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Impact of Morphometric Parameters on Flood Susceptibility in the Teesta River Basin, West Bengal

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Abstract
Flooding is one of the most recurrent natural hazards affecting the Teesta River Basin in West Bengal, causing extensive damage to life, property, and infrastructure. The present study examines the impact of morphometric parameters on flood susceptibility within the Teesta River Basin using geospatial techniques. Morphometric characteristics such as drainage density, stream frequency, bifurcation ratio, basin relief, elongation ratio, and form factor play a crucial role in controlling runoff behaviour and flood generation. Using digital elevation models (DEM) and GIS-based spatial analysis, the basin was delineated into sub-watersheds, and linear, areal, and relief morphometric parameters were computed. These parameters were integrated to assess flood susceptibility across different sub-basins. The results indicate that sub-watersheds characterized by high drainage density, high stream frequency, low elongation ratio, and steep relief exhibit greater flood susceptibility. The lower reaches of the Teesta River Basin in West Bengal are particularly vulnerable due to combined effects of morphometry, monsoonal rainfall, and anthropogenic interventions. This study highlights the significance of morphometric analysis as a cost-effective and reliable tool for flood risk assessment and watershed-level planning. The findings can assist planners and policymakers in formulating flood mitigation strategies and sustainable river basin management plans.

Keywords: Morphometric analysis, Flood susceptibility, Teesta River Basin, GIS, Watershed prioritization

1. Introduction

One of the common and most devastating types of natural hazards occurring in the river basins in South Asia is flooding the Himalayan and sub-Himalayan regions. These areas have a complex geomorphology and a high amount of monsoonal rainfall, sensitive geology, and rapidly changing land-use that contribute to the risks of floods. The Teesta River Basin, a vast transboundary river system having its source in the eastern Himalayas and discharging to Sikkim and West Bengal to Bangladesh, is a good example of a river basin, which is inclined to floods and, in addition, where both natural and man-made factors interact to increase hydrological risks (Sarkar et al., 2022; Mitra et al., 2024).

The West Bengal region of the lower basin of Teesta River is prone to seasonal floods and has created severe socio-economic and environmental impacts. Most common effects of floods include loss of life, riparian population, agricultural land, infrastructure failure, and enhanced erosion of riverbanks. The situation has been even more problematic in the recent decades with the change in the rainfall patterns, the aggradation of the sediments, and the failures of the embankments, not mentioning the unplanned human actions in the floodplain (Das et al., 2022; Das, 2023). The physical controls of the flood behavior of this basin are therefore extremely important in the appropriate assessment of the flood risks, and to the mitigation planning.

One of the many physical factors of the flood is basin morphometry that is critical in the regulation of the production of run off, concentration of the flow, and drainage effectiveness. Morphometric parameters are quantitative indices of drainage network structure, basin morphology and relief morphology, which may provide crucial data as to the hydrological conduct of a watershed when precipitation falls. The size, time and span of flood peaks are influenced by its parameters such as drainage density, stream frequency, ratio of bifurcation, stream elongation, form factor as well as basin relief (Biswas and Chakraborty, 2016; Kumar et al., n.d.). High surface runoff caused by high density of the drainage system and steep relief in the watersheds generally causes high vulnerability to floods, but flow concentration and propagation of flood waves is determined by the form of the basin.

Recent advancements in remote sensing and Geographic Information Systems (GIS) have resulted in the fact that morphometric analysis increased its accuracy and efficiency significantly. Morphometric evaluation is an effective, inexpensive, and reliable instrument, especially in the data sparse regions, such as the foothills of the Himalayas, which may be successfully implemented using high-resolution digital elevation models (DEMs) to identify drainage networks and basin characteristics (Poddar et al., 2022). Consequently, morphometric analysis has been widely applied in ranking watersheds in regions with soil erosion, flood prone mapping, and watersheds where rivers like the Teesta exist (Sarkar et al., 2023; Sonker et al., 2023).

Though extensive literature has been formulated on the risk of flooding in the Teesta River Basin, a large portion of it has been done on the upper reaches of the Himalayas or multi-criteria methods, which are land use, rain, and socio-economic. An analysis of the direct impact of morphometric parameters on the flood susceptibility of the West Bengal segment of the basin has relatively minor literature. As a result of the increased frequency and intensity of floods in this region, more specific morphometric analysis is needed to identify weak sub-watersheds and the geomorphic influence on floods.

In this connection, this paper shall consider the influence of the morphometric parameters on the flood vulnerability of Teesta River Basin, West Bengal through the GIS techniques. The study will contribute to enhanced understanding of the flood dynamics and make a sound decision to control the sustainable river basin after considering the linear, areal, and relief of morphometric properties at the sub-watershed scale.

