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Research Article

Effects of detached breakwaters on drowning due to rip and circulation currents

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Abstract
Rip currents are a hazardous phenomenon for beachgoers worldwide. These narrow currents in the surf zone move quickly in an offshore direction and can occur near hard structures such as jetties, piers, breakwaters, and rocks. This study examines the hazard rate (HR) for swimming in different water depths due to rip currents and coastal circulation currents (vortices), as well as the effects of detached breakwater structures on rip and coastal circulation currents (RACC) at the surf zone. The objective is to find a solution to the problem of drowning due to rip currents resulting from the presence of detached breakwaters. Physical and numerical modeling, field measurements, and shore surveying were used to achieve the study's goals. The study was conducted in the wave flume at Abu-Quire Research Station, Alexandria Egypt, for different scenarios. The numerical model (MIKE 21) was applied on the northwestern coast of Egypt about 21 km west of Alexandria. The results showed that the HR for swimming in water depths more than 1.50 m ranges from high to extreme hazard (1.275 m2/s: 2.2 m2/s), and the rip current velocities near the breakwaters are high, ranging from 0.05 m/s up to 1.05 m/s. Their length can extend from 30.0 m up to 200.0 m offshore. It was concluded that the RACC is caused due to the detached breakwaters, as well as the interaction between the boundaries and the beach bed. The proposed solution for RACC formations due to the presence of detached breakwaters is the partial closure of openings between the existing detached breakwaters using submerged breakwaters.

Keywords
***Rip and coastal circulation currents, Hazard rate, Drownings, Submerged breakwater, Al nakheel beach*.**

1.Introduction
Drowning caused by rip and coastal circulation currents (RACC) is one of the worst hazards on beaches globally. This paper presents a study that examines the effects of detached breakwater structures on RACC in the surf zone, using physical and numerical modeling. The study aims to propose a solution to RACC formation due to the presence of detached breakwaters in the surf zone. The methodology includes four different scenarios of physical and numerical modeling, field measurements, and shore surveying. Experimental works were carried out for different scenarios in a wave flume, while a numerical model (MIKE 21) was applied to the northwestern coast of Egypt.

Previous studies have been carried out on rip currents and submerged breakwater characteristics, and the morpho-dynamics was studied in the vicinity of a submerged detached breakwater using the Delft3D model. The study shows that the coastal circulation pattern around the structure is asymmetric and composed of two cells induced by the divergence of cross-shore currents generated in the submerged breakwater towards the shore. The study also demonstrates the coastal circulation patterns that occur in the structure's vicinity, which influences the coastline's evolution [1].

The wave-induced currents in the vicinity of detached breakwaters were studied, showing that the currents in the vicinity of breakwaters are reduced as the crest of the breakwater is lowered. However, several eddies may be generated behind submerged breakwaters that could be dangerous for swimmers [2]. The world health organization (WHO)

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announced in 2021 that 7% of all deaths worldwide are due to drowning [3]. Rip currents, which are rapid offshore flows caused by the breaking of nonuniform waves, are a significant cause of surf zone fatalities, accounting for approximately 60%-80% of such deaths in the United States, Australia, and many other regions over recent years [4–8].

The present study includes an abstract, introduction, and literature review. The materials and methods section is divided into two parts. The first part involves sample collection and numerical modeling, where four scenarios were conducted: (1) reference case with the existing detached breakwater, (2) removal of the existing detached breakwater, (3) partial closure of the detached breakwater using submerged breakwaters, and (4) complete closure of the gap between the detached breakwater using an emergent breakwater structure. Wind directions were considered in all scenarios. The second part involves experimental work and field data, where three cases were studied: one opening, two openings, and three openings between the detached breakwater to investigate the effects of the breakwater on rip currents and vortices. The study includes calculations of the rip and coastal circulation rate of hazard, as well as an economic comparison of the proposed scenarios. The study concludes with a discussion, recommendations for decision-makers, and suggestions for future work.

2.Literature review

The coastal communities consider rip currents to be a significant natural hazard to beach recreational safety [9]. Extensive field observations on rip currents concluded that their development depends on the wave climate and topographic effects [10, 11]. A study on rip currents showed that they are associated with a vortex pair that propagates offshore and grows in the surf zone [12]. The vortex force formalism was used in a study on rip currents, which demonstrated how it generates rip currents [13]. Numerical computation was used to study the generation of rip currents, and it was found that they are stimulated by spatial variations in breaking wave height, which create wave set-up gradients that force water to flow [14, 15].

According to a study on drowning and surf rescue, rip currents are a leading cause of drowning and surf rescue worldwide [16–18]. A study on fatalities due to rip currents in the United States showed that swimmers are pulled directly out to sea due to rip currents [19]. A study on the hazard of rip currents in Egypt showed that about 7% of different accidents in Egypt are due to drowning, according to official data from the Central Agency for Public Mobilization and Statistics issued in 2018 [20]. The instinctive reaction of a misinformed swimmer caught in a rip current was studied, and the simulation of human behaviors showed that this instinctive reaction can lead to fatigue, panic, and, in some cases, drowning, according to independent analyses by the national oceanic and atmospheric administration (NOAA) in 2019 [21].

According to a study on rip-related deaths per year in Australia, 89% of the 25,000 surf rescues conducted by lifeguards per year are due to rip current accidents, and there is an average of 21 rip-related deaths per year [22]. Another study on rip currents found that many beach users rely on lifeguard experience and signage to be aware of surrounding rip currents [23]. Work required to reach the shoreline against rip current direction increases with escape speed, as shown in a study on rip currents and swimming [24]. Different types of rip currents can originate from nearshore morphology [25, 26]. In a study on rip currents at Woolamai Beach, Australia, the average rip current length and width were 300 m and 20-100 (m), respectively, and the average velocity was from 0.5-0.9 (m/s) [27]. Mathematical models of 2-D wave-induced nearshore currents were used in another study on rip currents, which showed that the average velocities of rip currents ranged from 0.10-0.60 (m/s), and MIKE 21module can be used to acquire the characteristics of rip currents [28]. Al-Nakheel beach in Egypt has been the site of many drowning incidents, with 942 victims from 2005 up to 2019 [29]. More than twenty people reportedly died while swimming at Al-Nakheel beach in recent months in 2018 [30].

A study on rip current detection using an artificial intelligence algorithm that analyzes images and video at oblique angles found that the proposed system can classify, localize, and improve rip current detection with 89% accuracy [31]. An innovative deflector system was proposed to mitigate the effects of rip current drowning by deflecting floating bodies caught by rip currents. The study used experimental works, field measurements, and numerical works to conclude that the use of proposed deflectors can mitigate the effects of rip current drowning [32]. Another study on remote-sensing-based techniques for rip current and rip channel detection found that the proposed technique can detect rip currents and rip channels with accuracies of 67.3% and 96.2%, respectively

[33]. The aforementioned literature discusses the characteristics and formation of rip current phenomena, as well as the hydrodynamics of rip currents. It also highlights the issue of drowning caused by various types of currents, particularly rip currents and vortices in the surf zone. The literature presents statistical data on accidents and deaths resulting from rip currents in different regions worldwide, and it outlines methods for detecting rip currents and rip channels. Additionally, the literature explores ways to mitigate the negative effects of rip current drowning using algorithms, numerical modeling, and physical experiments.

3.Materials and methods

3.1Sample collection and numerical model

The study region is a coastal area of West Alexandria City that extends for 21 km. It is located between longitudes (29˚ 43' E) and (29˚ 42' E) and latitude (31˚ 6' N), as shown in *Figure 1*. The coast of the study area is a popular seaside resort, and the beachfront extends to about 1200.0 m. *Figure 2* shows seven detached breakwaters made of dolos units submerged in a water depth between (-4.0 m and -5.0 m) in front of the shoreline, which is about 1 km long. Each individual breakwater is 100.0 m in length, 200.0 m away from the shore, and spaced at 50.0 m intervals [34]. The Western Nobaria Drain is located to the west of the detached breakwater outlet, with two jetties on both sides. Cross sections perpendicular to the baseline on beach profiles extend to 6.0 m of water depth or a maximum distance of 2000.0 m seaward. Sediment samples were collected every 200 m or as possible, as shown in *Figure 3*, along with each profile from the beach using a grab sampler. Different scenarios were conducted from physical models and laboratory works for different study areas. Applying (MIKE 21), the bathymetry mesh of the Egyptian north coastal zone between longitudes (29˚ 43' E) and (29˚ 42' E) and latitude (31˚ 6' N) was initiated and optimized to a satisfactory level. The bathymetry is shown in shaded contour lines in *Figure 3*. The different parameters of waves were calculated using measured data from the Coastal Research Institute (CoRI). For the study area, the most frequent wave height (H_s) is 4.8 m for northwest. The H_s is 4.5 m for north and 2.4 m for northeast, respectively. The periodic time (T_p) is 11.5 seconds for northwest, 10.6 seconds for north, and 7.5 seconds for northeast, respectively. The directions are 315º northwest, 45º northeast, and 00º north. The numerical model stability should be secured if the courant–friedrichs–lewy (CFL) number is less than 1.00. Therefore, the default value of the critical CFL number is set to be 0.8. For the flood, dry, and wet depths of water, the default values are: drying depth (0.005 m), flooding depth (0.05 m), and wetting depth (0.10m). The Manning number is specified as 32 m1/3/s, which is common for coastal and marine applications because the relative variation of the water depth is considered in the model. Calibration was carried out by choosing eight points in the study area. These points have latitudes and longitudes from point 1 to point 8 as (757832.1769, 3443457.815), (758222.6062,3443769.851),(758361.1329,3443977.638),(758613.0363,3444081.891),(758786.745,3444247.688),(759003.4673,3444393.933),(759203.5577, 3444534.907),and(759393.8992,3444705.979),respectively.

The selected points are located at different distances along the shoreline. The selected points are at (1.00:1.5) m depth under the sea water level, the traveling times of the floating bodies and distances between points are measured, and the velocities of currents are calculated. It ranged between 0.2 m/s to 0.5 m/s, and the directions of the currents are from west to east in cross sections 1, 2 and 3 but in section 6 the direction is from east to west. The directions are inclined in an offshore direction in section 4 and towards the shore in sections 5, 7 and 8. Model calibration is made via regression analysis by comparing the modeled longshore currents data with those measured by the CoRI as in *Figure 4*. The resulted regression analysis confirms that model results and observed currents are matched well with a higher R^2 of 0.95.

3.2The experimental work and field data

The objective of this study is to investigate the impact of detached breakwater structures on RACC in the surf zone. The experiments were conducted in an 8.0×0.6×0.6 m wave flume with a water depth of 30.0 cm. Nearshore wave types were simulated using frequencies ranging from 25 Hz to 50 Hz, resulting in wave heights ranging from 4.0 cm to 13.0 cm. Three cases were tested, with the breakwater having one, two, and three openings, respectively. Additionally, four different scenarios were considered which are as under.

