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Optimization of Countermeasures to Stable and Protect Navigation Channels in Dinh An Estuary and Coastal of Tra Vinh Province, Vietnam

Viet Thanh Nguyen, Anh Dan Nguyen, Vinh An Le

Faculty of Civil Engineering, University of Transport and Communications, Hanoi, Vietnam

Abstract

The new navigation channel for large vessels entering the Hau River through the Kenh Tat and Quan Chanh Bo channels was announced in January 2016. The navigation channel route through Dinh An estuary in Soc Trang province to Can Tho port was not deeply concerned by the agency because of the sedimentation phenomenon, which was very serious and complicated. Only small vessels of 1,000-2,000 DWT can pass through the Dinh An estuary navigation channel, whereas large vessels pass through the Kenh Tat and Quan Chanh Bo channels. However, the new navigation channel entering the Hau River is also seriously sedimented, especially in the Cua Dai An area, where the tributary route starts from the Hau River through the Quan Chanh Bo channel and the estuary area in the Duyen Hai harbor basin. These are two important bottlenecks that drastically reduce the throughput capacity of this new navigation channel. This paper proposed five options for the spatial arrangement of works to stabilize and protect the channel through the Dinh An estuary. A MIKE 21 couple mode was used to simulate hydrodynamic and sediment transport in the study area, and the impact of these options on the characteristics, including water level, flow velocity, and bottom topographic change, was analyzed and evaluated. Based on these results, an optimal solution was suggested.

Keywords: Dinh An estuary, Hydrodynamic, Sediment transport, Tra Vinh province

1. Introduction

1.1. Literature Overview

Many seaports are located in estuaries, and the navigation channel entrance faces many challenges in maintaining the design water depth. Regulation work in estuaries and coastal areas has gained many experiences, such as the navigation channel in Mississippi, Changjiang, Qiantang, and Pearl River estuaries [1]. Estuary and coastal areas were more intensively exploited during this century because economic and demographic demands induced an increasing need for new land, better marine facilities for trade and other communications, and better protection against the sea.

The effects of training wall construction in the estuary of the River Lune, United Kingdom The effects of training wall construction in the estuary of the River Lune, United Kingdom, were investigated by the flow model of the morphological algorithm. The results showed that due to the training walls, the initial changes were artificially imposed on the Lune estuary before allowing the hybrid method to further simulate the evolution of the estuary, and these changes affected 5% of the volume of the estuary [2].

Based on the hypothesis that the deposition in Mersey was controlled by hydrodynamic flow and related sediment transport outside the estuary induced by training wall construction, the Mersey Estuary has now evolved toward a stable state. The results of the hydrodynamic model simulated in 1906, 1936, and 1977 estimated the potential sediment transport changes outside the Estuary. They indicated a significant increase in potential sediment supply to the mouth of the EEstuary during peak accretion [3].

Tönis et al. [4] investigated the development of the sand volume in the Haringvliet estuary, Netherlands, after

Address for Correspondence: Viet Thanh Nguyen, Faculty of Civil Engineering, University of Transport and Communications, Hanoi, Vietnam
E-mail: vietthanh@utc.edu.vn
ORCID ID: orcid.org/0000-0003-3964-2871

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closure using bathymetric measurements from 1970, 1972, 1979, 1980, 1986, and 1990 until 1999. The results showed that the changes in sand volume above the Dutch Ordnance Level (NAP) of 10 m relative to 1970 had been determined. The area of these volumes was carefully chosen to diminish the effects of all other human interventions.

Zhao et al. [5] applied Delft 3D to study the combined effect of river discharge regulation and estuarine morphology on the salinity dynamics of the Yangtze estuary of the Changjiang River. The results indicate spatial changes in salinity due to the morphological evolution of the estuary.

In Vietnam, numerous researchers have studied estuarine regulation and achieved significant achievements in improving maritime and inland waterway transport. An evaluation of the back siltation volume of each excavation and dredging period from 2010 to 2014 in the Bach Dang navigation channel to Hai Phong port was conducted by Nguyen et al. [6]. The results indicated that numerous factors, such as sediment and hydrodynamic conditions, are the major reason for increasing back siltation in the Bach Dang navigation channel. Based on the research and solutions for preventing sedimentation in the Thuan An estuary and for protection from erosion of the coastline from the Thuan An to Hoa Duan coasts, a series of countermeasures were proposed, and an analysis of advantages and disadvantages was conducted to select the solution for the protection of coastal erosion and estuary stability [7]. Nguyen et al. [6] proposed two regulation schemes for improving water depth and reducing sedimentation in Phan Thiet fishing port, Binh Thuan province, Vietnam, and showed that capital dredging of the harbor basin and navigation channel is required according to scheme No. 1 and then careful monitoring of the effects of the scheme by follow-up surveys at least twice a year, and review of the plan taking into account the priority, timing, and extent of the facilities [8]. Nguyen et al. [9] investigated factors controlling the variation of sediment transport in the Nhat Le Estuary, Quang Binh province, Vietnam. The results showed that nearshore waves controlled sediment transport and estuarine morphology. Other research on the hydrodynamic and sediment transport of the Mekong River Delta has been conducted to provide solutions for coastal protection, erosion prevention, and estuary regulation [10-19].

1.2. Case Study

Navigation channels for large vessels entering the Hau River to load or unload cargo in Can Tho Ports play an important role in the development of the Mekong Delta economy. This study studied the Dinh An estuary's navigation channel, as shown in Figure 1. This dynamic and unstable channel has a high back siltation intensity [20-24]. The mechanism of back siltation discussed by Nguyen et al. [25] indicated that five factors control the back siltation process in the Dinh An navigation channel, including the increasing elevation gap between the channel and the nearby seabed, the disadvantages of the hydrodynamic regime, many sources of sediment, salt edge, and mixing and wave-induced sediment transport in the navigation channel.

