

Controls on the occurrence of various types of rip current along the Mazandaran Coast –Southern Caspian Sea

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Mazandaran coast, can be classified into three wave-dominated beach types. Moderate to high rips stability (and risk) of transient and topographic rips are generated in eastern and central coasts, respectively, which are a product of dissipative and intermediate modes, wave hydrodynamics, sediment conditions and beach morphology. Generation of morphologically controlled rips in central Mazandaran can result in a permanent threat because of a fixed alongshore non-uniform bathymetry. Transient rips in eastern coasts is a product of dissipative mode with flat bathymetry. However, a uniform and steep beach bottom causes strong Backwash along reflective western coast. On the average, all Mazandaran coasts maintain their beach states seasonally with only small changes in morphodynamic conditions.

[Keywords: Caspian Sea, Mazandaran coasts, Rip Current, Beach State, Wave Hydrodynamics, Bed Morphology.]

Introduction

Rip currents are narrow shore-normal, seaward-flowing currents that originate within surf zone, extend seaward of the breaking region¹, and can reach velocities as high as 2 m/s². They are a main part of nearshore circulation² that play a key role in beach and surf zone morphodynamics, and on the dispersion of material across the surf zone³. Also, rip currents shape the sandy shoreline and are important for transporting large amounts of sediments and other materials offshore^{4,5,6} and thus changing the beach morphology with potentially large consequence for the stability of the beach. Rip currents form a serious threat to swimmer and account for more than 80% of lifeguard rescue efforts^{7,8}. These currents are the number one natural hazard in south coast of the Caspian Sea (CS)⁹, hence named as the "Killer Currents". Therefore, knowledge of rip current generation and its threat is important in order to assess a good coastal management and engineering design. Identifying the beach hydrodynamics and

morphology conditions that play a main role in dangerous rip currents evolution is essential to predicting the rip current threat at a beach to warn people about its hazard and save lives.

The primary driving mechanisms for rip current circulation are longshore variations of the incident wave height² and radiation stress¹⁰. Longshore variation of the radiation stress gradient is caused by differential wave transformation in the longshore direction¹⁰: this may be due to:

1. Topographic variation¹¹
2. Spatial variability of the incident wave field due to wave groups¹²
3. Interaction of the incident wave field and the wave-averaged mean current^{13,14,15}
4. Interaction of the incident wave field with lower frequency waves such as edge waves^{11,16,17}

The first mechanism leads to relatively fixed "Topographic Rips"¹⁰ which are controlled by a topographic feature, usually a solid structure such as a headland, reef, groyne or jetty¹⁸. Also they can occur on sandy beaches with rip channels and bar-trough morphology.

Other generation mechanisms can occur on a longshore uniform beach without topographic control. Since radiation stress field is spatially and temporally variable due to one of the other three mechanisms above, it leads to Transient rips which occur in differing locations¹⁰.

The occurrence of rip currents has been explained by numerous theories derived from different mechanisms¹². Since 1991, several methods have been developed to predict rip currents at beaches^{7,8,19}. Remote Video Camera Imagery of surf zone area²⁰, Easy-to-Use Charts preparation^{7,8,19} and Data Mining Methods², which are applied by lifeguards for rip assessment in order to classify the meteorological and oceanographic variables that play a role in the evolution of rip currents, have been used in predicting the rip current threat. Also, as have been applied in a few studies, investigating bed profile and beach states simultaneously is an appropriate attempt for determining the rip current occurrences and threats. Short (2006b) provides an overview of beach systems together with the occurrence of various rip currents throughout Australian coasts²¹. He assessed the roles of waves, sediment, and tide range in contributing to beach type, particularly through Ω and concluded that Intermediate beach states are all characterized by rip currents.

Materials and Methods

Wright and Short²² (1984) found beach states can be quantified by the dimensionless fall velocity, as follows^{23,24}:

$$\Omega = H_b / W_s T \quad (1)$$

Where H_b is the breaker wave height (m), W_s is the sediment fall velocity (m/s), and T is the wave period(s). This model is based on non-dimensional relative tide range parameter (RTR):

$$RTR = TR / H_b \quad (2)$$

Where TR is spring tide range (m), and beaches with $RTR < 3$ are referred to wave-dominated' beaches. Also Sunamura Beach model (1984) for wave-dominated beaches is presented as follows²⁵:

$$k^* = H_b^2 / g D_{50} T^2 \quad (3)$$

Where D_{50} is average sediment diameter (m) and $g = 9.8 \text{ m/s}^2$. Based on these models, beach states depend on the wave height and sediment conditions, are classified into Dissipative, Reflective or one of the four Intermediate states: Longshore Bar-Trough (LBT), Rhythmic Bar and Beach (RBB),

Transverse Bar and Rip (TBR), and Low-Tide Trace (LTT)⁶.

Dissipative beaches refer to beaches that have undergone a period of erosion and are quite flat². The incoming wave transports the sediment offshore and occupies the maximum wave energy spectrum²⁶. Reflective beaches refer to beaches with lower energy spectrum²⁶, characterized by a steep beach profile without bars and have the coarsest sediments²¹. Intermediate coasts have a medium range of energy between Dissipative and Reflective beaches i.e. intermediate beach states contain both reflective and dissipative components². Among characteristics of these beaches is a longshore change in seabed such as existence of sand bars and channel¹⁰.

Bed profile for different beach types is displayed in figure 1, and the range of changes for Ω and k^* is given in table 1.