- Reference case: standing detached breakwater without any changes.
- Removal of the standing detached breakwater.
- Partial closure of the standing detached breakwater using submerged breakwaters.
- Complete closure of the gap between breakwaters using emergent breakwaters.

To achieve the research goals, experiments were conducted six times with different frequencies and three times with different breakwater openings, using the same water depth. In addition, four different scenarios were tested. Field data were collected from CoRI and the Egyptian Authority for shore protection (SPA) to establish numerical models. *Table 1* presents the latitude, longitude, water depths, and distances of 16 cross sections ranging from 0.00 to 800.00, with water depths from 0.0 to -12.0 at the study area shown in *Figure 5.*

3.3The calculation of the hazard rate (HR) due to RACC

The losses due to drowning from RACC can be assessed using the HR as shown in *Table 2* [35]. In this study, the scenario of partial closure of openings between breakwaters, and waves in northwest (NW) direction will be used only as a proposed solution. The HR described in *Table 2* can be applied to beachgoers who have different heights, and weights which can then be evaluated in association with escape strategy results [35]. The HR for varying heights and weights under varying current velocities can be calculated as shown in Equation 1.

$$HR = (d) \times (u+0.5) \quad m^2/s \qquad (1)$$

Where d is the depth of water in meters (m), and u is the average value of RACC in m/s.

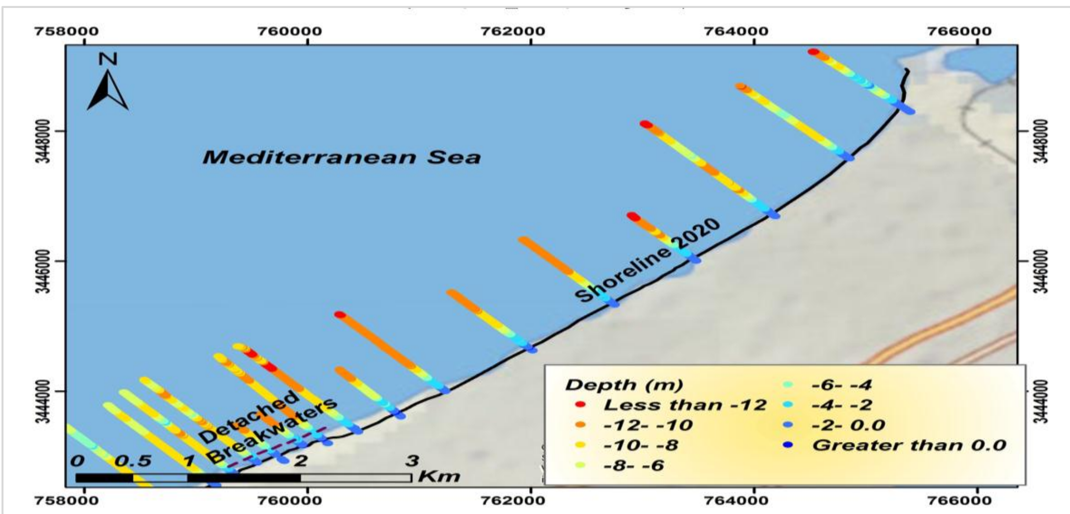


Figure 1 The sixteen cross-sections and water depth from (0.0: -12.0) at Al Nakheel Beach Egypt

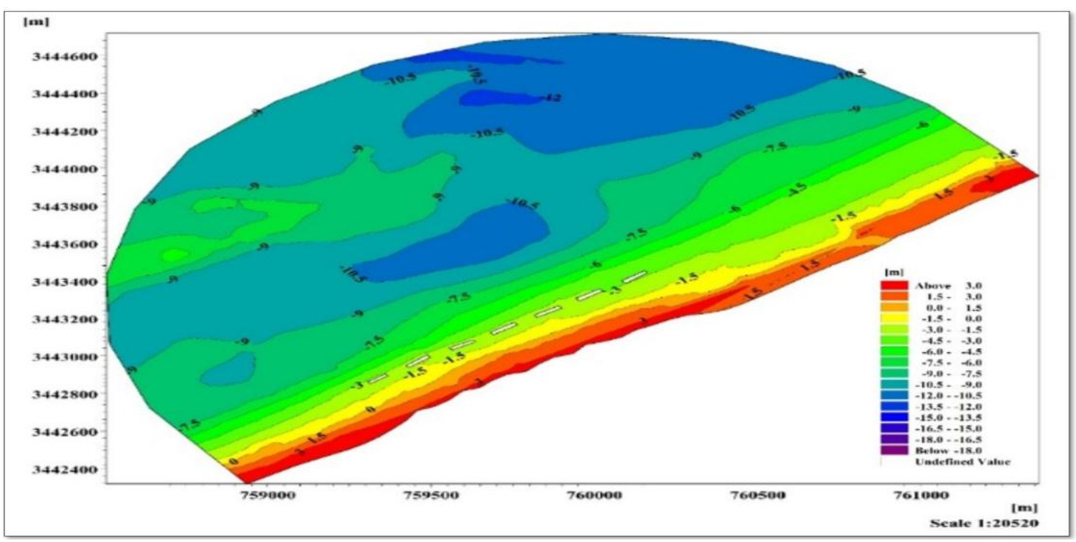


Figure 2 The bathymetry around breakwaters at Al Nakheel Beach Alexandria Egypt

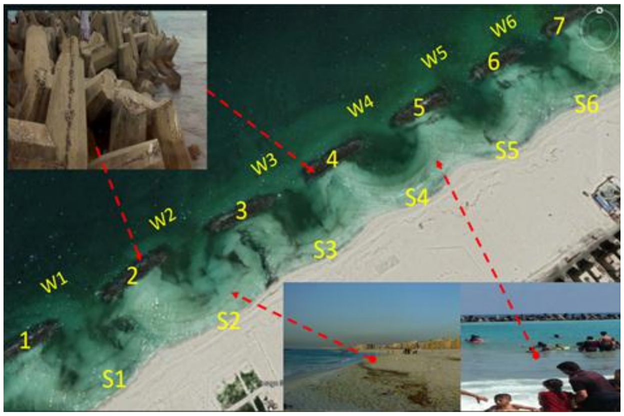


Figure 3 The seven dolos detached breakwaters at Al Nakheel Beach Alexandria Egypt

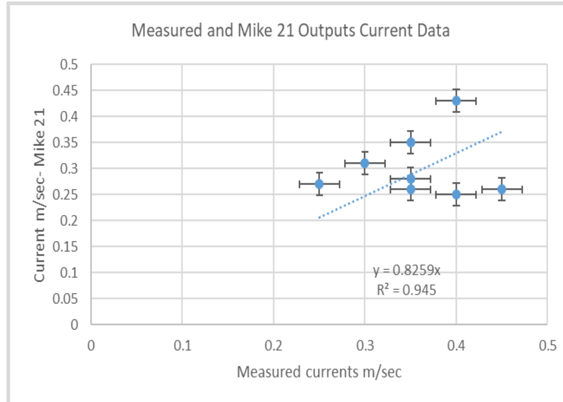
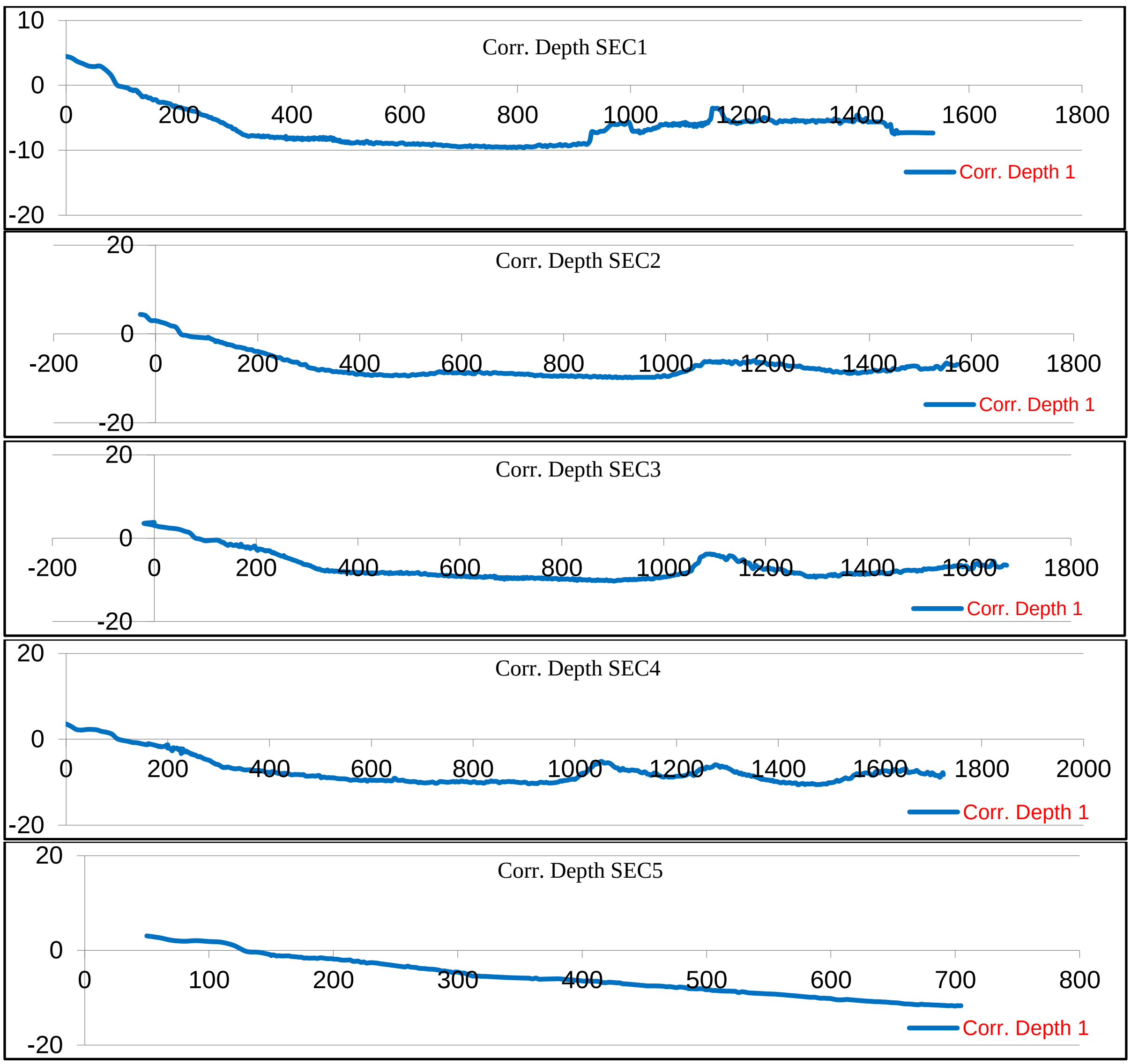