2. Literature Review

Over the years, the morphometric analysis has come to be regarded as a scientific and quantitative method of comprehending the hydrological behavior of river basins as the basis of the assessment of flood susceptibility. Morphometric parameters are geometries of the drainage systems and properties of the basin that directly regulate the runoff, the velocity of the flow, and the intensity of the flood. The parameters are more significant in the Himalayan river systems and sub-Himalayan river systems like the Teesta due to steep slope, tectonic movement and intensity of rainfall and active channel behavior.

Among the earliest comprehensive studies were conducted by **Biswas and Chakraborty (2016)** in the north (West Bengal) with its focus on the watershed prioritization based on the geo-morphometry and land-use parameters in the watershed of Neera. Their attempts demonstrated that the density of drainage, ratio bifurcation and relief parameters are very effective in controlling the surface runoff and risk of floods. The article has pointed out that watersheds of the high drainage density and relief are more susceptible to quick development of a run-off and can be subjected to floods and erosion. Based on this background study, it was ascertained that morphometric methods are relevant to flood related works in the Himalayan foothill regions of West Bengal.

In the case of working on morphometric research of the Teesta River Basin of the West Bengal and the Sikkim regions, **Sarkar et al. (2022)** employed hazard degree (HD) and principal component analysis in the form of a weighted sum method. They analyzed the rating that high frequency stream, density and ruggedness sub watersheds of the drainage are more numerous in flood risk. By including morph metric parameters in a composite flood hazard system, the authors were able to demonstrate the usefulness of morphometry-based prioritization in flood risk management. The findings of their research apply to the present study as it shows the spatial variation of the flood prone area of Teesta Basin.

Poddar et al. (2022) employed a subjective multi-criteria decision-making (MCDM) model that assumes the use of geospatial to model the degree of flood vulnerability within Teesta River Basin in West Bengal. Although their methodology has put into consideration various environmental variables, morphometric parameters were concluded to be major control mechanisms of flood prone areas. This paper has pointed out the impact of the basin shape, density of drainage, and the stream order on the concentration of the runoff and magnitude of flooding. The authors concluded that morphometric analysis combined with GIS provides an effective paradigm of flood susceptibility mapping.

Das (2023) examined the hydrological changes and the adaptation strategies of the rural people in the lower Teesta River Basin in West Bengal. Though the socio-hydrological were given priority, the study did not overlook the fact that the morphometric features of the basin (low gradient floodplains and complex drainage systems) enhance the impacts of floods. Combined with the failures of embankment, sedimentation, morphometric constraints add to the intensity and the frequency of floods along the lower basin as Das highlighted. This research brings the human element to the morphometry-driven flood processes.

The article by Sarkar, Sarma, and Gayen (2023) concentrated on the Erosion and Watershed prioritization by examining the multi-criteria decision-making methodologies of the sub watersheds of Teesta River in Sikkim and West Bengal. They found that the morphometric parameters are highly correlated with soil erosion and areas prone to floods. The ratio of high relief, ruggedness, number, and drainage density were observed to be significant pointers of hydrological unsteadiness. The article in question reinforced the idea that morphometric parameters can be successfully applied as the proxies in the evaluation of the flood risks in mountainous river basins.

The upper Teesta River Basin morphometric and neotectonics study by **Sonker, Tripathi, and Singh (2023)** was conducted using the methods of geospatial. Their research established that tectonic activity might significantly cause drainage patterns, stream alignment, basin asymmetry; therefore, flood behavior. The high values of the bifurcation ratios and abnormal drainage patterns were associated with structural controls which intensify the incidence of flood when there is an extreme rainfall. Despite the interest it shows in the upper basin, the work is an informative account of geomorphic actions that can have an impact on the flood regime through the Teesta system.

To the area of flood effects, **Mitra, Das, and Mandal (2024)** developed a geospatial model of the floods in Teesta River and approximated its impact on individuals residing in the riverbanks in eastern India.

They analyzed using the focus on the fact that the frequency of flooding is high in the regions of low relief and high density of the drainage system and channel instability. The authors have pointed out that along with the analysis of the frequency of floods, the parameters of morph metrics can be used to determine high-risk regions effectively and help with disaster management planning.

The usefulness of morphometric analysis can also be improved by comparing the Himalayan rivers. **Kumar et al. (n.d.)** compared the impact on morphometry of Chenab and Teesta rivers and made a conclusion that the geometry and relief of the basin is the main determinant of hydrological reaction. They compared them and found that the long basin and steep upper parts of the Teesta are the sources of fast development of run off and floods along the river.