CS (36° to 47° N and 46° to 52° E) is the largest enclosed body of water in the Euro-Asian continent²⁷. The main sources of water inflow come from the Volga, Ural and Kura rivers, which contribute to over 90% of the total runoff to the Sea²⁸. The sea level of CS is 27.5 meters below the open sea surface²⁹ and is controlled by river discharge, precipitation and evaporation and is very sensitive to changes in the climate system over the region²⁸. This lake is divided into three parts regarding depth and sea bed topography: northern, central and southern parts, respectively. The Northern CS is very shallow, with average depths shallower than 5m³⁰; the central part with a gentle sea bed slope and an average depth of 190 m and southern part has an average depth of 350 m³¹. The CS shelf areas account for 62% of total Lake with depth less than 100m³². The Mazandaran coast is located in the central part of the CS's south coast at 50° 34' to 53° E as shown in figure 2.

Owing to the closed basin and absence of the astronomical tide³³, its beaches with an RTR of less than 3 are referred to as wave-dominated beaches. Also, according to south CS Lifesaving Association⁹, every year more than two hundred deaths caused by drowning occur in this region³⁴. Many of the "deaths by drowning" may be connected to rip currents because of the lack of knowledge about rip current occurrence. But prediction of rip currents has not been investigated in the very popular Mazandaran beaches. Therefore, this study seeks to present an improved rip current predication model under various beach hydrodynamics and characteristics and as a method to predict these

dangerous current and reduce the risk for bathers and swimmers. The aims of this article are (i) to report on the range of beach types around Mazandaran coasts, together with the role of waves characteristic and sediments features in their formation; (ii) to describe the seabed morphology distribution and variability of these beaches around Mazandaran coasts; and

(iii) to discuss the occurrence of various types of rips and their risks which will lead to the formation of surf lifesaving clubs to reduce bather deaths and serve as a reference guide to coastal scientists, managers and beach users. This approach can be used for each beach that influenced by rips.

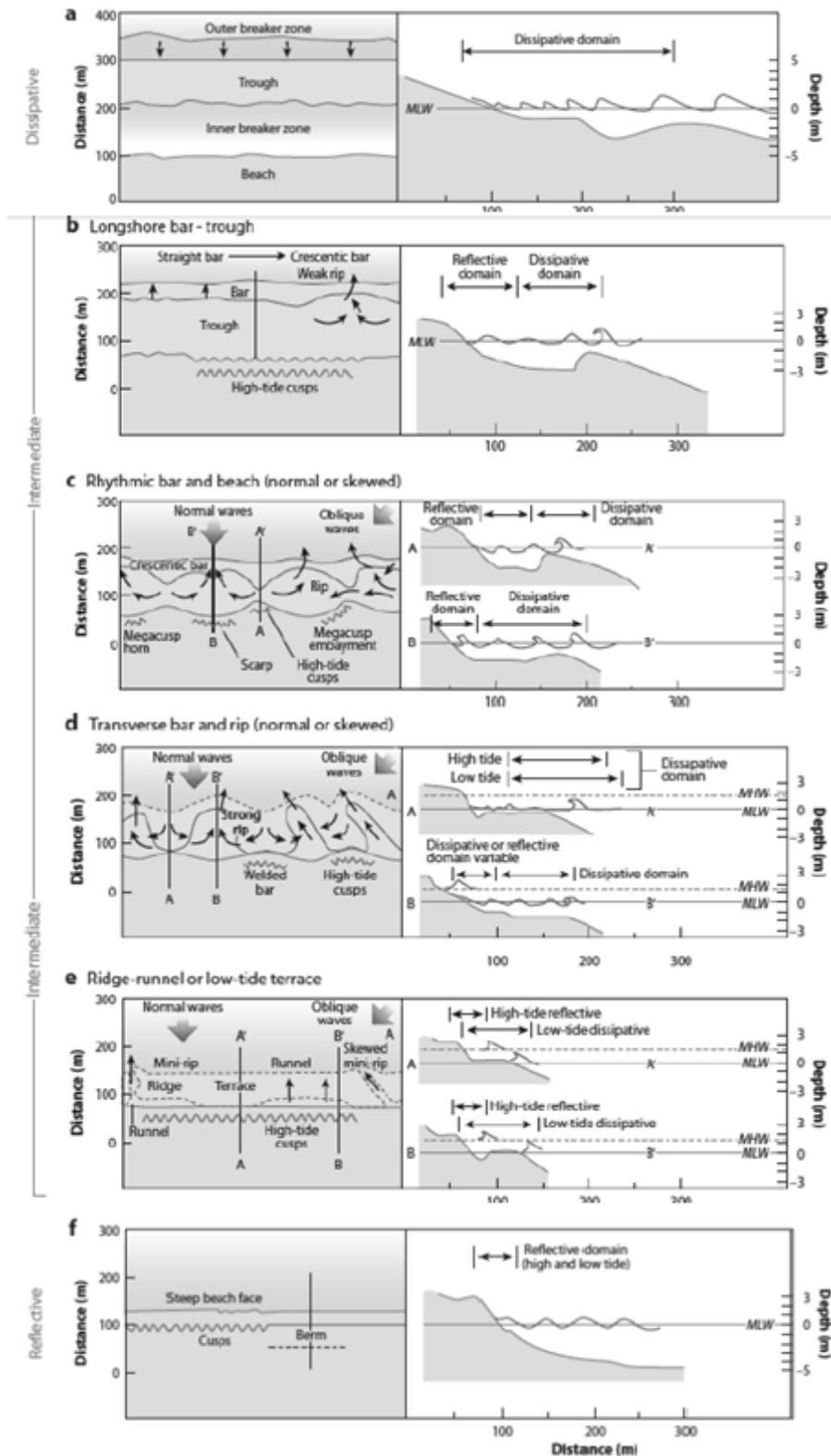


Fig.1- Beach profile in wave-dominated coasts: Dissipative (a), Intermediate (b, c, d, and e), and Reflective (f) (Short, 1999)