Figure 4 Model calibration using regression analysis between the measured and output data



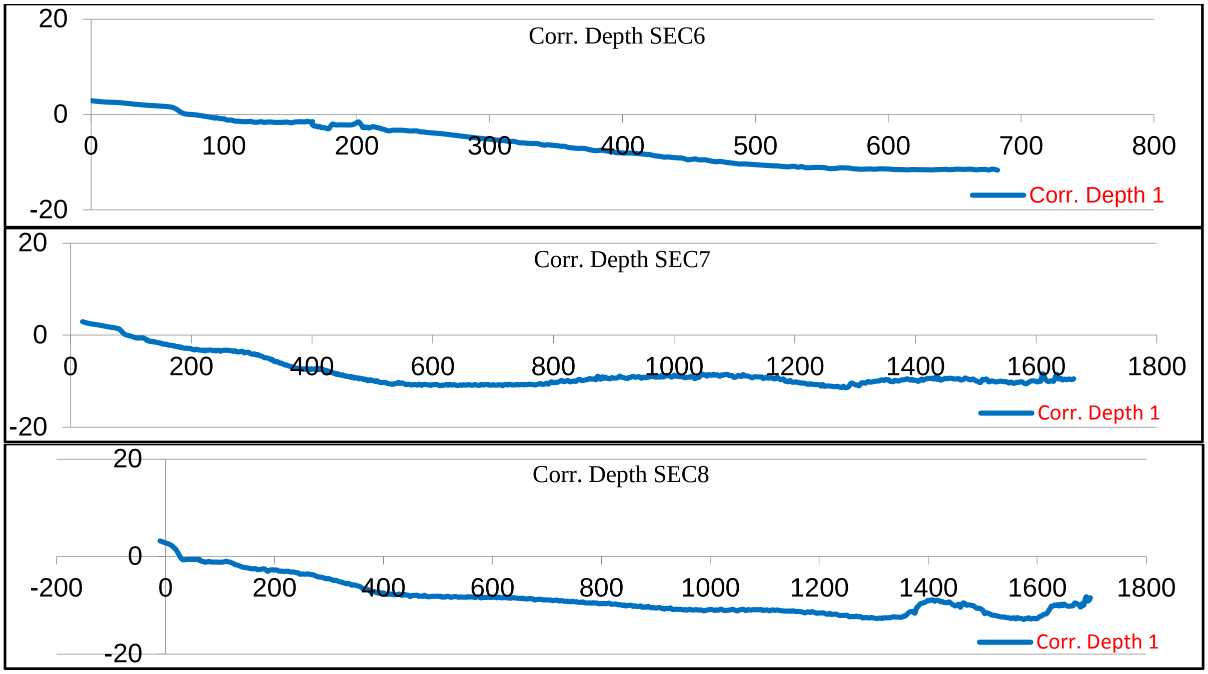


Figure 5 At Al Nakheel Beach, Egypt, there are sixteen cross-sections showing water depths ranging from 0.0 to -12.0 at the breakwaters. In this study, eight of these cross-sections were analyzed to investigate the impact of the detached breakwater structures on RACC in the surf zone

Table 1 Displays the latitude, longitude, and water depths of 16 cross-sections at different distances ranging from 00.00 to 800.00 and water depths from 0.0 to -12.0 in the study area. These cross-sections were analyzed to investigate the impact of the detached breakwater structures on RACC in the surf zone

S. No.	Latitude	Longitude	Water Depth (M)			
			Distance from 0.0 to 200.0 m	Distance from 200.0 to 400.0 m	Distance from 400.0 to 600.0 m	Distance from 600.0 to 800.0 m
1	757832.1769	3443457.815	0.00-5.00	5.00 - 9.00	9.00 - 9.500	9.500 - 10.00
2	758222.6062	3443769.851	0.00-5.00	5.00 - 9.90	9.500 - 9.00	9.00 - 10.00
3	758361.1329	3443977.638	0.00-3.00	3.00 - 8.50	8.500 - 9.50	9.500 - 10.00
4	758613.0363	3444081.891	0.00-2.500	2.500 - 8.00	8.00 - 10.00	10.00 - 10.00
5	758786.745	3444247.688	0.00-2.500	2.500 - 7.00	7.00 - 10.50	10.50 - 12.50
6	759003.4673	3444393.933	0.00-2.00	2.00 - 8.00	8.00 - 12.00	12.00 - 12.50
7	759203.5577	3444534.907	0.00-4.00	4.00 - 7.00	7.00 - 10.50	10.50 - 10.00
8	759393.8992	3444705.979	0.00-2.500	2.500 - 8.00	8.00 -8.500	8.50 - 10.00
9	759792.8705	3444972.196	0.00-3.00	3.00 - 3.00	3.00 - 7.00	7.00 - 11.00
10	760174.7657	3445330.082	0.00-4.500	4.50 - 8.00	8.00 - 10.00	10.00 - 10.50
11	760687.3518	3446263.208	0.00-5.00	5.00 - 7.00	8.00 - 9.00	9.00 - 10.00
12	761503.7929	3446868.646	0.00-3.00	3.00 - 6.00	6.00 - 9.00	9.00 - 11.00
13	762256.432	3447477.053	0.00-2.500	2.500 - 7.00	7.00 - 8.50	8.50 - 13.00
14	762982.4111	3448172.625	0.00-3.00	3.00 -7.00	7.00 -10.00	10.00 - 8.00
15	763665.4568	3448936.369	0.00-2.500	2.500 - 7.00	7.00 - 8.50	8.50 - 7.00
16	764334.5209	3449446.368	0.00-1.00	1.00 - 6.00	6.00 - 4.00	4.00 - 3.00

Table 2 The HR due to RACC

Hr (M^2/S)	Losing footing probability in currents		
	From	To	-
Low	0.00	0.75	-
Moderate	0.75	1.25	The danger for some e.g., children
High	1.25	2.5	Danger for most
Extreme	2.5	More than 2.5	Danger for all

4.Results

To investigate the impact of the detached breakwater structures on RACC in the surf zone, hydrodynamic and bathymetric data were collected and analyzed using field, experimental, and numerical methods for different cases and scenarios. This section presents the results obtained from the different scenarios considered.

4.1Results based on experimental works

Figure 6 presents the results obtained from the wave flume and lab conditions, revealing the circular shape of waves and shoreface changes induced by the presence of detached breakwaters. These changes are attributed to the contribution of diffraction phenomena and are observed at various locations, including the heads of breakwaters, upstream breakwaters, downstream breakwaters, and frontal area of the shore. The bed changes resulting from the presence of detached breakwaters are also noticeable. These effects are observed in all three cases for openings of the detached breakwaters (one opening, two openings, and three openings). In addition to wave-induced changes, currents are generated in the vicinity of breakwaters. *Figures 7, 8*, and *9* demonstrate that currents are observed at the heads of breakwaters, in the area between shoreline and breakwaters, and downstream of breakwaters. Three types of currents are observed: coastal circulation currents (CC), rip currents, and longshore currents. The experiments were repeated using the wave flume to investigate the effects of the partial and complete closure of the detached breakwater using submerged and emergent breakwaters, respectively. The results indicate that partial closure led to a small circular shape of waves and shoreface changes due to the formation of low values of CC and rip currents. On the other hand, complete closure resulted in the absence of CC and rip currents.

4.2Results based on numerical works

4.2.1Reference case: standing detached breakwater without any changes

After applying three cases of wind directions; north (N), NW, and northeast (NE); using the (MIKE 21) flow model, the obtained current velocities (direction and speed) for the first scenario are:

4.2.1.1For the case of wind in N direction

Breakwaters B1 to B7 are located at (3442900 N, 759400 E). Currents are generated at the heads of breakwaters, in the area between shoreline and breakwaters, and downstream breakwaters as shown in *Figure 10*. These currents have three types: CC, rip currents, and longshore currents. The velocities of rip currents at B1 are from 0.64 to 0.72 m/s in a direction parallel to the shore in a southwest (SW) direction, near breakwaters. The average depth at this location is about -5.00 near breakwaters. The values of currents are not safe for swimming, but the direction of currents helps swimmers to escape from drowning.

At B2, the currents have three types: rip currents, longshore currents, and CC. The velocities of rip currents range from 0.16 to 0.36 m/s with a NW direction inclined to the shore, towards the opening between breakwaters B1 and B2. The velocities at this area can easily draw swimmers to another extremely dangerous area downstream breakwaters, where the velocity of currents is more than 0.96 m/s and depths of water are from -5.0 m to -9.0 m, so there are no chances for escaping from drowning. Another type of current is parallel to the shore and near it, with depths less than -2.00 m. These conditions of current directions are safe for swimmers. Similar observations are noticed at breakwaters B7, B4, B2, and B6, where the velocities range from 0.16 to 0.56 m/s, and their directions are NE to NW.

In this case, the depth of water is very important for non-swimmers because the depth of water is more than -2.00 m, so it is not safe for them. The depth ranges from -2.00 to 4.00 m at B7, the velocities range between 0.16 to 0.64 m/s, and depths from less than -1.00 m to -3.00 m upstream in the area between the shore and breakwaters.

The effects of the breakwaters on rip currents and CC are very clear. Rip currents are formed at the head of breakwater B1 in a NW direction with an average velocity of about 0.64 m/s. Rip currents are also formed at the heads of breakwaters B7, B4, and B5 with the same direction and values. The direction of currents at breakwater B6 is NE. CCs are formed between breakwaters B1, B2, and B3 in a clockwise direction, also at the region between breakwaters from B2 to B5 in the same direction, and in the region between breakwaters B5, B6, and B7 in a clockwise direction. CCs have values from 0.16 to 0.64 m/s, which are dangerous for swimmers because the depths are more than -2.00 m.

