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RESEARCH ARTICLE

ANALYSIS OF EXTREME RAINFALL AND FLOOD EVENTS: A CASE STUDY OF THE NILWALA RIVER BASIN

Rajawatta KMW*, Ranahansi HKN, and Jayaweera WMCS

Department of Biosystems Technology, Faculty of Technology, University of Ruhuna, Sri Lanka

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Abstract

The analysis of extreme hydrological events in river basins and rainfall trends is crucial for reducing vulnerability to flooding and developing flood mitigation strategies. Understanding the correlation between flooding and rainfall patterns helps identify flood-prone areas within the region, plan infrastructure, and improve early warning systems, ultimately mitigating the negative impacts of future flood events and protecting communities and resources. The objective of this study was to determine the relationship between rainfall and anomalous flood occurrence in the Nilwala River Basin (NRB) using statistical analyses. The study was conducted in the southern province of Sri Lanka.While NRB is characterised by monsoon-induced flooding, an unusual flood event was reported recently. Thalgahagoda, Panadugama, Pitabeddara and Urawa represent the four main gaging stations (GS) of NRB. Water level (m) and rainfall (mm) data were collected from each GS for September, October, November, and December over four consecutive years (2021, 2022, 2023, and 2024). The study investigated differences in water levels and rainfall among stations, and the correlation between rainfall and flooding patterns, by analysing the collected data using One-way analysis of variance (ANOVA) and Duncan's multiple range test (DMRT). All stations recorded a significant increment of their highest peak water levels in 2023, compared to previous years: Thalgahagoda (1.69 ± 0.47), Panadugama (5.35 ± 0.99), Pitabeddara (1.84 ± 0.68), and Urawa (1.17 ± 0.51) indicating a potential rise in flood intensity while rapid recovery of water levels was reported in every GSs (1.15 ± 0.39), (4.40 ± 1.07), (1.22 ± 0.55) and (0.63 ± 0.34) respectively in 2024. Results revealed no statistically significant differences in rainfall amounts across the years considered, with only slight variation in mean rainfall values. However, Pitabeddara consistently recorded the highest rainfall in all three years, peaking at 26.46 ± 33.15 mm in 2023. The findings indicate that although interannual rainfall was not significant over the period considered, the downstream section of the basin has been affected by the observed anomalous flood levels. However, the results show a weaker correlation between rising water levels during flood events and consistent rainfall patterns, indicating the potential influence of anthropogenic activities. Overall, the study emphasizes the urgency of enhancing flood management strategies and investigating potential anthropogenic factors, particularly in flood-prone areas such as Thalgahagoda and Panadugama.

Keywords: Flood Risk, Flooding Trends, Nilwala River Basin, Rainfall, Water Level

INTRODUCTION

Climate change is one of the challenging ecological phenomena of the twenty-first century. (Dietz, Shwom and Whitley, 2020). The scientific community widely studies climate change because it is a major global problem. Most climate models indicate that precipitation extremes have intensified due to global warming (O'Gorman, 2015). A significant influence of global warming on precipitation variability is evident. Increased heating can cause higher evaporation rates. Thus, atmospheric water vapour increases due to the air's increased water-holding capacity. Hence, extreme events, such as storms, extratropical rain, and tropical cyclones, are occurring more frequently, driven by increased moisture and producing more intense precipitation trends even where total precipitation is decreasing. These factors can lead to frequent floods (Trenberth, 2011).

Corresponding author: wathsala@btec.ruh.ac.lk

Floods can have severe impacts through various pathways, including substantial property losses, damaged infrastructure, economic disruption, and increased risk of disease outbreaks, which directly affect public health (Louw *et al.*, 2019). Urban floods are intensified by rapid urbanization, which has disrupted transportation networks, hindering daily functioning and recovery potential (Ji *et al.*, 2022). Therefore, flood conditions are strongly linked to climate change, with global warming intensifying flood risks worldwide. There is a complex relationship between floods and climate change, which is a critical area of study (Burn and Whitfield, 2023).

