Watershed delineation in South Bengal Ganges Delta Region of Bangladesh using satellite imagery and digital elevation model

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Abstract
Coastal Bangladesh has experienced large scale changes in erosion and deposition in the Meghna Estuary and the big islands due to the Ganges–Brahmaputra-Meghna stream background. Also, the coastal area is prone to natural disasters almost in every year which creates a change in the ground water level, increases the surface water infiltration, soil salinity, and flood level. Considering these facts of the coastal area of Bangladesh, watershed delineation can contribute to proper planning and management of watershed to mitigate the surface and groundwater problems. Therefore, in this paper GIS and remote sensing techniques were used to identify the exact water course using spatial data to know the current watershed condition of the South Ganges Delta Region of Bangladesh. Here, Hydrology Toolset was utilized to analyze and identify correct watershed flow direction, network density, and confluence thresholds using digital elevation model (DEM) of the study area. The well-known D8 algorithm deployed to calculate the stream flow from each cell to its downslope neighbor and 100–1500 thresholds to determine the flow directions and transform the streams into line features for watershed network density measurement. The results showed that the length and density of the networks were proportional to the threshold. In consequence, the density of the stream network increased dramatically with the soaring of thresholds. Therefore, the results also revealed that when the convergence threshold set to 900, the extracted stream network appeared the closest to the exact water flow in the research area. It showed various sharp flows of the stream network, their length and density, as well as the convergence threshold. The findings of this study can help to quantify the watershed basin and river flow watercourses that can contribute to plan and manage future flood forecasting method of the study region.

Keywords Bangladesh · Watershed delineation · Flow direction · DEM

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Introduction

A watershed is a drainage area on the surface from which excess water is collected and distributed to connected sources through a specific outlet (Gurjar et al. 2017). Watershed had an interaction for making a limit that addresses the contributing zone for a particular control point or water outlet (Sit et al. 2019). Groundwater represented 97% of the world’s accessible freshwater assets which is also connected to fresh steam sources and widely preoccupied throughout the world (Guppy et al. 2018). In the perspective of Bangladesh, a coastal region is an area that lies between the land and seashore boundaries which make difference along with two types of lands (Hasan et al. 2021). Throughout the last 50 years, the coastal land use of Bangladesh has gone through significant changes (Parvin et al. 2017). Bangladesh is overwhelmed by the Ganges–Brahmaputra–Meghna stream framework, which conveyed a huge number of ton dregs from upstream, and stores it in the Bay of Bengal through Lower Meghna (Islam et al. 1999). As a result, coastal Bangladesh has experienced huge changes in erosion and deposition, mainly in the Meghna Estuary and the big islands (Ferdous and Rahman 2019). The southwest coastal region of Bangladesh is continuously attacked by the cyclone, salinity, storm surge, floods, sea-level rise, the social change and movement, upstream water withdrawal, and waterfront polders (Mallick et al. 2017). Therefore, this region has a huge change in the groundwater level, reduces the surface runoff, and increases the infiltration of the surface water bodies; damage drainage density and erosion of surface soil, poor vegetation quality (Ibrahim-Bathis and Ahmed 2016), salinity reducing plant growth (Romero-Aranda et al. 2001), increase in the flood hazard due to the connected effects of high river flow rates and high sea levels at the river outlet (Santiago-Collazo et al. 2019). Li et al. (2019a) indicated that watersheds were divided into the following three types: overland catchment, lake, and reservoir. Hollenhorst et al. (2007) explained seven watershed delineation approaches: three main and four are sub-watershed delineation approaches, such as hierarchically obtained watersheds, segment-sheds, complex specific watersheds, minimum area threshold, core high energy, stream interfluve delineation, and clustered stream delineation. In Bangladesh, Arefin et al. (2020) evaluated the watershed prioritization that studied using a geographic information system and remote sensing techniques for soil erosion and water quality. Accordingly, Gurjar et al. (2017) stated that rainwater drainage is the main source of drinking water in watersheds, and they played a major role in conserving runoff water from multiple sources but (Santiago-Collazo et al. 2019) extreme coastal flooding posed a significant threat to human life and infrastructure in low-gradient coastal watersheds, which could be vulnerable to flooding from both heavy rainfall and storm surge. As a result, Stein et al. (2017) attempted to determine whether the watershed seemed to be a significant case study because it contains a variety of stream types, including occurrence of flows and heavily impacted attains which are influenced by various hydrologic changes including urban runoff, flood control, and reservoir management. Correspondingly, Nichols et al. (2013) observed that stream infiltration and related downstream flow loss were rather extreme, as not only all the runoff caused on the watershed’s upper end but also affected the reservoir at the watershed’s outlet. And, Zhang et al. (2016) obtained that suitable ranges of stream water flow in terms of magnitude, rate, and frequency were also identified for the environmental flow management.