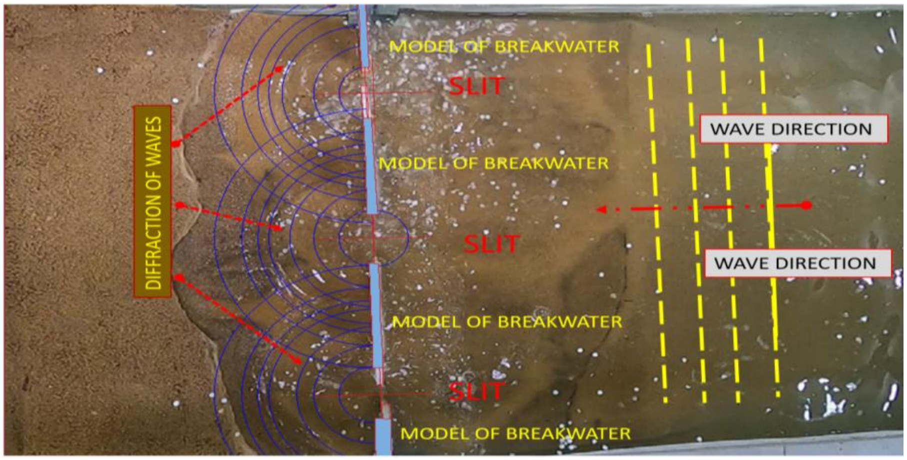


Figure 6 The effects of diffraction phenomena at break waters in case of three openings

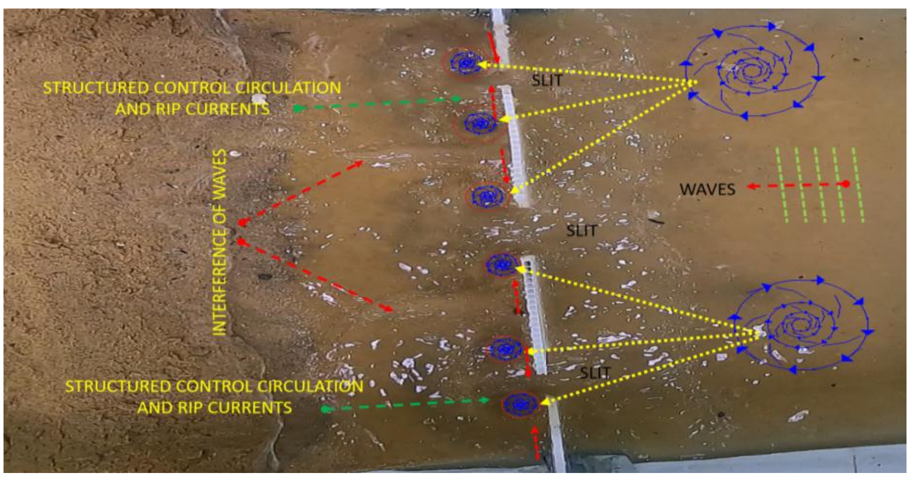


Figure 7 The different vortices at break waters in case of three openings

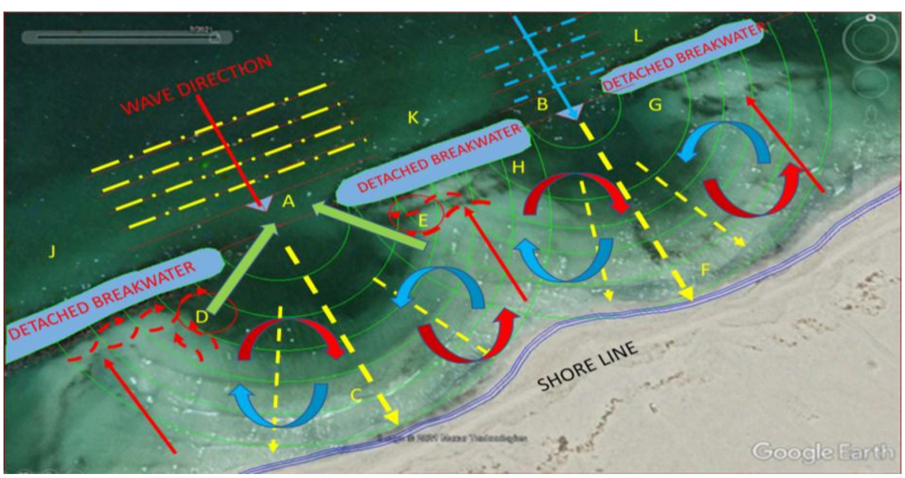


Figure 8 The CC (vortices) and rip currents due to breakwaters in the study area

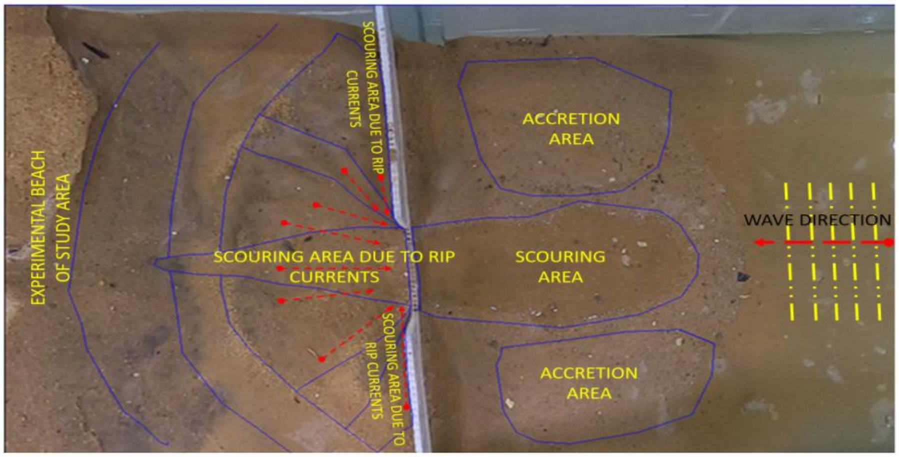


Figure 9 The accretion and scouring around breakwaters in case of one opening

4.2.1.2Applying (MIKE 21) for the case of wind in the NE direction

In *Figure 11*, it can be seen that rip currents are formed in two directions, NE and NW, at the heads of breakwaters B1 and B2. The velocities of rip currents in the area from the shore to breakwaters range from (0.54 to 0.66) m/s. Downstream of breakwaters B1 and B2, the currents range from (0.74 to over 0.84) m/s. These currents are very dangerous for swimmers due to the presence of concrete dolos units and dolomite rocks, as well as the depth of water, which is more than (-5.0) m/s from still water level (SWL) in this area. The CC at breakwaters B1 and B2 are negligible and have no effects on swimmers, but the rip currents in this area are not safe for swimmers. The area between breakwaters B2, B3, and B4 has RACC, with the values of rip currents ranging from (0.3 to 0.60) m/s. The directions of rip currents are in the west and NW directions. The CC are obvious in the anticlockwise direction, with values ranging from (0.30 to 0.60) m/s. The directions of rip currents are in the west and NW directions, and the CC are obvious in the anti-clockwise direction, with values ranging from (0.24 to 0.54) m/s. The CC are formed at distances about one-half the distance between the shore and breakwater. These currents are safe near the shore but dangerous near the heads of breakwaters for swimmers.

The area between breakwaters B5, B6, and B7 has very weak CC, but it has strong rip currents. The values of rip currents range from (0.24 to 0.66) m/s, and most of these currents flow in the west direction. The area from the shore to breakwaters B5, B6, and B7 is safe for swimmers, except for the area between breakwaters B6 and B7.

4.2.1.3Applying (MIKE 21) for the case of wind in the NW

Figure 12 shows that this is the worst-case scenario for swimmers due to the presence of both rip currents and CC currents. The rip currents at breakwaters B1 and B2 have values ranging from 0.45 to more than 0.60 m/s, with directions of NE and N. The rip currents at breakwaters B3, B4, and B5 have values between 0.3 and 0.50 m/s, with directions of N and NE. The CC currents at these breakwaters are in a clockwise direction, with values between 0.20 and 0.4 m/s. Breakwaters B6 and B7 have strong CC currents with values between 0.4 and 0.6 m/s in a clockwise direction. The rip currents at these breakwaters have values ranging from 0.5 to above 0.60 m/s in the north direction. Overall, the conditions for RACC are not safe for swimmers.

4.2.2Removal of the standing detached breakwater (removing the existing breakwater)

4.2.2.1Applying (MIKE 21) for the case of wind in the N direction

In *Figure 13*, all currents have disappeared except for longshore currents with values ranging from 0.10 to more than 0.96 m/s. These currents run parallel to the shore in the SW direction. Swimming is safe for beach users up to a distance of about 200 m cross-shore. However, beyond that point, the currents become dangerous. While all coastal circulation and rip currents have disappeared, longshore currents still exist at distances greater than 600 m from the shore, running in the NE direction.

4.2.2.2Applying (MIKE 21) for the case of wind in the (NE) direction

Figure 14 shows that the RACC has disappeared, except for longshore currents running parallel to the shore in the SW direction with values ranging from 0.18 to more than 0.84 m/s. Swimmers should stay within a safe distance of less than 200 m from the shore. Longshore currents are also formed far from the shore at distances greater than 400 m in the NE direction with values ranging from 0.18 to 0.36 m/s.

4.2.2.3Applying (MIKE 21) for the case of wind in the (NW) direction

In the third scenario, partial closure of the detached breakwater (using submerged breakwaters) was tested using (MIKE 21) for wind coming from the north direction. The currents have slightly disappeared, except at breakwaters B1 and B7, where CC appeared in an anticlockwise direction, with values ranging from 0.10 to more than 0.48 m/s, as shown in *Figure 15*. Rip currents are formed in the west direction at the head of B1, with values of about 0.48 m/s. Small currents are formed in the area from B1 to B7, and the velocity of all currents is less than 0.32 m/s. Swimming for beach users is safe for a distance of about 200 m cross-shore in the area from B2 to B6, but it is dangerous at breakwaters B1 and B7.

4.2.3Partial closure of the standing detached breakwater using submerged breakwaters (using submerged breakwaters)

4.2.3.1For the case of wind in the N direction

In *Figure 16*, the currents have slightly disappeared, except at breakwaters B1 and B7, where CC currents appeared in an anticlockwise direction, with values ranging from 0.10 to more than 0.48 m/s. Rip currents are formed in the west direction at the head of B1 with values of about 0.48 m/s. Small currents are formed in the area from B1 to B7, and the velocity of all currents is less than 0.32 m/s.

