded the danger level for multiple months, from March to October (Fig. 14).

However, the monthly minimum level never went above the risk threshold. The monthly water level was rising as expected for both the maximum and minimum, but the monthly minimum was rising more quickly. The monthly maximum water level was 53.64 mMSL on March 28, 2004, dropped to 51.46 mMSL on April 26, 2021, and then increased once more to 52.57 mMSL on June 22, 2016. Following that, it decreased in July (52.47 mMSL, 24/07/2016) and increased in August (52.82 mMSL, 1/08/2022) declined once more in September (01/09/2022; 52.5 mMSL), after staying the same for October (52.50 mMSL, 20/10/1999) it dropped till December (50.49 mMSL, 08/12/1999). It increased little in January (50.50 mMSL, 02/01/2022), decreased over again in February (50.26 mMSL, 05/02/2022), and reached its maximum in March. While it is clear that the monthly minimum and maximum did not follow a set sequence of increases and decreases, in most cases, the monthly minimum climbed in tandem with the monthly maximum, or vice versa.

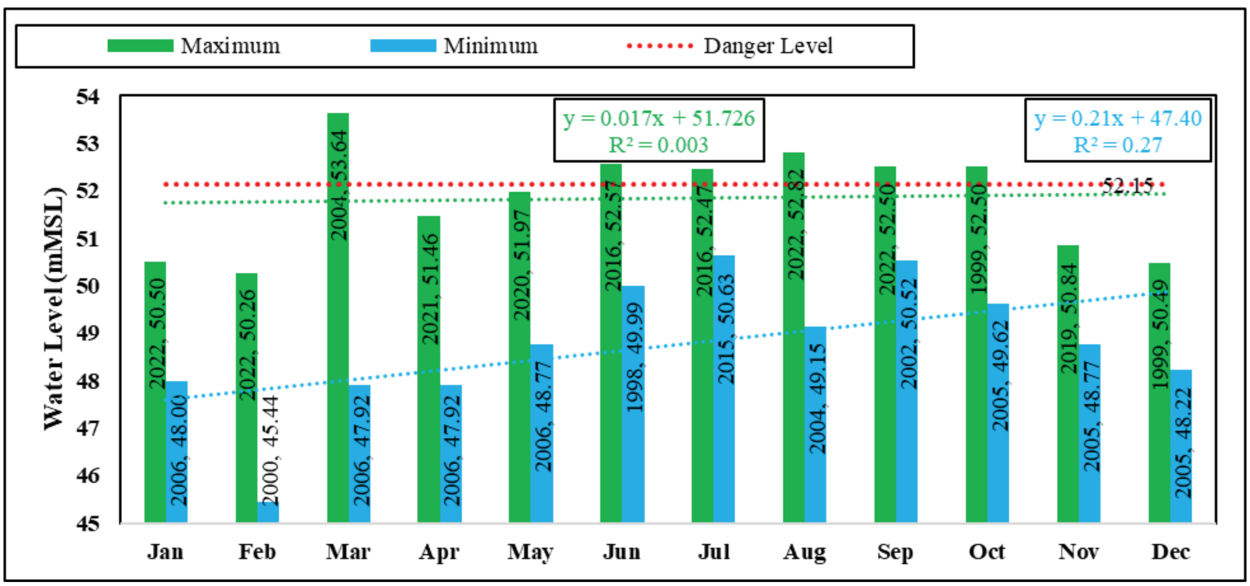


Figure 14: Monthly Highest and Lowest Water Level of Doani Station

Annually Documented Highest and Lowest Water Levels at Doani Station

The annual maximum and lowest water levels at the Doani station are depicted in the accompanying figures (Fig. 15 and 16). The annual maximum water level indicated a rapid change and did not follow any consistent pattern before 2004. The annual minimum never went beyond the danger level, although the annual maximum was above it for several years. The annual maximum water level was 53.64 mMSL (28/03/2004), 51.46 mMSL (06/10/2001), 52.18 mMSL, 0.42mMSL, and 52.12mMSL, according to the maximum, minimum, average, standard deviation, and median. The annual minimum was 49.22 mMSL (30/12/2022), 47.92 mMSL (01/03/2006), 48.51 mMSL, 0.33 mMSL, and 48.55 mMSL following the same variables. During the investigation, both water levels showed growing features; nevertheless, both the annual minimum and annual maximum exhibited a notable increasing rate over the study period.