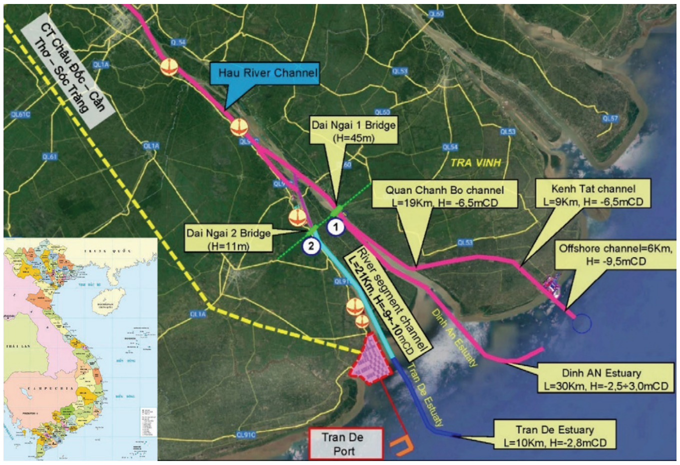

Figure 1. *Study area of Dinh An estuary and the coast of Tra Vinh province*

Many scientists and consulting companies in Vietnam and other countries have conducted basic studies and proposed navigation channel routes to improve the water depth and stability of the navigation channel. In 1998, the Heacon consulting company from Belgium conducted a project titled "Feasibility Study for the Improvement of the Entrance Channel to the Bassac River" and proposed five options for the regulation of the navigation channel in Dinh An estuary. The navigation channel has a width of 100 m and depth of -4.7 m, allowing vessels 5,000 DWT to enter during the high tide period with 6 h of waiting time. The vessel's 20,000 DWT half load can be entered with a waiting time of approximately 4.5 h. If a vessel with 20,000 DWT half load entered continuously, the proposed channel width was 110 m. The basic dredged volume was approximately 2.8-3.0 million cubic meters of silt and exceptionally fine sand. The annual maintenance dredged volume was approximately 4.0 million cubic meters. Under extreme conditions, this volume reached approximately 5.0-5.5 million cubic meters [26].

The project "Feasibility study for improvement of the Bassac River" was conducted by SNC-Lavalin International Incorporation, Canada, in association with Royal Haskoning, Delft Hydraulics, the Netherlands, and Southern Transport Engineering Design Incorporation (TEDI-South), Vietnam in 2002 [23]. Based on the investigated data and assessment methods, they proposed four schemes of navigation channels, including a movable navigation channel, a fixed navigation channel (dredging or not dredging), a fixed navigation channel that supplemented the discharge from the Tran De distributary, and a new channel from the Quan Chanh Bo channel and a new section of the bypass, as shown in Figure 1.

Dang and Nguyen studied the influence of the enlargement of the Quan Chanh Bo channel on hydrodynamic and sediment transport in the Dinh An estuary, Vietnam. The results indicated that the Quan Chanh Bo and Kenh Tat channels significantly changed the hydrodynamic, wave, and sediment transport modes of the Dinh An estuary and the surrounding coastal area. Particularly, when the current velocity in this area increased, the deposition in Dinh An decreased, while the deposition tended to increase in the Quan Chanh Bo channel. In addition, erosion was observed in the Kenh Tat channel [27].

Based on the new navigation channel from the Hau River to the Quan Chanh Bo channel and then to the Kenh Tat channel (Figure 1), the PortCoast Consultants studied hydrodynamics, wave transformation, and sediment transportation in a large-scale model and selected a new navigation channel combined with the Duyen Hai port. Two jetties protected the sea segment of the new navigation channel, and the entire navigation channel for large vessels entering the Hau River through the Kenh Tat and Quan Chanh Bo channels was put into use in January 2016. The new navigation channel was effective in the first few years. However, after approximately two years of use, sedimentation began to develop strongly, especially in the Dai An estuary, the Quan Chanh Bo channel entrance, and the Duyen Hai port basin [28]. Because of the appearance of the fluid mud layer in the navigation channel, sedimentation became more serious [29].

Nguyen and Zheng studied four regulation options to reduce deposition in the navigation channel of Dinh An estuary without the new channel (Figure 1). They proposed conducting capital dredging (Option 1) and conducting surveys at least twice a year. If the situation is negative, Option 2 should be selected for regulation in the navigation channel [30].

This article proposed five options (Option 2 to Option 6) for the spatial arrangement of works to stabilize and protect the channel through the Dinh An estuary. Hydrodynamic and sedimentary regimes in the study area were simulated using numerical simulation with a coupled model. Based on the results, this paper analyzed and evaluated the effect of proposal options on natural conditions (Option 1), such as water level, flow velocity, and bottom topographic change, and proposed the optimal solution.

2. Data Characteristics

The tidal regime in the Tra Vinh Sea is meso-tidal with tidal ranges from 2.5 to 4.1 m [25,31]. Wind data from 1988 to 2020 at Con Dao Island, far from the Tra Vinh coast, at approximately 150 km indicated that the dominant wind direction is W and SW in the summer and NE in the winter. The maximum wind speed is about 12 m/s in W and SW, and about 16 m/s in the NE [20]. Offshore wave at 9.17^0N, 107.08^0E, the wave height ranges from 0.88 to 3.58 m and the wave period changes from 4.3 to 9.6 s in the dry season. Wave height of 1.29 m and period of 5.8 s in the flood season.

The median particle size ranged between 2.5 and 3.9 μm. The percentage of clay fraction (particle size <2 mm) is approximately 15-20% of the suspended sediment [18,32]. sediment transport from the Bassac River had a high transport rate of approximately 22 million tons per year in 1992; however, it reduced to 47.4 million tons in 2020 [33].

3. Numerical Simulation and Verification

In this study, the MIKE 21 program was used in the simulation. The coupled model was constructed using Mike 21 HD, SW, and MT modules and verified by the observation data presented in [23]. The model with the computational domain covered the upstream (Tra Vinh and Dai Ngai stations) and adjacent areas around the Dinh An Estuary, with the plan dimensions being around 120x120 km. The south boundary, north boundary, and offshore boundary were approximately 50, 60 , and 70 km from the Dinh An Estuary, respectively. An overview of the model used in the analysis is shown in Figure 2.

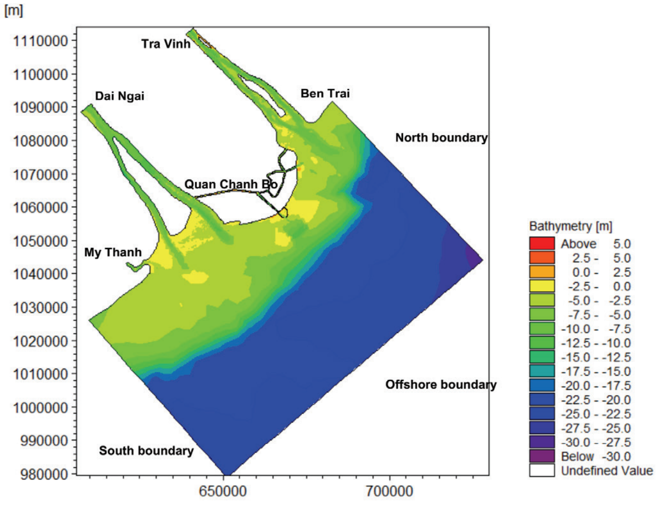

Figure 2. *Domain of the numerical model*

Hydrodynamics model setup with Tra Vinh, My Thanh, and Dai Ngai boundaries in the upstream and three boundaries in the sea. The discharges measured in November 2017 were used for three upstream boundaries. The water levels at My Thanh and Ben Trai were used for the South and North boundaries, respectively. Offshore boundary used water level estimated from the Tide Prediction of height of Mike 21 Tool box, and the data was calibrated by the water level at My Thanh and Ben Trai stations.