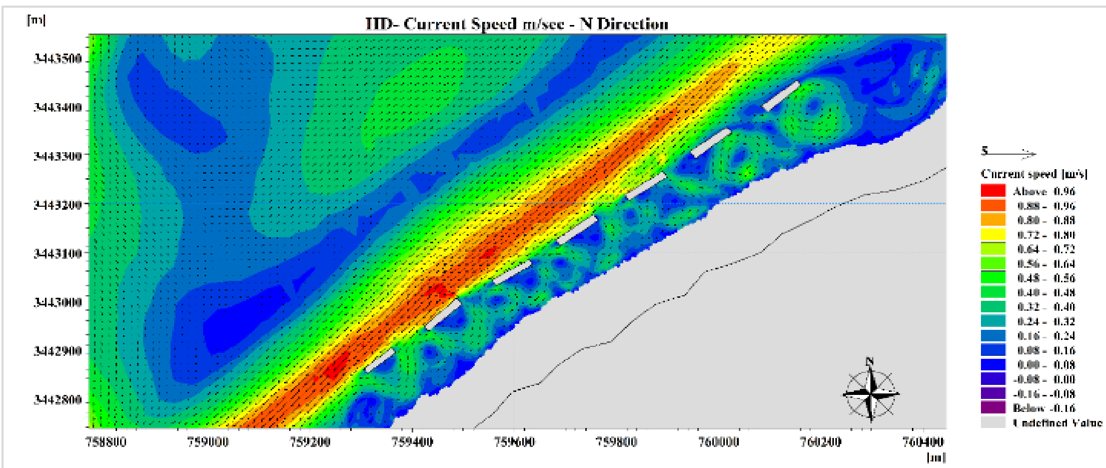


Figure 10 The different currents at break waters (Scenario-1 in N direction)

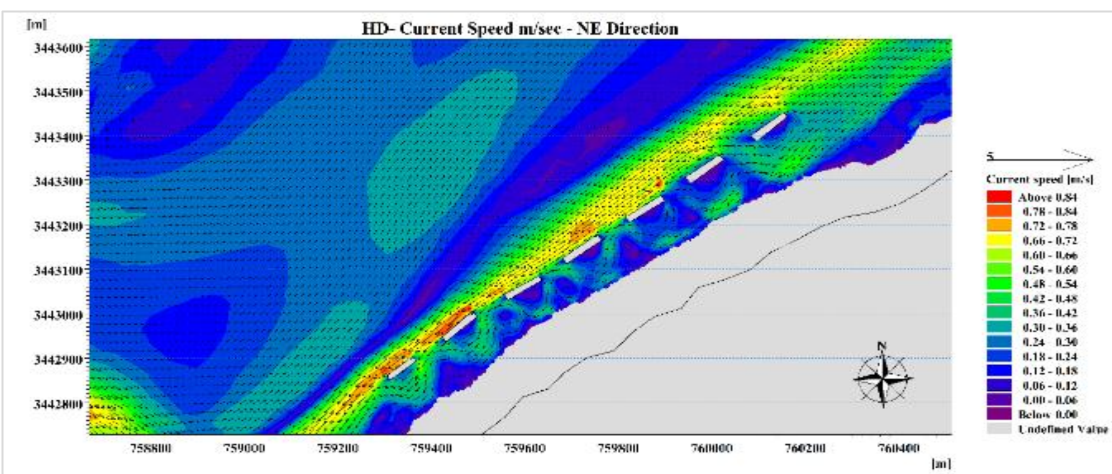


Figure 11 The different currents at break waters (Scenario-2 in NE direction)

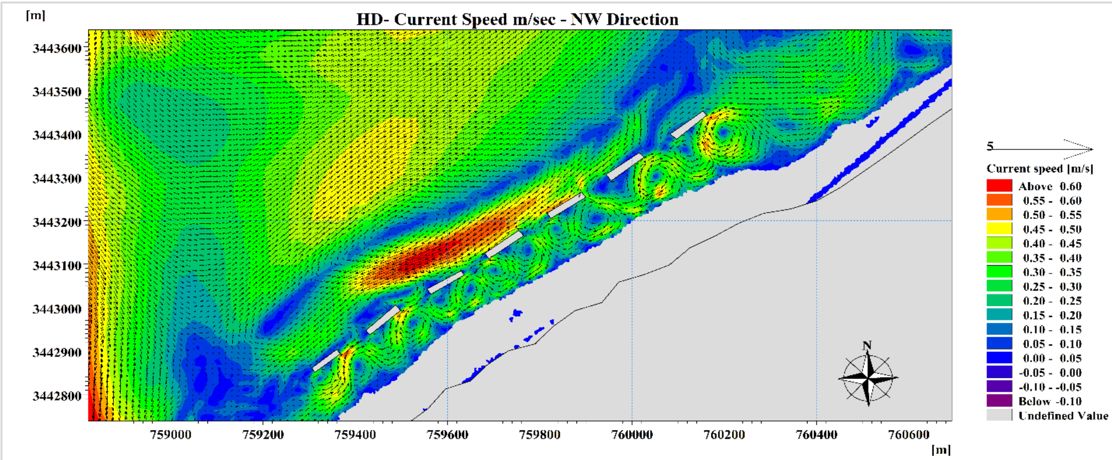


Figure 12 The different currents at break waters (Scenario-3 in NW direction)

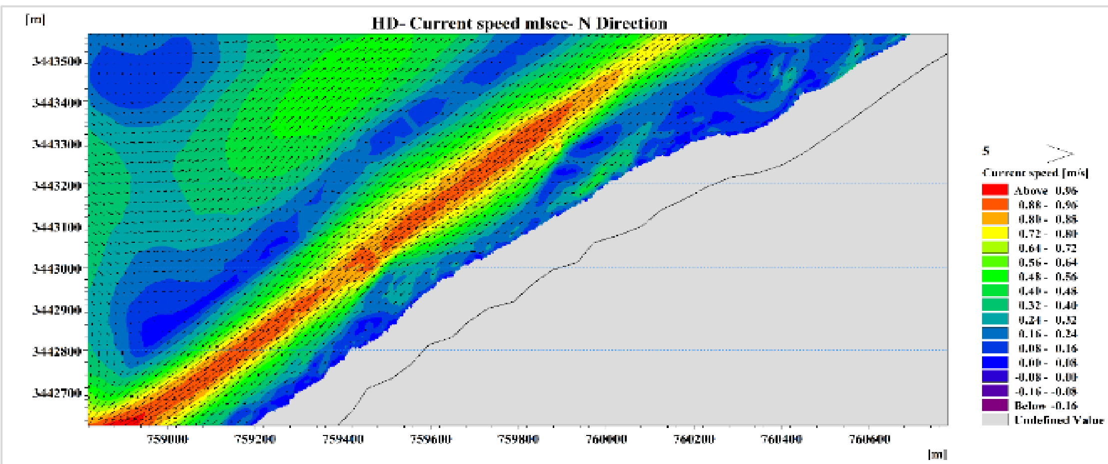


Figure 13 The different currents at break waters (Scenario-2 in N direction)

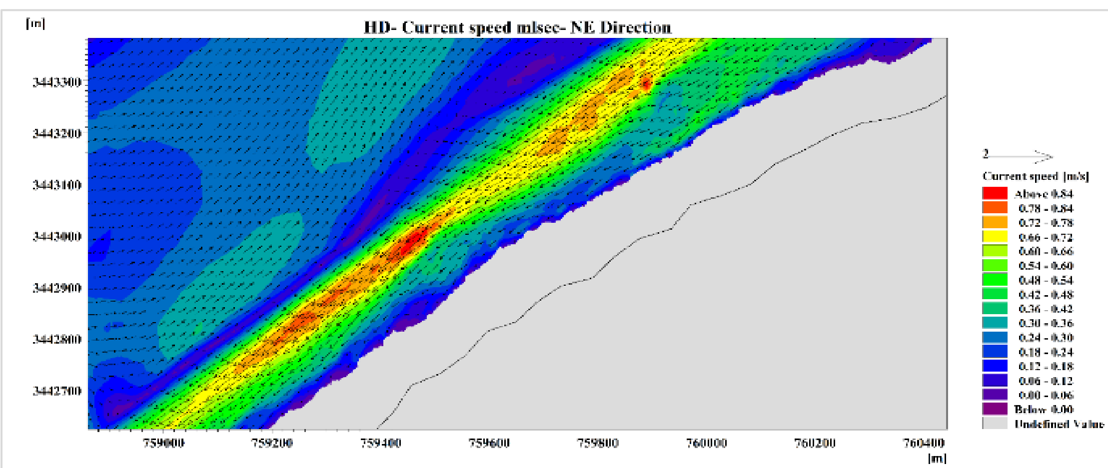


Figure 14 The different currents at break waters (Scenario-2 in NE direction)

4.2.3.2For the case of wind in the NE direction

As shown in *Figure 17*, the RACC has disappeared, except for longshore currents parallel to the shore with values ranging from 0.18 to less than 0.30 m/s in the SW direction.

Therefore, swimmers should maintain a safe distance of less than 200 m from the shore.

4.2.3.3For the case of wind in the NW direction

Figure 18 shows that coastal circulation and rip currents were formed at breakwaters B1 and B7. Coastal circulation appeared in a clockwise direction with values ranging from 0.10 to more than 0.45 m/s. Rip currents were formed in the NE direction at the head of B1, with values of about 0.45 m/s. Due to these conditions, swimming is not safe for beach users within a cross-shore distance of approximately 200 m in the area between B1 and B7.

4.2.4Complete closure of the gap between breakwaters using emergent breakwaters

4.2.4.1For the case of wind in the N direction

All currents disappeared except at breakwaters B1 and B7, where CC appeared in an anticlockwise direction with values ranging from 0.10 to more than 0.48 m/s. Rip currents were formed in the west direction at the head of B1 with values of about 0.48 m/s. Small currents were also formed in the area between B1 and B7, with velocities less than 0.32 m/s.

4.2.4.2For the case of wind in the NE direction

The RACC has disappeared except for longshore currents parallel to the shore, which have values ranging from 0.04 to less than 0.05 m/s in the SW direction.

4.2.4.3For the case of wind in the NW direction

No coastal circulation or rip currents were formed at breakwaters B1 and B7, but longshore currents parallel to the shore with a value of 1.05 m/s were observed in the NE direction.