From a different research, it is known that watershed delineation helps to identify surface water features within a watershed and comprehends the downstream effects when arranging and executing water quality and amount-related assurance and relief activities (Demir and Beck 2009). With regard to the Sustainable Development Goal’s 6, target will be achieved and add value to ensure availability and sustainable management of water (Hoekstra et al. 2017), and additional targets were increasing water-use efficiency, improving water quality, better water management, reducing water pollution, protecting ecosystems, involving local communities, and strengthening international cooperation (Mraz et al. 2021). It also helped for future planning, improvement, and management of groundwater resources because groundwater played a significant role in the socio-economic improvement of watersheds (Pinto et al. 2017). Therefore, this research aims to identify the present watershed conditions in the southeastern coastal region, the Panpatti Union of Galachipa Upazila in Patuakhali District, Bangladesh by using geographic information system (GIS) and remote sensing (RS) techniques. In this research, it is going to evaluate the flow direction and flow accumulation of watershed with different threshold values using spatial data.

Methodology

Study area

The Panpatti Union is one of the southeastern areas under Galachipa Upazila, Patuakhali, Bangladesh which has direct ocean connectivity and dynamic topography, particularly water inflowing characteristics. Geographically this region is located in the tropic of cancer (Mondal and Debnath 2017) and exists between 22°4’50.53”N to 22°8’10.62”N latitude and 90°27’27.57”E to 90°25’13.70”E longitude. The mighty tidal river Bura Gauranga flowed alongside the study location, which is also a historical site of the 1971 Liberation War.
Methodological approaches

This research conducted on the study area (Fig. 1) primarily focused on GIS and RS analyses. It included the steps of determining the exact flow direction using a digital elevation model (DEM) and justifying the watershed flow in this catchment area. The 12.5-m UAVSAR DEM data (acquisition date — 08 February 2021) was collected from NASA’s designated websites (https://asf.alaska.edu/) (Fig. 2a and b) which was in post winter season because at that time mostly river had its natural flows; Landsat 8 (https://earthexplorer.usgs.gov/) and Google Earth aerial imagery were used for validation. The processing method used in this paper was predominantly Hydrology Toolbox and ESRI Arc hydro extension in ArcGIS 10.8 software. The basic steps were to analyze and identify correct watershed flow structure, network density, confluence thresholds using DEM and other data from the study region (Li et al. 2019a). Sequentially, fill, flow direction, and flow accumulation operation are mobilized by using DEM data.
The well-known D8 algorithm was used to calculate the streamflow from each cell to its downslope neighbor or neighborhoods in the backend processing of flow direction on a geographical surface (Fig. 2c and d). This technique will follow and approach the stream from each pixel to adjacent pixels using eight distinct stream angle values. The multi-D8 calculation was able to communicate various stream headings from a hub cell in a remarkable parallel manner as a result of the flat coastal topography, resulting in no confusion when multiple streams were encoded and decoded in digitized representations (Li et al. 2019a) by using an inflow direction tool. Accumulation of flow direction calculated the thresholds. For testing the exact flow of the stream, set the logic “flow accumulation < = testing thresholds” in a raster calculator. The study area is flatter as the mean sea level. For that reason, the 100–1500 thresholds were used (Li et al. 2019b) as testing parameters to determine the real flow directions and transform the streams into
line features for length calculation to measure the watershed's network density. Also, a stream definition tool from Arc hydro toolset was used for defining the type of flow. And so, the following equation (Eq. 1) denotes the network density of the research area.