The spectral wave model setup based on the model suggestion, the offshore wave boundary applied measurement data at W7 (9°30'0.00" N, 106°30'0.00" E) in November 2017 with maximum wave height and period of 2.54 m and 12.99 s. The mean wave direction was 58.85^0. South and North are parallel boundaries. The three upstream boundaries are closed boundaries.

Mud transport model setup based on suspended sediment concentration (SSC) measured in three upstream boundaries. The North and South boundaries applied the section boundaries type with SSC ranges from 0 (in offshore) to 0.15 kg/m^3 nearshore. The offshore boundary SSC is zero.

The coupled model was continuously verified using observation data in November 2017 [34]. The coupled model performance was assessed using the mean absolute error and root mean square error between the observed and simulated data [35,36]. The observed data were collected at point W7 (9°30'0.00" N, 106°30'0.00" E), far from the shoreline of about 5.5 km, from 12 to 18/9/2017. The results of the verification are shown in Table 1.

Table 1. *RMSE and MAE for model verification*

Parameters	RMSE	Difference (%)	MAE	Difference (%)
Water level at Ben Trai (m)	0.23	7.0	0.21	5.7
Water level at Dai Ngai (m)	0.28	8.5	0.27	7.8
Water level at My Thanh (m)	0.11	4.0	0.10	2.8
Water level at Tra Vinh (m)	0.20	6.8	0.16	5.3
Salinity at Ben Trai (PSU)	1.2	20.3	1.1	19.4
Salinity at Dai Ngai (PSU)	1.1	18.2	0.9	14.2

As mentioned above, this study conducted numerical analysis for six options. Option 1 was simulated with the existing state (without any structures), as shown in Figure 3. From Options 2 to 6, there were five solutions with different layouts of structures. This paper evaluated the advantages and disadvantages of each Option from 2 to 6 and then compared them with Option 1. On the basis of these comparisons, the most reasonable option was proposed.

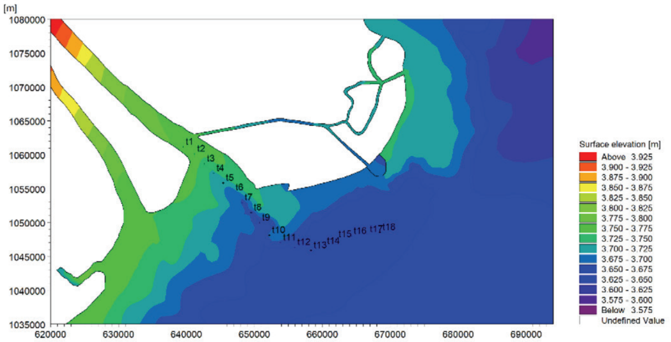

Figure 3. *Layout of Option 1 (Without structures)*

Figure 4 shows the layout of Option 2. This option is proposed to provide a defined channel by two jetties between the river mouth on both sides. There were two jetties running along the navigation channel. The north jetty started at the Ho Tau headland and consisted of two segments. The length of the first segment (N1) was 5.03 km, that of the second segment (N2) was 4.35 km, and that of the third segment (N3) was 10.14 km. The south jetty has three-segment symbols of S1, S2, and S3, with lengths of 16.45, 7.06, and 10.44 km, respectively. It departed from the right bank of the estuary, including. The crest level of all structures determined on the basis of the TCCS 02:2017/CHHVN [37] was +4.0 m (CD system). The heads of the two jetties were extended until a contour line of -9.0 m. The total length of the two jetties was 54.47 km. This option only focused on the stability and protection of the navigation channel in the Dinh An estuary.

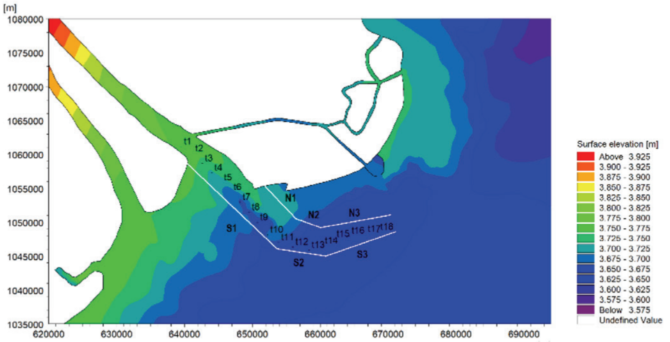

Figure 4. *Layout of Option 2*

Option 3 provided a channel defined by a jetty on the south bank of the navigation channel, which is the same as Option 2, as presented in Figure 5. Three groins, N1, N2, and N3, were located on the north bank of the Dinh An estuary. Groin N1 started at Ho Tau headland and had a length of 4.42 km, groin N2 had a length of 6.15 km, and groin N3 had an length of 8.75 km. The total length of the structures was 53.27 km, and the crest level of all structures was +4.0 m (CD system). Three groins regulate river and coastal flow to stabilize the navigation channel and limit erosion in the coastal area from north of the Dinh An estuary to the Duyen Hai port.

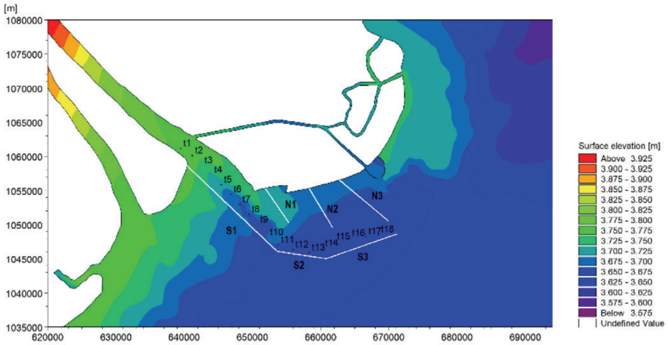

Figure 5. *Layout of Option 3*

The layout of Option 4 is shown in Figure 6. Option 4 had the south jetty the same as Option 2. On the north bank, there were two groins and two detached breakwaters. The groins N1 and N3 were the same as Option 3, and the two detached breakwaters D2 and D3 had lengths of 5.08 km and 4.44 km, respectively. Groin N3 was the same as N3 in Option 3, with an 8.75 km length. The total length of the structures was 56.64 km, and the crest level of all structures was +4.0 m. Two groins (N1 and N3) were combined with two detached breakwaters (D2 and D3) to reduce wave energy and coastal erosion of the Tra Vinh coast.

