FLOW PATTERN AND ASSOCIATED BED DEFORMATION IN THE OFF-TAKE REGION OF GORAI RIVER, BANGLADESH

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ABSTRACT

The flow pattern and morphological characteristics of the Ganges River are the main factors controlling the flow diversion into the Gorai River. The present study discusses the morphological behavior and its control in the Ganges reach to obtain suitable flow diversion towards the Gorai River, using a depth averaged two dimensional numerical model. Two separate domains (grid system) have been used for numerical simulation: one analyzes the flow patterns and morphological change solely in the Ganges reach, and the other discusses the morphology and flow diversion into the Gorai River, combining both the Ganges and the Gorai reaches. The effects of the different sets of countermeasures by means of the spur dikes on the morphological changes in the off-take area were investigated numerically with attention focused on the flow pattern and flow diversion reproduced near the Gorai off-take area. The results show that the present method can evaluate the flow pattern and morphological change exhibited by each countermeasure; thus, it can assess the effect of countermeasures on the sandbar formation and flow diversion process on the Gorai River.

Keywords: Flow diversion, Channel morphology, Sedimentation, Gorai off-take, Countermeasures.

INTRODUCTION

The Gorai River is one of the major sources of freshwater supply to the southwestern region (SWR) of Bangladesh. The flow discharge of the Gorai River has a significant effect on the lives, livelihoods, environment, and sustainable development of this region. Salinity intrusion in the southwestern coastal area, the ecosystem, and biodiversity of the world's largest mangrove forest, the Sundarbans, is also greatly influenced by the freshwater supply through the Gorai River. After the commissioning of the Farakka Barrage (18 km upstream from Bangladesh –India borderline) in 1976, there is a declining tendency of yearly minimum discharge (Source: BWDB) in the Ganges River during the dry season (Figure 1). The satellite images show that the right bank line of the Ganges River from the Hardinge Bridge to the Gorai off-take (16 km) eroded a maximum of 1.80 km (from 1987 to 2019) and created a curvature shape just upstream of the off-take (Figure 2). For this curvature effect, flow is directed towards the left bank, and sedimentation deposition occurs in the off-take area. In addition, the eroded sediment from this curvature area is deposited in the downstream area, especially in the Gorai off-take area, which creates the blockage of flow diversion into the Gorai River (Sudipta Kumar Hore, 2013). The combined effects of flow declination in the parent river, sediment behavior, and morphological changes in the vicinity of the off-take area are the main reasons for excessive sediment deposition. As a result, the flow diversion has been drastically reduced in the last few decades.

To improve this flow blockage situation, the Bangladesh Water Development Board (BWDB) conducted several dredging programs from the last few years to maintain the flow into the Gorai River. The dredged channel was maintained for one year, and after a flood, the flow blockage re-occurred. Therefore, continuous dredging is required to overcome this problem, which is very expensive, and some countermeasures for low maintenance are challenging for Bangladesh. A detailed analysis of the morphological characteristics of this area is important to understand the sandbar formation behaviors to develop any structural countermeasures to improve the existing conditions. The present study discusses

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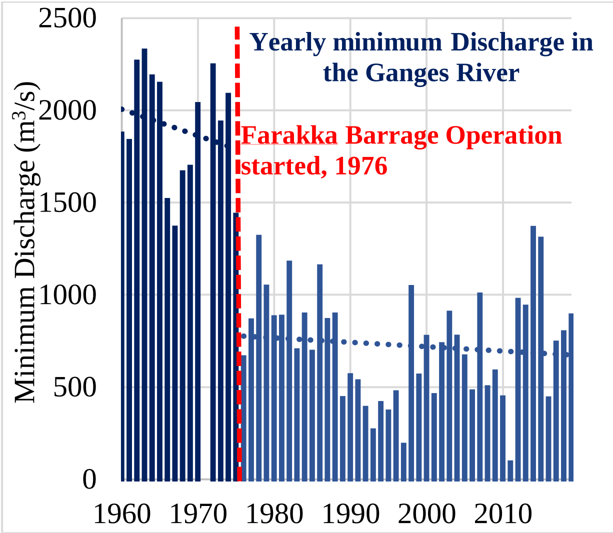