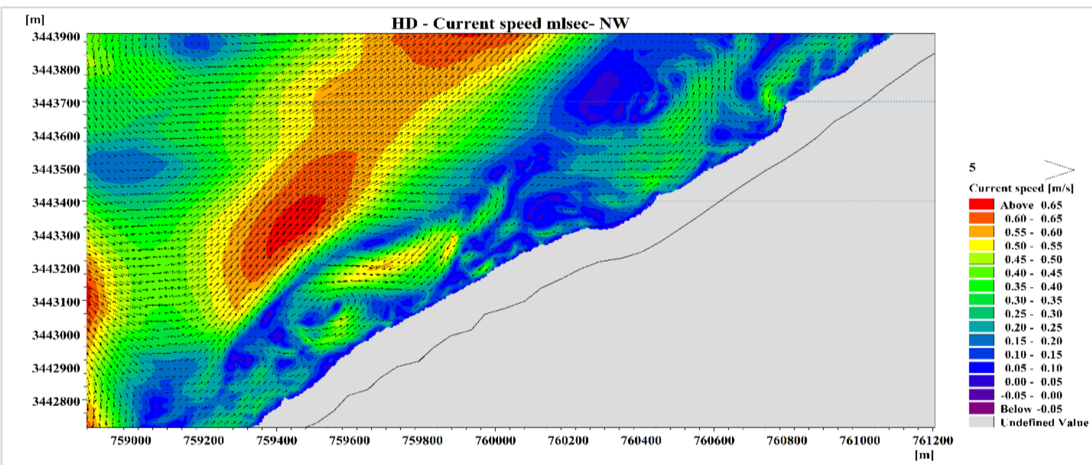


Figure 15 The different currents at break waters (Scenario-2 in NW direction)

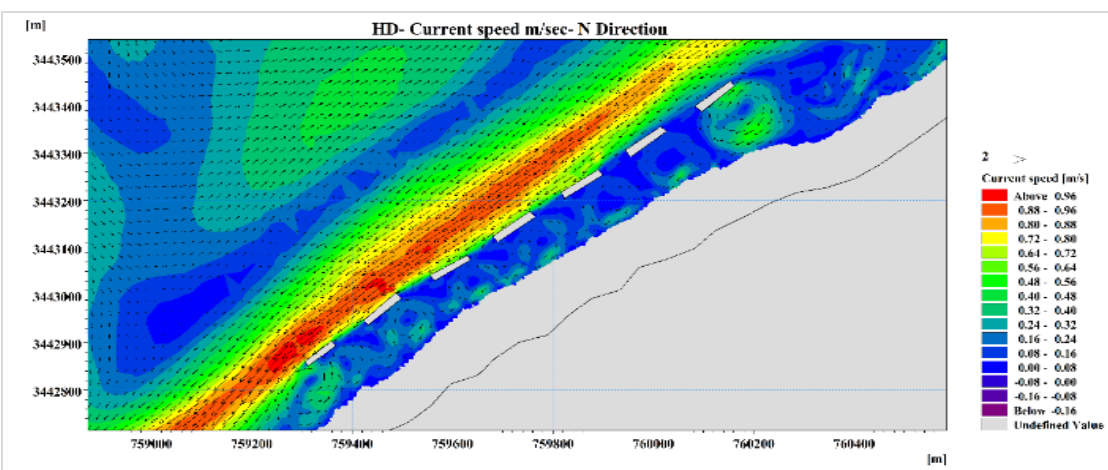


Figure 16 The different currents at break waters (Scenario-3 in N direction)

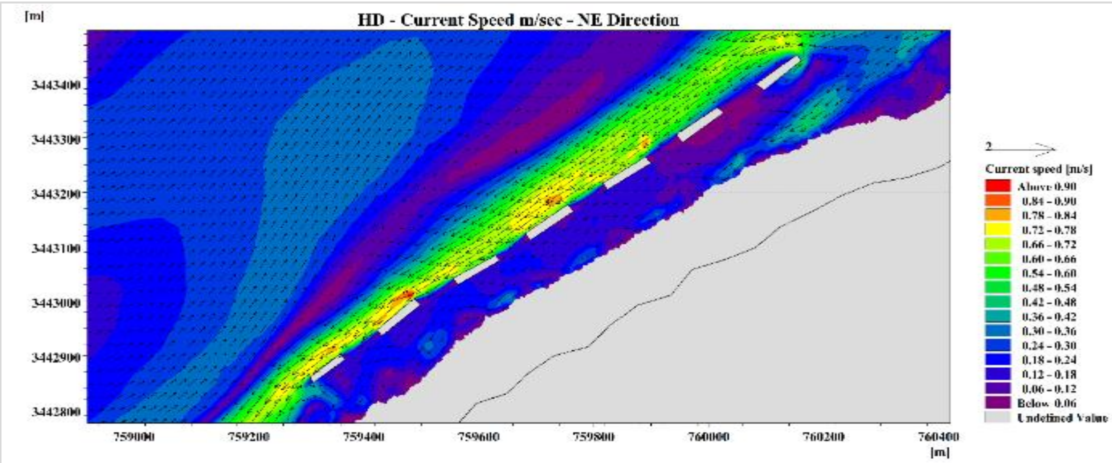


Figure 17 The different currents at break waters (Scenario-3 in NE direction)

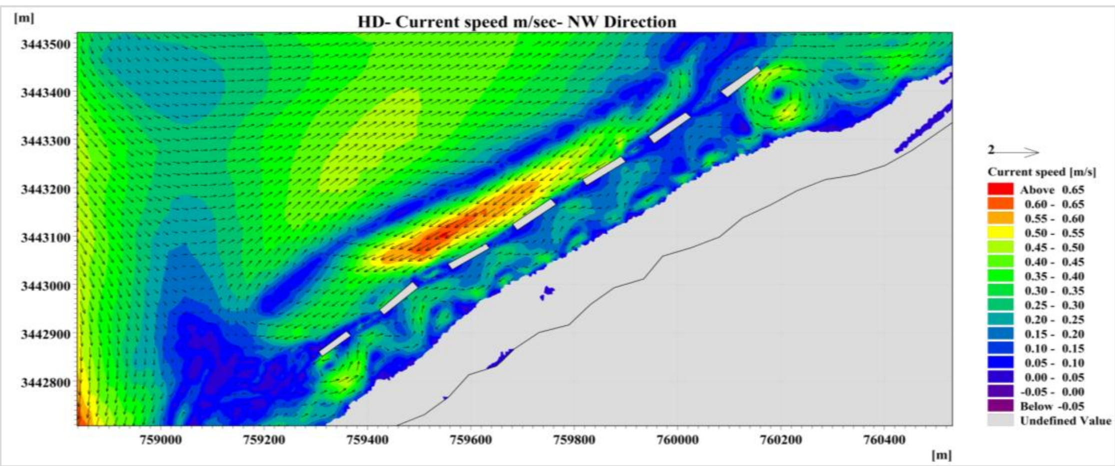


Figure 18 The different currents at break waters (Scenario-3 in NW direction)

4.2.5Fourth scenario-completely closing the gap between detached breakwater

4.2.5.1By applying (MIKE 21) for the case of wind in the N direction

Most types of currents disappeared, except at breakwaters B1 and B7, where CC was observed in an anticlockwise direction with values ranging from 0.10 to more than 0.48 m/s. Rip currents were also observed, formed in the west direction at the head of B1 with values of about 0.48 m/s. Small currents were formed in the area between B1 and B7, as shown in *Figure 19*, and the average velocity of all types of currents was less than 0.32 m/s. Swimming is safe for beach users within a cross-shore distance of about 200 m from the shoreline in the area between B1 and B7. However, swimming near the heads of breakwaters B1 and B7 is dangerous.

4.2.5.2Applying (MIKE 21) for the case of wind in the NE direction

Rip currents and CC were not observed, but longshore currents parallel to the shore with values ranging from 0.04 to less than 0.05 m/s in the SW direction were observed as shown in *Figure 20*. It is safe for swimmers to stay within a distance of 200 m from the shore.

4.2.5.3 Applying (MIKE 21) for the case of wind in the NW direction

CC and rip currents were not observed at breakwaters B1 and B7, except for longshore currents parallel to the shore with values of 1.05 m/s in the NE direction, as shown in *Figure 20*. Swimming near breakwaters is not safe due to the strong currents. Comparison of our results with previous studies on beaches around the world demonstrated the significant impact of detached breakwater structures on the occurrence of CC and rip currents. We considered different scenarios for the existing breakwaters without any modifications when the wind was blowing from the north direction. Rip currents with velocities ranging from 0.64 to 0.72 m/s were observed at B1, parallel to the shore towards the breakwaters. At B2, we observed rip currents, longshore currents, and CC with velocities ranging from 0.16 to 0.36 m/s in the NW direction towards the opening between breakwaters B1 and B2. Swimmers can easily be drawn to the dangerous area downstream of the breakwaters, where the velocity of currents is more than 0.96 m/s. Similar observations were made at breakwaters B7, B4, B2, and B6, with velocities ranging from 0.16 to 0.56 m/s in the NE to NW directions. Rip currents were observed at the heads of breakwaters B1, B7, B4, and B5 with an average velocity of 0.64 m/s in the NW direction. Rip currents were also observed downstream of breakwaters B1, B7, B4, and B5 with the same direction and values. At breakwater B6, the direction of currents was NE. CC were observed between breakwaters B1, B2, and B3 in a clockwise direction, as well as between breakwaters B2 and B4, and B4 and B5 in the same direction with values ranging from 0.16 to 0.64 m/s. When the wind was blowing from the NE direction at breakwaters B1 and B2, rip currents were observed in two directions NE and NW at the heads of breakwaters with velocities ranging from 0.54 to 0.66 m/s. Downstream of breakwaters B1 and B2, the currents were from 0.74 to more than 0.84 m/s. The CC at breakwaters B1 and B2 were negligible. Between breakwaters B2, B3, and B4, CC and rip currents were observed with velocities ranging from 0.3 to 0.60 m/s. Rip currents were in the west and NW directions, while the CC were observed in the anticlockwise direction. Similarly, between breakwaters B5, B6, and B7, the CC were weak, but strong rip currents were observed with velocities ranging from 0.24 to 0.66 m/s.

4.2.6HR due to rip currents and vortices

4.2.6.1The case of wind in the NW direction

The study area mainly experiences waves coming from the northwest direction; therefore, the present study only considers the effects of these waves on the HR. In future studies, researchers can investigate the impact of waves coming from other directions on HR, as shown in *Figure 21*. Rip currents are observed in the west and north directions, with velocities ranging from 0.40 to 0.60 m/s. Clockwise CC is formed in the NE of the study area with velocities ranging from 0.20 to 0.4 m/s. In addition, CC is also formed in the SW of the study area.

Figure 22 illustrates the values of rip currents and water depths from the shoreline to detached breakwaters for waves in the NW direction. The study area is divided into twenty-one different zones, which are categorized by three different water levels in the cross-shore direction for seven breakwaters from (B1 to B7). These water levels range from zero level (0.00) at the shoreline to water depth (–1.00), from water depth (–1.00) to water depth (–2.00), and from water depth (–2.00) to water depth greater than (–2.00) at the detached breakwaters. The HR is calculated using Equation 1 as shown in *Figures 22* and *23*, and the results are presented in *Figure 24.*

Figure 24 shows that the HR values at (B1, B2, B6, and B7) range from 2.00 m^2/s to 2.2 m^2/s, indicating an extreme hazard for swimmers to drown if they swim in water depth from (–2.00) to water depth greater than (–2.00) at these breakwaters. The HR values are constant at (B3, B4, and B5) at 1.80 m^2/s, indicating a high hazard for swimmers to drown if they swim in water depth from (–2.00) to water depth greater than (–2.00) at these zones.