In Sri Lanka, flooding is a common and recurrent phenomenon which is heavily influenced by monsoon-induced rainfall during the two main monsoon periods, namely, the Southwest (May–September) and the Northeast (November–February) monsoons (Alahacoon *et al.*, 2018). Flood-induced property damage, infrastructure damage, and fatalities have been reported every year (Abeysiriwardana and Wijesekera, 2022). Thus, the analysis and identification of flood patterns are crucial for mitigating negative environmental impacts.

The Nilwala River Basin (NRB) was the study area, originating in the wet zone highlands of Panilkanda in Deniyaya. Thus, NRB flows from an altitude of about 980 m, passes through different terrain, and finally falls into the sea of Thotamuna. The river's flow pathway ranges from higher altitudes to gentle slopes, covering both rural and urban areas, including Bopagoda, Akuressa, Kadduwa, and Matara (Ratnayake *et al.*, 2010). The NRB is frequently flooded due to extreme rainfall and other geographical factors. The studies have shown that the basin experiences frequent flooding during the southwest monsoon and second inter-monsoon periods, impacting water availability (Panditharathne *et al.*, 2022). The area receives considerable rainfall throughout the year, with average annual rainfall ranging from above 3000 mm in the upper river basin to 1900 mm in the lower river basin (Ratnayake *et al.*, 2010). Although this NRB area is generally affected by floods during the monsoon seasons, particularly the southwest monsoon, continuous flooding was observed in 2023 compared with the previous two years (Disaster Management Centre, Sri Lanka, 2023). Because of this uncertain situation, there were negative impacts on people's daily lives, as well as significant damage to paddy cultivation and other plantations, such as cinnamon and tea. These factors emphasized analysis of the flood patterns in this area and determination of root causes.

Flooding phenomena are strongly related to meteorological factors, especially precipitation, the primary driver of these events. Hence, it is necessary to study its meteorological causes to understand the flooding as an ecological phenomenon (Breugem *et al.*, 2020). In contrast, anthropogenic factors have primarily affected recent flooding conditions, rather than meteorological causes (Stefanidis and Stathis, 2013). It is crucial to identify the core issue in a flooding phenomenon. This study focuses on understanding the root causes of this recent anomalous flood occurrence in NRB.

Here, the analysis has utilised readily available secondary data, such as water level and rainfall data, which are published and updated by the disaster management centre in Sri Lanka. Ultimately, the study aims to determine the relationship between rainfall and anomalous flood occurrence in the Nilwala River Basin (NRB) using statistical analyses. The findings will support the identification of the factors for this flood condition and the development of targeted flood mitigation strategies for the NRB and other flood-prone regions in Sri Lanka.

METHODOLOGY

The NRB is in the Matara district; the basin covers Sri Lanka and 90% of the district's area (Madhushani *et al.*, 2024). The area of the basin is approximately 1032 km² in area and 72 km in length, with an altitude ranging from 0 to 950 m above mean sea level, and situated between latitudes 5.8–6.4° N and longitudes 80.4–80.7° E. (Bandara, 2024). The NRB contains four major gauging stations (GSs): Thalgahagoda, Panadugama, Pitabeddara and Urawa, which are established and maintained by the Hydrology and Disaster Management Division of the Department of Irrigation, Sri Lanka. Here, Thalgahagoda and Panadugama represent the basin's downstream regions, whereas the upper basin is represented by Pitabeddara and Urawa (Department of Irrigation, 2019).

Hydrological data, including river water levels (m) and 24-hour rainfall (mm), were collected from the Sri Lankan Disaster Management Centre website under the category "River Water Level and Flood Warning." programme. Flood conditions were classified based on predefined water-level thresholds set by the irrigation department of Sri Lanka. According to these thresholds, flood conditions are categorised into four levels: normal, alert, minor flood, and major flood (Disaster Management Centre, Sri Lanka, 2023). Geographical coordinates, drainage areas and threshold values for each GS are given in Table 1.