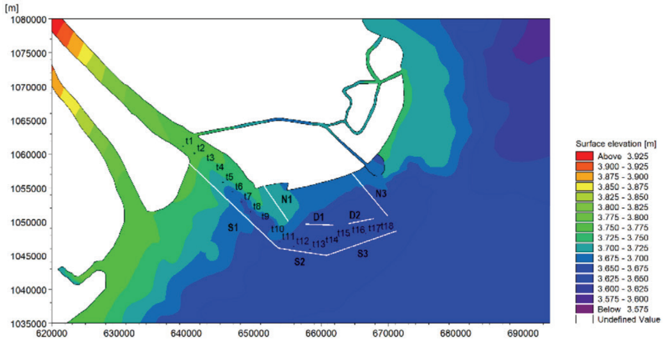

Figure 6. *Layout of Option 4*

The layout of Option 5 was the same as that of Option 4. However, groin N3 north of the estuary was excluded, as shown in Figure 7. The length of the detached breakwater D2 was 6.03 km. The total length of the structures was 49.48 km, and the crest level of all structures was +4.0 m (CD system). This option also mainly focused on the stability of the navigation channel, and it could reduce the southeast wave impacting the coast of Tra Vinh province.

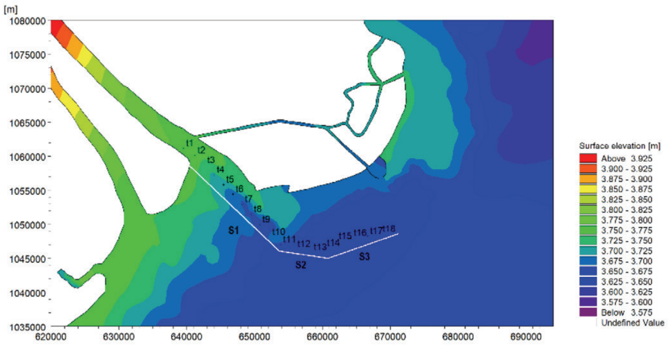

Figure 7. *Layout of Option 5*

Figure 8 illustrates the layout of Option 6. It had a south jetty like Option 2 and a T-shaped groin north of the estuary. The T-shaped groin had two segments: segment N1 had a 7.81 km length and segment N2 had a 7.56 km length. The total length of the structures was 49.32 km, and the crest level of all structures was +4.0 m (CD system). This alternative protected the channel and the coast of Tra Vinh province from waves generated by both northeast and southeast winds.

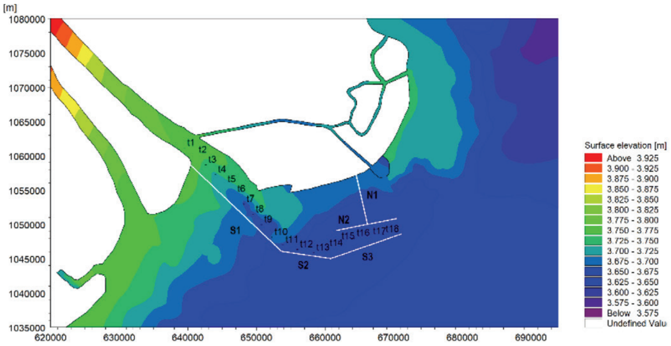

Figure 8. *Layout of Option 6*

The verification results in Table 1 indicate that the coupled model was consistent with the observation data and had the reliability to simulate hydrodynamics, wave propagation, and sediment transport. After model verification, six options were simulated by the coupled model in the dry season (May 2004) and flood season (Sep 2004). The numerical model analyzed the influence of countermeasures on water level, current speed, and bed thickness change. Based on the characteristics of these factors, this study adopted countermeasures for the stability and protection of the navigation channel in Dinh An estuary.

4. Results and Discussion

4.1. Change in Water Level

The water level changed due to regulation structures through 18 points symboled from T1 to T18 along the navigation channel (The locations of 18 points are shown in Figure 3). The maximum, minimum, and average water levels of Options 1 to 5 changing along the navigation channel were compared with those of Option 1 (without structures).

A comparison of the maximum water level changes along the navigation channel of the five options in the dry season is plotted in Figure 9a. The results indicated that the regulation structures reduced the water level along the navigation channel. Options 3 and 6 were similar and gave the lowest values with a maximum water level lower than Option 1, approximately 0.35-0.67 m. In contrast, Option 5 showed the highest maximum water level among the five options. It was just lower than Option 1, around 0.07 to 0.31 m.

The results of the minimum water level change along the navigation channel shown in Figure 9b demonstrate that the presentation of regulation structures led to an increase in the minimum water level along the navigation channel. The minimum water level of Option 2 from T1 to T14 increased from 0.42 to 0.75 m and then rapidly decreased; in Option 3, it increased from 0.37-0.64 m from T1 to T16 and rapidly decreased and was only higher than Option 1 by approximately 0.12-0.13 m; in Option 4, it gradually increased by approximately 0.16-0.46 m; in Option 5, it increased from 0.16-0.38 m from T1 to T14 and then rapidly decreased; and in Option 6, it increased from 0.45-0.63 m from T1 to T15 and then rapidly decreased. However, it was still higher than Option 1, about 0.08-0.15 m.