The knowledge of the Teesta system is assisted by other works elsewhere. Hossain and Mumu examined lower Teesta River Basin of Bangladesh which is a flood prone area using GIS and remote sensing. Their findings showed that morphometric features of the drainage density and slope of the basin are a large predictor of flood inundation patterns, which supports the applicability of morphometric regulating the flood patterns across boundaries.

Bibi et al. (2025) relied on more recent geomorphometric analysis of the Teesta and Dharla river basins to emphasize the contribution that the basin morphometry makes to the hydro-logical extremes. In their GIS-based study, they found that high relief regions and structurally controlled drainage systems have a relationship with high flood risk.

Overall, the literature review allows for concluding that morphometric parameters are highly significant factors to determine the risk of floods in the Teesta River Basin. However, most of the studies use multi-factor models or focus upon the upper basin dynamics. A sub-watershed-based assessment of the morphometric regulators in relation to the vulnerability to floods in the West Bengal portion of Teesta Basin is insufficient. The gap in the current research is that it undertakes a systematic study of the morphometric parameters and their direct impact on the flood susceptibility in GIS-based research.

Research Gap

Although there have been increased flood susceptibility and morphometric analysis literature on the Teesta River Basin, there are certain gaps in research particularly with regards to the portion of the West Bengal basin. The existing studies have been significant to the body of knowledge about the flood hazard through the geomorphetric, hydrological, and geospatial approach but the shortcoming is identified by the scope, scale and methodological orientation which would involve additional research.

First, most of the previous investigations have been carried out in the upper Teesta River Basin specifically in Sikkim wherein steep and tectonic slopes, flash floods and controls can be traced. Even though the given studies contribute to the attainment of significant data concerning the mountainous hydrological processes, the results of these studies cannot be directly applied to the Lower Teesta Basin located in West Bengal and its less steep wasteland, floodplains, aggraded sediments, and changed riverbeds. An analysis of a region specific to the geomorphic and hydrological difference between the upper and lower basin is lacking.

Second, many projects on flood vulnerability in Teesta Basin adopt such multi-criteria decision-making (MCDM) models or integrated hazard models as a combination of morphometric, climatic, land-use and socio-economic indicators. Although such techniques are comprehensive, the direct and independent influence of morphometric factors on the occurrence and spread of floods is normally hidden. It has therefore not been studied much on the actual contribution of the basin geometry, the nature of drainage networks and relief features to the regulation of flood prone areas, particularly on the sub-watershed level.

Thirdly, there is no systematic prioritization in sub-watershed (that is at the level of morphometric controls in the West Bengal section of the Teesta Basin). Most of the studies carry out the basin at a greater spatial scale that limits their use in local flood control, watershed planning, and mitigation steps. The fine-scale morphometric analysis can present the spatial variation of the susceptibility of floods, and this usually cannot be seen on the basin-wides measures.

Fourth, the comparative studies of the linear, areal, and relief parameters and the relatability of the parameters to the potential of floods have not been rightly pointed out in the literature in spite of the fact that the high-resolution morphometric analysis has been conducted using the GIS and the remote sensing. Many projects are biased selectively on several parameters without taking the aggregate hydrological values in the form of an organization's susceptibility model.

Finally, increasing impacts of human-induced activities such as embankment, the change in land-use and river management have altered the natural drainage behaviour in the lower Teesta Basin. However, the literature that expressly investigates the impact of these anthropogenically induced changes in their interaction with natural morphometric traits and their impact on the susceptibility to floods is scarce.

It is against this background that the present research will focus on providing a narrowed, GIS based study on morphometric phenomenon and its implications on flood prone regions of the Teesta River Basin, West Bengal. By insisting on the sub-watershed level analysis and isolating of morphometric controls the study ought to contribute towards making flood risk identification more accurate and should be instrumental in making effective flood mitigation planning based on regions.

3. Methodology

In the present research paper, the flood potential of Teesta River Basin, West Bengal, has been determined by a GIS-based morphometric procedure. The research setting is the lower stretch of Teesta River in west Bengal comprising Darjeeling, Kalimpong and Jalpaiguri. Methodology involves identification of basins, extraction of morphometric parameters, and the process of establishing flood susceptibility at the level of sub-watershed.

The Teesta River Basin and the sub-watersheds were delineated in a GIS environment, using common hydrological tools and in high-resolution Digital Elevation Model (DEM). The drainage networks were extracted using the flow direction and flow accumulation algorithms. Stream ordering was done by the Strahler method to establish the drainage hierarchy. Morphometric parameters were calculated and classified depending on the analysis of the drainage and basin geometry as linear, areal, and relief parameters.