Table 1- The range of changes of parameters determining beach state, (Short, 1999)				
models	Model name	Intermediate state	Dissipative state	Reflective state
	Ω Dimensionless fall velocity	$6 \leq \Omega \leq 1$	$6 >$	$1 <$
	k Beach stability (transport direction)	$20 \leq k \leq 3.5$	$20 >$	$3.5 <$

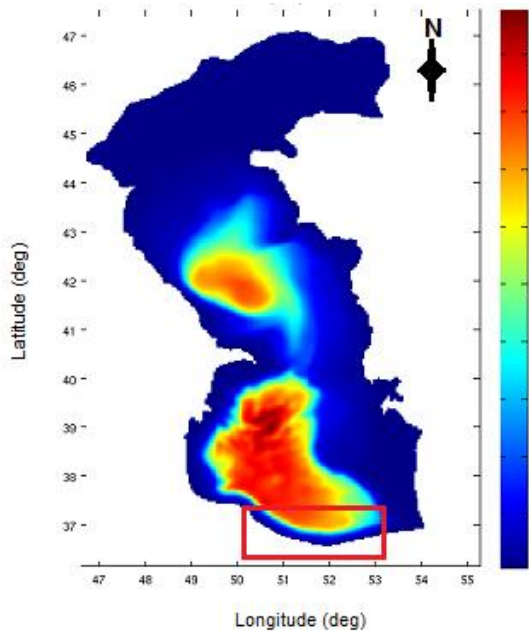


Fig.2- The Caspian Sea bathymetry (m) and Mazandaran coasts (red rectangular) in the south coasts of the Caspian Sea

This study focuses on determining beach state through Ω and k parameters and investigating surf zone bed profile changes in order to develop a relationship between various rip current occurrences and their risk prediction on the Mazandaran coasts. This is achieved through the following process:

(1) Selecting study sites: In order to obtain site specific information, some criteria such as

involving the highest number of drowning and bathing hazard, distance from man-made and natural structures (port, headland, etc.) and river mouths were considered. Thus a total of seven stations were selected in the eastern (Neka, Larim and Babolsar), central (Mahmud-Abad, and Kohnesara) and western (Noshahr and Nashtarood) parts of Mazandaran coasts. Locations of these stations are shown in figure 3.

(2) Iranian Seas Wave Modeling II (ISWMII) ³⁵ wave database was developed for CS region over a period of 9 years (2003-2011). Wave data was hindcast using the SWAN model by European Centre for Medium-Range Weather Forecasts (ECMWF)-Operational wind datasets. Deepwater wave characteristics (H_s , T_{m02} and wave direction) at selected stations were derived from the ISWMII and their conditions were investigated. The breaker depth (d_b) was calculated using equation 4 and the breaker height (H_b) was calculated using equation 5 which considered refraction and shoaling effects for a wave which breaks perpendicular to the shore ³⁶. In these equations C_0 and θ_0 are deep water wave velocity and wave angle, respectively.

$$d_b = (1/g^{1/5} k^{4/5}) (H_0^2 C_0 \cos \theta_0 / 2)^{2/5} \quad (4)$$

$$H_b = \left(\frac{k}{g}\right)^{1/5} (H_0^2 C_0 \cos \theta_0 / 2)^{2/5} \quad (5)$$

$$C_0 = gT/2\pi \quad (6)$$

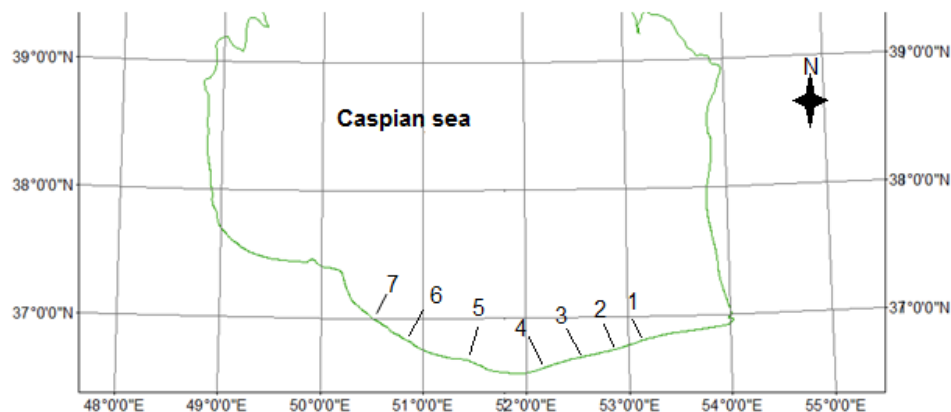


Fig.3- Location of the selected cross-section stations on Mazandaran coasts. Station 1: Neka, Station 2: Larim, Station 3: Babolsar, Station 4: Mahmud-Abad, station 5: Kohnesara, Station 6: Noshahr and Station 7: Nashtarood

All parts of the Mazandaran coast are generally exposed to moderate to intense northern, northwestern and northeastern winds, which produce short-period waves at the shore ($H_b=0.35$ m; $T_{m02}=1.8-2.15$ s). Moreover it is exposed to persistent swell, with a mean significant wave height (H_s) of 2 m ($4 \text{ m} < H_{\text{max}} < 6 \text{ m}$, $12 \text{ s} < T < 22 \text{ s}$). Moving from eastward along the Mazandaran coast, the dominant wave shifts from the northwest-north to north direction and frequency of high waves ($H_s > 2$ m) and low waves ($H_s < 0.5$ m) increases, simultaneously. On the average, although wave hydrodynamics decrease towards the west the frequency of high northwest to northeast wave increases.

(3) Large-scale topographic map (1:25,000) of the study area from the shore to a depth of 40 meters was provided from National Cartographic Center of Iran (NCC) with 1m depth interval, from which morphological characteristics of the coasts such as beach slope, alongshore variability in bathymetry and the coastline angle were obtained. Bathymetric map shows an alongshore non-uniformity in the sea bed up to a depth of 4 m of central stations and uniformity for eastern and western stations.