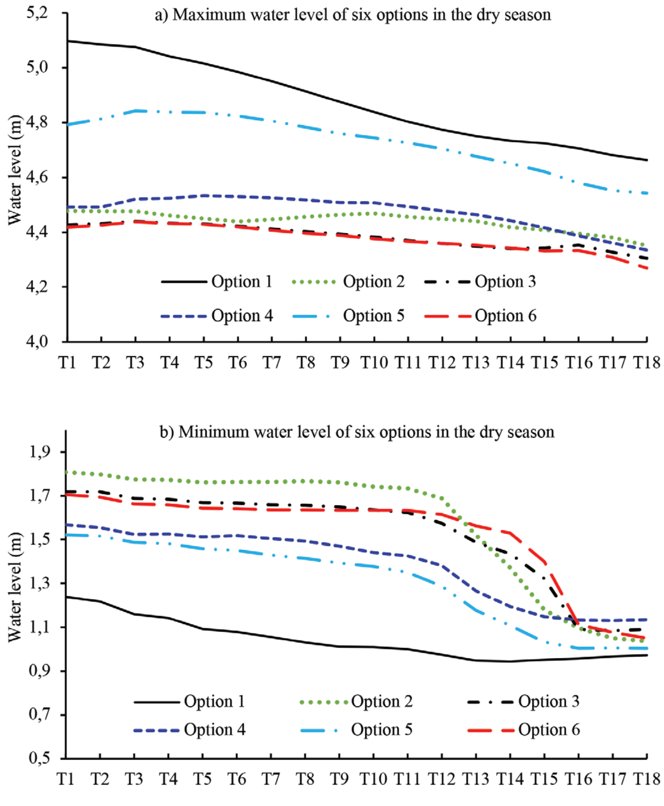

Figure 9. *Comparison of the maximum and minimum water levels of the six options in the dry season*

The average water level change along the navigation channel of the six options in the dry season is plotted in Figure 10. The result indicated that, after arranging the regulation structures, the average water level undergoes two distinct periods with a division around T14 and T15; from T1 to T15, the average water level was higher than Option 1, and from T15 to T18, it was lower than Option 1. This showed that the water level change of Option 4 gradually changed along the navigation channel.

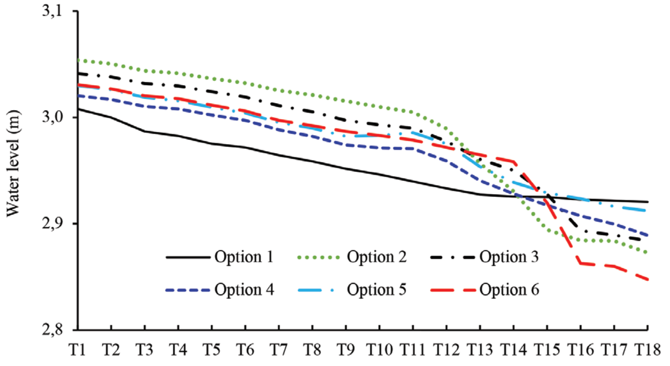

Figure 10. *A comparison of the average water level of the six options in the dry season*

In the dry season, the results indicate that Options 4 and 5 caused gradual changes in water levels. Two options did not cause the water level to change dramatically as the remaining options, especially in the area from T12 to T16. Similarly, the water level changed through 18 points along the navigation channel due to the regulation structures. The results of the maximum, minimum, and average water level changes in the six options are summarized as follows.

The maximum water levels of the five options of regulation work are lower than Option 1. In Option 2, it decreased from 0.25 to 0.16 m from T1 to T14 and then increased slightly from T15 to T18. However, it was still lower than that in Option 1, from 0.16 to 0.19 m; in Option 3, the maximum water level decreased from 0.18 to 0.33 m from T1 to T15, and then it increased about 0.16-0.21 m from T15 to T18. Option 4 gradually decreased by about 0.11-0.22 m along the navigation channel; Option 5 gradually decreased from T1 to T10 and then changed slightly offshore; Option 6 changed the maximum water level like Option 1. However, it was lower than Option 1, about 0.2-0.3 m (Figure 11a).

Figure 11b shows the results of the minimum water level change along the navigation channel. The regulation structures led to an increase in the minimum water level along the navigation channel. The water level changed slightly in Option 2 from T1 to T10. It was higher than Option 1, about 0.60-0.77 m. However, from T11 to T18, it rapidly decreased and was only higher than Option 1, approximately 0.05 m. In Option 3, it mostly remained stable from t1 to t6 and then gradually decreased from T5 to T12. After that, it decreased from T13 to T16 and remained constant from T17 to the sea. Option 4's minimum water level was higher than that of Option 1. It increased slightly from T1 to T6 and then gradually decreased from T6 to T13. It slowly decreased from T13 to T16 and did not change from T17 to the sea. The water level in Option 5 was the same as that in Option 4. However, the water level change intensity was smaller than that in Option 4. In Option 6, it slightly changed from T1 to T13 and rapidly decreased from T13 to T16. Finally, it stabilized in the offshore area.

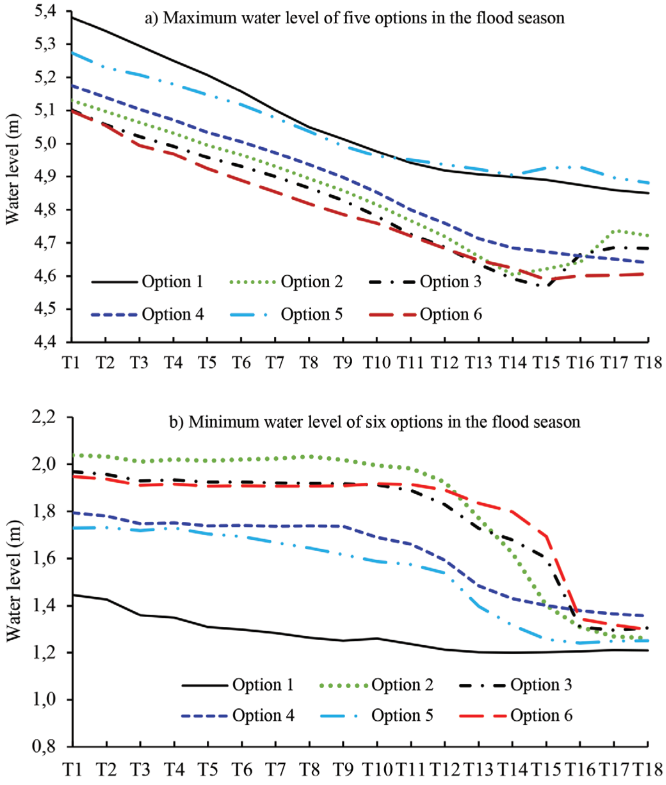

***Figure 11**. A comparison of the minimum water level of six options in the flood season*

The average water level change along the navigation channel of the six options in the flood season is plotted in Figure 12. As shown in the figure, after arranging the regulation structures, the average water level was higher than that of Option 1. The highest value occurred in Option 2. Option 2, 3, and 6 rapidly decreased from T12 to T16. Option 4 and 5 gradually decreased along the navigation channel, and Option 5 was lower than the others. The results also indicated that the two options, 4 and 5, did not cause dramatic water level changes compared with the other options, especially in the area from T12 to T16.