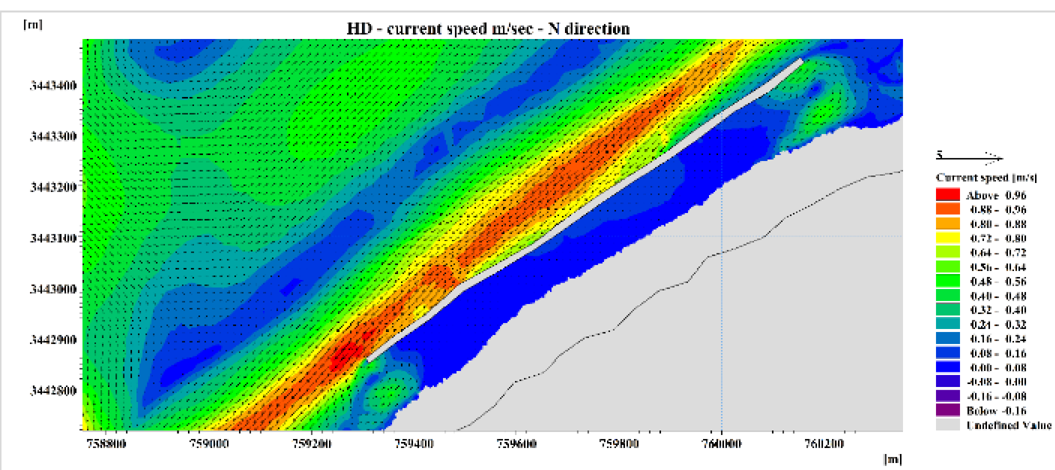


Figure 19 The different currents at break waters (Scenario-4 In N Direction)

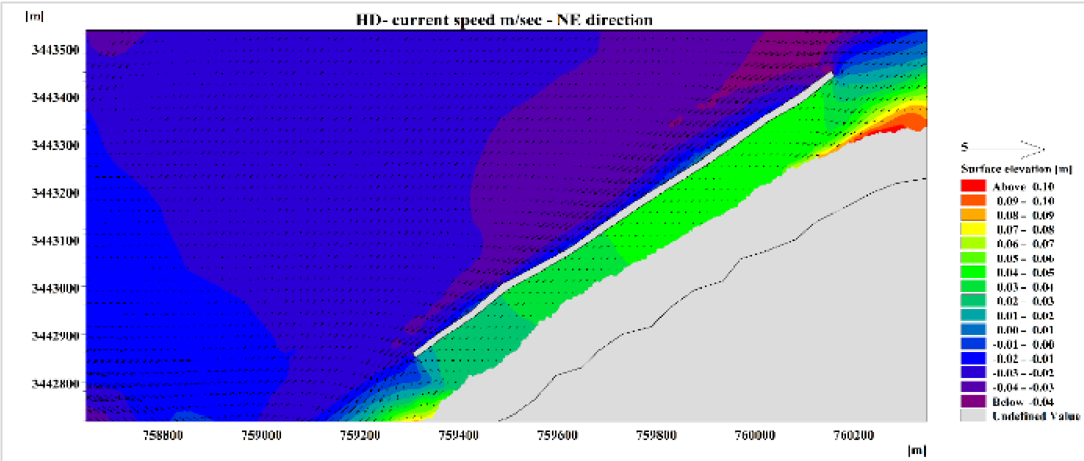


Figure 20 The different currents at break waters (Scenario-4 in NE direction)

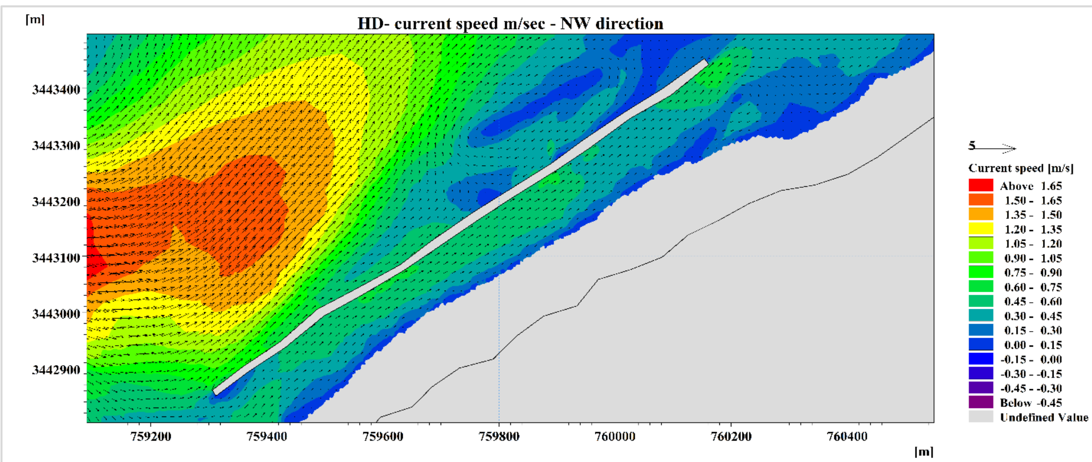


Figure 21 The different currents at break waters (Scenario-4 in the NW direction)

Furthermore, the HR values at (B1, B3, B4, B5, B6, and B7) range from 1.275 (m^2/s) to 1.50 (m^2/s), indicating a high hazard for swimmers to drown if they swim in water depth from (–1.00) to water depth (–2.00) at the detached breakwaters. The HR value at B2 is 0.450 (m^2/s), which is classified as a moderate hazard for swimmers to drown if they swim in water depth from (–1.00) to water depth (–2.00) at the detached breakwaters, as shown in *Figure 25*.

Figure 26 shows that the HR values change at B7 from 0.40 (m^2/s) to 0.50 (m^2/s) for CC only, but there is no change at (B1, B3, B4, B5, and B6). The RACC values change to become longshore currents, indicating no hazard for swimmers to drown if they swim in these areas.

In summary, the HR values vary depending on the water depth and the location of the breakwater. Swimmers should be cautious when swimming in water depth from (–2.00) to water depth greater than (–2.00) at (B1, B2, B6, and B7) due to the extreme hazard of drowning, and in water depth from (–1.00) to water depth (–2.00) at (B1, B3, B4, B5, B6, and B7) due to the high hazard of drowning. Children should also be cautious when swimming in water depth from (0.00) to water depth (–1.00) at these zones, as there is a moderate risk of drowning.

4.2.7The economic comparison between different proposed scenarios

This study presents an economic comparison between the previously proposed solutions. The economic comparison is made among scenarios 2, 3, and 4 only, because no changes are made in scenario 1. The calculations for scenarios are made for a submerged breakwater with a length of 1050.0 m, a width of 18.0 m, and a crest level of -0.75 m from the still sea water level. Dredging is done for 200 m from breakwaters to the shoreline, with a depth of -3.00 m. The economic comparison is based on the average market prices in Egypt in the year 2022. *Table 3* shows that scenario 4 has the highest cost, while scenario 2 is the most economical. However, the difference between scenario 3 and scenario 2 is very small. According to the calculated HR and the velocities of currents, scenario 3 is safer than scenario 2. Therefore, the proposed solution for rip and coastal circulation current formations due to the presence of detached breakwaters is the partial closure of openings between detached breakwaters using submerged breakwaters.

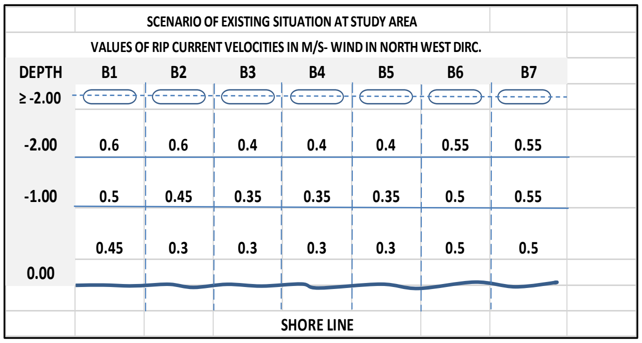


Figure 22 The values of rip currents and water depths from the shoreline to detached breakwaters, the waves are in the NW direction

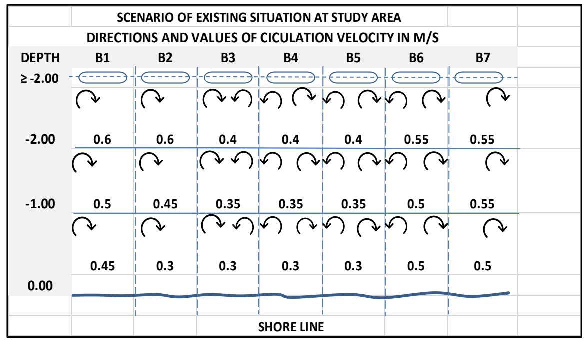


Figure 23 The values and directions of CC and water depths from the shoreline to detached breakwaters, waves are in the NW direction, whereas (-ve) currents are clockwise direction

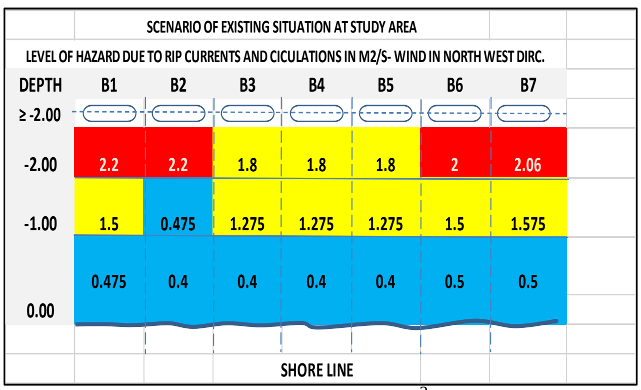


Figure 24 The HR due to RACC in (m^2/s), the depth of water in meters, and the average value of RACC in (m/s), waves in the NW direction

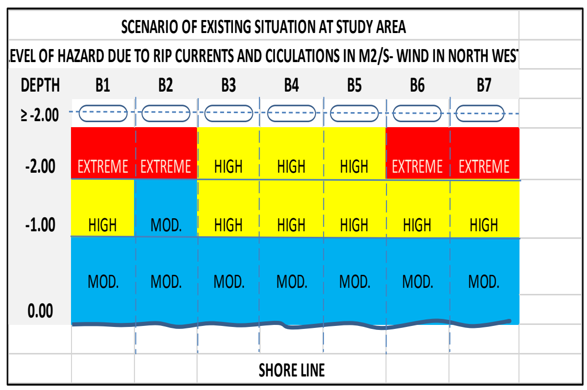


Figure 25 The classification of drowning HR due to trip and coastal circulation currents, the red color for extrem hazard, the yellow for high hazard, and the blue for moderate hazard, wave in the NW direction

