Storage Redistribution for Flow Augmentation in the Estuarine Systems of the Ganges-Brahmaputra-Meghna Delta

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Abstract: - Estuarine systems of the Ganges-Brahmaputra-Meghna (GBM) delta drain the freshwater inflows coming from the upper catchments of the GBM basins to the Bay of Bengal (BoB). In addition to these freshwater flows, seawater enters the systems through the drainage outlets into BoB. Also, there are cross channels connecting different regions of the estuarine systems. This study applies a one-dimensional hydrodynamic model to the estuarine systems. The result of the model is used to compute the inflows, outflows, and storages of the systems. Using these values, a water balance model is developed that conserves the total storage of the systems attained naturally. The water balance model can be used to redistribute the water storage from a water-surplus region to a water-deficient region through the cross channels by conserving the system storage. The isolines are used to compute the total available channel capacities for different ecosystem resources, i.e., agriculture, fishery, and forestry. The total available channel capacities can be used as an upper limit in re-distributing the storage among the different estuarine systems. This approach can be considered as an alternate approach to augment flow in the water-deficient Sundarbans region.

Key-Words: - Flow augmentation, water balance model, storage, hydrodynamic model, water deficiency, water surplus, water redistribution, GBM delta.

Received: December 23, 2024. Revised: June 2, 2025. Accepted: June 25, 2025. Published: July 14, 2025.

1 Introduction

The estuarine systems of the Ganges-Brahmaputra-Meghna (GBM) delta, situated in the southwest region of Bangladesh, drain the combined flows of the Ganges, the Brahmaputra, and the Upper Meghna rivers. Ecologically important Sundarbans mangrove forest, [1], [2] is located in the western part of this estuarine system. A decrease in freshwater flow, particularly in the western part of the estuarine systems, is causing salinity to increase in the Sundarbans mangrove forest, resulting in the death of some saline-sensitive species, [3], [4]. Efforts are being made to augment the flow in the region by excavating the main freshwater inflow source, the Gorai River, but with no sustainable results, [5], [6], [7]. The proposal is to construct the expensive Ganges Barrage, which is expected to augment the flow in the region, [8]. There is another option for flow augmentation in the region, which is still unexplored, and is to redistribute the water storage from a water-surplus zone to the water-deficient zone. Unlike the other two options (Gorai River excavation and construction of Ganges Barrage), this option is environment-friendly and conserves the natural water balance in the region. This approach was partially attempted about 200 years ago, during the period of British rule in the region. The then British Engineers excavated the Beel Route in early 1900 that connects the eastern and the central part of the estuarine systems, [9], [10]. This man-made canal is still there and plays an important role in transferring water from the eastern zone to the western zone (will be discussed in detail in the later part of the paper). The idea of the paper evolved considering the role of the Beel Route in the overall water storage distribution in the region.

The central research question is thus set as: “Is it possible to use the existing cross channels or excavate additional cross channels to re-distribute the available water storage from a water-surplus region to the water-deficient western region where Sundarbans is located?” Accordingly, the objectives of the paper are (1) Quantification of water availability in different parts of estuarine systems (2) Investigation of the roles of the existing cross channels (3) Identifying the water-surplus region to divert the water from there to the water-deficit Sundarbans region (4) Investigating the possibilities of re-distribution of water storages from the water-surplus region to the water-deficit region through the cross channels and (5) Determining the upper limit of the channel capacities necessary to maintain the system balance in the re-distribution process.

This paper is the first of its kind that uses volumetric flow analysis and a water balance model to determine the water storage in this region, and suggests options for storage redistribution from a water-surplus region to a water-deficient region. This kind of flow augmentation can be considered a sustainable and environment-friendly option in comparison to an unsustainable solution of Gorai River excavation or constructing the expensive Ganges Barrage. Although the water balance model is a familiar concept in hydrology [11], [12], we did not find any study where this type of model is applied in complex estuarine systems. Similarly, the concept of storage is mainly used for static reservoir storage assessment [13] or simply in water management design for water allocation [14]. The novelty of the research is the development and application of a water balance model to compute the storage redistribution in a complex estuarine system. The model can be calibrated with the proposed link coefficients.

The structure of the paper is arranged as follows. After the introduction in section 1, the flow distribution pattern in the estuarine systems of the GBM delta is described in section 2. The methodologies, including the application of the numerical model, are described in section 3. The next five sections sequentially describe the way to achieve the five objectives mentioned in the introduction. Among them, section 4 describes the quantification of water availability, and section 5 describes the roles of cross-channel flows. Based on the water availabilities, the water-surplus and water-deficit regions are identified and are described in section 6. The sections related to the method of re-distribution of water storage and setting the upper limits of the channel capacities are described in sections 7 & 8. The conclusion is presented in section 9.