Figure 1: Yearly minimum flow in the Ganges river

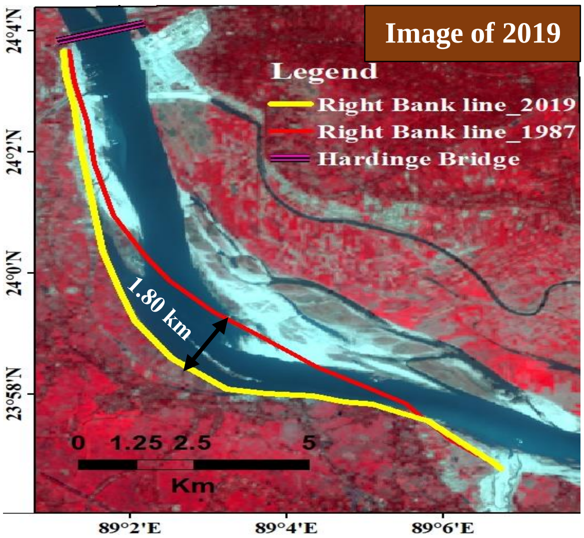


Figure 2: Right bank shifting of the Ganges river

a flow pattern and geomorphological change, which is reproduced for each countermeasure using spur dikes, to obtain a suitable countermeasure. In numerical analyses, recently observed field survey cross-section data with a fine grid (100 m × 50 m and 50 m × 50 m) system was used, and both the Ganges and the Gorai channel were covered.

METHODOLOGY

In a river system, the flow has a strong influence on the sediment transport process, and sediment transportation creates a geomorphological change, which causes the flow pattern to change. To evaluate these interrelations by means of numerical simulation, depth-averaged two-dimensional forms of governing equations are employed in this study.

The mass conservation equation for the water flow body is given as:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(uh)+\frac{\partial}{\partial y}(vh)=0 \tag{1}$$

where h is the flow depth, t is the time, and u and v are the x and y components of the depth-averaged flow velocity, respectively.

The x and y components of the momentum conservation equation for water flow are expressed as:

$$\frac{\partial uh}{\partial t}+\frac{\partial uuh}{\partial x}+\frac{\partial uvh}{\partial y}-gh\frac{\partial}{\partial x}(h+z_b)-\frac{\tau_x}{\rho}+\frac{1}{\rho}\{\frac{\partial}{\partial x}(h\,\sigma_{xx})+\frac{\partial}{\partial y}(h\tau_{yx})\}\text{ and} \tag{2}$$

$$\frac{\partial vh}{\partial t}+\frac{\partial uvh}{\partial x}+\frac{\partial vvh}{\partial y}=-gh\frac{\partial}{\partial y}\,(h+z_b)-\frac{\tau_y}{\rho}+\frac{1}{\rho}\{\frac{\partial}{\partial y}\,(h\,\sigma_{yy})+\frac{\partial}{\partial x}\,(h\tau_{xy})\} \tag{3}$$

where, g is the acceleration due to gravity, ρ is the mass density of water, Z_b is the bed elevation, σ_{xx}, σ_{yy}, τ_{xy} and τ_{yx} are depth-averaged Reynolds' stresses, τ_x and τ_y are the x and y components of bed shear stress. The terms in Equations (2) and (3) are quantified by using the following relations;

$$\frac{\tau_b}{\rho}=\frac{u^2+v^2}{\left[6.0+2.5\ln\left({}^{h}/_{k_s}\right)\right]^2}\dots(a)\qquad \frac{\tau_b}{\rho}=u_*^2\dots(b)\qquad \tau_x=\tau_b\frac{u_b}{\sqrt{u_b^2+v_b^2}}\dots(c)\qquad \tau_y=\tau_b\frac{v_b}{\sqrt{u_b^2+v_b^2}}\dots(d)$$

$$\frac{\sigma_{xx}}{\rho}=2\epsilon\frac{\partial u}{\partial_x}-\frac{2}{3}k_t\dots\dots(e)\qquad \frac{\sigma_{yy}}{\rho}=2\epsilon\frac{\partial v}{\partial y}-\frac{2}{3}k_t\dots\dots(f)\qquad \frac{\tau_{xy}}{\rho}=\frac{\tau_{yx}}{\rho}=\epsilon\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\dots\dots(g)$$