(4) Lifeguard Rescues data from 2001 to 2005 was used to estimate the number of people exposed to this natural hazard. According to these reports, Babolsar, Mahmud-Abad and Noshahr are ranked as first to third in terms of the number of drowning caused by rip currents.

(5) Bed profile survey was developed along cross-shore sections from shoreline to a depth of 10 meter (Fig. 3) by Ports and Maritime Organization (PMO) supports. As beach profiles can change considerably during a year as a result of accretion and deposition, these measurements have been done seasonally at selected sites.

(6) Sediment sampling has been carried out from the shoreline to a depth of 10 m by PMO. Sediments were collected in about four depth points in all specific stations in different seasons. The grain size was classified based on Wentworth's sediment classification³⁷. Sediment gradation curves were provided and D_{50} in surf zone area has been estimated. All Mazandaran beaches are predominately composed of fine to coarse sand (0.1 to 2 mm), with a mean grain size of 0.6 mm. Existence of the river mouths, man-made structures (such as ports) and human

interference have led to a westerly increase in grain size from eastern ($D_{50} \sim 0.15$ mm) to central ($D_{50} \sim 0.29$ mm) and western ($D_{50} \sim 1.47$ mm) sections. Also, there are megacusps associated with intermediate beach rhythmic topography on the east half of Mazandaran coasts (Fig. 4a), whereas it is not observed in the west half (Fig. 4b).



(a)



(b)

Fig.4- Coastal feature a) Cusps in Babolsar area with fine sand sediment b) sand-rubble sediment in Kohnesara area without cusps

(7) The sediment fall velocity is calculated based on Stokes equations³⁸:

$$W_s = [(s - 1)g](d_{50}^2/18\theta) \quad d_{50} \leq 100 \mu\text{m} < 1 \quad (7)$$

$$W_s = \left[(1 + (.01(s - 1)gd_{50}^3/\theta^2))^{.5} - 1(10\theta/d_{50}) \right] d_{50} < 1000 \mu\text{m} < 100 \quad (8)$$

$$W_s = 1.1[(s - 1)gd_{50}]^{.5} d_{50} \geq 1000 \mu\text{m} \quad (9)$$

Where $s = 2.65$ (Specific gravity) and θ is the kinematic viscosity coefficient.

(8) Finally, Ω and k^* are computed to determine the Beach State at each station.

The beach state is determined by hydrodynamic mechanisms and subsequently reinforced by feedback between the hydrodynamics and morphological features are likely to change seasonally.

Therefore, in the current study, beach state is determined annually and seasonally, as well. Some of the values calculated at each station are given in table 2.

Results

This paper has emphasized the dependence of rip current type on various beach states. The probability of occurrence of some form of rip current varies with morphologic state, on the one hand, and wave conditions and sediment size, on the other. Central CS beaches have been classified into three wave-dominated types of Wright and Short²². The relationship between the beaches and wave height (H_s), mean

sediment grain size (D_{50}), Ω , mean wave period (T_{m02}) are provided in figure 5. The Ω (k^*) parameter ranged from 2 to 14 (2.06 to 24.83) with no significant seasonally changes (tables 3-5). The various kind rip current occurring on the Mazandaran beaches are described in the following sections.

The eastern Mazandaran beaches, including Neka, Larim and Babolsar have a moderate slope (~ 0.0051), and are relatively high mean Ω (k^*) at 12 (24.83) (Table 3) which is located in the dissipative mode. Persistent high energy waves ($H_s > 2.5$ m) and abundant fine sand in their inshore zone ($D_{50} \sim 0.147$ mm, Table 3) are main reasons to categorize them in dissipative state. As Dissipative beaches occupy the high-energy end of the beach spectrum and have fine sediment (Fig. 5b and 5c), the eastern coasts are extremely stable in this state and persistent where they occur.

Table 2- Characteristics of each station including location, beach slope and shoreline angle, and sediment diameter at each station.

Station	Station Position	Beach Slope	Coastline angle (deg)	D_{50} (mm)	Fall velocity (m/s)
Neka	(53.18 , 36.83)	0.0042	18	0.158	0.016
Larim	(52.93 , 36.76)	0.0058	13	0.146	0.014
Babolsar	(52.67 , 36.72)	0.0053	11	0.138	0.013
Mahmud-Abad	(52.31 , 36.46)	0.0226	14.53	0.33	0.039
Kohnesara	(51.67 , 36.60)	0.0858	-14	0.25	0.033
Noshahr	(51.53 , 36.65)	0.039	-25.84	1.018	0.118
Nashtarood	(51.02 , 36.88)	0.007	-26	1.93	0.17

Table 3- Seasonally and annually beach models calculated in Neka, Larim and Babolsar coasts (eastern beaches)

Station	Annually		Spring		Summer		Autumn		Winter	
	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*
Neka	12.29	24.82	11.94	23.41	11.84	23.04	11.55	21.95	12.27	24.74
Larim	13.40	24.21	12.82	22.17	12.91	22.48	13.06	22.99	13.58	24.85
Babolsar	14.78	25.46	14.03	22.94	14.24	23.64	14.52	24.57	15.0	26.23