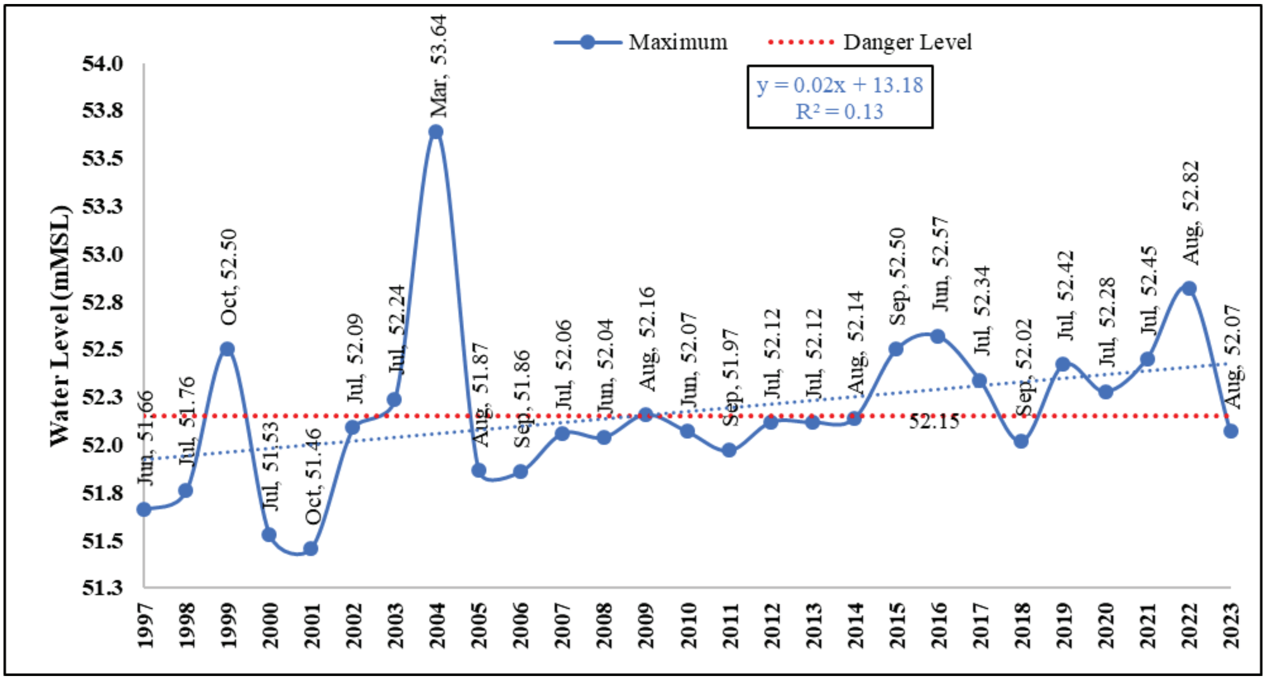


Figure 15: Annual Maximum Water Level of Doani Station

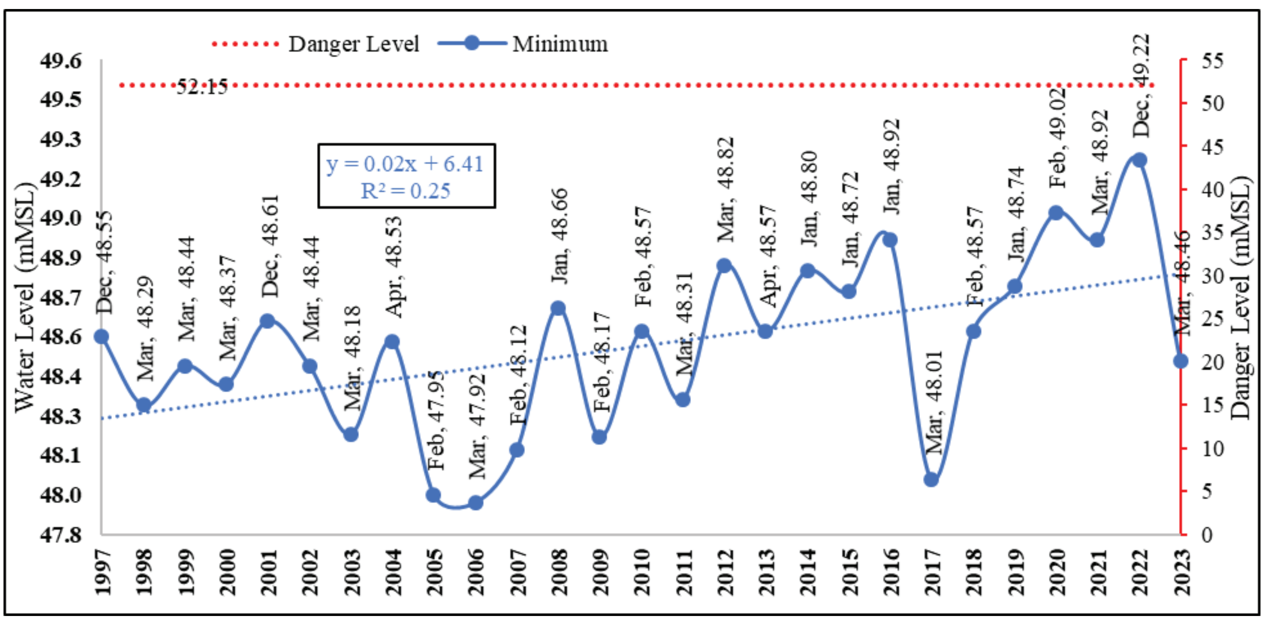


Figure 16: Annual Minimum Water Level of Doani Station

Monthly Documented the Highest and Lowest Water Level at Haripur Station

As with the other stations, the monthly highest and lowest water levels increased, throughout the study period, the two water levels increased at nearly the same pace (Fig. 17). Following March (19.3mMSL, 24/03/2022), the monthly maximum water level began to rise. It peaked in May (27.17mMSL, 29/05/2018), following which it proceeded to decline until March. In contrast, for the monthly minimum, the lowest water level was 16.90 mMSL on 29/03/2018, and 04/04/2018, before rising to 20.18 mMSL on 11/07/2001, and remaining at the lowest level in March.