where τ_b is the bed shear stress, u_b and v_b are the x and y components of velocity near the bed surface, respectively, $u_*$is the shear velocity, and ϵ is the eddy viscosity. The mass conservation equation of bed sediment (equation of bed elevation) for uniform sediment size is expressed as follows:

$$\frac{\partial Z_b}{\partial t}+\frac{1}{1-\lambda}+\left(\frac{\partial q_{bx}}{\partial y}+\frac{\partial q_{by}}{\partial y}+E\;-D\right)=0 \tag{4}$$

q_{bx} and q_{by} are the bed-load transport rate in the X and Y directions, respectively, and λ is the porosity of the bed sediment.

The formula for the bed-load transport rate proposed by (Egashira, 1997) is expressed as:

$$q_{b^*}=\frac{4}{15}\frac{K_1K_2}{\sqrt{f_d+f_f}}\tau_*^{\frac{5}{2}} \tag{5}$$

where, K_1, K_2, f_d, and f_f are specified theoretically.

The mass conservation equation for suspended sediment can be described as follows:

$$\frac{\partial \bar{c}h}{\partial t}+\frac{\partial r_1\bar{u}\bar{c}h}{\partial x}+\frac{\partial r_1\bar{v}\bar{c}h}{\partial y}=\frac{\partial}{\partial x}\left(h \in_x \frac{\partial \bar{c}}{\partial x}\right)+\frac{\partial}{\partial y}\left(h \in_y \frac{\partial \bar{c}}{\partial y}\right)+E-D \quad (6)$$

where $\bar{c}$ is the depth-averaged value for sediment concentration, $\bar{u}$,$\bar{v}$, $\in_x$,and $\in_y$ are x and y components of velocity and dispersion coefficient respectively, E is the erosion rate, D is deposition rate and r_1 is the correction factor. Harada et al.(2019) specified the erosion rate using entrainment velocity (W_e):

$$E=W_e c_s \quad (7)$$

where c_s is the sediment concentration in the surface layer.

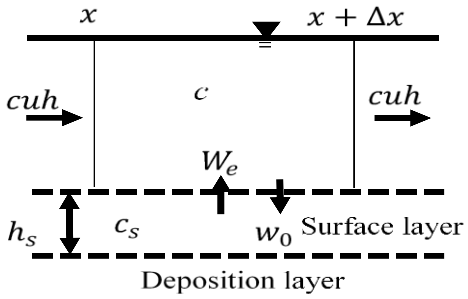


Figure 3 : Schematic diagram for sediment

To evaluate the erosion velocity (W_e), they employed a formula obtained from density stratified flow.

$$\frac{W_e}{u}=\frac{\mathrm{K}}{R_{i*}}\ \left(R_{i*}=\frac{\frac{\Delta\rho}{\rho}gh}{u^2}\ and\ \ K=1.5\times10^{-3}\right) \quad (8)$$

where R_{i*} is the Richardson number, $\Delta\rho$ and is the density difference between the water layer and the bed surface layer.

DATA

Detailed field survey data observed in the year 2016 (before the flood) were used to identify the initial morphology. For the boundary condition, the observed time series discharge of the flood hydrograph (150 days) for 2016 was used at the Hardinge bridge station (unsteady flow). The calculation conditions are shown in Table 1.

Table 1: Calculation conditions for numerical simulation

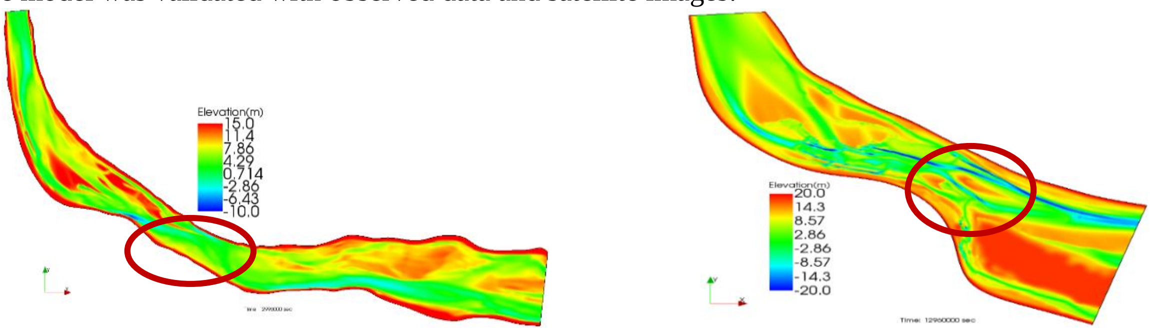
Average river bed slope	1 in 14,000 (0.00007)	Finite differential method for advection term	upwind scheme
Uniform particle size	0.25 mm	Calculation time step	0.5 sec
Sediment transport type	Bed load and suspended load.	Bed deformation is considered to starts after	10 hours
n – value	0.026	Relaxation coefficient	0.8
Maximum number of iterations of water surface computation			10

