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On the compilation of the bathymetric data of the bay of Bengal domain in the nodal points of triangular mesh to be compatible for the implementation of finite element method

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Abstract

This study focuses on the compilation of bathymetric data for the Bay of Bengal domain, specifically for the area between 15°N to 23°N latitudes and 85°E to 95°E longitudes, to ensure compatibility with the Finite Element Method (FEM). A high-resolution color map of the region was generated using ArcGIS software, which served as the basis for discretizing the domain into a triangular mesh. Bathymetric data for the Bay of Bengal, including the Meghna River, was then compiled using a combination of recent data from the Bangladesh Inland Water Transport Authority (BIWTA) and generated data, which were interpolated using a two-way cubic spline interpolation method. The Modified Inverse Distance Weighted Interpolation (MIDWI) method was employed to map this bathymetric data to the nodal points of the triangular mesh, ensuring accurate representation of the seafloor's varying depths. This work is essential for developing a reliable storm surge prediction model for the Bay of Bengal using FEM, as it provides the necessary geometric and bathymetric details required for precise numerical modeling.

Keywords: Bathymetric Data; Bay of Bengal; Triangular Mesh; Modified Inverse Distance Weighted Interpolation; Finite Element Method

1. Introduction

The coast of Bangladesh is frequently devastated by storm surges, causing significant loss of life and property each year. As noted in [1], an average of 5–6 storms form annually in this region, accounting for 80% of global storm surge casualties. The coastal belt of Bangladesh is particularly vulnerable due to its densely populated low-lying islands, highly curved coastlines, and significant river discharge, among other factors [2]. Developing an effective storm surge prediction model for this region is therefore essential. The shallow water equations (SWEs) are the primary mathematical framework used to develop such models, requiring numerical solutions on a coastal geometry with appropriate initial and boundary conditions that account for the major factors contributing to high surges.

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Figure 1 Colour image of the Bay of Bengal Domain (between Latitudes 15°N and 23°N and Longitudes 85°E and 95°E)

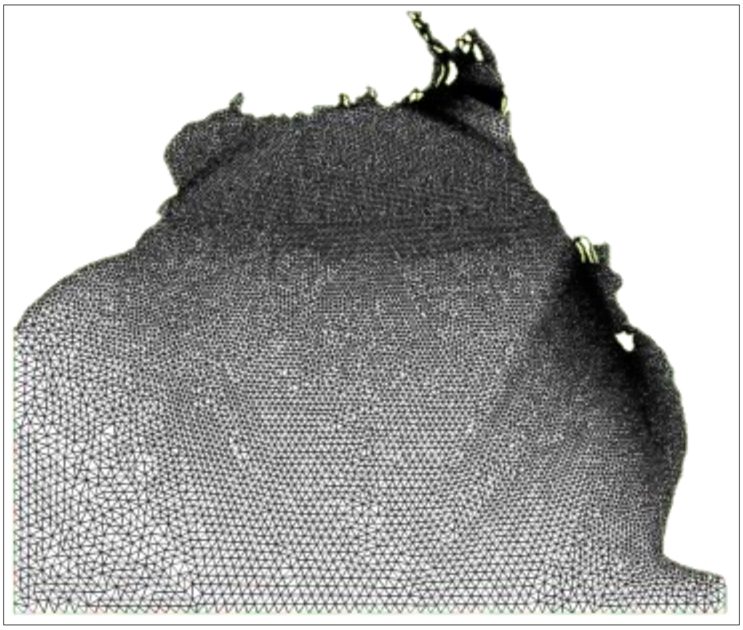

Figure 2 The Bay of Bengal Domain (between Latitudes 15°N and 23°N and Longitudes 85°E and 95°E) with triangular mesh

The geometric domain must be accurately approximated, particularly considering the numerous rivers and islands along Bangladesh's coast [1]. Previous studies have approximated the Bay of Bengal domain using Cartesian coordinates [3] and polar coordinates [4] for the implementation of the Finite Difference Method (FDM). However, FDM is more suited for rectangular or square domains, while the Bay of Bengal's domain is highly irregular. The Finite Element Method (FEM), which is more appropriate for irregular domains, allows for the use of both rectangular and triangular meshes, with the latter being more suitable for complex shapes. To accurately model the effect of islands and rivers, a higher mesh resolution is required near the coastal region than in deeper waters. While FDM would require nesting to achieve this, FEM allows for higher resolution anywhere within the domain without additional complexity.

