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Seasonal variability of rip current probability along a wave-dominated coast using high resolution satellites and wave data

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Abstract: Rip currents at RK Beach, Visakhapatnam in the northern coastal Andhra Pradesh are causing havoc to the beach users. Recent studies revealed that rip currents are responsible for most drownings happened along this beach. This creates an interest in the public and raises a research challenge on what factors favorable for such dangerous currents. It has been well established that waves and beach morphology play an important role in the formation mechanism of the rip currents. However, due to limited studies, their variability with the season is less understood. In this paper, we have utilized high-resolution satellite imageries and wave data from the nearby buoy to establish a relationship between beach stage and wave parameters. RK beach is a wave-dominated coast and receives persistent swells during south-west and post monsoon seasons. The strong swells during monsoon season and extreme events induce changes in the beach morphology and thereby changes the beach stage from dissipative type to reflective type followed by an intermediate stage. High-resolution optical satellite imageries have been processed using ArcMap and cropped to the study region. Beach types have been identified in few satellite imageries to understand the beach response to the prevailing waves for the period 2013-2017. The study revealed that the rip current probability is higher during intermediate beach stage, and is responsible for major drowning cases along the study area.

Key words: rip currents, beach stage, RK Beach, satellite data, buoy data, GIS

1. Introduction

Many beaches worldwide are characterised by the presence of narrow and seaward flowing rip currents that extend from the shoreline, through the surfzone and sometimes even few kilometres away. Rip currents are fundamentally generated due to the action of breaking waves owing to alongshore gradients in wave-induced radiation stresses and pressure (Bowen, 1969). The offshore flow velocities of rip currents range between 0.3 - 2 m/s (MacMahan et al., 2004). Rip currents can occur along any coastline due to the interaction between waves, currents, water level and near shore bathymetry and these currents flow faster near the water surface (Haas and Svendsen, 2002). Rip currents can quickly carry the surfzone bathers to the offshore with all swimming abilities (Drozdzewski et al., 2015).

Rip currents are one of the most common causes for drownings at the beach in south India. On average, 39 people per year are drowning due to rip currents in the Indian beaches (Arun Kumar and Prasad, 2014). Most of the drowning cases are under reported due to lack of knowledge and popularity in the country. It was estimated that around 320 beach users drowned due to rip currents in the Visakhapatnam beaches during the 2000-2010 (Arun Kumar and Prasad, 2014). Out of all beaches, Rama Krishna (R.K.) beach is declared as the most dangerous for having more than 159 drowning deaths. In Visakhapatnam, more drowning cases due to rip currents were reported during August and October months. The causative factors that drive these dangerous currents are less understood due to manifold complexity in the processes. Waves, tides and nearshore bathymetry are the three important factors seem to be responsible for the majority of the cases. In general, rip current velocities vary with the tide with greater velocities found at low tide and lower velocities found at high tide in response to changes in wave energy dissipation (Aagaard et al., 1997; Brander, 1999; Brander and Short, 2000). It is believed that heavy surf as a consequence of storms will lead to erosional rips (Short, 1985), which develop with a quasi-regular spacing as a consequence of flow and morphological instabilities (Turner et al., 2007). Consequently, rip current velocities increase in response to increasing wave heights and decreasing tidal elevations (MacMahan et al., 2005). In addition to the erosion rips, accretion and topographically controlled rip current systems exist in nature. Topographical rip currents are controlled by the local geology and shelf bathymetry that controls the refraction patterns and wave focussing.

In this study, we are attempting to understand which dominant beach type is responsible for drownings at RK Beach using in-situ wave data and satellite remote sensing.