2 The Estuarine Systems of the GBM Delta

As shown in Figure 1 (Appendix), the discharges coming from the Ganges, Brahmaputra, and Upper Meghna rivers drain through the complicated estuarine networks in the southwest region of Bangladesh. The combined flows of the Ganges and Brahmaputra rivers come through the Padma River, and after joining with the Upper Meghna, the bulk of the combined flow discharges through the Lower Meghna estuary. The estuarine systems receive the freshwater flow from the above rivers, mix with saline water due to the large tidal prism, and eventually discharge into the Bay of Bengal. The eastern part of these estuarine systems is known as the Eastern Estuarine System (EES), the central part is known as the Central Estuarine System (CES), and the western part is known as the Western Estuarine System (WES). These EES, CES, and WES are connected through several cross channels. The Ganges, before joining with the Brahmaputra, bifurcates as the Gorai, which is the main flow-carrying channel for the WES. In the same way, the Padma, before joining with the Upper Meghna, bifurcates as the Arial Khan River and acts as a major source of freshwater for the CES. The CES also receives water from the EES through three small spill channels. The Beel Route, a man-made canal excavated from the Arial Khan [10], is also a major source of freshwater from the EES to the CES. Freshwater sources for the WES, where the ecologically important Sundarbans mangrove forest [1] is located, are much less. The only visible source of freshwater for the WES is the bifurcated branch of the Gorai. The Gorai itself is almost dying due to a shortage of flow from the Ganges, [5], [6], [7]. The other bifurcated branch of the Gorai, named the Madhumati, acts as a freshwater source for the CES. The other small channels of WES have lost their roles as freshwater sources. Among the other estuaries, the Tetulia and Lohalia are the parts of the EES, the Bishkhali, Baleshwar, and Burishwar constitute the CES, and all other estuaries of the Sundarbans system, including the Rupsha and Pasur systems, are parts of WES. Existing cross channels that connect these estuarine systems are the three spill channels of Lower Meghna, Beel Route, Ghashiakhali channel, and the Madhumati channel. The roles of these cross channels are vital for facilitating the exchange of flow from a water-surplus zone to a water-deficit zone. The WES receives a very small amount of freshwater flow from Gorai. On the other hand, the EES receives large amounts of fresh water from the Lower Meghna and supplies some of this to the CES through the spill channels. As there is a very small number of cross channels that connect the WES to the rest of the systems, there is a large difference of water storage among the different parts of the estuarine systems, especially between CES and WES.

The dynamics of these estuarine systems are controlled by the freshwater entering through the Gorai, Arial Khan, and Lower Meghna inlets and the seawater entering through the mouths of the estuaries of EES, CES, and WES. The large freshwater input and the saline water intrusion due to strong tidal forces make these estuarine systems suitable for the existence of diverse ecosystem resources, [15]. In addition to the tidal force, there are seasonal variations of freshwater flows in different flooding scenarios, resulting in variations of water storage and its distribution among the different parts of these estuarine systems, [16]. The variations of the hydrodynamic conditions cause different combinations of water balances that ultimately lead to spatial and temporal movement of the saline fronts within the estuarine systems, [17], [18]. As a consequence, the threshold isohalines for different ecosystem resources, for example, agriculture, fishery, and forestry, also move, [19], [20]. In addition to filling the deficit water storage with the surplus water storage within different parts of the estuarine systems, re-distribution of the water storage among different parts of the estuarine systems can change the position of isohalines. This approach may be used to ensure sufficient water availability in different parts of the estuarine systems and the sustainability of various ecosystem resources in the region.

3 Methodology for Computation of Water Volume

As the main focus of this study is the volumetric analysis of water, a one-dimensional model like HEC RAS [21] is found to be suitable. The HEC RAS is applied to dynamically compute the water volumes entering and leaving the systems. The HEC RAS model can accommodate the branching of river networks with multiple junctions. The model requires upstream and downstream boundary conditions and a detailed bathymetry of the river network. A time series of discharge has to be specified as the upstream boundary condition, with a time series of water levels for the downstream boundary condition.

Cross-sectional data for each of the estuaries in the estuarine systems of the GBM delta are provided from the secondary source of the Bangladesh Water Development Board (BWDB) and the primary source from the ESPA-Delta project, [22]. The domain of the measurements covers the entire study reach. This makes it possible to prepare an accurate bathymetry to be used by the models. The discharge data are collected from the BWDB. The tidal water level data is collected from the Bangladesh Inland Water Transport Authority (BIWTA). Measured discharges are used as the upstream flow boundaries located in the major rivers, i.e., the Ganges, the Brahmaputra, and the Upper Meghna. As downstream water level boundaries, the HEC RAS uses the BIWTA hourly tidal water level data.

The HEC RAS model is calibrated and validated against the measured water levels in three different locations of the three different estuarine systems, i.e., one in EES, one in CES, and one in WES. For selecting the benchmark for the model calibration and validation [23], an average flood year condition is selected. In this case, the year 2000 is selected as the average flood year, based on the criterion used by the BWDB, which is 20% - 24% of the country is flooded, [24]. During the calibration exercises, model reliability is calculated for each of the model runs by computing a reliability indicator, [25]:

$$Reliability = 100 - \frac{\frac{1}{n}\sum_{t=1}^{T}\left|W_{Measured}^{t} - W_{Model}^{t}\right|}{\sqrt{\frac{1}{n}\sum_{t=1}^{T}\left(W_{Measured}^{t} - \overline{W_{Measured}}\right)^{2}}} * 100 \quad (1)$$

Here, *Reliability* is a model reliability measure indicator. *Reliability = 100 %* means the model is 100% reliable compared to measured values. Here $W_{Measured}^{t}$ and W_{Model}^{t} are the measured and the model values at any instant of time t, $\overline{W_{Measured}}$ is the average of the measured values, t is any time instant, T is the total duration for both the measured and model values, and n is the total number of values.