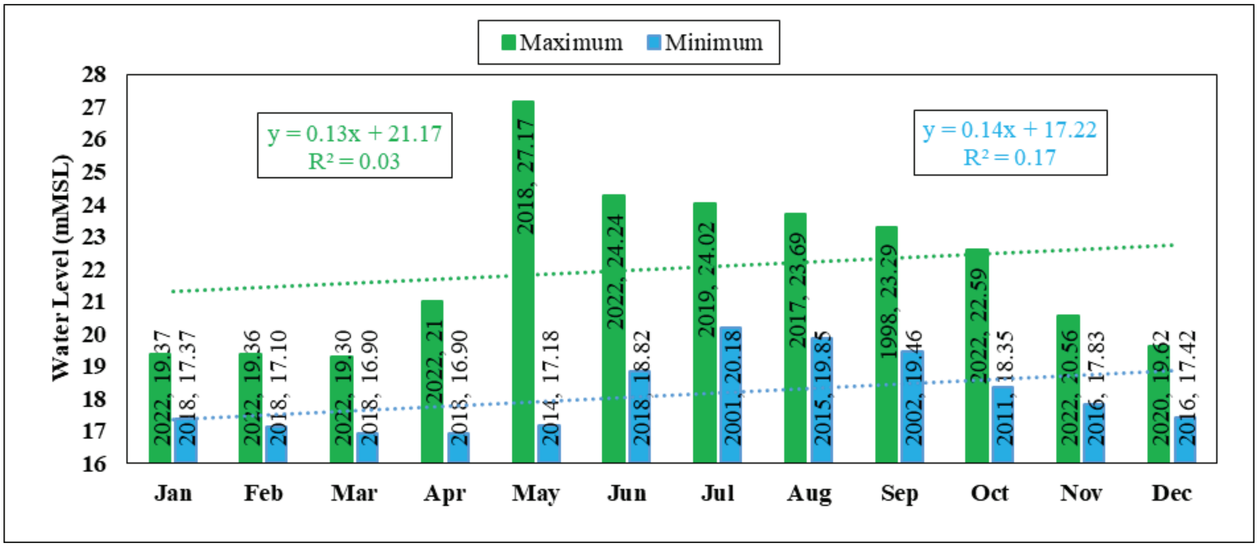


Figure 17: Monthly Maximum and Minimum Water Level of Haripur Station

Annually Documented the Highest and Lowest Water Level at Haripur Station

Throughout the whole study period, the annual maximum water level exhibited a notable trend, except 2018, when it achieved its highest peak (27.17mMSL, 29/05/2018). Conversely, the annual minimum did not adhere to a set pattern (Fig. 18 and Fig. 19).

The analysis revealed two distinct situations in which the yearly minimum was falling and the annual maximum was rising. The average, median, standard deviation, minimum, and maximum water level values for the yearly maximum are 23.22 mMSL, 23.21 mMSL, 1.0 mMSL, 21.64 mMSL (17/09/2006), and 27.17 mMSL (29/05/2018). In contrast, the yearly minimum was 17.92 mMSL, 17.96 mMSL, 0.52 mMSL, 16.9 mMSL on 29/03/2018, and 18.85 mMSL on 18/03/2022.