Network Density = Length of Streams/Area of total Watershed (1)

The key justification method for derived watershed delineation as well as accurate stream network information was convergence threshold determination during the validation process. The exact stream flow was determined by the threshold value's variance. Using the correlation coefficient statistical formula, 100–1500 were chosen to describe the second-order derivative of the network density and actual flow direction in this paper. Finally, an observatory process was used, which included the Normalized Difference Water Index (NDWI), aerial imagery comparison, and topography such as contour validation, to ensure that the specified flow direction was as accurate as the real one. The NDWI was

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**Fig. 3** Methodological steps
primarily interested in spectral curve and hydration data from satellite band imagery. The near infrared (NIR) and green bands of satellite imagery were used to present the quantity of water on the surface, with water values ranging from 0 to 0.5 (Hasan et al. 2021). The following equation (Eq. 2) showed the Landsat 8 imagery NDWI calculation method.

\[
\text{NDWI} = \frac{\text{B}_3 \text{ (green)} - \text{B}_5 \text{ (NIR)}}{\text{B}_3 \text{ (green)} + \text{B}_5 \text{ (NIR)}}
\] (2)

The water lines extracted from NDWI then compared with aerial imagery of Google Earth to ensure that the flow direction is more reliable. On the subject of contour lines, they were formed from DEM data in topography validation, and these contour lines were represented with triangulated irregular network (TIN) by setting the contour interval 4 meters. Eventually, the full representation of methodological approaches indicated in (Fig. 3).

Results and discussions

A DEM is a useful tool for simulating natural geography and depicting a topographic surface in three dimensions. It called a mountain topography because it showed mountain-like landforms and contour lines, as well as their features, where mountains and hills occur. The elevation aspect of the research region was represented by a DEM, which had a higher value of 21 and a lower value of—78. The directional values for flow direction range from 1 to 128 as determined by the D8 algorithms. With regard to the density of the stream network, it is illustrated in Fig. 4(a). The lowest threshold of 100 obtained the network density of 5.550 (km/km²), while the network length was 116.958 km (Table 1). When the threshold was set to 200, the length and network density were figured approximately 80.830 km and 3.836 (km/km²), respectively. The length and network density were 66.608 km and 3.161 (km/km²) after rising the threshold at 300. It implied that the length and density of the network were proportional to the threshold. Yet, compared to the other higher threshold value like 1000, the gained length and network density values were showed as 33.886 km and 1.608 (km/km²). Indeed, as the threshold was soared, length and density decreased.

Eventually, when the threshold tested as the topmost value of 1500, the network length was determined at 25.907 km, and the density was 1.229 (km/km²). At 400, where the contour interval was 4, the flow direction became apparent. Since the 100 threshold was not clear in this table,

Table 1 Stream network density

| Threshold | Length (km) | Network density (km/km²) |
|-----------|-------------|--------------------------|
| 100       | 116.956     | 5.550                    |
| 200       | 80.830      | 3.836                    |
| 300       | 66.608      | 3.161                    |
| 400       | 56.945      | 2.702                    |
| 500       | 50.861      | 2.414                    |
| 600       | 46.646      | 2.214                    |
| 700       | 42.288      | 2.007                    |
| 800       | 39.314      | 1.866                    |
| 900       | 36.160      | 1.716                    |
| 1000      | 33.886      | 1.608                    |
| 1100      | 31.932      | 1.515                    |
| 1200      | 30.646      | 1.454                    |
| 1300      | 28.864      | 1.370                    |
| 1400      | 27.384      | 1.299                    |
| 1500      | 25.907      | 1.229                    |

Fig. 4 (a) Relationship between stream network density and thresholds and (b) second order convergence thresholds
the threshold was seen from 200. The density of the stream network increased dramatically with the increase of thresholds, as seen in Fig. 4(b), but the rate of soaring convergence thresholds became gentler; particularly after the threshold value of 900, channel pattern was so sharp, and the actual network was identified. Figure 5 also shows multiple flow threshold values, with 900 being the optimal flow path threshold, and value 4 denoting the river’s direct network and 3 to 1 denoting the stream’s branch and sub-branch. The relationship between density and threshold was essentially represented by the modular function $y = 73.077x - 0.553$, where the correlation coefficient $R^2$ was large at 0.997. For added assurance, compare the flow path of the mathematically measured thresholds to the topography of the sample region (Fig. 6c). Since the topography is flat and the coastal features are lower in this area, slop paths are also explicitly measured perpendicular in contour lines, and the flow path through is perpendicular to the slope. The water area calculated from NDWI matched with topographic features which was quite like the flow direction path cross-section. The sharp values as the measured exact threshold of flow direction in the study area validated using satellite imaging of water areas (Fig. 6a and b).