The model parameters selected in this way during the calibration process give the reliability of the model for the particular combination of model parameters. The model reliability for the HEC RAS model for this particular application is found to be approximately 70%. After calibration, the model is validated with the selected set of parameters by applying it in the study region and comparing the model performance in the Lower Meghna estuary for the average flood condition. The calibration and validation performance of the model is shown in Figure 2 (Appendix).

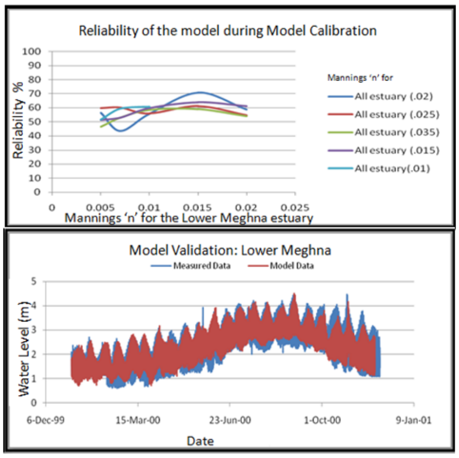

Fig. 2: Calibration and validation of the HEC RAS model

The model computes discharge at different parts of the estuarine systems at the model time step (1-hour interval) for a whole year duration. The model is applied to compute discharge and water level for different discharge scenarios. The discharge scenarios considered are: (1) Average (2) Dry, and (3) Wet. As mentioned earlier, the definitions of discharge conditions and the selection of individual years that represent these are selected by using the criterion used by the BWDB [24]. By following this criteria, the year 2000 is selected as the average year (the flooded area of the whole country is about 24%), the year 2001 is selected as the dry (the flooded area of the whole country is about 3%) and year 1998 is selected as the wet year (flooded area of the whole country is about 68%). From the model computed discharge time series, the water volume for a particular year is computed by using the equation:

$$V_{R_i} = \int_0^T Q dt \tag{2}$$

where V_{Ri} is the volume of water for a particular river, R_i, $Q(t)$ is the instantaneous discharge for that particular river and T is the total duration of the hydrograph. The total volume of water for an estuarine system is calculated as:

$$V_T = \sum_{i=1}^{N} V_{R_i} \tag{3}$$

where N is the total number of estuaries for a particular estuarine system.

4 Quantification of Water Availability

The yearly freshwater flow volume that enters the estuarine systems through the three river channels, namely, the Gorai River, the Arial Khan River, and the Lower Meghna River (Figure 1, Appendix) is computed using the model-generated discharge hydrographs and by using Eqs. 2 & 3. The flow volume is computed for different flooding conditions, i.e., average year, dry year, and wet year. Computed flow volumes and percentage distribution of these among different estuarine systems are shown in Table 1 (Appendix) and Figure 3. Total freshwater flow that enters the estuarine systems varies from 1.0 trillion m^3 to 1.65 trillion m^3. Distribution of freshwater flow shows that regardless of the flooding conditions, the percentage contribution of each of the inflow inlets remains the same. The major flow is carried by the Lower Meghna, followed by Gorai and Arial Khan. It should be mentioned here that the water volume computed here is the total volume for a whole hydrological year, comprising the dry season and the wet season.

In the tidal estuarine systems, the flood volume is the seawater volume entering from the sea into the estuarine systems. On the other hand, the ebb volume is the total water volume leaving the estuarine systems to the sea. The computed flood volume and ebb volume from the model are given in Table 2 (Appendix), and the percentage distribution of these volumes among different estuarine systems is shown in Figure 4 (Appendix). The total amount of water entering from the sea varies from 1.90 trillion m3 to 2.48 trillion m3. The majority of this water enters through the EES because of the wide mouth of the Lower Meghna estuary. The interesting feature is the second highest contribution, which varies from 25% to 38% of the total flood volume, and it comes from the WES outlet. This is significant in the sense that this flood volume brings seawater with high salinity to the Sundarbans system, [26], [27]. On the other hand, the very low flood volume of CES is the reason for the low salinity level in the CES, [28]. The ebb volume represents the total amount of water going out of the system. This amount varies from 3.04 trillion m3 to 3.74 trillion m3, and most of the water (69% to 71%) is drained through the EES outlet, more specifically through the wide mouth of the Lower Meghna estuary. The contribution of WES varies from 19% to 23%, which is significant because most of the estuaries of WES have no freshwater input, [6].

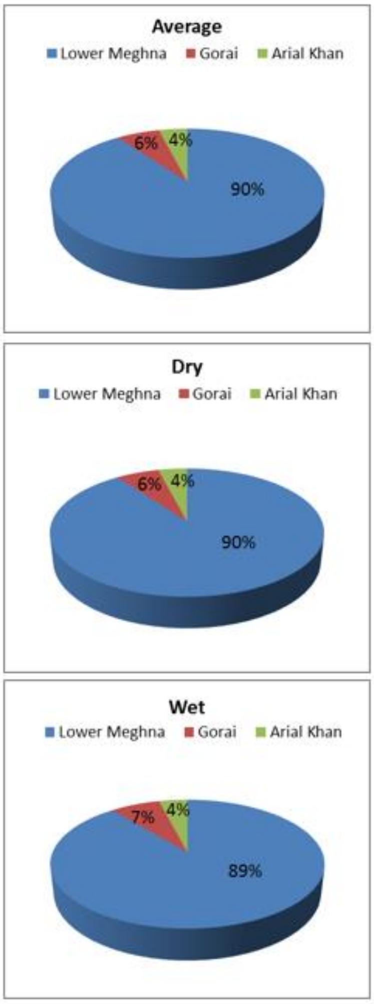

Fig. 3: Percentage distribution of freshwater flows among different estuarine systems