Table 1: Geographical coordinates, drainage areas and threshold values of main gaging stations in NRB

Station	Coordinate	DA (km^2)	Threshold Values		
			Alert (m)	MnF (m)	MjF (m)
Thalgahagoda	(6°00′40″N, 80°31′35″E)	852	1.4	1.7	2.8
Panadugama	(6°06′30″N, 80°28′40″E)	445	5	6	7.5
Pitabeddara	(6°12′47″N, 80°28′31″E)	310	4	5	6.5
Urawa	(6°14′12″N, 80°34′18″E)	59	2.5	4	6

DA: Drainage area, MnF: minor floods, and MjF: Major flood
Values below the alert levels are considered normal water levels; if they exceed the defined water levels, they are categorised as the relevant flood levels

Hydrometeorological data were collected from each GS for September, October, November and December in the following years: 2021, 2022, 2023, 2024 (n = 1076 data points). Because the disaster management center continuously published flood warnings during this period, both water level and rainfall were analysed separately. The data set was comprehensively analysed using Minitab 19 (Minitab LLC, USA). A time series plot was created for each GS, month-wise and year-wise, to represent the fluctuations visually. At the same time, the study assessed whether statistically significant differences exist in water level measurements across the four selected years using a one-way ANOVA and DMRT. A Spearman's correlation analysis was conducted to determine the relationship between water levels and rainfall. A confidence level (p) of 0.05 was assumed for the analysis.

RESULTS AND DISCUSSION

Identifying the key drivers of anomalous flood events is essential for mitigating adverse effects in the area and maintaining socio-economic balance within the region. Flooding is a recurrent phenomenon in NRB due to its geographical location within the lowland wet agro-ecological zone, which is characterised by relatively intense rainfall throughout the year (Kumara, 2022). A statistical analysis of rainfall and water levels recorded in this river period (2021-2024) was conducted to determine whether rainfall positively affects the rapid increase in water levels observed in 2023. Abdulkareem and Sulaiman (2016) determined the maximum, minimum, and mean precipitation as part of data quality control and, accordingly, identified the highest and lowest values in the data. Matveevich (2023) compared the four meteorological stations using the average monthly total temperature across all years and identified differences in maximum temperature among the stations. Similarly, the maximum, minimum, and mean water-level values were determined at each GS in NRB.

According to the descriptive analysis, a considerable increase in both average and maximum water levels was observed in 2023 compared to the previous two years across all GSs (Table 2). The average water level provides a general indication of the typical water conditions at each station for a given year. Panadugama GS exhibited the highest mean and maximum water levels among the major stations (Table 2).

Table 2: Comparison of water levels (m) from 2021 to 2024

Station	Maximum				Minimum				Mean(m)			
	2021	2022	2023	2024	2021	2022	2023	2024	2021	2022	2023	2024
Thalgahagoda	1.76	1.66	2.92	1.95	0.43	0.33	0.50	0.44	1.19	1.06	1.69	1.15
Panadugama	6.34	6.11	7.24	6.58	2.76	2.76	3.09	0.60	4.39	4.30	5.35	4.40
Pitabeddara	2.38	2.90	5.29	4.07	0.50	0.69	0.82	0.67	1.25	1.37	1.84	1.22
Urawa	1.45	1.65	4.44	1.81	0.09	0.10	0.50	0.16	0.61	0.63	1.17	0.63

The column called maximum shows the highest water level recorded at each station for each year. Column called minimum represents the lowest water level recorded, and column "mean" represents the average water level recorded in each year

Furthermore, temporal variability graphs visually represent the observed flood variation, with the 2023 data series showing a noticeable deviation from other years. In addition, Thalgahagoda and Panadugama exhibited more frequent fluctuations in 2023 than Pitabeddara and Urawa (Figure 1). In contrast, the upstream stations, Pitabeddara and Urawa GSs, contributed less to the flood anomaly in NRB by maintaining mean water levels near normal, at 1.84 m and 1.17 m, respectively, in 2023.