Domain Information

Domain for the Ganges reach		***Combined domain for the Ganges and Gorai***	
Length	38 km (from the Hardinge bridge to 22 km downstream of the off-take)	Length	18 km (from around 12 km upstream to 6 km downstream)
Average Width	2850 m	Average Width	4500 m
Cell size	Δx=100 m & Δy=50 m	Cell size	Δx=50 m & Δy=50 m
Cell number	23,128 nos. (i= 392, j=59)	Cell number	33,431 nos. (i= 331, j=101)

RESULTS AND DISCUSSION

The model was validated with observed data and satellite images.



(a) Flood computation result along the Ganges reach

(b) Flood computation result for the off-take area and the Gorai river

Figure 4: Morphology after one flood simulation (150 days)

Figure 4 (a) and (b) show the sandbar and channel patterns after one flood computation without a countermeasure; (a) shows the Ganges reach, and (b) shows the off-take area combined with the Gorai River. The simulation results indicate that (without any countermeasure), owing to the sandbar existence on the left side and middle in the curvature area, all flows are concentrated in the right bank of the Ganges river. For the curvature effect, flow is diverted towards the left bank area far from the Gorai off-take. As a result, the shear velocity decreased, and sediment deposition occurred in the off-take area (brown circle). Numerical simulations were conducted for the eleven countermeasures by means of the spur dikes to improve the flow diversion into the Gorai River. For the first step, three different sets of countermeasures (options A, B, and C) were investigated.

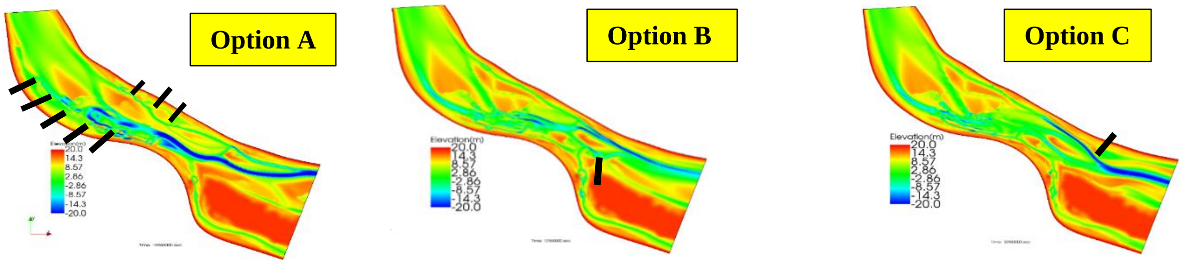


Figure 5: One flood (150 days) simulation result with spur dike location (/)