5 Roles of Existing Cross-Channels

The cross channels are the channels that connect different parts of the estuarine systems, i.e., connecting EES & CES and connecting CES & WES. The role of these cross channels is important in the sense that flows are exchanged between different regions through these cross channels. It was described in Section 4 that EES carries the bulk of the flow in these estuarine systems. So, the exchange of flows between EES and the rest of the regions (directly or indirectly) will ensure the supply of fresh water in those regions. The identified cross channels are (Figure 1, Appendix): (1) 3 spill channels of the Lower Meghna estuary (2) the Beel Route (3) the Ghasiakhali Channel, and (4) the Madhumati Channel. As shown in Table 3 (Appendix), flows between EES & CES and between CES & WES are two-way, but the net cross-channel flow direction is from EES to CES and from WES to CES. This makes WES particularly deprived of any other freshwater source except the Gorai River. The computed water volume from the model in these cross channels and the percentage distribution of flows among different estuarine systems are shown in Table 3 (Appendix) and in Figure 5. The figure shows that the major cross-channel flows (80% to 85%) are from EES to CES and the rest 15% to 20% is from WES to CES. Among the cross channels, three spill channels connecting EES & CES are the most active and mostly supply water from EES to CES. The Beel Route, excavated by British Engineers about two hundred years ago, is still an active channel. This channel also supplies water, mostly from EES to CES. The link between CES and WES is maintained by the two cross-channels, Ghashiakhali and Madhumati. The net flow direction for the Ghashiakhali channel is from CES to WES. This flow direction may be due to a higher tidal range in the east than in the west, [29]. The Madhumati channel is a one-way channel and supplies water only from WES to CES. So, Ghashiakhali channel can be used as a cross-channel to augment flow in WES by diverting water from CES.

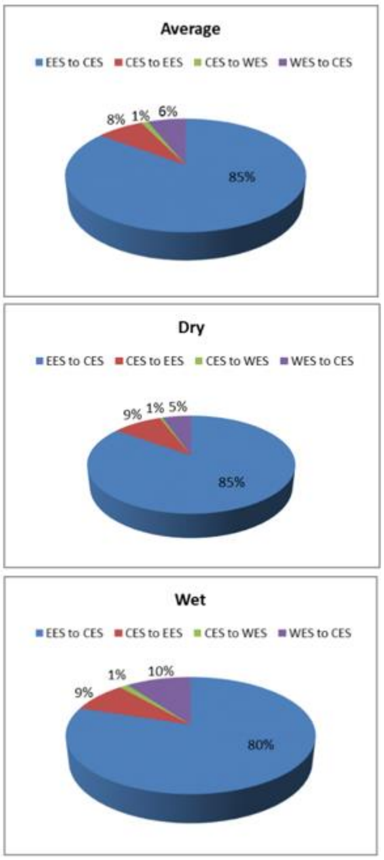

Fig. 5: Percent distribution of cross-channel flows among different estuarine systems

6 Water-surplus and Water-deficit Regions

The total input volume of the estuarine systems is the sum of the freshwater volume (Table 1, Appendix), the flood volume (Table 2, Appendix), plus the contribution from the cross channels (Table 3, Appendix). The total output, on the other hand, is the total ebb volume (Table 2, Appendix) going out from the estuarine systems. The storage volume is the difference between the total input volume and the total output volume. When the storage is computed as an annual volume, the effects of neap-spring variations are averaged out. The computed storage, or more precisely change in storage, for different estuarine systems in different discharge conditions is shown in Table 4 (Appendix). The CES for all the discharge scenarios contains the maximum storage in the estuarine systems (varies from 92% to 100%). The EES, on the other hand, is a deficit system along with the WES. The ecologically sensitive WES contains the maximum storage of 8% in the dry year. But it is most likely that the water contained in the storage is mainly salt water because in a dry year, most of the water entering the system is from the sea, which is about 72% of the total inflow. In an average year and a wet year, this amount is about 58% of the total inflow into the system.

7 Redistribution of Water Storage

The results presented in sections 4 to 6 above are used to develop a water balance model [30] for the estuarine systems to establish the criteria of storage re-distribution in the study area. The mass balance is maintained by ensuring that the total change of storage will remain the same for any combination of flow distribution. The objective of developing the water balance model is to compute the amount of flow necessary to divert from a surplus region (for example, CES) to a deficit region (for example, WES), keeping the overall water storage of the system unchanged, and thus ensuring not to change the system dynamics.

The estuarine system is idealized as a combination of three linear systems, WES, CES, and EES, linked with cross channels as shown in Figure 6. The definitions of the symbols are given in Table 5 (Appendix).