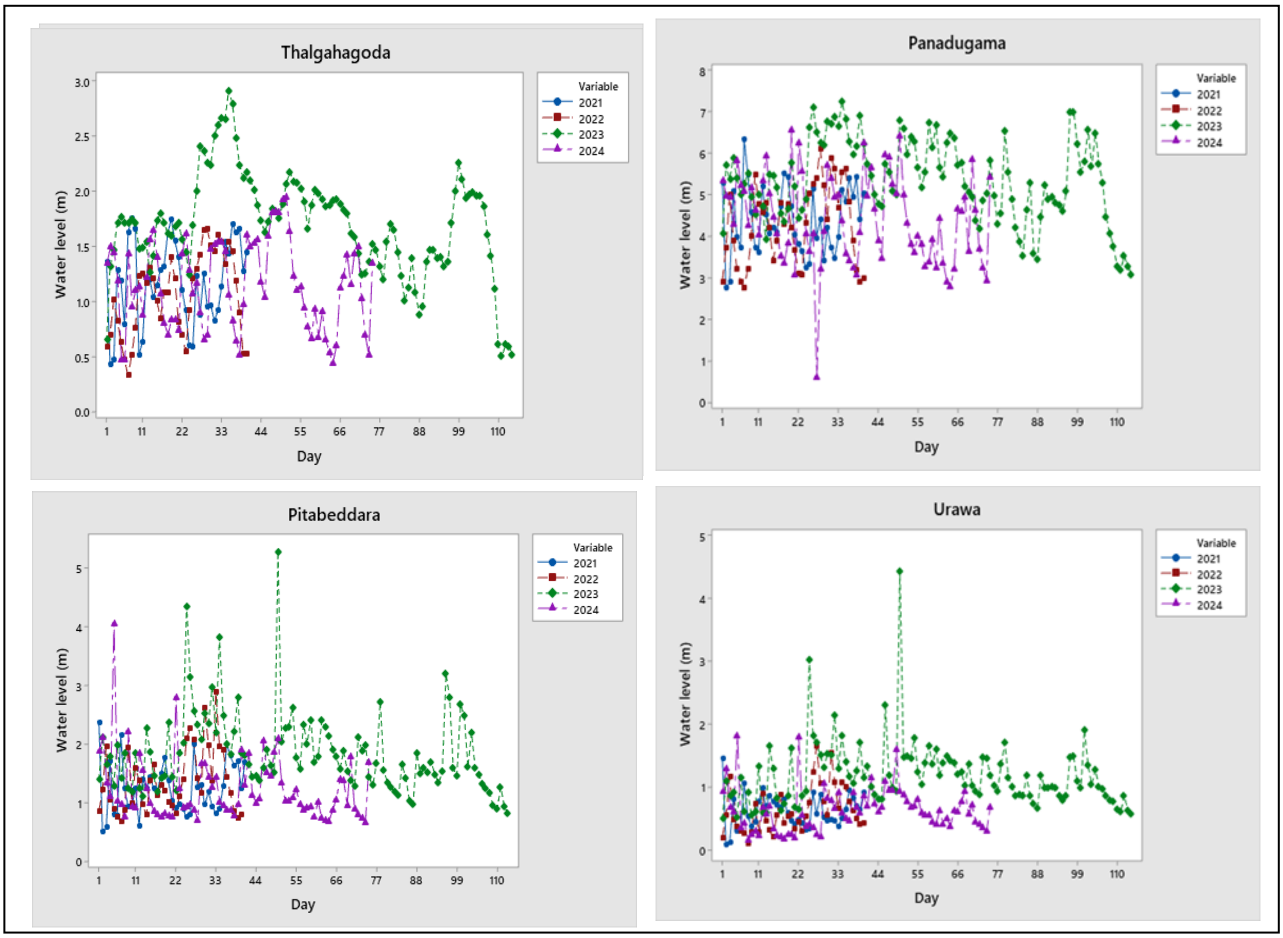

Figure 1: Temporal variability of water levels in main gaging stations from 2021 to 2024

Although Thalgahagoda GS has the largest drainage area (852 km^2), a significant increase in water level ($p < 0.001$) was recorded in 2023, exceeding the major flood level (Table 3). Similarly, Panadugama, Pitabeddara, and Urawa stations exhibited significant differences ($p < 0.001$) in water levels in 2023 compared to the previous two years. However, the maximum water levels across all GSs remained at minor-flood levels in 2023. Interestingly, both the mean and maximum flood levels declined to normal water levels in 2024 at all GSs (Tables 1 and 2).