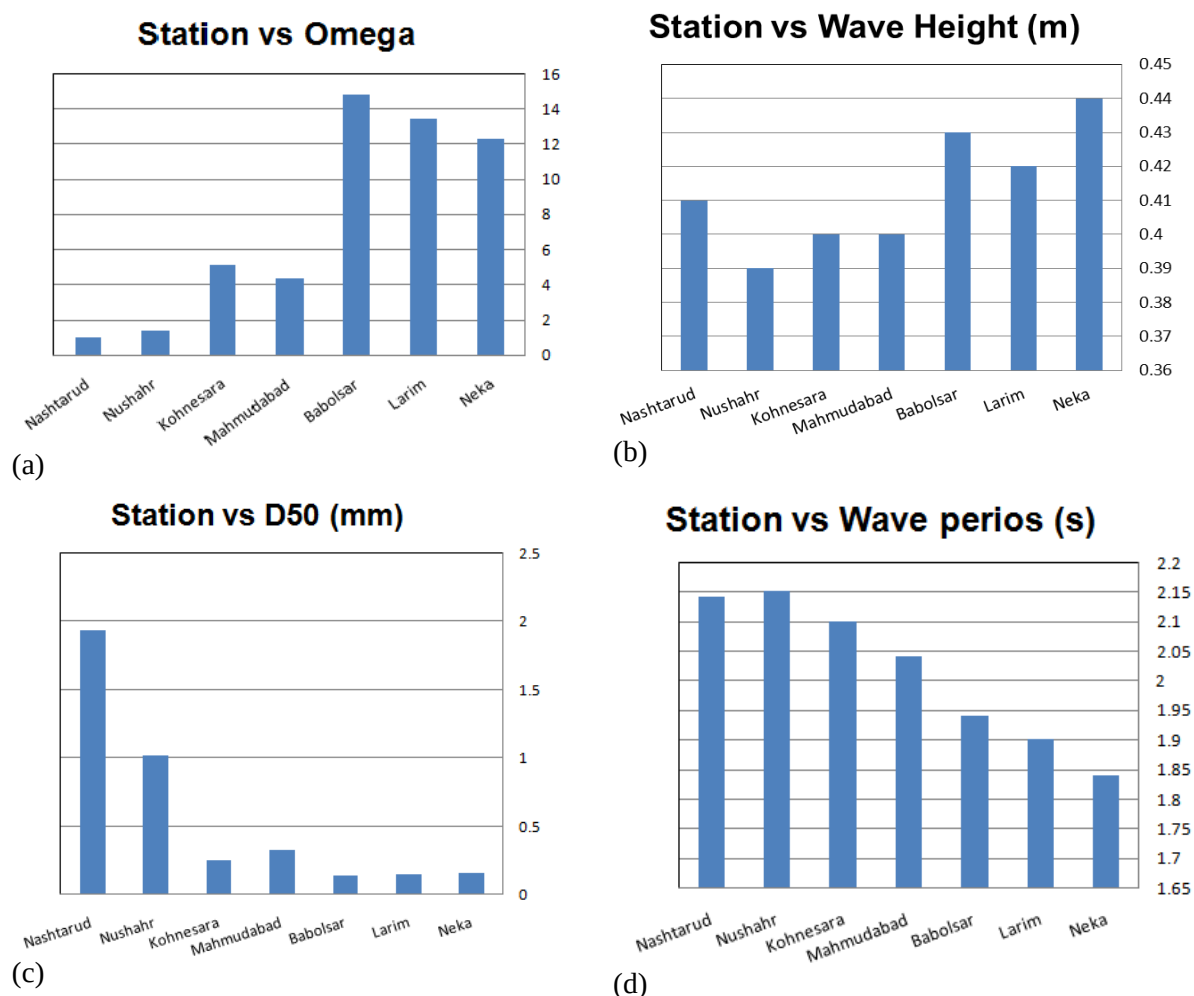


Fig.5- Relationship between beach and (a) Ω ; (b) wave height; (c) D_{50} ; (d) wave period.

Moving west to Neka to Babolsar, there is a similarity in wave hydrodynamics but the seabed sand size tends to be finer (Table 2) which causes Ω and dissipation to increase along this direction. Eastern coasts are exposed to short period waves ($T_{m02} < 2s$, Fig. 5d) that last for short time periods. They also have no longshore variation in surf zone's bed which results in radiations stress gradients due to other reasons rather than topographic variations. As a result the longshore-uniform morphologies give rise to Transient Rip currents generation through strong normal wave breaking or onshore water flow, the locations of which are entirely independent of topographic variation and will occur in differing locations. Therefore, they can migrate in response to the variation of the incident wave field, and they are proposed as an alternative explanation for low frequency oscillations attributed to shear waves³⁹. Transient rips in eastern beaches, by definition, are temporary features with specific lifetime and periodic fluctuations in the time domain¹². Their

durability time is directly related to the wave period (also beach slope), therefore, from Neka to Babolsar beaches, the durability of the rip currents will increase because of increasing in wave period (Fig. 5d)

The central Mahmud-Abad and Kohnesara beaches have a mean Ω (k^*) of 4.5 (10.71) and intermediate characteristics (table 4). The bed morphologies of these beaches are influenced by human disturbance and because of the existence of several river mouths, the rubble concentrations increases and the sand concentrations decreases. Therefore, they have fine to medium sediments size (0.25-0.33 mm, Table 2), moderate bed slope (0.03-0.1, Table 2) and occupy middle wave energy spectrum (Fig. 5b). All of these characteristics are main factors contributing to their Intermediate mode. A longshore sandbar at depth of 5 m in the surf zone area of Kohnsara beach (Fig. 6) indicates one of the following Intermediate states: LBT or RBB (Fig. 2).

Also, at most locations along Mahmud-Abad coast two adjacent sandbars are present. These so-called shore-parallel sandbars are sea bottom elevations, which run almost parallel to

the coast. The first bar is usually close to the beach (at 3m depth) and the second bar is in seaward of the breakwater (at 5m depth) (Fig.7).