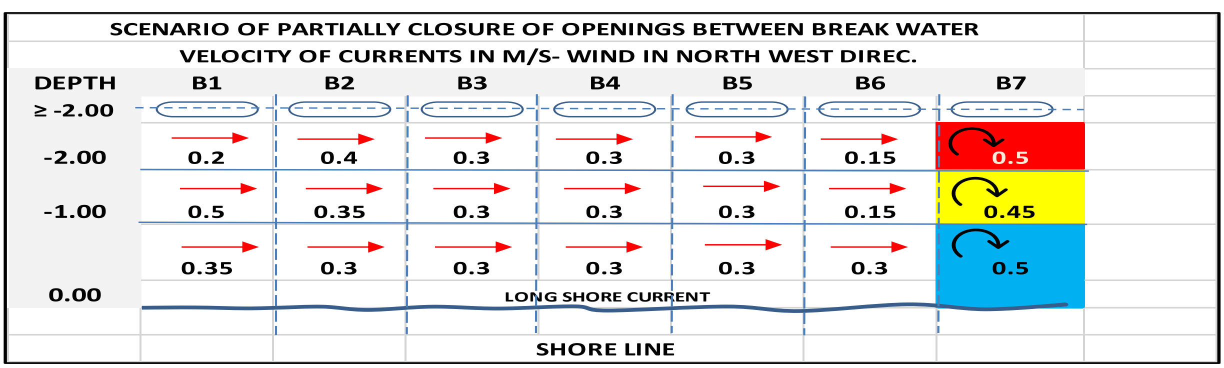


Figure 26 The RACC in (m/s), the depth of water in meters, scenario of partial closure of openings between breakwaters, and waves in the NW direction

Table 3 The economic comparison between different proposed scenarios in $1000

No.	Description	Scenario 2			Scenario 3			Scenario 4		
		Quantity	Unit price	Total price	Quantity	Unit price	Total price	Quantity	Unit price	Total price
		×1000	$/unit	×$1000	×1000	$/unit	× $1000	×1000	$/unit	×$1000
1	Dredging to level - 0.30	200.0 m^3	13	2600	200.0 m^3	13	2600	200.0 m^3	13	2600
2	Excavation works & stockpiling outside	350.0 m^3	10	3500	350.0 m^3	10	3500	350.0 m^3	10	3500
3	Sand nourishment using filling materials from outside	13.50 m^3	4	54	13.50 m^3	4	54	13.50 m^3	4	54
4	One-ton dolomite stone removal	45.00 ton	45	2025	0.00 ton	45	0.00	0.00 ton	45	0.00
5	One ton dolomite stone removal &replacement	0.00 ton	90	0.00	3.00 ton	90	270	0.00 ton	90	0.00
6	One-ton dolomite stone import & placement	0.00 ton	160	0.00	12.00 ton	160	1920	78.75 ton	160	12600
7	Five-ton concrete Dolos units' removal	11.50 Dolos	100	1150	0.00 Dolos	100	0.00	0.00 Dolos	100	0.00
8	Five-ton concrete Dolos units' removal & replacement	0.00 Dolos	140	0.00	5.20 Dolos	140	728	0.00 Dolos	140	0.00
9	Five-ton concrete Dolos units import & placement	0.00 Dolos	280	0.00	1.50 Dolos	280	420	19.950 Dolos	280	5586
	Total price for each scenario × $1000			9329	-	-	9492	-	-	24340

5.Discussion

The present study investigates the impact of detached breakwater structures on RACC (vortices) in the surf zone. However, it is important to consider the limitations of the study in future investigations and extensive works. The study area is a popular seaside resort with a beachfront of approximately 1200.0 m. The study focuses on seven detached breakwaters made of dolos units submerged in water depths ranging from -4.0 m to -5.0 m. These breakwaters are situated along a shoreline of about 1 km long, with each individual breakwater being 100.0 m in length, 200.0 m away from the shore, and spaced at 50.0 m intervals. Cross sections perpendicular to the baseline on beach profiles extend up to 6.0 m of water depth or a maximum distance of 2000.0 m seaward. The study finds that field velocities of currents range between 0.2 to 0.5 m/s, with current directions ranging from west to east in some cross sections and from east to west and towards the shore in others. The experiments show that the presence of detached breakwaters causes the formation of the curved shape of wavefronts and shoreface changes, with the contribution of diffraction phenomena being evident in forming the shape of the shore. Bed changes are observed at different locations in between breakwaters, at the heads of breakwaters, upstream breakwaters, downstream breakwaters, and in the frontal area of the shore. The study identifies three forms of currents in the study area: rip currents, vortices, and longshore currents. The presence of detached breakwaters and the interaction between the bottom and lateral boundaries cause rip currents and vortices, while downstream breakwaters and the area between the shoreline and breakwaters generate longshore currents. The study's findings are consistent with previous studies. In a study on the morphodynamics in the vicinity of a submerged detached breakwater using the Delft3D model, the coastal circulation pattern around the structure was shown to be composed of two cells induced by the divergence of the cross-shore currents generated in the submerged breakwater towards the shore. The study also demonstrated the coastal circulation patterns occurring in the vicinity between the structure and the shoreline, which influenced the coastline's transformation. Additionally, many eddies may be generated behind submerged breakwaters [1, 2]. The comparison between the present study findings and previous studies strengthens the observations of field and experimental works, physical model results, and observed currents well. This present paper reveals that CCs occur between breakwaters in clockwise and counterclockwise directions, with velocities ranging from 0.10 to more than 0.48 m/s. The velocities of currents beside the breakwaters are almost large values. The speeds of the rip currents can range from 0.05 m/s up to 1.050 m/s and can be extended to 30 m up to 200 m towards the offshore. Previous studies indicated that the development of rip currents greatly depends on the wave climate and the topographic effect, as mentioned in [5, 6, 8]. A study on rip currents showed that rip currents are associated with a vortex pair that propagates offshore direction and grows in the surf zone [12]. Another study showed that the vortex force formalism generates rip currents [13]. The structure of rip currents for Muriwai Beach (New Zealand) was studied, and the reported values for the average rip current length and width were 400 m and 150 m, respectively, and the average velocity of rip current was 1.4 m/s. The present paper studies the HR due to RACC in m^2/s. The present study shows that the HR for swimming in water depths more than 1.50 m ranges from high to extreme hazard (1.275 m^2/s - 2.2 m^2/s) because the vortices occur between breakwaters in clockwise and counterclockwise directions with velocities ranging from 0.10 to more than 0.48 m/s. Previous studies showed that rip currents are a main cause of drowning and surf rescue, and worldwide many unknown causes of drownings are likely linked to rip currents [15–18]. A study on rip currents based on field observations showed that the rip velocity value is between 0.2 and 0.3 m/s and may reach 0.7 m/s [25].

In another study, the structure of rip currents for Woolamai Beach, Australia, was investigated, and the reported values for the average rip current length and width were 300 m and 20-100 m, respectively. The average velocity of rip currents was found to be between 0.5-0.9 m/s [27]. Another study on rip currents used mathematical models of 2-D wave-induced nearshore currents, and it showed that the average velocities of rip currents ranged from 0.10-0.60 m/s, and the characteristics of the rip currents can be determined by applying the (MIKE 21) module [28]. The aforementioned discussion shows that the comparison between the present study's findings and previous studies strengthens the observations of field and experimental works, physical model results, and observed currents.

In a study on the economic considerations of submerged breakwaters, it was found that the construction cost of submerged breakwaters may be lower than that of other breakwater structures due to their lower crest elevation and the need for fewer construction materials. A similar study found that low-crested breakwaters are comparatively affordable [36, 37]. A study on the impact of submerged breakwaters on hydrodynamics concluded that submerged breakwaters are an ideal approach for protecting bays in Egypt [38]. Another study on the impact of submerged breakwaters on coastal tourism showed that beach protection using submerged breakwaters can sustain the coastal tourism industry within coastal communities [39]. In a study on the impact of submerged breakwaters on ecology carried out in Dubai, it was found that hard-bottom habitats were formed due to the use of submerged breakwaters because they acted as large-scale man-made reefs that support a wide range of marine ecology [40]. A study on the environmental impacts of submerged and emerged breakwaters concluded that to ensure a safe and sustainable coastline, decision-makers should consider different environmental factors [41]. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion

It is concluded that the hazard rating (HR) for swimming in water depth more than 1.50 m ranges from high to extreme (1.275 m^2/s: 2.2 m2/s) due to the occurrence of CC between breakwaters in both clockwise and anticlockwise directions, with velocities ranging from 0.10 to more than 0.48 m/s. The velocities of currents beside the breakwaters are relatively high. The speeds of the rip currents can range from 0.05 m/s up to 1.050 m/s, and they can extend from 30 m up to 200 m towards the offshore. The RACC are caused due to the presence of detached breakwaters and the interaction between the seabed and the lateral boundaries. The study presents various scenarios to address rip and CC formation caused by detached breakwaters. The fourth scenario suggests complete closure of gaps between detached breakwaters, but the more feasible and cost-effective solution is the third scenario, which involves partial closure of the openings between detached breakwaters using submerged breakwaters. The study indicates that this proposal is the most applicable and conservative approach, with the lowest HR and economic cost in surf zones worldwide. However, the study recommends conducting more extensive studies to assess the environmental impact of the proposed solutions. Additionally, future research can focus on economic studies for the proposed solutions.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Reda M. A. Hassan: Conceptualization, investigation, data curation and physical modeling works; writing original draft; writing, reviewing and editing the paper, **Ahmed Slama Elstohey:** Data collection, reviewing of references, and numerical modeling works.

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Appendix I

S. No.	Abbreviations	Description
1	B1	Breakwater Number One
2	CFL	Courant–Friedrichs–Lewy
3	CoRI	Coastal Research Institute
4	CC	Coastal Circulation Currents
5	Delft3D	Open-Source Software and Facilitates The Hydrodynamic, Morpho-Dynamic, Waves, Water. Delft3D is an Integrated Modelling Which Simulates Two-Dimensional (In Either The Horizontal Or A Vertical Plane) and Three-Dimensional Flow.
6	Hs	Significant Wave Height
7	HR	Hazard Rate for Swimming in Different Water Depths Due to RACC (vortices)
8	RACC	Rip and Coastal Circulation Currents
9	SPA	Egyptian Authority for Shore Protection
10	SW	Southwest Direction
11	SWL	Still Water Level
12	MIKE21	It is a Professional Software, Feature-Packed Coast and Marine Modelling, Leading Software Package for 2D Modelling of Hydrodynamics, Waves, Sediment Dynamics, Water Quality and Ecology.
13	NOAA	National Oceanic and Atmospheric Administration
14	N	North Direction
15	NWRI	National Water Research Center,
16	NE	North East Direction
17	NW	North West Direction
18	WHO	World Health Organization