Table 3: Mean water levels (m) recorded at the four gaging stations during 2021-2024

Station	2021	2022	2023	2024
Thalgahagoda	1.18 ± 0.38^b	1.06 ± 0.38^b	1.69 ± 0.47^a	1.15 ± 0.39^b
Panadugama	4.39 ± 0.82^b	4.30 ± 0.97^b	5.35 ± 0.99^a	4.40 ± 1.07^b
Pitabeddara	1.25 ± 0.45^b	1.37 ± 0.55^b	1.84 ± 0.68^a	1.22 ± 0.55^b
Urawa	0.61 ± 0.27^b	0.63 ± 0.37^b	1.17 ± 0.51^a	0.63 ± 0.34^b

Values are presented as mean ± standard deviation. Means within the same row that differ by letters are significantly different at $p < 0.05$ according to DMRT

Similarly, Tingsanchali and Promping (2022) have collected daily water levels from two GSs and analysed household-level flood hazard and vulnerability in the upper Nan River Basin, Thailand. The study suggests that flood vulnerability can increase from upstream to downstream along the riverbank. Further, precipitation variability, higher population, lower elevation, and greater distance from the river have been identified as contributing factors to the flood conditions.

Moreover, it is crucial to assess catchment characteristics in a basin to identify the root causes of anomalous streamflow, including topographic conditions, soil type, vegetative cover, and land-use data (Satriagasa, Tongdeenok and Kaewjampa, 2023). In the NRB, both upstream catchments (Urawa and Pitabeddara) have similar catchment characteristics, which reduce the flood vulnerability. Land use for homesteads is below 50% of the total area of both catchments. Also, the forest cover area (35%) in Pitabeddara exceeds the homestead percentage. Sandy-textured soils dominate both sub-catchments, covering about 55% of the catchments and other soil types are distributed in similar proportions comparatively (Dissanayake and Wickramaarachchi, 2025). Canopy cover naturally contributes to flood mitigation by enhancing rainfall interception and regulating throughfall, which reduces the volume and rate of surface runoff (Cochran, Clark and Lalor, 2005). On the other hand, sandy-textured soils facilitate greater infiltration and groundwater recharge, due to their high permeability. Therefore, it reduces surface runoff generation and mitigates flood occurrence (Ali *et al.*, 2021). Downstream stations are characterised by lower vegetation cover, high population density, and the absence of infrastructure for flood mitigation (Panditharathne *et al.*, 2022). Therefore, these regions are highly susceptible to flood anomalies, according to this study.

On the other hand, Selvarajah *et al.* (2021) identified precipitation as a key driver for developing an integrated approach to assess the hydrometeorological characteristics of the Mahaweli River Basin, Sri Lanka. They used daily rainfall data from 32 stations within the basin.

Mean monthly precipitation and daily mean precipitation were compared and analysed statistically with observed data to ensure the statistical significance of the precipitation occurrence (Rajawatta *et al.*, 2014). Yang *et al.* (2010) analysed precipitation extremes at 42 stations in the Pearl River Basin, China, using a 5% significance level. The results indicated no significant differences in precipitation extremes across 40 stations, whereas 2 stations showed statistically significant differences. Similarly, these results reveal that the four primary GSs showed no significant difference ($P > 0.05$) in rainfall records over the four years (Table 4).

Table 4: Mean 24-hour rainfall (mm) recorded at the four gauging stations during 2021–2024

Station	2021	2022	2023	2024
Thalgahagoda	16.9 ± 21.9^{ab}	12.7 ± 18.6^{ab}	12.7 ± 18.6^{ab}	12.2 ± 19.2b
Panadugama	20.2 ± 23.1^{a}	14.3 ± 20.9^{a}	21.1 ± 27.1^{a}	18.6 ± 27.2^{a}
Pitabeddara	24.1 ± 21.1^{a}	22.6 ± 30.7^{a}	26.5 ± 33.2^{a}	18.4 ± 35.5^{a}
Urawa	18.0 ± 16.5^{a}	21.2 ± 24.9^{a}	22.1 ± 24.3^{a}	15.6 ± 22.3^{a}

Values are presented as mean ± standard deviation. Means within the same row that differ by letters are significantly different at $p < 0.05$ according to DMRT

Moreover, the rainfall patterns have exhibited minimal deviation across the four years, despite elevated overall precipitation levels (Figure2).