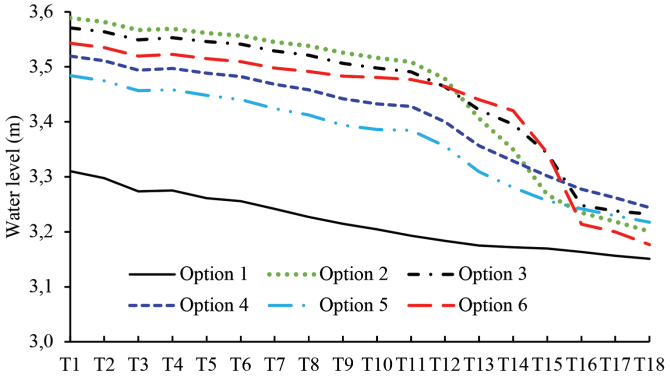

***Figure 12**. A comparison of the average water level of the five options in the flood season*

4.2. Current Speed Change

In this section, the speed of the high flood tide, high ebb tide, low flood tide, and low ebb tide currents in the dry season changed because of the regulation structures considered through 18 points along the navigation channel (The locations of 18 points were shown in Figure 3).

The maximum high flood tide current speed along the navigation channel is plotted in Figure 13a. The result indicated that after arranging the regulation structures, the maximum current speed of Options 2, 3, and 6 underwent two distinct periods with a division at T13. From T1 to T12, the maximum high flood tide current speed of the five options was lower than that of Option 1. However, from T13 to T18, they increased and increased. These options showed a high current speed increase dramatically from T14 to T18. The result of Option 4 showed undergoing two distinct periods with the division point at T12. From T1 to T12, it fluctuated around 1.0; from T14, it increased significantly toward the seaside. For Option 5, the trend from T1 to T12 was mostly similar to Option 4, but from T12, it was the opposite, with the current speed decreasing.

The average high flood tide current speed change along the navigation channel is plotted in Figure 13b. The figure shows that the regulation structures of Options 2 and 6 decreased the current speed from section T1 to T11. However, the current speed rapidly increased again from T11 to T16. Options 4 and 5 showed that the current speed was reduced and lower than that of Option 1 from section T1 to T5, then increased and higher than Option 1. From sections T14 to T18, the current speed of Option 4 increased significantly, while Option 5's speed decreased slowly, similar to the trend of Option 1.

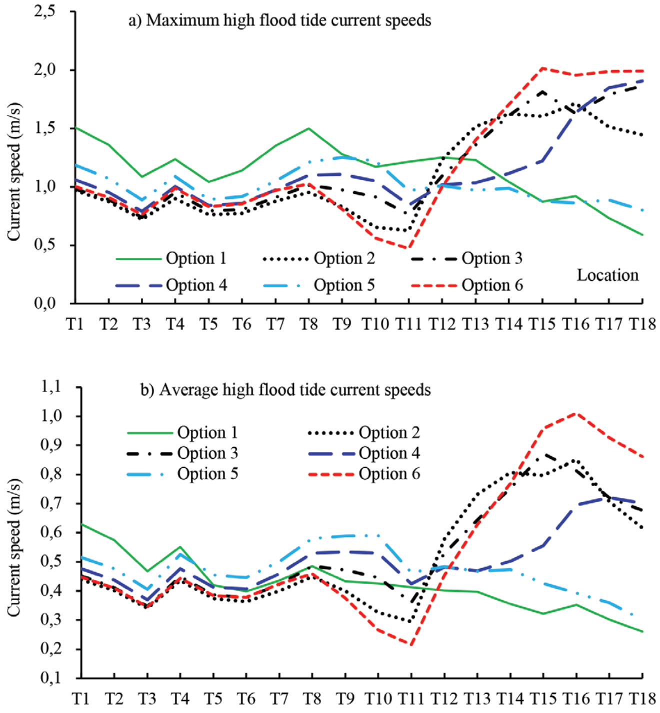

***Figure 13**. High flood tide current speeds during changes in the dry season*

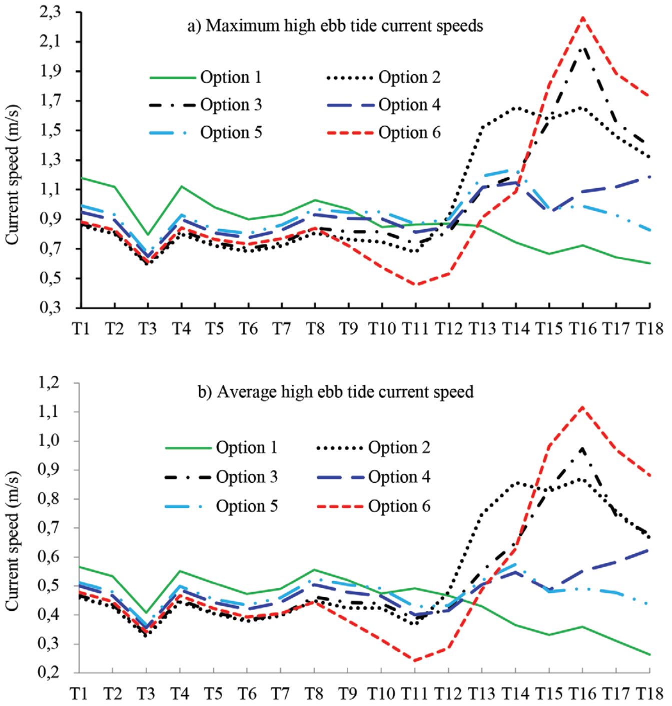

***Figure 14**. High ebb tide current speed changes during the dry season*

Figure 14a presents the results of the maximum high ebb tide current speed change along the navigation channel. After arranging the regulation structures, the maximum current speed of all options underwent two distinct periods with a division at section T13. From section T1 to T12, the maximum high ebb tide current speed was lower than that of Option 1, except for Options 4 and 5 in section T10. From section T13 to T18, they increased and were higher than those of Option 1. Especially in Options 3 and 6, the current speed increased dramatically and peaked at section T16 with a value equal to three times that of Option 1.

Figure 14b plots the average high ebb tide current speed change in the dry season. Similar to the maximum average of high ebb, tide current speeds changed along the navigation channel and underwent two distinct periods with a division at section T13. From sections T1 to T12, the average high ebb tide current speed was lower than that of Option 1. However, from sections T13 to T18, they were larger than those of Option 1. The results also showed that Options 2, 3, and 6 conducted high-current speeds in the offshore navigation channel, especially at section T16.

The results indicated that Options 4 and 5 induced a moderate current speed change. Both options induced an increase in the current speed in the curvature and offshore segments (from section T13 to T18) of the navigation channel.