Table 4- Seasonally and annually beach models calculated in Mahmud-Abad and Kohnesara coasts (middle beaches)

Station	Annually		Spring		Summer		Autumn		Winter	
	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*
Mahmud-Abad	4.35	10.15	4.16	9.28	4.29	9.85	4.31	9.98	4.42	10.51
Kohnesara	5.1	11.27	4.66	9.45	4.79	9.97	5.33	12.40	5.38	12.60

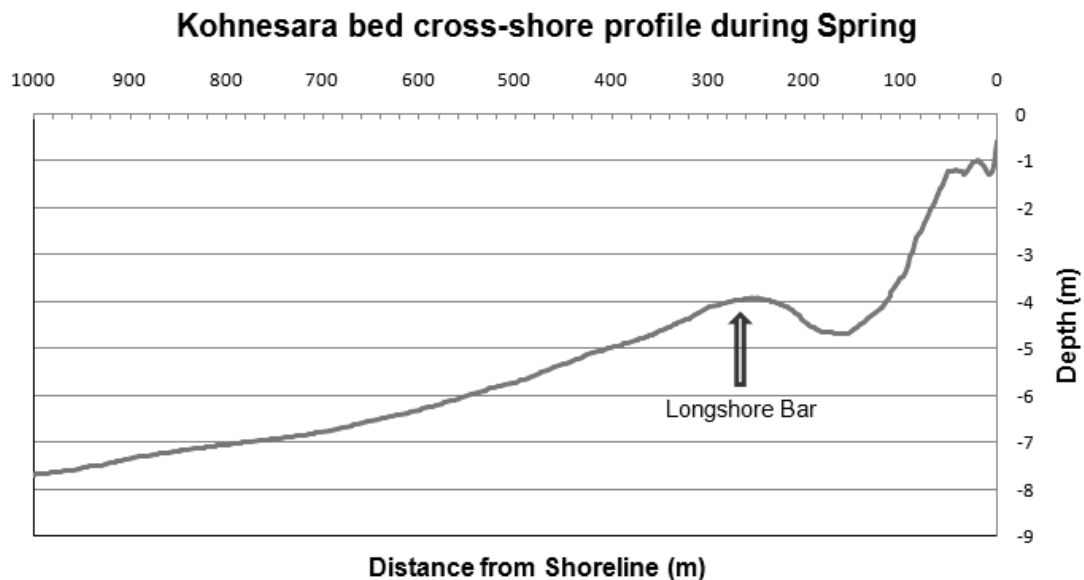


Fig.6- Cross-shore bed profile diagram at Kohnesara station during spring (retrieved from Ports and Maritime Organization)

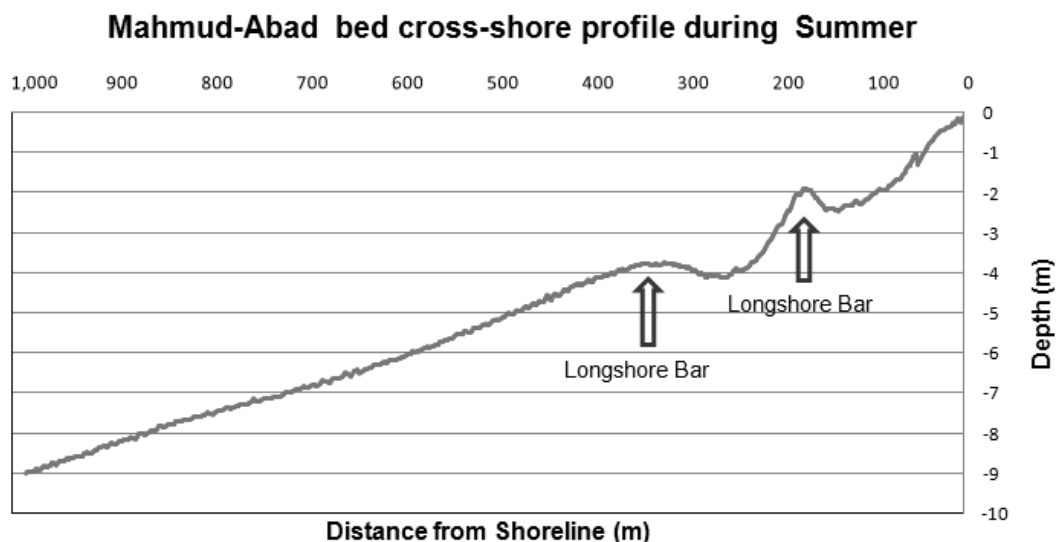


Fig.7- Cross-shore bed profile diagram at Mahmud-Abad station during summer (retrieved from Ports and Maritime Organization)

On the either side of the Kohnesara, there are two deep water rip channels (Fig. 8), of which the right channel is deeper. Therefore, this kind of longshore variation in the bottom

topography of Mahmud-Abad indicates the LBT state.

Because of these irregularities in Mazandaran beach topographies, wave breaking

in the deeper channel is weaker than over the shallower bar, which results in waves focusing on the bar region. The refraction of the waves causes the wave energy to concentrate at the sides of the bar instead of the rip channel. The uneven distribution of the wave energy and variable wave breaking results in a non-uniform longshore wave set-up within the surf zone. The resulting longshore pressure gradient drives the water towards the direction of the rip channel where it flow seaward as rip currents controlled by bathymetry. Therefore, on the average, the central Mazandaran beaches have rip-dominated intermediate inner bars with permanent rip currents.

Man-made structures (such as Noshahr port and Hotels) and existence of river mouths have resulted in the western Mazandaran beaches having very coarse sandy sediments ($D_{50} = 1.02 - 1.93$ mm). Mean $\Omega(k^*)$ of 1.1 (2.06) at Noshahr and Nashtarood beaches are an indicative of low waves, which together with the steep slope of these beaches contributes to their Reflective mode (Table 5). On west Mazandaran coasts, the active nearshore zone reaches at least 500m from shoreline (Fig. 9) and the most frequent H_s is less than 1 m. Although Ω in Noshahr surf zone has a boundary value (1.37) between the Intermediate and the Reflective states (Table 5), k^* model (at the average of 2.60), steep bottom slopes and nonexistence of any alongshore

topographical change (Fig. 9), confirm its Reflective state.