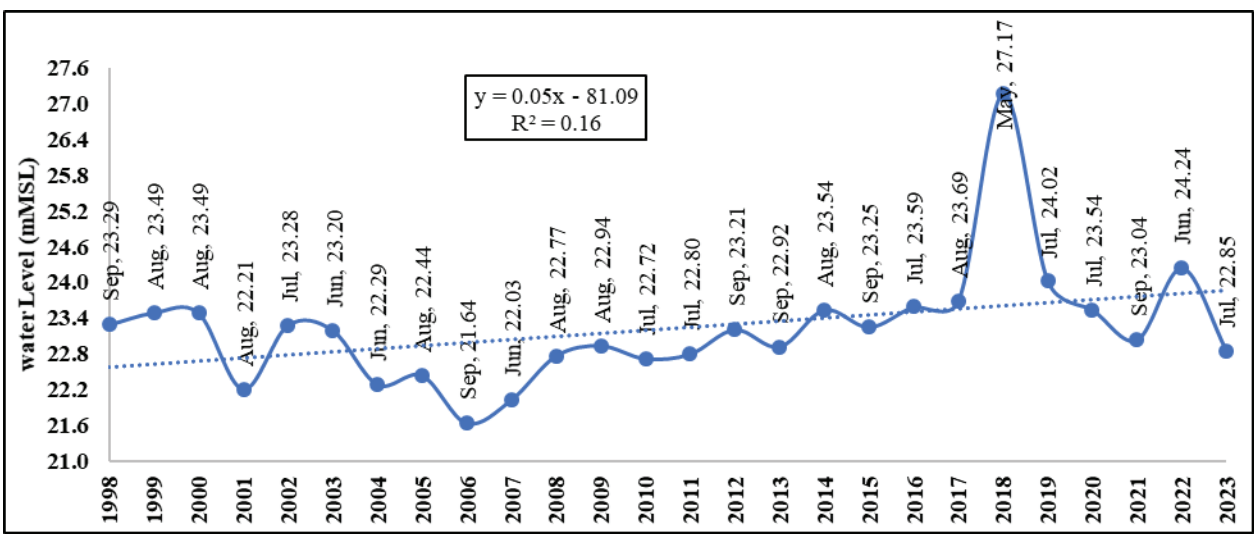


Figure 18: Annual Maximum Water Level of Haripur Station

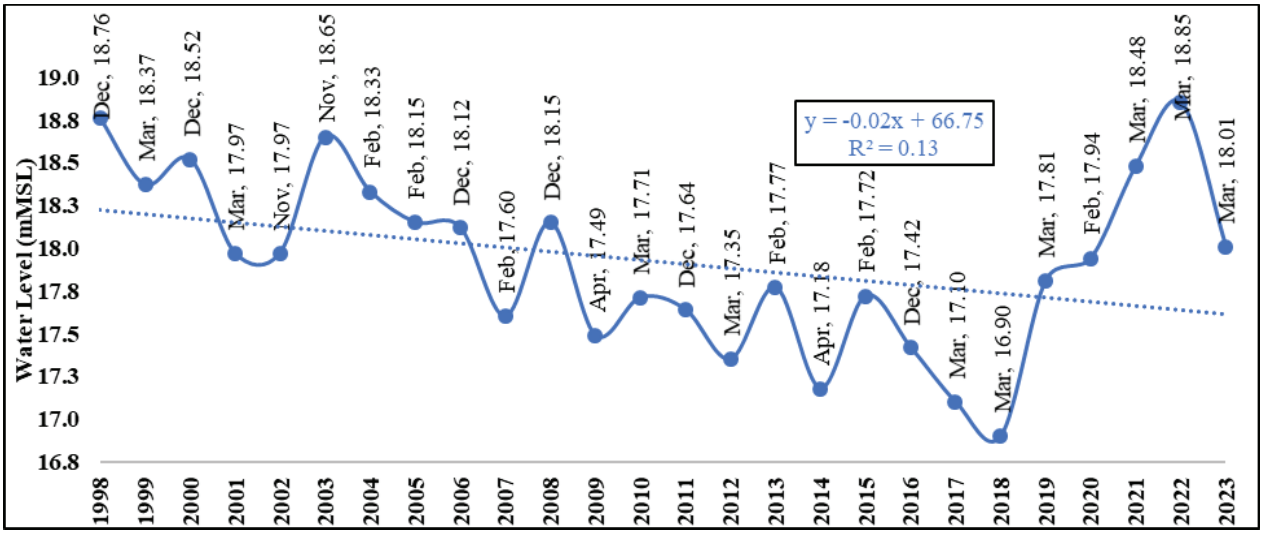


Figure 19: Annual Minimum Water Level of Haripur Station

DISCUSSION

The results involved the measured discharge of Dalia and Kaunia (approximately 71 km south of the Teesta Barrier at Dalia), and the water level measurements of Kaunia, Dalia, Haripur, and Doani (on the opposite side of Dalia, Fig. 1). The graphical analyses such as line plots, trendlines, and bar charts, show that there are major changes in the river's behavior, characterized by decreasing discharge and rising water levels. To interpret the variability, the HILOW framework is used to assess the imbalance between peak and low flow conditions.

The monthly discharge line plots also indicate a high degree of seasonal dependence with peaks in the monsoon and very low values in the dry season. This means that the Teesta River is highly sensitive to changes in monsoon rainfall, which makes it more susceptible to water shortage in the event of prolonged dry seasons. This seasonal disparity has significant consequences on irrigation, agriculture and domestic water consumption in the downstream areas. The trendline analysis further reveals a consistent long-term decline in maximum discharge at both Kaunia and Dalia stations. This indicates an increasing HILOW condition, suggesting that the river is becoming more hydrologically unequal, with water availability concentrated in the monsoon season. This finding is consistent with Mondal and Islam (2017), who reported decreasing flow in the Teesta River due to upstream regulation. Similarly, Khan (2018) demonstrated that climate variability and upstream interventions significantly affect water availability in the basin. By extending the analysis to a longer period (1995-2023) and incorporating multiple stations, the present study confirms that this declining trend has persisted and intensified in recent years. The sharp reduction in discharge after 2004, coinciding with the stabilization of the Teesta Barrage operations, further supports the influence of upstream infrastructure.