The linear parameters included the stream order, stream length, and bifurcation ratio, which are the measures of complexity of drainage network and structural controls. The parameters of areal such as drainage density, frequency of streams, form factor, ratio of elongation and circularity were calculated to determine the potential on the generation of runoff basin and shape. Parameters of relief including basin relief, relief ratio, and ruggedness numbers were determined to find the steepness of the terrain and energy situations that influence the velocity of flow.

Ranking of morphometric parameters was also used to analyze the flood susceptibility considering their hydrological effects to the runoff concentration and the frequency of floods. Parameters which stimulated increment of runoff and acceleration of flow accretion received higher susceptibility ratings. The weighted morphometric parameters resulted in the creation of a composite flood prone index. Sub-watersheds were categorized as having high, moderate, and low flood susceptibility values based on the index values. To display the space visualization of the results, thematic maps were employed to facilitate easy interpretation and comparison of the results.

4. Results and Discussion

A morphometric analysis of Teesta River Basin located in West Bengal reveals that there is a marked difference in space in drainage characteristics and basin structure across the sub-watersheds determined. These variations play a significant role as far as runoff behavior and flood prone areas of management in the basin are concerned.

Linear morphometric analysis indicates that this is characterized by the existence of a well-developed drainage network with higher order streams than the other parts of the basin. Some sub-watersheds have rather large bifurcation ratios representing structural control and geological influence on drainage development. The high range of bifurcation ratios is often associated with the increased response of runoff and high potential of a peak runoff in the periods of heavy rainfall. The effect of this aspect is to enhance the exposure of the floods, particularly the sub-watersheds located to the main channel of Teesta and the large tributaries of the channel.

The susceptibility of the basin to floods is also highlighted in the areal morphometric parameters. Sub-watersheds with good drainage density as well as stream frequency dominate the lower Teesta Basin. The high density of the drainage implies that the soil is impervious with a low infiltration rate that results in surface runoff. On the same note, high stream frequency denotes high concentration channels, and this increases the velocity of the runoff to the primary river system. All this puts the APIs at high risk of being flooded during rainy seasons which are during monsoons.

The parameters of basin shape of elongation ratio, form factor, and the ratio of circularity indicate that the basins in the area under study were predominantly elongated. Long basins will tend to form long peaks of floods in comparison to short-lived flash floods and therefore the basins will be involved in a long duration of floods in the downstream areas. The morphometric structure is one of the factors that make water in floodplains of lower Teesta Basin never flow even after high discharges, water stagnates during a prolonged duration.

The relief morphometric analysis reveals that the basin has a moderate-high relief in the upstream sub-watersheds and then the relief decreases to the floodplain that is of low relief in the downstream. Sub-watersheds with high ratio of relief and ruggedness count have high slopes and are more rapid and result in rapid generation of run off and sediment movement. The aggraded sediments are present in the low aspects of the channels rendering the rivers to degrade their carrying capacity and augmenting the risk of the rivers to flood.

The inbuilt flood susceptibility index has stated that the sub-watersheds of the lower Teesta Basin belong largely to the high and moderate flood susceptibility level. These areas are the same as those depicted to be at risk of floods and places where there are frequent occurrences of embankment breakage and riverbank erosion. The results verify that the morphometric parameters are capable of successfully identifying the flood-prone areas without necessarily having to use huge volumes of hydrological information.

The findings are in line with the previous study in the Teesta Basin and affirm the significance of the drainage density, basin relief, and basin shape in the control of floods. However, the present study gives a higher degree of spatial accuracy as it pays close attention to the section of West Bengal and analysis at the sub-watershed level. It is shown that basin-specific flood management taking note of geomorphic intrinsic constraints and climatic and anthropogenic factors is important.

5. Conclusion

It is evident in the current research paper that morphometric factors affect the flood vulnerability of Teesta River Basin, West Bengal, in a strong manner. Through the analysis of linear, area and relief morphometrics scale, sub-watersheds that are inherently pre-disposed to floods in terms of their drainage network system, basin shape and topographical cues have been discovered.

Increase in drainage density, frequency of streams, high basin relief, and long basin geometry are also morphometric aspects that result in high susceptibility to flooding. This river is particularly vulnerable to the low part of the Teesta Basin, having morphometric constraints which, in combination with the monsoonal rains, sedimentation cycle, and human activities, intensify the floods. The historicity of the morphometric analysis as a diagnostic tool is because spatial patterns based on the flood susceptibility index are homogenous in historically prone regions to floods.

The paper observes the importance of morphometric assessment, which is a cost effective and data effective instrument of detecting the presence of flood risks, especially in areas with limited hydro records. The findings can be applied in assisting the planning in watershed, flood management practices, and sustainable river basin management. Hydrological models, land-use dynamics, and climate change conditions can be integrated in the future to help predict the predictive capabilities of flood susceptibility estimates in Teesta River Basin.

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