The maximum high flood tide current speed change along the navigation channel during the flood season is plotted in Figure 15. The result indicated that the regulation works of Options 2, 3, and 6 changed underwent two distinct periods with a division at section Tt13. From sections T1 to T12, the current speed was reduced and lower than that of Option 1. However, from section T13 to T18, it increased and was higher than Option 1 by approximately twice. In Option 6, the current speed increased dramatically and reached its highest point at section T16. In Option 4, the current speed gradually changed from T1 to T15 and rapidly increased in the offshore part of the navigation channel. In Option 5, the current speed was changed and was almost lower than that in Option 1. The result showed that in section T11, the current speed was the lowest.

The average high flood tide current speed change along the navigation channel is plotted in Figure 16a. The results show that the regulation structures of Options 2, 3, and 6 changed and underwent two distinct periods with a division at T11. From T1 to T12, the current speed was lower than that of Option 1. However, from T13 to T18, it was significantly increased and larger than Option 1 by approximately two times. In Option 6, from section T11 to T16, it increased six times. In Option 4, the current speed gradually changed from T1 to T15 and rapidly increased. In Option 5, the current speed changed slightly, and the current range of Option 5 was the smallest.

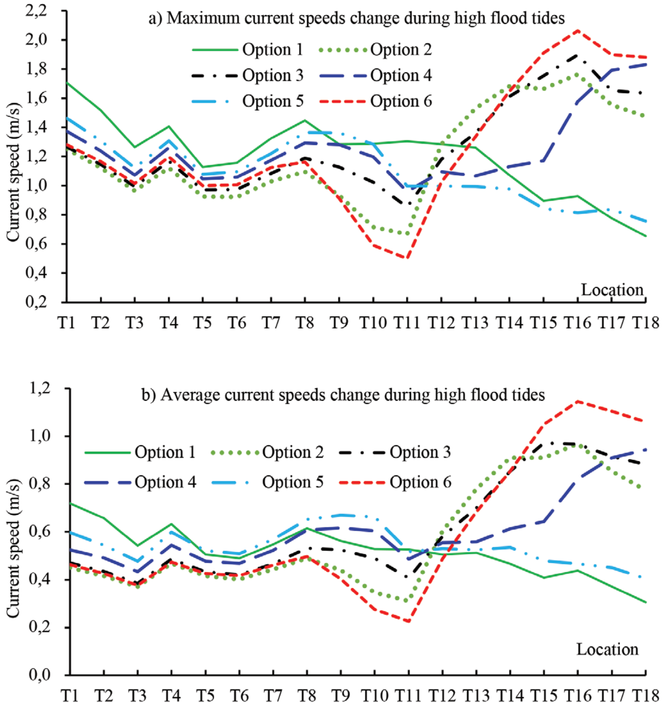

***Figure 15**. Current speeds change during high flood tides during the flood season*

The maximum high ebb tide current speed results are plotted in Figure 16b, which shows that the current tended to decrease upstream of the navigation channel. Subsequently, it increased from section T13 to T18, especially Options 2, 3, and 6. For the average high ebb tide, the current speed showed the same trend as the maximum current speed, as shown in Figure 16. These results indicated that Options 4 and 5 induced a medium change in the current speed. Both options increased the current speed at the offshore part of the navigation channel.

4.3. Change in the Longitudinal Profile of the Navigation Channel

The bed thickness change of the longitudinal profile of the navigation channel during the flood season is presented in Figure 17. The results showed that Options 1, 2, 5, and 6 induced depositions in the navigation channel. Options 1 and 5 induced deposition in the offshore part, whereas Options 2 and 6 did so around section T11. In contrast, Options 3 and 4 caused erosion of the navigation channel, and the erosion intensity of Option 4 was higher than Option 3.

The change in bed thickness of the longitudinal profile of the navigation channel in the dry season is presented in Figure 18. As seen from the figure, in Option 1, deposition appeared in the estuary and offshore part of the navigation channel. Erosion was observed in the middle of the navigation channel. In Option 2, high deposition occurred