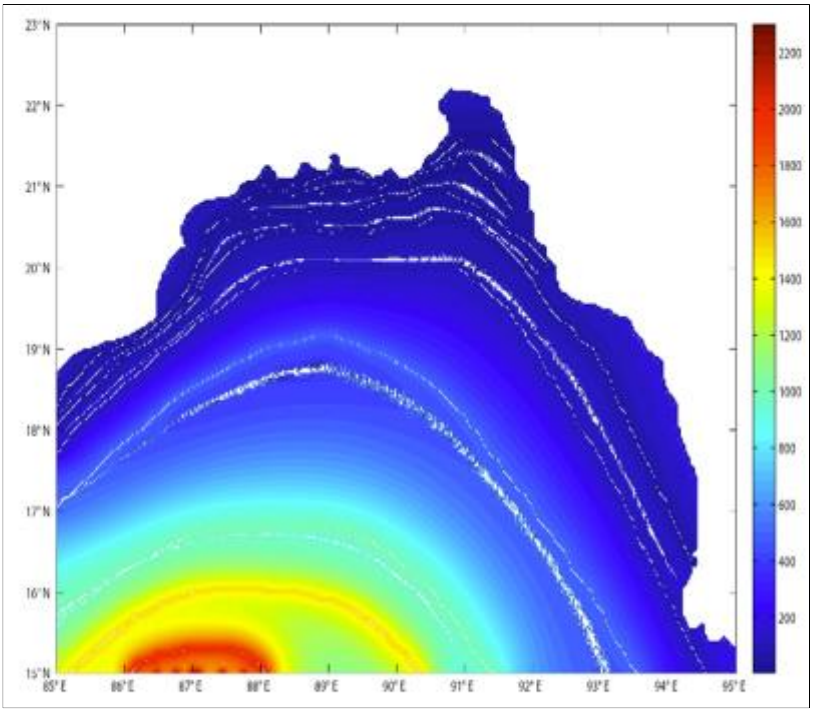

Figure 3 The bathymetry data of the Bay of Bengal Domain (between Latitudes 15°N and 23°N and Longitudes 85°E and 95°E)

Considering these factors, the Bay of Bengal domain has been approximated using a triangular mesh for FEM implementation in previous studies, though earlier approximations either neglected islands and rivers [5] or only included a few major islands [6]. For more accurate results, all major islands should be considered, as discussed in [1]. The most recent approximation [7] includes all major islands, but previous studies assumed constant water depth, which is unrealistic. The bathymetric data, which is crucial for accurate storm surge modelling, has been generated for the Bay of Bengal region [8]. The challenge now lies in accurately incorporating this bathymetric data into the nodal points of the triangular mesh. This study aims to address this challenge, ensuring the data is properly integrated for use in developing a storm surge prediction model for the Bay of Bengal using FEM.

2. Methodology

Firstly, a high-resolution colour map of the Bay of Bengal domain, spanning latitudes 15°N to 23°N and longitudes 85°E to 95°E (as shown in Figure 1), was generated using ArcGIS software. This map served as the foundational base for the study. Following the method outlined in [4], the domain was then discretized into a triangular mesh structure, which is particularly well-suited for representing complex geometries such as coastal regions with numerous curves and irregularities (see Figure 2). This triangular mesh provides a flexible framework that allows for the detailed representation of the coastline, including the islands and river mouths that characterize the Bay of Bengal.

Next, using the approach described in [8], the bathymetric data for the Bay of Bengal was generated (see Figure 3). This bathymetric data is critical for accurately representing the varying depths of the seabed across the domain, which directly influences the behaviour of water movement, especially during storm surges. Additionally, the most recent bathymetric data for the Meghna River was obtained from the Bangladesh Inland Water Transport Authority (BIWTA) to ensure that the model reflects current and accurate topographic conditions (see Figures 4–8). Incorporating this data was essential for accurately capturing the influence of river discharge on coastal flooding and storm surge behaviour.

After collecting and generating the necessary bathymetric data, the next step was to identify the coordinates of each nodal point within the triangular mesh generated for the discretized domain, as referenced in [7]. This process involved extracting precise spatial coordinates from the mesh, which are crucial for mapping the bathymetric data to the corresponding nodal points.