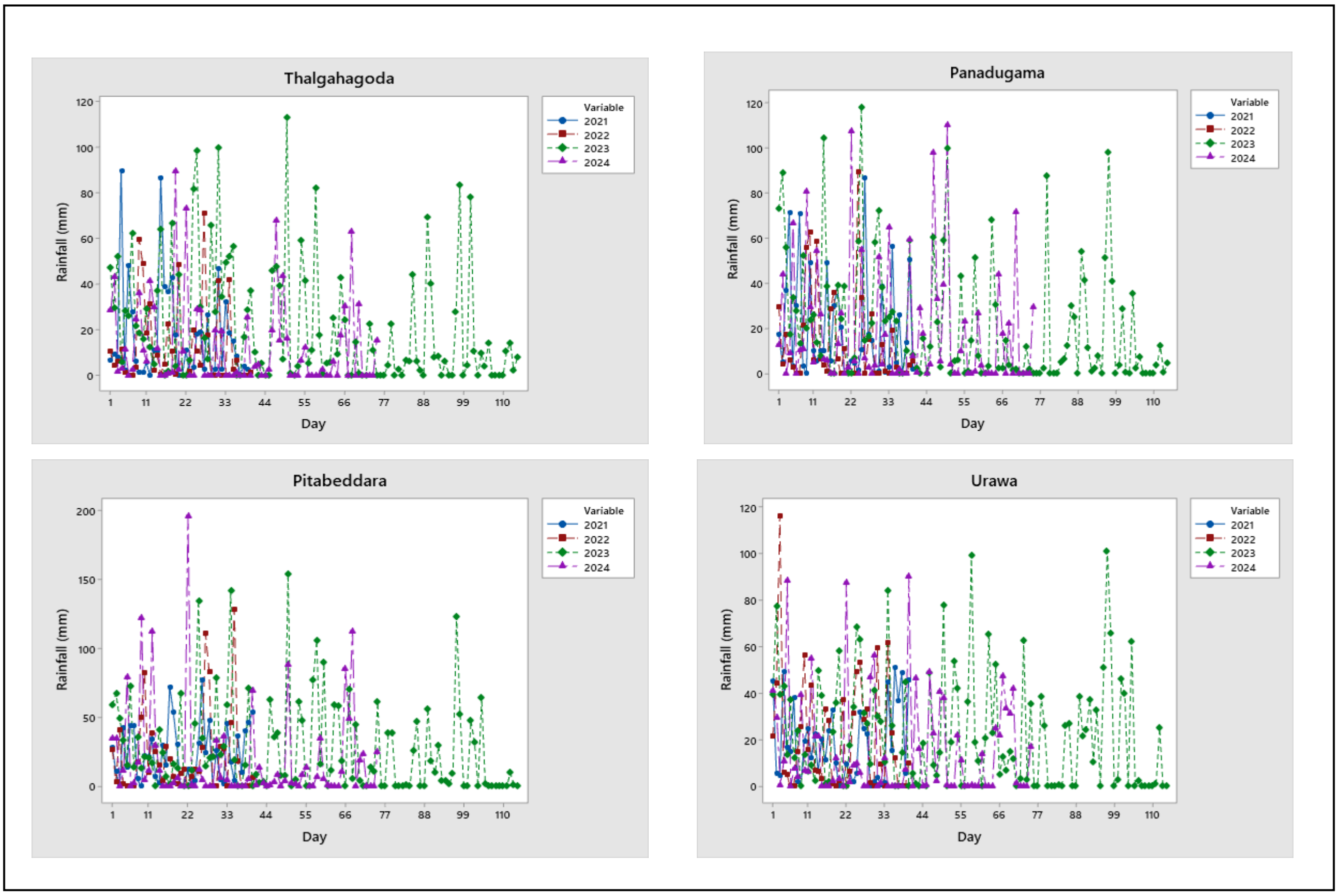

Figure 2: Temporal variation of rainfall in main gaging stations in 2021,2022,2023,2024 years