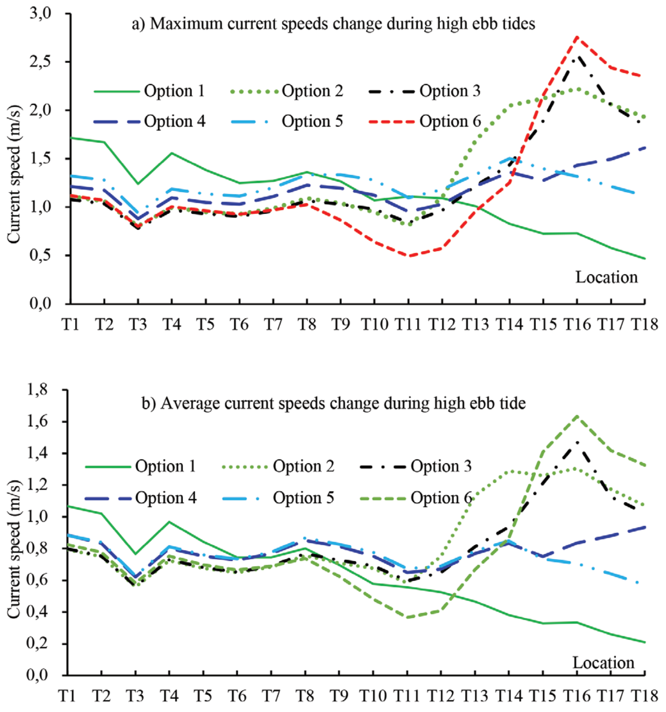

***Figure 16**. Current speeds change during high ebb tides in the flood season*

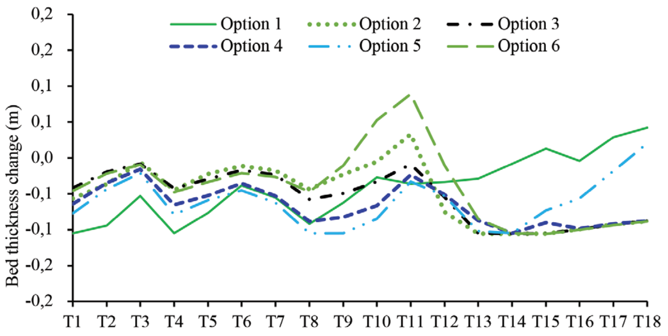

***Figure 17**. Total change in seabed thickness along the navigation channel in the flood season*

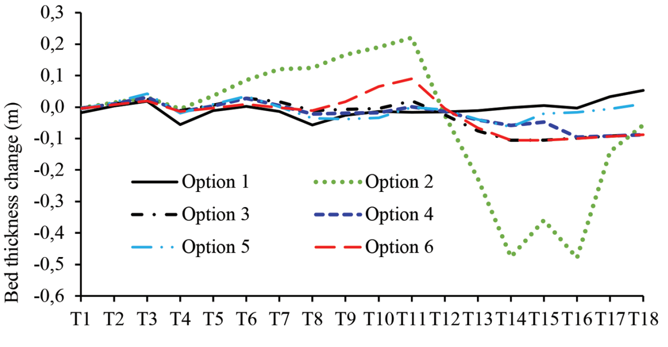

***Figure 18**. Bed thickness changed along the navigation channel during the dry season*

from the estuary to section T11, and the navigation channel was eroded from section T12 to offshore and especially from section T14 to T16. The channel bed eroded significantly by 0.45 m after 18 days. In Option 3, the channel bed deposited slightly from section T1 to T11 and eroded from T11 to T18. The erosion was approximately 0.1 m after 18 days. In Option 4, the deposition was found in sections T2 to T7. The erosion was presented from sections T8 to T18, increasing at the offshore part of the navigation channel. Option 5 increased the deposition at the offshore part of the navigation channel, whereas in Option 6, the channel bed was deposited in the upstream part, especially around sections T10 and T11.

4.4. Evaluate the Advantages and Disadvantages of the Options

Option 1 (Without structures) meets the natural equilibrium and supports environmental values with minimal human impact. Without any technical solutions, it will reduce the impact on the environment. The tidal flats stabilize without continual disturbance, and the ecosystem matures. It becomes more available as a habitat for invertebrates and a feeding area for wading and other birdlife. However, some disadvantages could occur, such as potential perceived negative implications for flood management and a possible negative impact on the ports and back siltation often occurring in the navigation channel.

In Option 2, the structures removed the constant, which was needed to dredge the navigation channel, increase the channel flow velocity, induce sediment in suspension, and prevent deposition. Aesthetics were improved by removing "unsightly" mud flats in the Dinh An estuary, and the people enjoyed the benefits of a large recreational area on the foreshore on both sides of the jetties. In addition, it reduced greenhouse gas emissions from dredging activities. Option 2 dramatically changed the water level and current speed for the disadvantage, especially from sections T11 to T16. The results also indicated high deposition at Dinh An Estuary and the head of the north jetty. The deposition at the head of the north jetty tended to move south during the flood season. The erosion occurred significantly from section T13 to T17, and the erosion depth reached 1.2 m in the dry season. A major discharge of greenhouse gasses was released during construction activities. There was a considerable risk of damage during flooding due to overtopping, saturation, debris, and potential perturbations to the north jetty area related to changed tidal conditions (reduced tidal prism).

The structures of Option 3 removed the constant that needed to dredge the navigation channel, improved opportunities for reclamation activities around the groin system, and recreational and water sports-based tourism. It reduces greenhouse gas emissions from dredging activities. However, the drawback included dramatically changing the water level and current speed, especially from sections T15 to T18. Potential deposition occurred in groin systems. The deposition area in the northeast of groin N3 moved southward, and a huge volume of greenhouse gasses was spread during construction activities. The unconsolidated area for the new channel presented difficulties due to the slippage loss of mudflats, which induced biodiversity and ecological habitat loss. The risk of damage during flooding is lower than that of Option 2.

The good point of Option 4 was the removal of the constant need to dredge the navigation channel. In addition, it increased the current speed in the navigation channel to keep the sediment in suspension and reduce deposition. Thus, it improved the opportunities for reclamation activities in the north bank for recreational and tourism water sports-based activities. It also reduces greenhouse gas emissions from dredging activities. The disadvantages could appear, such as potential deposition between groins and detached breakwaters, and a huge volume of greenhouse gasses can be spread during construction activities. The unconsolidated area for the new channel presented difficulties from slippage-loss of mudflats induced biodiversity and ecological habitat loss, potential perturbations to the groin area related to changes in tidal conditions (reduced tidal prism), and loss of intertidal and associated environmental impacts.

Option 5 had benefits similar to Option 4. The advantages of Option 6 were the same as those of Option 4, and the disadvantages consisted of potential deposition at both sides of the T-shaped groin, and the others were the same as Option 5.

4.5. Selection Criteria

A multi-criteria analysis process includes reviewing the critical aspects of technical, environmental, social, and economic impacts as follows:

a. Technical criteria

- The structures eliminate the constant need to dredge in the navigation channel.
- Increase current speed in navigation to keep sediment in suspension and reduce deposition.
- Ensure safety of vessel operation in the navigation channel.
- Improved opportunities for reclamation activities.

b. Environmental impact criteria

- Aesthetics are improved by removing "unsightly" mud flats in the Dinh An estuary.

- Reduced greenhouse gas emissions from dredging activities.

The public may benefit from the recreational area on the foreshore.

c. Social and Economic Impact Criteria

- Improved opportunities for recreational and tourism activities.
- Local economic growth.
- Flood mitigation.

4.6. Propose Countermeasures for the Navigation Channel in the Dinh An Estuary

The results above and the selection criteria showed that Option 4 almost satisfied the requirements. The main characteristics of Option 4 were as follows:

- The south jetty consists of three segments: S1 has 16.45 km, S2 has 7.06 km, and S3 has 10.44 km.
- Groin N1 started at Ho Tau headland and has a length of 4.42 km, and the N3 groin has an 8.75 km length.
- Detached breakwaters D2 and D3 are 5.08 km and 4.44 km long, respectively.
- The total length of the structures was 53.27 km.
- The crest level of all structures was +4.0 m (CD).

5. Conclusion

Countermeasures significantly influence the hydrodynamics and sediment transport of the Dinh An estuary and coastal Tra Vinh province. The maximum water levels of all proposal options in the dry and flood seasons are lower than natural conditions (Option 1), while the minimum water levels of the five options in both the dry and flood seasons are higher than natural conditions (Option 1). The average ebb tide current speed increases in the offshore segment that provides flow to keep the sediment moving and prevent sedimentation in the navigation channel. Option 4 was proposed to satisfy almost all requirements of the technical, environmental impact, social, and economic impact criteria.

Authorship Contributions

Concept design: V. T. Nguyen, Data Collection or Processing: V. T. Nguyen, Analysis or Interpretation: V. T. Nguyen, A. D. Nguyen, and V. A. Le, Literature Review: V. T. Nguyen, A. D. Nguyen, and V. A. Le, Writing, Reviewing and Editing: V. T. Nguyen, A. D. Nguyen, and V. A. Le.

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