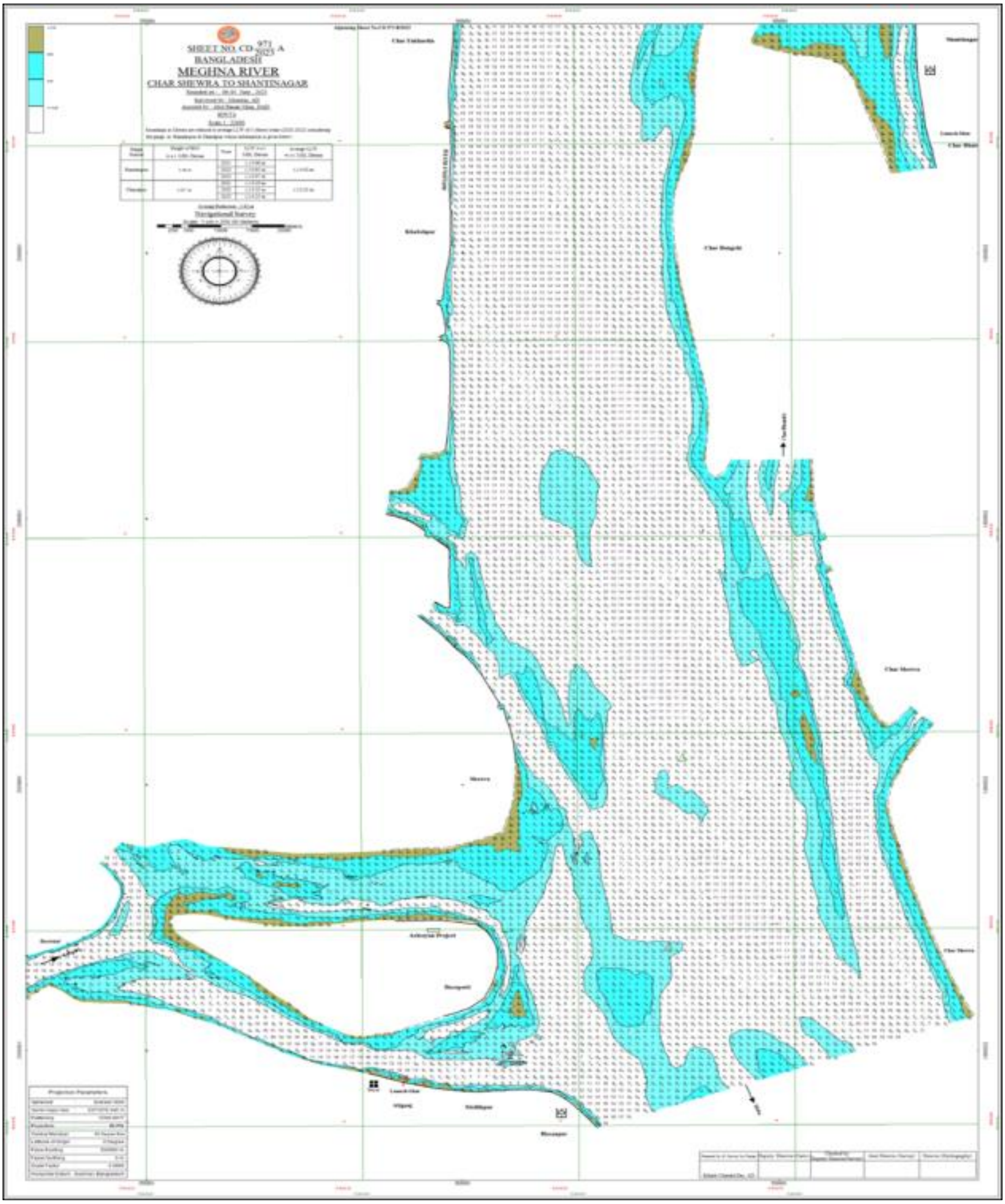

Figure 4 The bathymetry data of a part of the Meghna River (source BIWTA)