Western Reflective beaches have the lowest waves ($H_b = 0.39$ m. Fig. 5b) and coarsest sediments ($D_{50} > 1$ mm, Table 2) of the wave-dominated beaches. As a result of the barless steep beach profile, the wave breaks directly closed to the coast and the beaches reflect a major part of the incoming wave; therefore, the probability of the formation of rip current is very low at Noshahr and Nashtarood stations however they do experience strong Backwash generated by the reflecting waves.

Rips strength increases with increasing normal incident wave energy¹ and seasonal wave roses for the Mazandaran coast indicate that modal incident waves are higher in the autumn and winter, (e.g., Babolsar wave rose in Fig. 10 in which northwest to north waves are perpendicular to the shore); resulting in stronger rips. Also, seasonal assessment of Mazandaran surf zone beach profiles showed that temporal variation in profile shapes within the beach surf zone and nearshore are not considerable. Hence, Ω and k^* of each beach maintains their values seasonally because the temporal changes of surf zone morphodynamics are not enough to change the Mazandaran beach mode during the year (Tables 3 to 5).

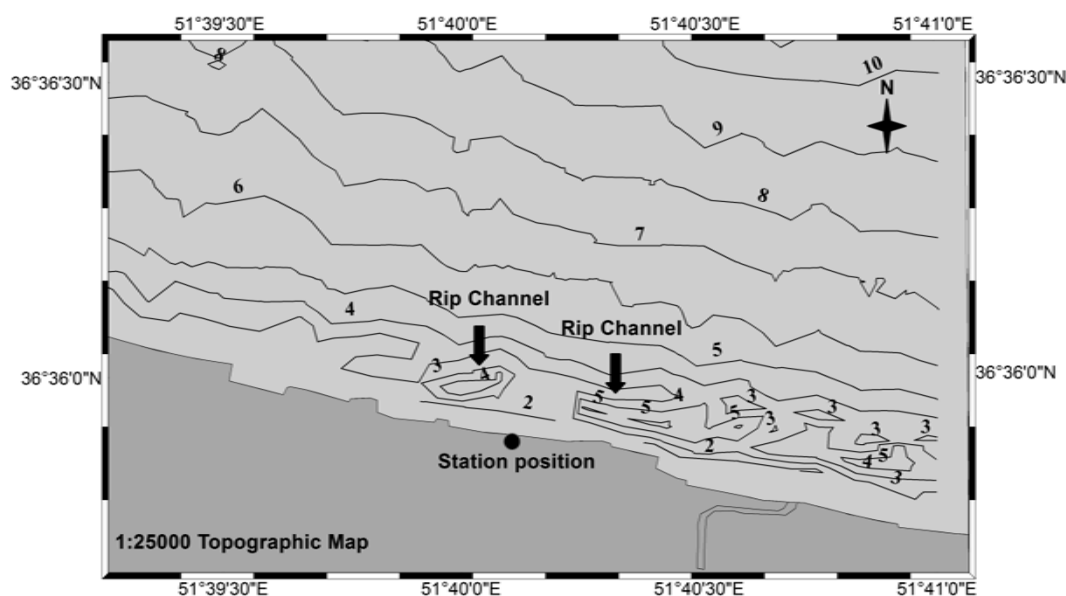


Fig.8- Kohnesara topographic map which shows 2 rip channels around Kohnesara station (retrieved from National Cartographic Center of Iran (NCC))

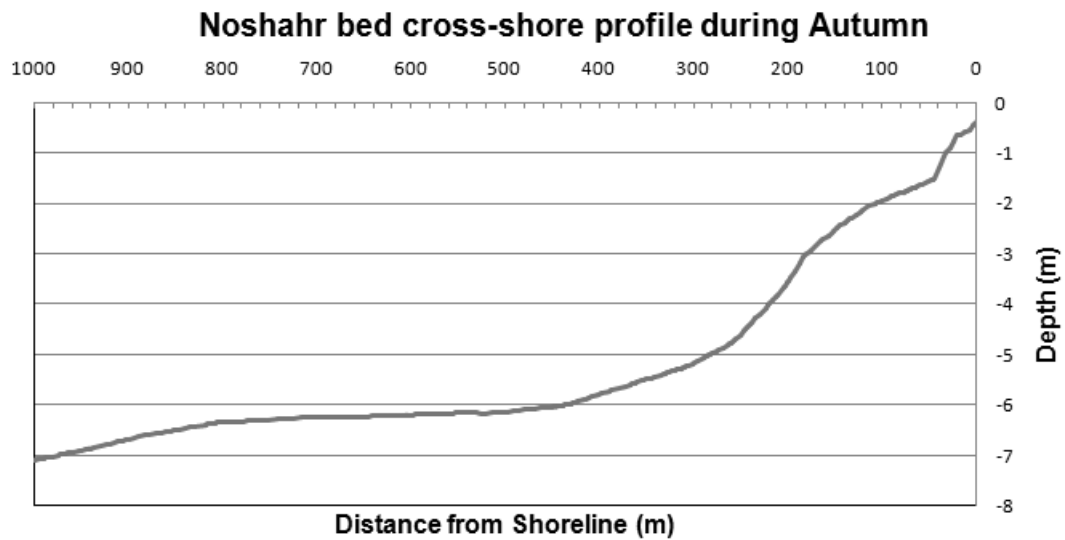


Fig.9- Cross-shore bed profile diagram at Noshahr station during autumn (retrieved from Ports and Maritime Organization)