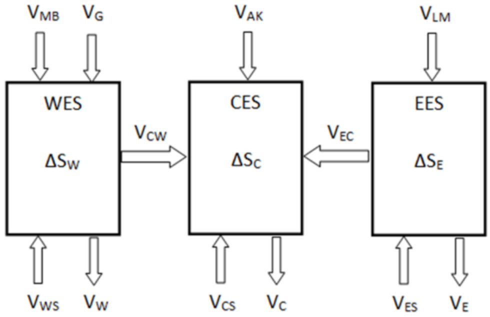

Fig. 6: Schematic model of the idealized estuarine systems

Annual flow volumes are seen as inputs to and outputs from the systems. Considering the flat topography and an annual budget, we propose a linear relationship between upstream freshwater inflow volumes and cross-channel flow volumes and introduce two link coefficients, K_C and K_E, that influence the cross-channel flows. The link coefficients link the cross-channel flows with the freshwater inflows.

Thus, the cross-channel flow volumes can be determined from:

$$V_{CW} = K_C*(V_G - V_{AK}) \tag{4}$$

$$V_{EC} = K_E*(V_{LM} - V_{AK}) \tag{5}$$

The water balance equations for the system using the schematic model shown in Figure 2 are:

$$V_{MB} + V_G + V_{WS} - V_W - K_c * (V_G - V_{AK}) = \sum\Delta S - \Delta S_C - \Delta S_E \tag{6}$$

$$V_{AK} + V_{CS} - V_C + K_C * (V_G - V_{AK}) + K_E * (V_{LM} - V_{AK}) = \sum\Delta S - \Delta S_W - \Delta S_E \tag{7}$$

$$V_{LM} + V_{ES} - V_E - K_E * (V_{LM} - V_{AK}) = \sum\Delta S - \Delta S_C - \Delta S_W \tag{8}$$

In equations (6) to (8), all other values except K_C, K_E, and one storage value (either ΔS_W, ΔS_C, or ΔS_E) are considered unknown. All the required volumes are known from the numerical model results and are given in Appendix in Table 1, Table 2, Table 3 and Table 4. So, 3 unknowns from 3 equations can be computed by simultaneous solution of equations (6), (7) & (8). The desired change of storage volume can be given as input. In addition, a summation of storage is also given as input to conserve mass. After getting K_C and K_E from above, the required cross-channel flows can be computed from equations (4) and (5). Using the above procedure and for the known storages, K_C and K_E values are determined for an average, a dry, and a wet year, and are given in Table 6 (Appendix).

The system balance indicates an overall increase in storage while the increase/decrease in storage in the three sub-systems is determined by K_C and K_E. This also indicates an opportunity for transferring surplus storage from one sub-system (e.g., CES) to another (e.g., WES), which is a deficit system, by changing the cross-channel flows. This feasibility is investigated first by establishing the linear relationships in Eqs. (4) and (5). Numerical model results show that for the same freshwater flow into the three sub-systems, K_C and K_E vary linearly with V_{CW} and V_{EC}, respectively (Figure 7). Then, changes in cross channel flows are achieved by changing K_C and K_E, assumed to be the same for all years, which also results in storage change in the sub-systems. The system is conserved in all cases since the overall storage change remains the same. Example results of these trials are given in Table 7 (Appendix).

Either equations (4) & (5) or Figure 7 can be used to compute the cross-channel flows by appropriately computing the link coefficients. First, the amount of storage to be increased for a deficit region is determined. Then by solving the water balance equations (6), (7) & (8) the required link coefficients are computed for the changed storage. The required cross-channel flows are then computed by using equations (4) and (5). As it is not possible to increase the freshwater inflow coming from outside of the system, and also it is not possible to reduce the amount of water going out from the system without any intervention, the only option to augment the storage is to manipulate the cross-channel flows. This approach will ensure that mass conservation of the system is achieved by natural balance.

Table 7 (Appendix) shows two examples where any arbitrary amount of storage for the deficit region WES is increased by diverting water from CES to WES and thereby, by reducing the cross-flow from WES to CES. As mentioned in Section 5, this water diversion can be made through the Ghashiakhali channel. In one of the options, it is decided to increase the storage of WES in a typical dry year from 0.02 trillion m^3 to 0.03 trillion m^3. By using the procedure described above, the required cross-channel flow towards CES is computed as 0.03 trillion m^3. Previously, this amount was 0.30 trillion m^3. Reduction of cross-channel flow towards CES will ensure the increase of cross-channel flow towards WES and thus increase the storage of WES. In this particular case amount of cross-channel flow to be increased towards WES is 0.27 trillion m^3, and this amount of water must the diverted from the surplus CES region. Ensuring 0.27 trillion m^3 of water as cross-channel flow to the WES is equivalent to increasing the average discharge of Gorai River by an amount of 8,500 m^3/s in addition to its present discharge. Table 7 (Appendix) shows another example where a further increase of WES storage is possible at the expense of further cross-channel flow reduction towards CES.