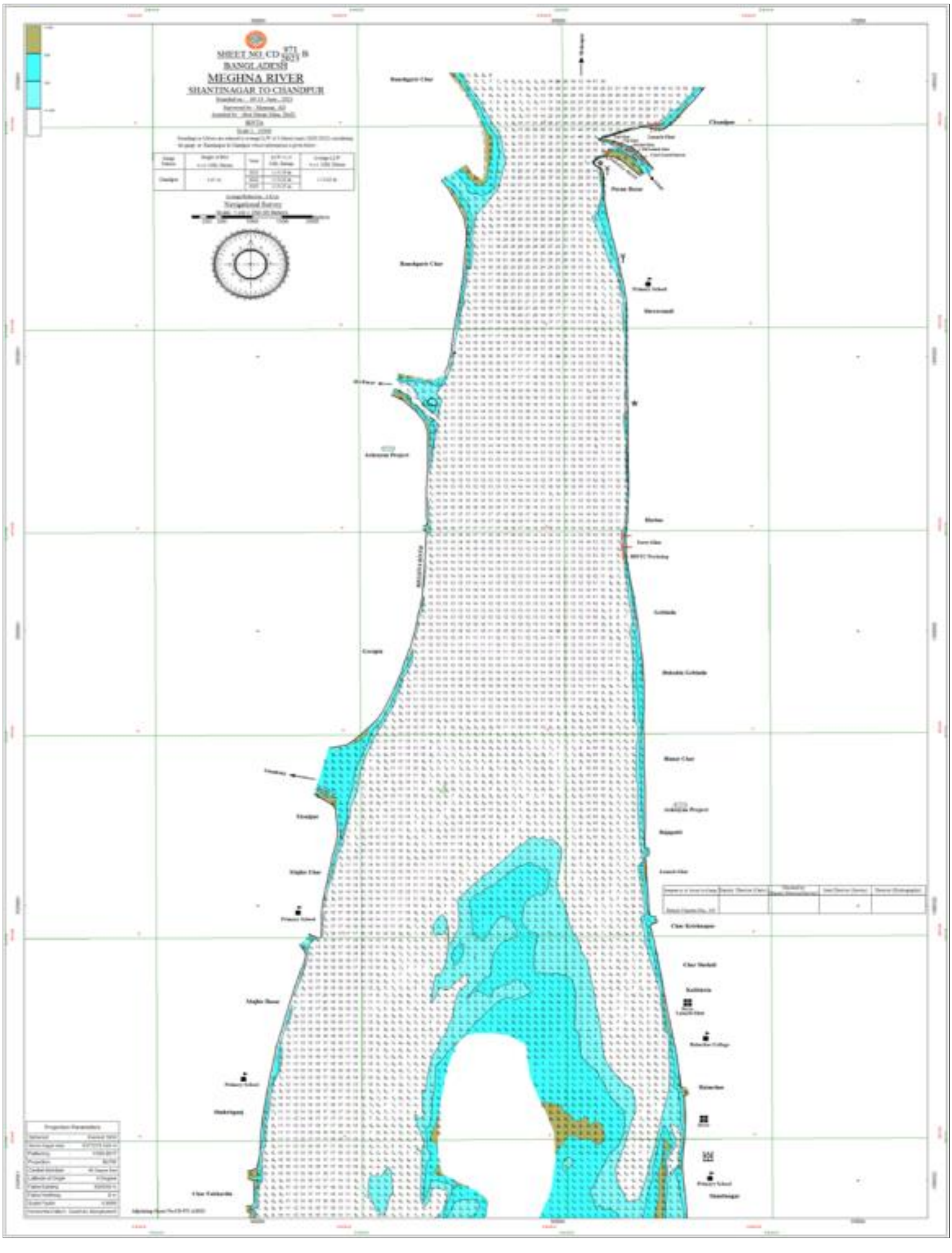

Figure 5 The bathymetry data of a part of the Meghna River (source BIWTA)