The graphs of the maximum and minimum discharge in a year show that there is a significant interannual variation, especially in the first few years of the study period (Figures 3,4,6, and 7). Such variability implies that it was high during the construction phase and the initial operating period of the barrage and then shifts to more predictable but lower discharge. This regulation has the effect of minimizing variability of natural flows, which are critical in terms of transporting sediments and stabilizing river channels.

In contrast to discharge, water level data show a consistent increasing trend across Kaunia, Dalia, Doani, and Haripur stations (Figures 8-19). The trendlines indicate that water levels frequently exceed danger thresholds during the monsoon season despite reduced discharge. This apparent contradiction suggests a decoupling of the discharge-water level relationship that strengthens the HILOW interpretation. It is influenced by sedimentation and reduced channel capacity, amplifying the imbalance between flow extremes. Similar findings were reported by Uddin et al. (2024), who identified significant morphological changes in the Teesta River due to sediment deposition and channel instability.

The increasing water levels are likely associated with channel aggradation caused by sediment accumulation. Reduced discharge limits the river's ability to transport sediment, leading to deposition within the channel and a gradual rise in the riverbed. As a result, even moderate flows can generate higher water levels, increasing flood risk in adjacent floodplain areas while simultaneously intensifying dry-season water scarcity.

Socio-economic and environmental implications of these hydrological changes are enormous. The Teesta River system is crucial in sustaining agriculture and livelihoods in the northern part of Bangladesh, and low flow during the dry season can have dire consequences on irrigation and food production. Meanwhile, the high level of water during the monsoon predisposes to flooding and erosion of the banks, which endangers the infrastructure and settlements. In general, all the graphical studies signal a shift of the Teesta River through a naturally dynamic body of water into a regulated and sediment-impacted body of water with reducing discharges and rising water levels. These trends indicate that conventional discharge water level interactions are changing as a result of upstream intervention and channel change procedures. Such transformations have important implications for flood risk, water availability, and sustainable river management, emphasizing the need for coordinated transboundary water policies and adaptive sediment management strategies. Therefore, the HILOW framework provides a simplified yet effective approach for evaluating hydrological inequality in transboundary rivers, offering insights beyond conventional flow-based analyses.

CONCLUSION

This study shows that the hydrological regime of the Teesta River has experienced a significant change in the last 29 years. Instead of being a naturally variable alluvial system, the river now has the features of a regulated and sediment-affected system, in which the magnitude of flows and the response of the channel are increasingly decoupled. The long-term flow analysis shows that there is a sharp decrease in the magnitude of flow, and the average maximum discharge is approximately 3171.75 m^3/s, with minimum discharge conditions often below 30 m^3/s showing that there is constant stress during the dry season. The integrated use of discharge and water level data demonstrates that the natural seasonal rhythm of the river has been changed due to the decreased upstream inflow and flow control. Concurrently, the reduced capacity of sediment transport has probably enhanced aggradation of the channels resulting in an increase in water level despite a decrease in the discharge. These changes have significant implications for river management. The growing asymmetry of monsoon flow concentration and dry-season scarcity is an indicator of mounting pressure on water supply, especially in downstream areas for irrigation and crop cultivation. At the same time, the high-water levels in the medium flow periods indicate the higher chances of flooding and bank instability even without extreme discharge events. The HILOW (Highest-Lowest Flow Variability) framework is an innovative strategy to gauge intra-annual flow inequality, giving a new understanding of hydrological stress in regulated rivers. In general, the results highlight that to manage the Teesta River effectively, it is important to go beyond flow-based studies and adopt a more comprehensive approach that involves flow regulation, sediment dynamics, and channel morphology. The interconnected nature of these processes will make it crucial to address them with the help of coordinated transboundary policies and adaptive management approaches that will make the basin hydrologically stable and secure in the long run.

ACKNOWLEDGMENTS

The authors express their gratitude to Bangladesh Water Development Board for logistical support during the data collection process.

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