Table 5- Seasonally and annually beach models calculated in Noshahr and Nashtarood coasts (western beaches)

Station	Annually		Spring		Summer		Autumn		Winter	
	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*	Ω	k^*
Noshahr	1.37	2.60	1.23	2.11	1.29	2.21	1.46	2.97	1.47	3.00
Nashtarood	0.99	1.51	0.91	1.27	0.90	1.25	1.05	1.67	1.07	1.78

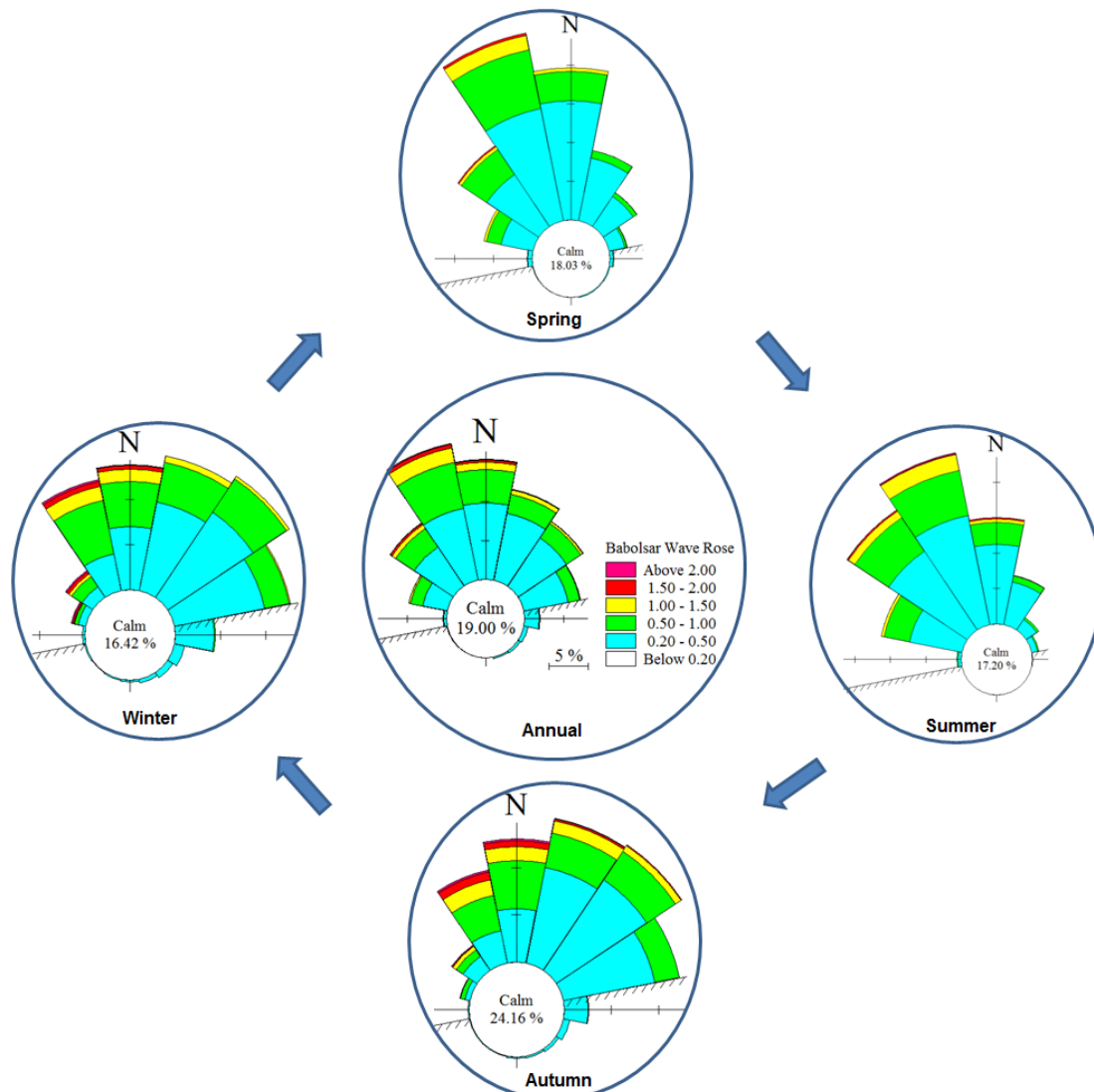


Fig.10- The annual and seasonal wave rose of deep water in Babolsar station for the depth of 93 meters.

Conclusion

This study has shown that rip current occurrence is a function of wave conditions, sediment and bathymetry variability in surf zone region. Wave hydrodynamics of Mazandaran coast and its seabed features and sedimentary systems have resulted in the formation of the three wave-dominated beach types. Due to decreases in the wave height and wave energy, increases in wave period, and changes in grain size from fine to very coarse sand, values of Ω and k^* decrease, as expected, from east to west along the Mazandaran coast. The eastern Mazandaran beaches have the highest wave energy, the shortest wave period and finest grain size producing moderate bed profile slope and longshore uniformity, which maintains dissipative beaches with Transient rips. The central Mazandaran central coasts, has fine to medium grain size and moderate wave energy which has resulted in Intermediate beaches with non-uniform low slope beach profiles. The permanent rip threat on the central beaches is associated with persistence surf zone topography features (bars and channels), which cause them to be the most hazard rip-dominated beaches in Mazandaran. The coarsest sands and maximum wave periods tend to occur on the low-energy Reflective beaches along the western coasts of Mazandaran. In addition to the Reflective state, steep barless bed slope increases the possibility of the formation of the strong backwash, while the potential of rip currents generation on this beach is very low. Such a relationship between the morphodynamic features of the coast and the beach state is consistent with Short's study of Australian beaches²¹.

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