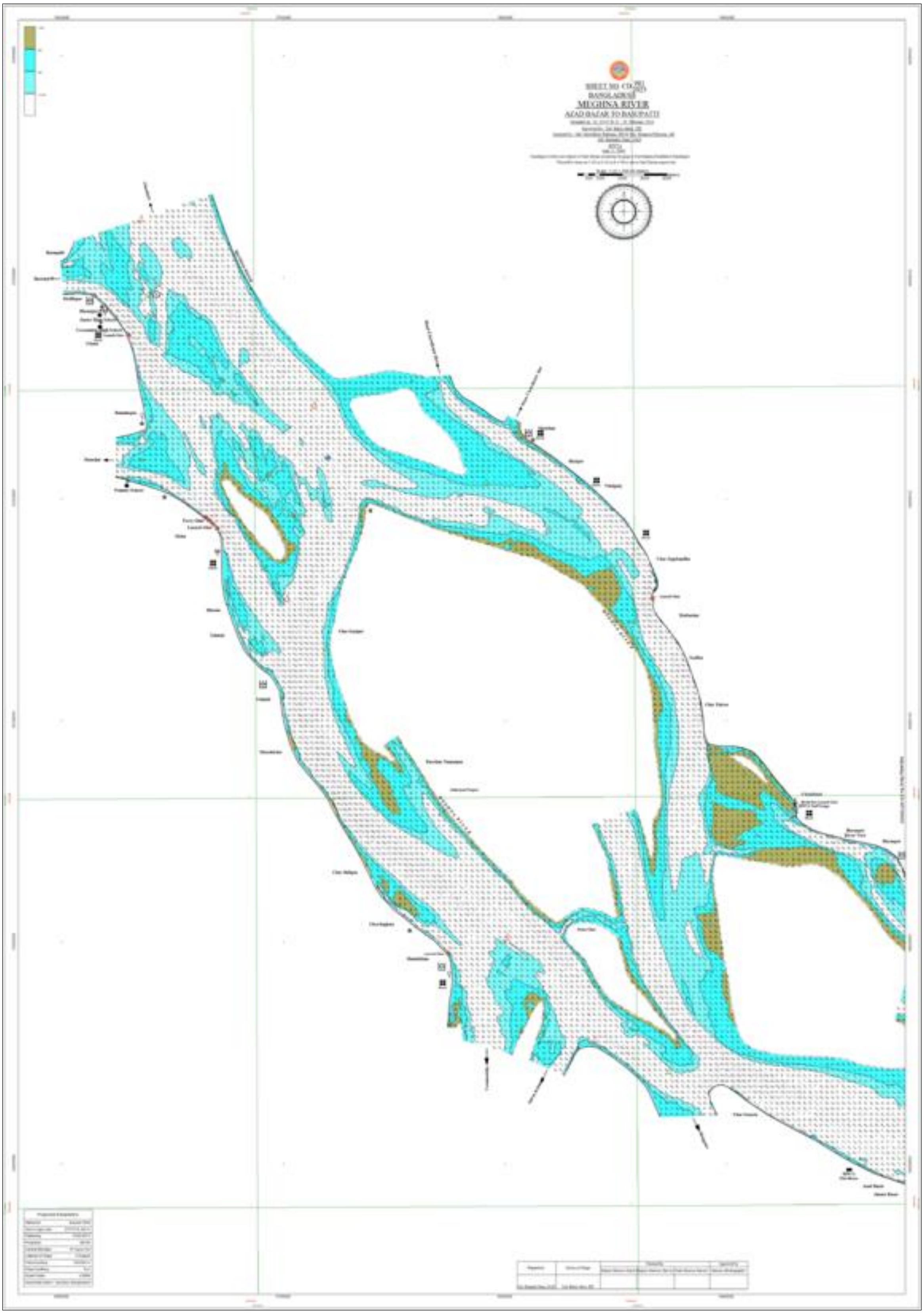

Figure 6 The bathymetry data of a part of the Meghna River (source BIWTA)

Following [9] the bottom topography of the Bay of Bengal region was recalculated using two-way cubic spline interpolation (see Figure 9). This interpolation was performed on a finite difference mesh generated across the domain, allowing for a smoother and more continuous representation of the seabed's depth variations. This step is particularly important for ensuring that depth values are accurately interpolated between known data points, reducing the potential for numerical errors in subsequent calculations.