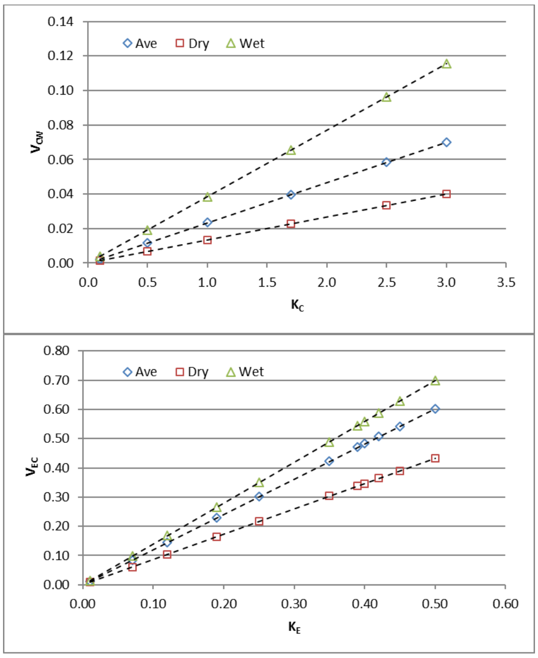

Fig. 7: Relationship between link coefficients and cross-channel flows

8 Upper Limit of the Channel Capacities

Each of the ecosystem resources needs a specific environment for its sustainability. For example, a particular fish suitable for freshwater will not be sustained in a saltwater environment. To delineate the available channel capacity for a particular ecosystem resource and a particular environment, the salinity model (details of the model are given in [17] is applied in different flooding conditions, and isohalines are drawn for the threshold values of different ecosystem resources. The ecosystem resources considered in this study are (1) Agriculture, (2) Forestry, and (3) Fishery. The threshold values of salinity for the suitability and sustainability of the ecosystem resources are – agriculture 7.5 ppt [31], forestry 8 ppt [32] and fishery 10 ppt, [33]. Here, agriculture is represented by salinity suitability for irrigation water, forestry is represented by minimum salinity tolerance by mangroves, and fishery is represented by capture fishery in open water bodies. The seasonal variations of isohaline lines are drawn for different flooding scenarios and using the particular water level for which the isohalines are drawn, the available channel capacities are computed. The results are shown in Table 8 (Appendix) along with isohalines for threshold salinities. The channel capacities are computed in terms of conveyance volume separately for the main channel and the floodplain. The channel capacities computed in this way and shown in Table 8 (Appendix) are higher than the actual storage shown in Table 4 (Appendix). This shows the possibilities of using the cross-channel flows to increase the storage in different regions of the estuarine systems. For example, actual total storage in the estuarine systems in a typical dry year is 0.20 trillion m^3, whereas the minimum channel capacity available for the same hydraulic condition, and to maintain a 'fresh' environment either for agriculture, fishery, or forestry, is 0.42 trillion m^3. This shows the possibility of storing another 0.22 trillion m^3 of water by diverting water through the cross channels. Theoretically, the system still should 'conserve', as the total channel capacity will not be exceeded. So, Table 8 (Appendix) can be used as the upper limits of the storage which will still ensure the conservation of mass for the system. These upper limits should be used as constraints while designing an optimum system.

9 Conclusions

Quantification of water availability in the estuarine systems shows that in the estuarine systems, total freshwater flow enters varies between 1.0 trillion m^3 to 1.65 trillion $m^{3,}$ and total saltwater flow enters varies between 1.90 trillion m^3 to 2.48 trillion m^3. Internally, these flows are distributed by the cross channels. The three spill channels, along with the Beel Route (the excavated channel by British Engineers about 200 years ago), are the most active cross channels connecting the eastern and the central estuarine systems. The Ghashiakhali channel is the only channel where water is still flowing from the central system to the water-deficient western system, where the Sundarbans mangrove forest is located. The central system is identified as the water-surplus region from where water can be diverted to the water-deficient western system through the Ghashiakhali channel. Upper limits of channel capacities for different ecosystem resources are recommended for this purpose and should be used as constraints when an optimum system is designed.

This approach is an alternate approach (compared to unsustainable Gorai river excavation or construction of expensive Ganges Barrage) to augment the flow in the water-deficient Sundarbans region. In subsequent studies related to this approach, the possibilities of excavating additional cross channels for more effective water diversion will be studied. Effects of flow diversion on the overall morphology and saline regime of the estuarine systems will also be studied.

Acknowledgments:
We would like to acknowledge the contribution of all the members associated with the research team who have direct and indirect input to this article.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process
The authors wrote, reviewed and edited the content as needed and verifies that none utilised artificial intelligence (AI) tools were used. The authors take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Anisul Haque developed the methodology. He did the analysis and overall planning of the paper. He also wrote the manuscript.
- M. Shah Alam Khan developed the water balance model.
- Sumaiya did the model execution and contributed to the analysis.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The third author Sumaiya received a Research Assistantship from NERC, ESRC, UK DFID, ESPA during the execution of this work as part of the ESPA Deltas project (Grant Reference Code : NEJ0027551).