![Diagram](image-url)
| Reference          | Method                              | Remarks                                                                 | Results                                                                                                                                 |
|--------------------|-------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Li et al. (2019a)  | Flow direction determination        | Accurate watershed delineation for runoff and water quality simulation   | The user’s accuracy of water was 90.3%; the overall accuracy was 89.3%; and the kappa coefficient was 0.793                             |
| Hollenhorst et al. (2007) | Stream threshold delineation       | Minimum thousands used to provide summaries for a variety of anthropogenic stressors within the Great Lakes | Core watershed for immediate high-energy site watersheds and agglomerated watershed based on a minimum area threshold for a high energy site |
| Arefin et al. (2020) | Stream network determination       | PCA analysis method to simplify influencing parameters that are responsible for watershed prioritization | Maximum 215 km² basin area, 108 km perimeter, and 27.74 km basin length were detected                                                  |
| Zhang et al. (2016) | Environmental flow and statistical analysis | Stream flow regime in terms of magnitude, rate, and frequency were further identified for environmental flow management in the North River and West River | The pulse rise rate decreased by 26.9% and 61.0%, and number of reversals increased by 40.7% and 46.4% in the North River and West River, respectively |
| Demir and Beck (2009) | Watershed modeling                 | Web-based GWIS is used                                                   | GWIS delivers a comprehensive capability for watershed visualization, mapping, and resource management                              |
| Pinto et al. (2017) | Stream network delineation          | GIS, RS, and analytic hierarchy process technique used to identify groundwater potential zones in the Comoro watershed | The poor and very poor groundwater potential zone covers about 87.8% (219.5 km²) of the watershed                                           |
| Li et al. (2019b)  | River network extraction            | Convergence threshold identification method used to define the exact water flow | The convergence threshold 11,000 which is closest to the actual river network                                                          |
| Our proposed framework (hydrology delineation) | Stream network delineation          | GIS and RS techniques are used to define the exact streamflow and validate convergence threshold flow with the Normalized Difference Water Index (NDWI), topography and aerial imagery | The accurate stream flow from the convergence threshold and observation is near about 900 where the co-relation coefficient is 0.997 |

Table 2: Overview of papers using hydrology analysis with their methodologies and output.
In this part, an important review of the profound study approaches in watershed delineation for several of the articles in (Table 2) was provided. In addition, here we examined the proposed strategy with other comparable profound learning, drew a conclusion, and a conversation table had been planned (Table 2) to comprehend the effect of the proposed structure over different studies. However, in this study, satellite image, GIS and RS techniques were used to delineate watershed. This study calculated the digital elevation model (12.5 m) and watershed data utilizing GIS and DEM information to detect the exact flow direction for a hydrological examination of every watershed.

The strategy for determining thresholds of the watershed by DEM increases the watershed delineation precision. The result defined the various sharp flows of the stream network and their length and density, as well as the convergence threshold and observatory method. So, this analysis will quantify the watershed basin, ecosystem, water quality, and river flow watercourse, as well as develop the flood forecasting method in the future, allowing the community to protect their lives and property.

Conclusions

Stream networking was so challenging in the study area due to massive depressions and subtle DEM variations because the landscape was low-lying and flat. The findings showed that when the convergence threshold was set to 900, the extricated stream network was the closest to the exact water flow in the research area, and the best results were obtained, which will provide data support for the basin’s ecological security. About the fact that the watershed extraction technique used in this paper is rational and sensible, it had a few limitations that should be addressed in future research. This research suggested a method for defining the watershed using high-resolution satellite imagery — Landsat 8 and DEM (12.5 m) — as the data source for the field area. A watershed was a division of land into different types of streams and other bodies of water. In the coastal region, the Panpatti basin, a watershed was defined as a delineation of different types of streams and other water body connections and sharp flow direction. The suggested technique is appropriate for the investigative region. This modern approach is more consistent with the actual precise watershed outline than the conventional method.

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Data availability The data sets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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