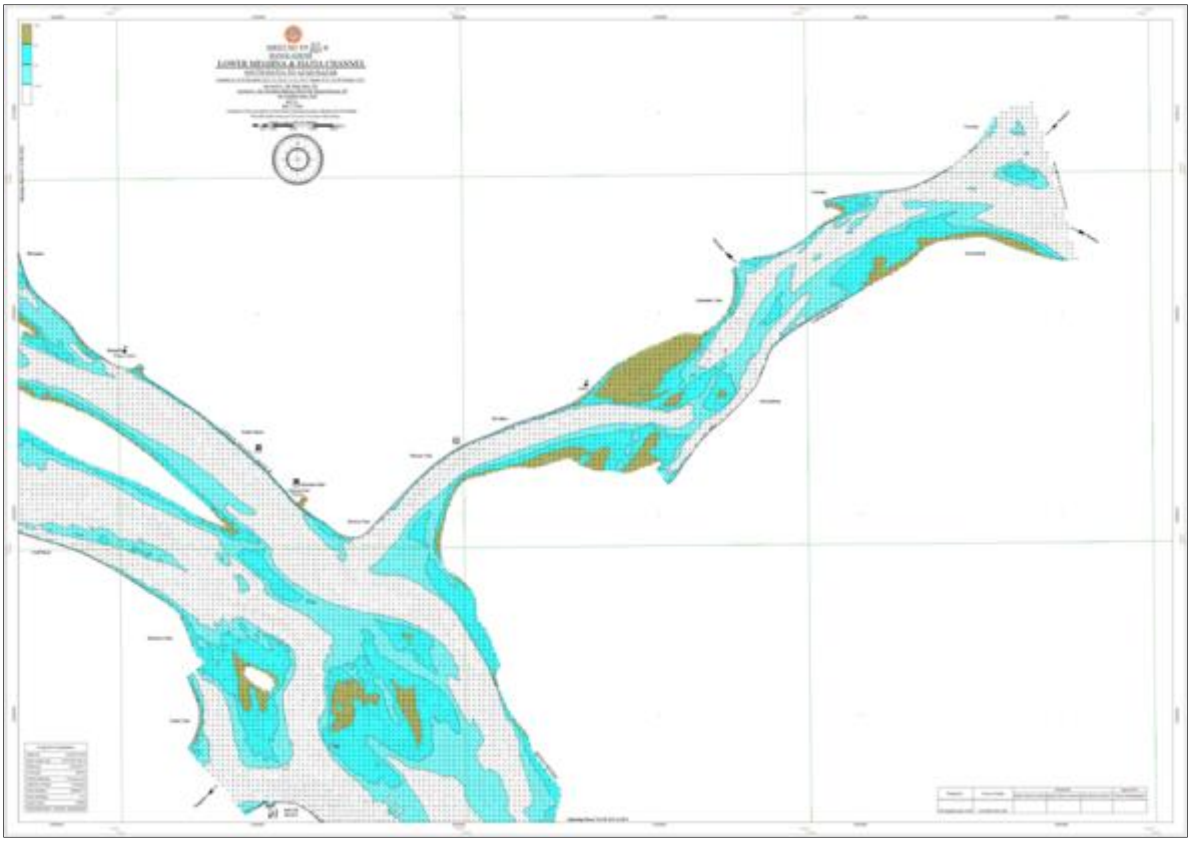

Figure 7 The bathymetry data of a part of Lower Meghna & Hatia Channel (source BIWTA)

Finally, the recalculated bottom topography was used as an initial input to provide accurate topographic information at every nodal point within the triangular mesh (see Figure 10). To achieve this, the Modified Inverse Distance Weighted Interpolation (MIDWI) method was employed. MIDWI was selected for its robustness in assigning depth values to irregularly spaced data points within the mesh. This method ensures that the bathymetric data is accurately interpolated and mapped to the triangular mesh's nodal points, providing a precise representation of the seafloor topography necessary for reliable numerical modelling.

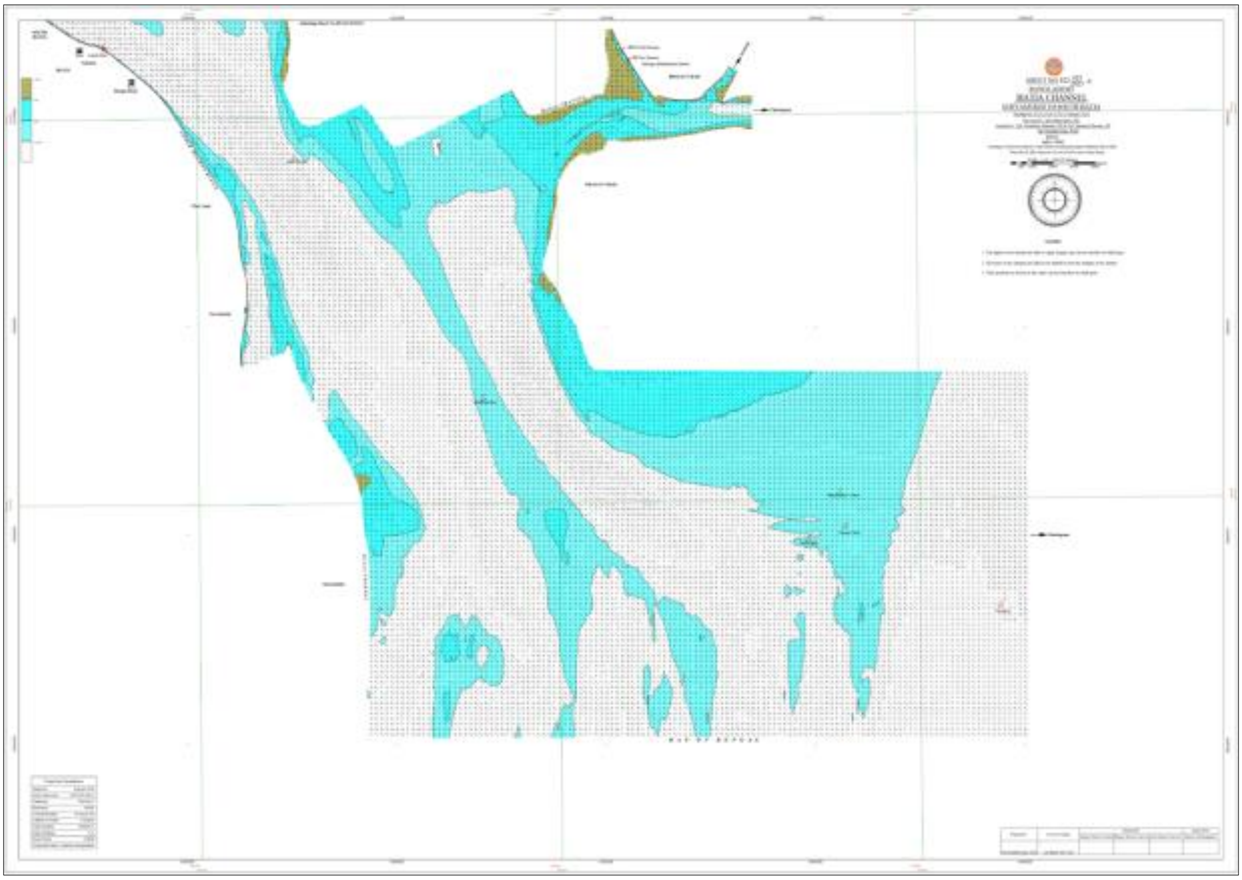

Figure 8 The bathymetry data of a part of Hatia Channel (source BIWTA)

2.1. The MIDWI Method

The Modified Inverse Distance Weighted Interpolation (MIDWI) method is a widely used interpolation technique in various fields of science and engineering. It is fundamentally based on the Inverse Distance Weighted Interpolation (IDWI) method, initially introduced by Shepard in [10], also known as Shepard interpolation. MIDWI enhances the traditional IDWI by optimizing the interpolation process to better suit the specific needs of complex datasets like those encountered in bathymetric modelling.