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

APPENDIX

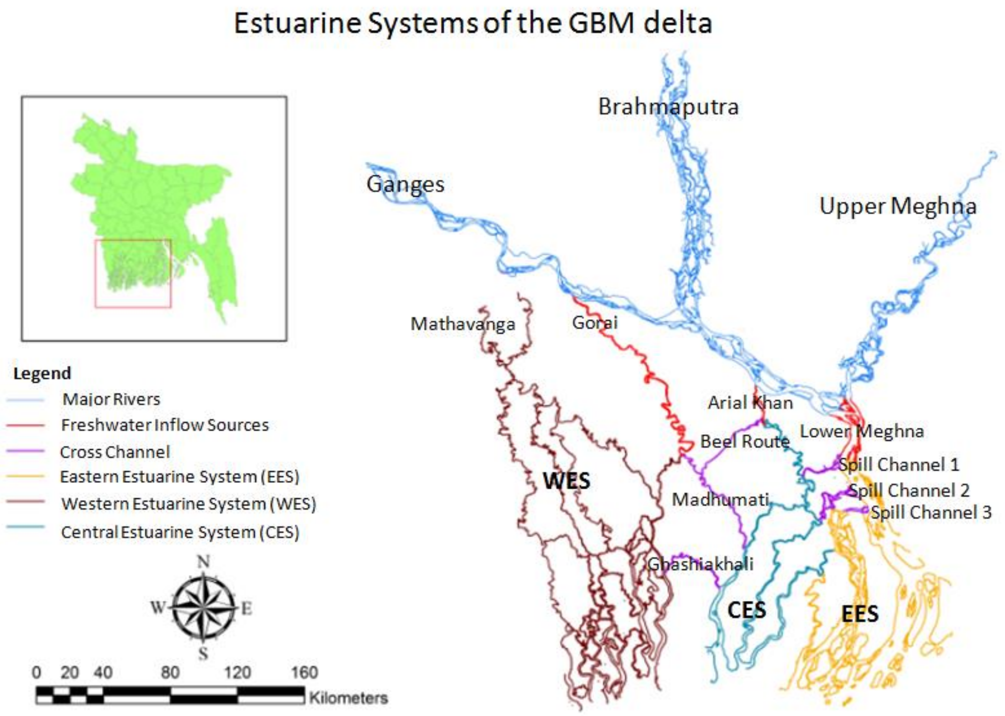

Fig. 1: Estuarine Systems of the GBM delta

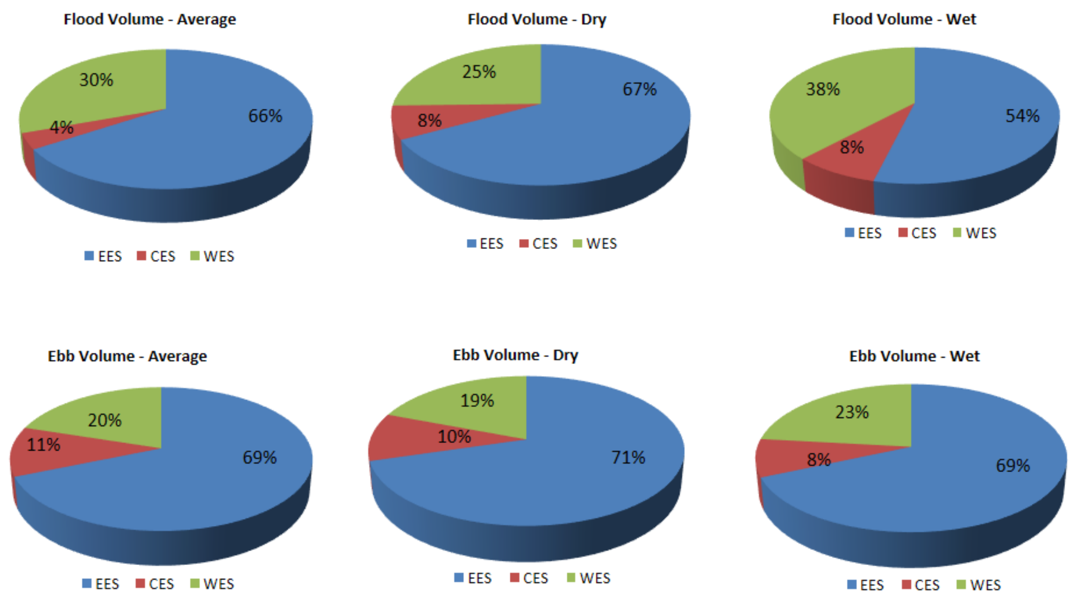

Fig. 4: Percentage distribution of flood and ebb volumes of water among different estuarine systems

Table 1. Freshwater Flow Entering into the Estuarine Systems

Condition	Yearly Water Volume Trillion m^3			Total Yearly Water Volume Trillion m^3
	Gorai	Arial Khan	Lower Meghna	
Average	0.0783	0.0549	1.2611	1.3943
Dry	0.0549	0.0416	0.9082	1.0047
Wet	0.1091	0.0706	1.4681	1.6478

Table 2. Flood and Ebb Volumes

Condition	Flood Volume (Trillion m^3)				Ebb Volume (Trillion m^3)			
	EES	CES	WES	Total	EES	CES	WES	Total
Average	1.25	0.07	0.58	1.90	2.09	0.34	0.61	3.04
Dry	1.66	0.19	0.63	2.48	2.31	0.34	0.63	3.28
Wet	1.20	0.18	0.85	2.23	2.56	0.31	0.87	3.74

Table 3. Cross-Channel Flows

Condition	Yearly Water Volume Trillion m^3												Total Yearly Water Volume Trillion m^3	
	Spill-1		Spill-2		Spill-3		Beel Route		Ghashiakhali		Madhumati			
	EES to CES	CES to EES	EES to CES	CES to EES	EES to CES	CES to EES	EES to CES	CES to EES	CES to WES	WES to CES	WES to CES	CES to WES		
Average	0.034	0.014	0.099	0.045	0.619	0.010	0.026	0.000	0.010	0.008	0.048	0.000	EES to CES	0.778
													CES to EES	0.070
													CES to WES	0.010
													WES to CES	0.056
Dry	0.036	0.005	0.095	0.042	0.508	0.024	0.023	0.000	0.004	0.000	0.042	0.000	EES to CES	0.662
													CES to EES	0.071
													CES to WES	0.004
													WES to CES	0.042
Wet	0.021	0.016	0.081	0.032	0.471	0.017	0.029	0.000	0.010	0.005	0.071	0.000	EES to CES	0.602
													CES to EES	0.065
													CES to WES	0.010
													WES to CES	0.076