A weak but statistically significant positive correlation is observed at Thalgahagoda ($r = 0.198$, $p < 0.05$) and Panadugama ($r = 0.344$, $p < 0.05$), suggesting a slight influence of rainfall on water levels. A moderately strong positive correlation ($r = 0.470$, $p < 0.05$) was observed at Pitabeddara station, while Urawa exhibited the strongest correlation ($r = 0.559$, $p < 0.05$), indicating that rainfall significantly impacts water levels at this station (Table 5). Overall, the correlation has weakened in Thalgahagoda and Panadugama compared with the Pitabeddara and Urawa stations, which are the main GSs of the upper NRB. River basins can exhibit significant water-level increases without a corresponding increase in rainfall due to various hydrological factors (Shokory, Tsutsumi and Sakai, 2016). In the cross-river basin in southeastern Nigeria, downstream sections showed significant water levels with minimal correlation with rainfall during monitoring. The study indicates a weak correlation between rainfall and water levels in the downstream section, whereas a strong correlation was observed in the upstream regions. Dhanapala *et al*. (2022) suggest that rainfall is not a significant factor in determining flood conditions in the NRB. This suggests that factors such as catchment size and geological features play a crucial role in water retention and discharge dynamics (Ekwere and Kudamnya, 2022).

Table 5: Correlation analysis between water level and rainfall at each gaging station

Station	Correlation coefficient (r)	Significant level (p)
Thalgahagoda	0.198	0.034
Panadugama	0.344	0.000
Pitabeddara	0.470	0.000
Urawa	0.559	0.000

Spearman's correlation was used, and the correlation is significant at the 0.05 level

Similarly, the Kosi river basin exhibited significant variations in water levels, while many river basins showed declining rainfall, indicating substantial water retention despite lower rainfall (Patel *et al*., 2021). According to the results in NRB, there is a variation in correlation between the upstream and downstream sections. These factors suggest variability in water retention and discharge across stations within the same river basin, which are key determinants of flooding conditions, alongside rainfall and certain climatological factors.

Moreover, Kumar *et al*. (2022) suggest that minimal interannual rainfall variability can occur even under high precipitation conditions. In the same way, rainfall can be significant, but interannual variability remains insignificant over short study periods, in which case, short-term water-level rise is a prominent factor to investigate (Ahmad *et al*., 2023; Alam and Majumder, 2022).

To find the core impact of uncertain flood conditions, considerable human interference is evident, including urbanisation, poor waste management, changes in land use due to building construction, and improper cropping systems, which can exacerbate short-term flood issues (Adelalu *et al*., 2021). Poor urban planning, including inadequate drainage systems that directly affect river catchment sizes and the non-enforcement of building codes, significantly contributes to flooding (Baddianaah, 2023). Also, activities such as ploughing and deforestation, without erosion control measures, accelerate surface runoff, leading to flooding and land degradation (Zuzuk et al., 2021). Ultimately, the findings need to be further investigated in relation to geographical, environmental, and socio-economic factors to identify the precise causes of the recent flood anomaly in the NRB.

CONCLUSIONS

The observed continuous flooding at the NRB in 2023 and the possible recovery of the water level within one year are statistically supported by hydrological data and demand urgent attention to identify core issues. The findings elucidate that rainfall did not directly contribute to the temporal flood condition. The weak correlation between rainfall and water levels in the downstream section, together with the strong correlation in upstream areas, suggests the influence of non-meteorological factors, which require further investigation. It is imperative to conduct a comprehensive investigation, especially in the lower catchments in the basin, on potential contributing factors such as construction activities, inadequate waste management practices, agricultural operations, and land utilisation patterns within the lower regions of the NRB.

AUTHOR CONTRIBUTION

KMW designed the experiments. WMCSJ, KMW, and HKN analysed the data and conducted experiments. HKN and KMW wrote the manuscript. KMW and WMCS reviewed the manuscript, and HKN revised it. All authors have read and approved the manuscript.

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