The MIDWI method is mathematically defined as follows:

Suppose that we have n points $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$ corresponding to the value $\zeta_1, \zeta_2, \cdots, \zeta_n$ for a function $\zeta(x)$ then:

$$\zeta(x) = \begin{cases} \dfrac{\sum_{i=1}^{n} w_i(x)\zeta_i}{\sum_{i=1}^{n} w_i(x)}, \text{if } d(x_i, x) \neq 0 \text{ for all } i \\ \zeta_i, \text{if } d(x_i, x) = 0 \text{ for all } i \end{cases}$$

where $w_i(x) = \frac{1}{d(x_i,x)^p}$ is the weight assigned to each data point based on its distance from x, and p is the order of interpolation. In our study, we set $p = 4$ to achieve a balance between smoothness and computational efficiency. The distance function $d : \Omega \times \Omega \rightarrow \mathbb{R}^+$ is defined as $d(x, y) = |x - y|$ for all $x, y \in \Omega$, where Ω represents the domain of interest.

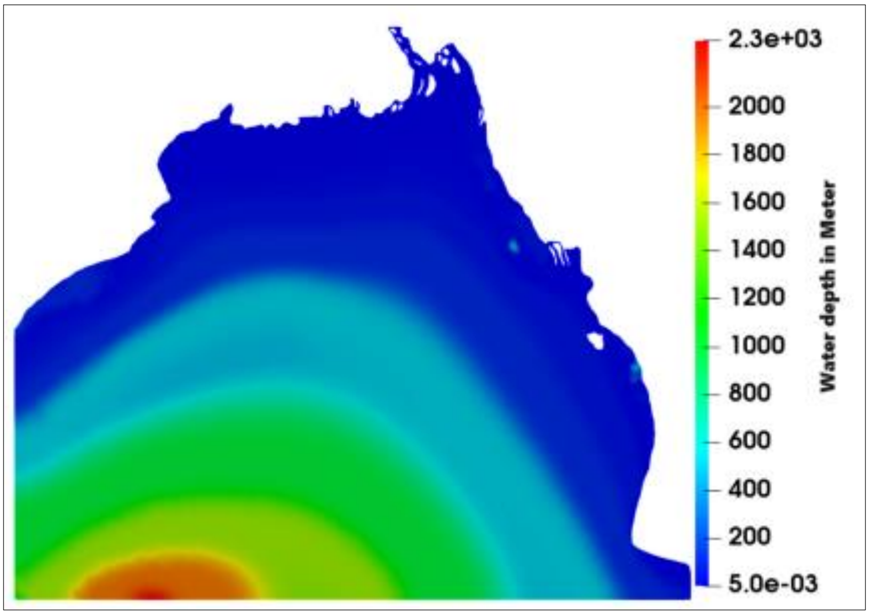

Figure 9 The surface map of computed bathymetry data for the Bay of Bengal domain

One of the key improvements introduced by the MIDWI method is the implementation of a nearest-neighbour approach. To reduce computational time while maintaining accuracy, only the ten nearest non-zero valued neighbours of a given point are considered when computing the unknown value of the function ζ. This optimization significantly reduces the computational load, making the method more practical for large-scale applications like the bathymetric modeling of the Bay of Bengal.