Table 4. Change in Storage

Condition	Estuarine System	Inflow Trillion m^3				Total Outflow Trillion m^3	Change in Storage Trillion m^3	Percent of only positive storage
		Fresh Water	Cross Flow	Sea Water	Total Inflow			
Average	EES	1.26	-0.42	1.25	2.09	2.09	0	0
	CES	0.05	+0.47	0.07	0.59	0.34	+0.25	100
	WES	0.08	-0.05	0.58	0.61	0.61	0	0
	TOTAL	1.39	0.00	1.90	3.29	3.04	+0.25	
Dry	EES	0.91	-0.30	1.66	2.27	2.31	-0.04	Deficit
	CES	0.04	+0.33	0.19	0.56	0.34	+0.22	92
	WES	0.05	-0.03	0.63	0.65	0.63	+0.02	8
	TOTAL	1.00	0.00	2.48	3.48	3.28	+0.20	
Wet	EES	1.47	-0.49	1.20	2.18	2.56	-0.38	Deficit
	CES	0.07	+0.57	0.18	0.82	0.31	+0.51	98
	WES	0.11	-0.08	0.85	0.88	0.87	+0.01	2
	TOTAL	1.65	0.00	2.23	3.88	3.74	+0.14	

Table 5. Definition of symbols of the schematized model

Parameter	**Description**	**Value**
V_{MB}	Freshwater inflow from the Mathavanga River	Zero
V_G	Freshwater inflow from the Gorai River	Table 1
V_{AK}	Freshwater inflow from the Arial Khan River	Table 1
V_{LM}	Freshwater inflow from the Lower Meghna estuary	Table 1
V_{CW}	Net cross flow from WES to CES	Table 4
V_{EC}	Net cross flow from EES to CES	Table 4
V_{WS}	Seawater inflow from sea to WES	Table 4
V_{CS}	Seawater inflow from sea to CES	Table 4
V_{ES}	Seawater inflow from sea to EES	Table 4
V_W	Outflow from WES	Table 4
V_C	Outflow from CES	Table 4
V_E	Outflow from EES	Table 4

Table 6. Link coefficients and storage change for average, dry, and wet years.

Condition	K_C	K_E	ΔS_W	ΔS_C	ΔS_E	$\sum\Delta S$
Average	2.064	0.3491	0.0023	0.5399	-0.2879	+0.25
Dry	4.128	0.2979	0.0169	0.5206	-0.3328	+0.20
Wet	2.314	0.0774	0.0231	0.5436	-0.4289	+0.14

Table 7. Cross channel flow and estuarine storage change for different link coefficients.

$K_C = 2.06 \quad K_E = 0.35$						
Condition	$\mathbf{V_{CW}}$	$\mathbf{V_{EC}}$	$\mathbf{\Delta S_W}$	$\mathbf{\Delta S_C}$	$\mathbf{\Delta S_E}$	$\mathbf{\sum\Delta S}$
Average	0.0482	0.4222	0.0001	0.2553	-0.0011	0.2543
Dry	0.0274	0.3033	0.0275	0.2223	-0.0451	0.2047
Wet	0.0793	0.4891	0.0098	0.5090	-0.3810	0.1378
$K_C = 0.5 \quad K_E = 0.1$						
Average	0.0117	0.1206	0.0366	-0.0828	0.3005	0.2543
Dry	0.0067	0.0867	0.0482	-0.0151	0.1715	0.2047
Wet	0.0193	0.1398	0.0699	0.0996	-0.0317	0.1378

Table 8. Available channel capacity of estuarine systems for different ecosystem resources

Conditions and Seasonality			Channel Capacity (Trillion m^3)					
			Main channel			Flood plain		
			Agriculture	Fishery	Forestry	Agriculture	Fishery	Forestry
Average	Dry Season	Fresh	0.4730	0.4750	0.4740	0.0520	0.0520	0.0520
		Saline	0.0180	0.0160	0.0170	0.0008	0.0007	0.0008
	Wet Season	Fresh	1.5600	1.5600	1.5600	0.3900	0.3910	0.3910
		Saline	0.0110	0.0080	0.0090	0.0002	0.0001	0.0001
Dry	Dry Season	Fresh	0.4240	0.4300	0.4270	0.0430	0.0430	0.0430
		Saline	0.0210	0.0150	0.0170	0.0010	0.0010	0.0010
	Wet season	Fresh	1.3200	1.3200	1.3200	0.3000	0.3000	0.3000
		Saline	0.0100	0.0080	0.0090	0.0003	0.0002	0.0003
Wet	Dry Season	Fresh	0.7100	0.7100	0.7100	0.1000	0.1000	0.1000
		Saline	0.0170	0.0120	0.0150	0.0007	0.0004	0.0005
	Wet Season	Fresh	1.7900	1.7900	1.7900	0.4810	0.4810	0.4810
		Saline	0.0070	0.0050	0.0060	0.0000	0.0000	0.0000