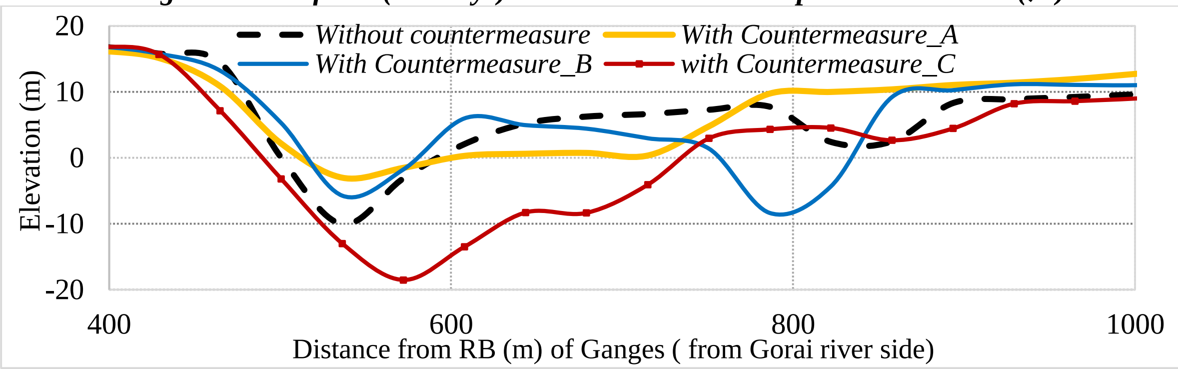


Figure 6: Cross-section comparison near the Gorai off-take

Figure 5 shows the result of bed deformation obtained from options A, B, and C. Figure 6 shows the cross-sectional shape developed near the off-take area with these countermeasures. For option A, a series of spur dikes are set in the right bank curvature area and the left bank to concentrate the flow along the middle of the Ganges River instead of through the right bank curvature area. A deep channel is created close to the off-take area, and no sandbar is formed in front of the Gorai River with this intervention. For option B, a spur dike is inserted in the mouth of the Gorai River. Though the Gorai channel is connected to the Ganges, sandbar formation occurred in the mouth of the Gorai river, and a deep channel is created far from the off-take. For option C, a single spur dike is fixed at the left bank of the Ganges river, around 1.50 km downstream from the opposite of the off-take. With this countermeasure, less sediment deposition occurs in the off-take area. However, the deep channel is generated near the left bank area of the Ganges river. For options A, B, and C, the overall cross-sectional areas below the water level +4.50 m improved by 1%, 19%, and 250%, respectively, compared to the case without a countermeasure. For the second step, options A and C were modified and investigated another four different sets of countermeasures.

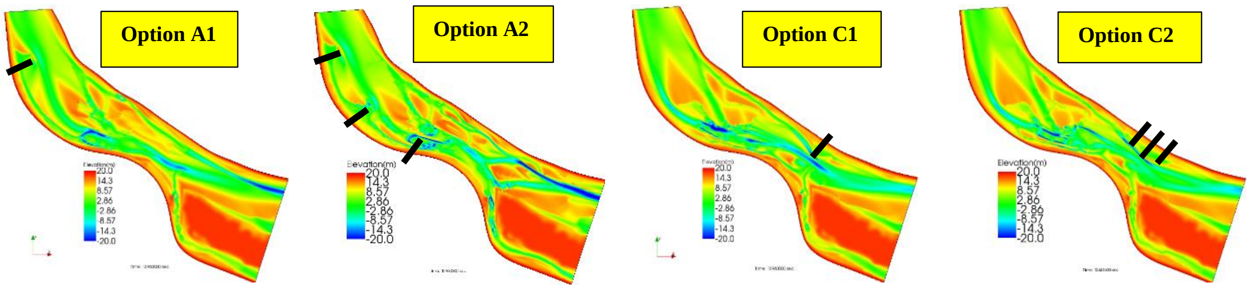


Figure 7: One flood (150 days) simulation result with spur dike location (/)