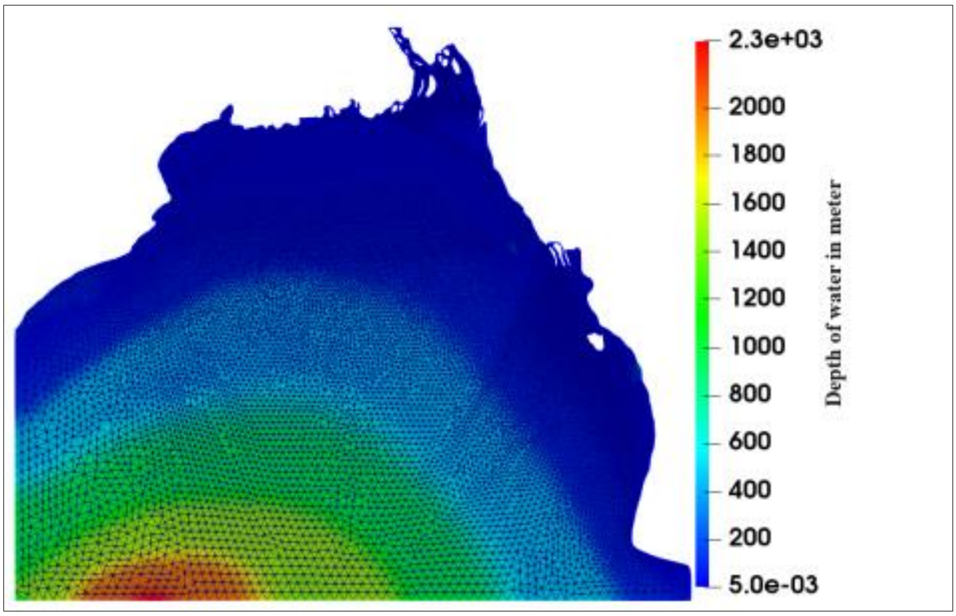

Figure 10 The surface with edge map of computed bathymetry data for the Bay of Bengal for triangular mesh

A MATLAB subroutine was written following the **Algorithm** given below to map the bathymetry data from the finite difference grid point (**FDGP**) to the nearest finite element nodal point (**FENP**)

Algorithm

Input:

- Bathymetry data on FDGP with coordinates
- Coordinates of finite element nodal points FENP
    - Steps 1: Check for coordinate match for FDGP and FENP if true then map the bathometry data directly.
    - Step 2: Calculate distance if the coordinates of FDGP and FENP do not match
    - Step 3: Sort Distances
    - Step 4: Select the 10 nearest points from Step 3 and their corresponding FDGP bathymetry data
    - Step 5: Calculate bathymetry data at FENP employing MIDWI method
    - Step 6: Repeat the process until a bathymetry data have been computed to all nodal points.

3. Results and Discussion

The results of this study demonstrate the effectiveness of the methodologies employed in accurately compiling and integrating bathymetric data into the nodal points of a triangular mesh for the Bay of Bengal domain. The generated triangular mesh successfully captured the complex geometrical features of the coastline, including the islands and river mouths. This detailed representation is critical for ensuring the accuracy of subsequent FEM simulations.

The bathymetric data, recalculated using two-way cubic spline interpolation, provided a smooth and continuous representation of the seabed's depth variations. The integration of the bathymetric data into the triangular mesh, using the MIDWI method, resulted in accurate depth values at each nodal point. The method's ability to handle large-scale datasets while maintaining computational efficiency is particularly beneficial for the extensive and complex domain of the Bay of Bengal. The MIDWI method's optimization through the nearest-neighbour approach significantly reduced computational time without compromising accuracy, making it a practical choice for large-scale applications like bathymetric modelling.

When compared to previous studies that assumed constant water depth or simplified domain geometry, this study offers a substantial improvement in the accuracy of storm surge predictions. The detailed bathymetric data, coupled with the accurate interpolation provided by the MIDWI method, ensures a realistic representation of the seafloor, which is essential for reliable numerical simulations. The study's findings underscore the importance of incorporating detailed bathymetric data in numerical models to enhance the accuracy of storm surge predictions.

Limitations and Future Work

Despite the advancements made in this study, certain limitations remain. The study relies on static bathymetric data, which does not account for seasonal variations or long-term changes in seafloor topography. Future research should focus on incorporating dynamic environmental data, such as real-time bathymetric updates and sediment transport modelling, to further refine the accuracy of storm surge predictions. Additionally, integrating climate change projections into these models could provide insights into the future impacts of storm surges in the region.

4. Conclusion

The compilation of bathymetric data for the Bay of Bengal domain in this study marks a significant advancement in preparing the region's geographic data for use in Finite Element Method (FEM) simulations. By generating a detailed triangular mesh and incorporating accurate, up-to-date bathymetric data from both generated sources and recent BIWTA data, this study provides a robust foundation for developing storm surge prediction models that can more accurately reflect the complex coastal and underwater topography of the Bay of Bengal. The implementation of the Modified Inverse Distance Weighted Interpolation (MIDWI) method has proven effective in ensuring that depth values are accurately mapped to the nodal points of the mesh, which is critical for minimizing numerical errors in storm surge simulations. This research not only addresses the challenge of integrating bathymetric data into FEM-compatible formats but also enhances the precision and reliability of future storm surge models for the region. Future work should focus on refining these models further by incorporating dynamic environmental data and real-time updates, thereby improving the prediction and mitigation of storm surge impacts on Bangladesh's vulnerable coastal communities.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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