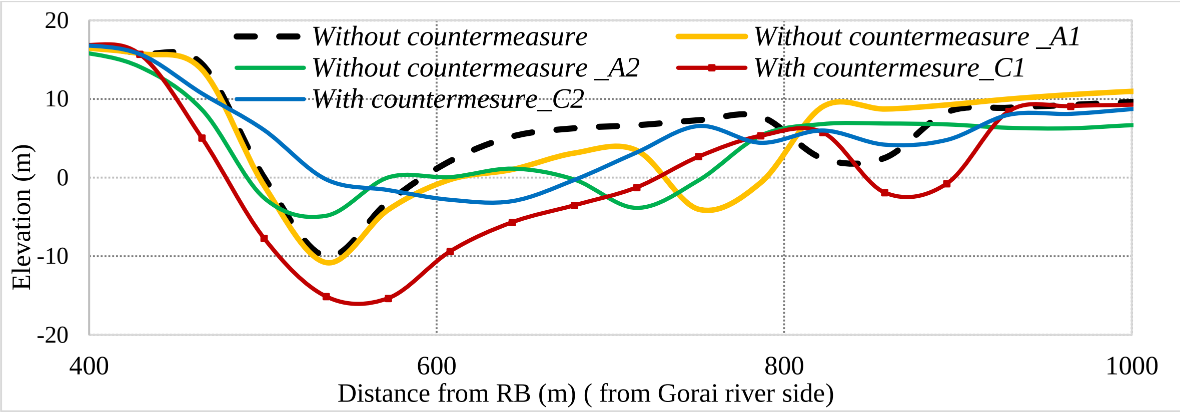


Figure 8: Cross-section comparison near the Gorai off-take

Figure 7 shows the result of bed deformation obtained from options A1, A2, C1, and C2. Figure 8 shows the cross-sectional shape developed near the off-take area with these countermeasures. For option A1, one single spur dike is inserted at the right bank of the Ganges River, approximately 12 km upstream from the off-take. With this intervention, no sandbar is formed and the deep channel existed near the off-take area. For option A2, three spur dikes are fixed in the right bank curvature area. There is no significant sandbar formation occurred, and an active channel exists near the off-take with this countermeasure. However, another deep channel is created near the left bank of the Ganges River. For option C1, a single spur dike is set just on the opposite side of the off-take area. With this countermeasure, no sandbar formed in the off-take area, but the main channel is shifted near the left bank. For option C2, three spur dikes are set instead of a single spur in the opposite bank of the off-take. No significant sandbar formed, but the main channel remained far from the off-take area. For options A1, A2, C1, and C2, the overall cross-sectional area below the water level +4.50 m improved by 68%, 44%, 237%, and 6%, respectively, compared to the case without a countermeasure.
In the last step, the study investigated the combined effects of some of the previous countermeasures.

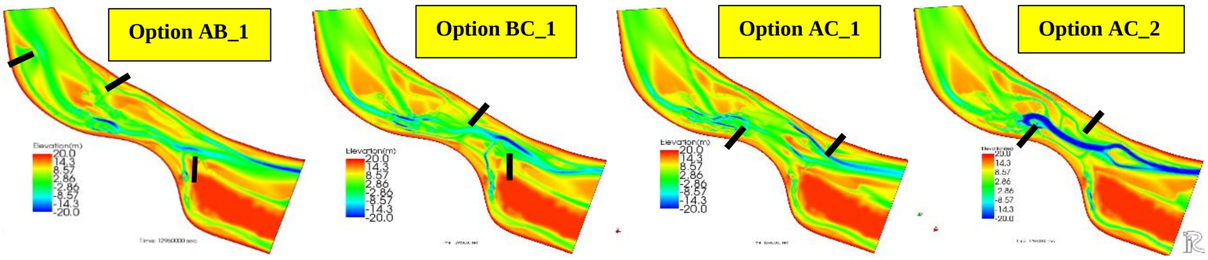


Figure 9: One flood (150 days) simulation result with spur dike location (/)

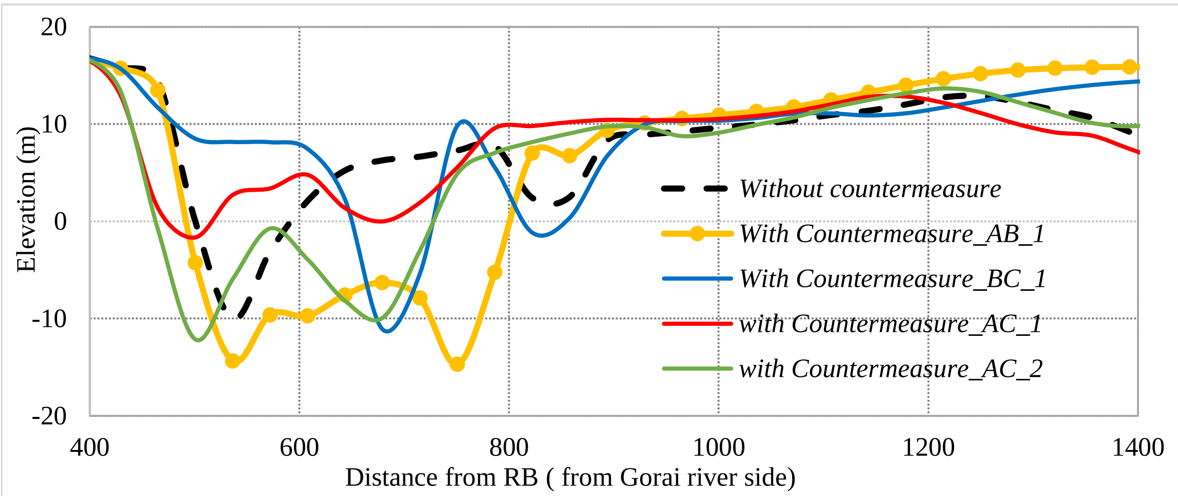


Figure 10: Cross-section comparison near the Gorai off-take

Figure 9 shows the results of bed deformation obtained from options AB_1, BC_1, AC_1, and AC_2. Figure 10 shows the cross-sectional shape developed near the off-take area with these countermeasures. For option AB_1, two spur dikes are fixed at the upstream of the off-take at both banks with addition of a single flow diversion spur at the mouth of the Gorai River. With this intervention, no sandbar is formed and the deep channel existed near the off-take area. For option BC_1, one left bank spur dike is inserted at 1.5 km upstream from the opposite bank of the off-take with the flow diversion spur dike at the mouth of the Gorai River. With this countermeasure, sandbar formed and the main channel shifted far from the off-take. For option AC_1, one single spur dike is set in the right bank curvature area with a left bank spur dike, just 1.5 km downstream from the off-take area. With this configuration of spur dikes, the main channel is shifted near the left bank and sandbar formed near the off-take area. For option AC_2, one single spur dike is considered in the right bank curvature area with a left bank spur dike, opposite of the off-take. With this countermeasure, the deep channel is created in the middle of the Ganges River, but sandbar exists near the off-take area. However, the overall cross-sectional area below the water level +4.50 m improved for options AB_1 and AC_2 by 279% and 157%, respectively, but for options BC_1 and AC_1, this area is decreased by 1% and 31%, respectively, compared to the case without a countermeasure.

For countermeasure options A, A1, A2, and AB_1, a deep channel exists near the off-take and no sandbar formation occurred in between the deep channel and the Gorai off-take mouth. Therefore, the cross-sectional area below the water level +4.50 m improved by 1%, 68%, 44%, and 279%, respectively, compared to the case without a countermeasure. Therefore, the specification of spur dikes in countermeasure AB_1 is more effective in improving the flow blockage problem in the Gorai off-take area.

CONCLUSIONS AND RECOMMENDATIONS

This study investigated the flow diversion from the Ganges river to the Gorai River by means of numerical simulation. Attention was given to the morphological changes and flow patterns and it was suggested that there is a possible countermeasure by means of the spur dikes to maintain a stream in the off-take area where channel closing due to sand bar migration is uncommon. In addition, this study will provide useful information for the Bangladesh Water Development Board to make decisions about the sustainable solution to this flow blockage problem. This study will also help policymakers to make decisions about the restoration of the Gorai River as a priority for the improvement of the freshwater supply in the southwestern region of Bangladesh for sustainable development. From a diplomatic perspective, the study will give international policymakers ideas about the Ganges water-sharing conflict with India. The study can be extended by evaluation of the stability of the proposed countermeasure together with the study on morphological characteristics of the Ganges and the Gorai reaches.

ACKNOWLEDGEMENTS

I would like to express my sincere honor and gratitude to my supervisors, Professor EGASHIRA Shinji, Dr. Eng. Professor of GRIPS, Research and Training Adviser of ICHARM, PWRI for his overall supervision, valuable suggestions, and motivation in my thesis work. In addition, I would like to express my heartfelt thanks and gratitude to YOROZUYA Atsuhiro, Associate Professor of GRIPS and senior researcher at the ICHARM, PWRI, Dr. Daisuke Harada, Associate Professor of GRIPS and Research Specialist, ICHARM, PWRI, and Dr. Robin Kumar BISWAS, Research Specialist, Water-Related Hazard Group, ICHARM, PWRI for their cordial cooperation, suggestions, encouragement, and guidelines at every stage of my work.

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