2. Study Area

The port city of Visakhapatnam (17º 41' N and 83º 17' E) is located almost midway between Chennai and Kolkata on the east coast of India. The valley city of Visakhapatnam is surrounded on three sides by rocky hills and on the other side, the shore of Bay of Bengal. The climate in this region is mainly controlled by the Indian monsoons. The annual average rainfall is about 975 mm. The wind blows from east and southeast during January – March, changes to south and south-west during October – December. The waves approach the coast from the southeast during monsoon months (March to September) and change to east through southeast during other months (Kumar et al., 2006). It is a wave-dominated coast with wave heights ranges from 0.5 – 2.0 m; higher during monsoon and cyclonic conditions and lower during other seasons.

Figure 1: Location map and study area (red circle denotes the position of wave rider buoy)

The wave-induced longshore currents along this coast are generally towards northeast from March to September and towards southwest from November to February with magnitudes, in general, vary between 0.02 to 0.3 m/s (Kumar et al., 2006). The estimated annual net littoral drift along this coast is about 0.5 - 0.7 million cubic meters towards north-easterly direction (Chandramohan and Liang, 1985; Kumar et al., 2001; Panigrahi et al., 2010). The tides in this region are semi-diurnal with a mean spring tidal range of 1.43 m and the neap tidal range of 0.54 m (Kumar et al., 2001). Depressions and Deep depressions occur frequently during SW monsoon season with maximum occurrence during August. Severe cyclones occur in the region during pre-monsoon months (April – May) and post-monsoon months (October – November).

3. Data and methods

3.1 Satellite data

Rip currents are very small-scale features and therefore their features or signals cannot be observed in coarser resolution satellite (LISS-III, LANDSAT etc.) imageries. Few High-resolution satellite imageries have been ordered from Pleiades, Digital globe, Airbus for the period 2013-17 and some of them were used in this paper. In addition, few imageries have been extracted from the Google Earth software. The details of the satellite data used in this paper are listed in Table 1.

3.2 Wave data

Wave data from the nearby wave rider buoy moored at 25 m depth (Figure 1) have been obtained for the study period from Indian National Centre for Ocean Information Services (INCOIS). The wave parameters like significant wave height (Hs), zero-upcross wave period (Tz), wave direction (θ) data are available at 30 minute interval and were converted to daily data for simplicity.

Table 1: Statistics of wave and computed morphological parameters for the reported drowning events as compared with the satellite imageries (GE = Google Earth, PL = Pleiades)

Drowning event	Satellite image (source)	Data availability (days)	Hs (m)	θ (deg.)	Tm (s)	β	W (m)	ε	Beach type
22-09-2013			1.81	160.30	7.27	0.06	71.89	18.45	LBT
	25-12-2013 (GE)	-7	0.71	168.56	5.94	0.11	19.01	4.39	LTT
01-01-2014			0.69	115.30	4.60	0.14	11.83	3.57	LTT
14-03-2014	14-03-2014 (GE)	0	0.62	165.90	6.56	0.10	18.68	3.64	LTT
	17-10-2014 (GE)								**LBT**
22-03-2015			0.62	171.60	5.80	0.11	15.72	3.55	LTT
	14-05-2015 (GE)		**1.37**		**8.03**	**0.07**		12.24	**RBB**
	29-05-2015 (PL)		**1.07**		**5.11**	**0.10**		**24.10**	**TBR**
11-10-2015		+1	0.99	157.50	6.12	0.09	29.51	7.51	TBR
	12-10-2015 (GE)		0.90	158.02	6.12	0.09	26.52	6.51	LTT
	17-01-2016 (GE)		**0.34**		**6.19**	**0.13**	**9.06**	**1.52**	**RFL**
08-05-2016			1.21	154.69	6.94	0.08	43.33	10.16	RBB
10-05-2016			0.92	136.41	6.85	0.09	30.30	6.44	LTT
	22-05-2016 (GE)	**+12**	**2.32**		**7.29**	**0.06**	**95.24**	**26.74**	**DIS**
28-05-2016			1.63	177.19	6.44	0.07	52.16	14.75	RBB
09-06-2016			2.10	163.13	6.04	0.07	67.21	22.99	DIS
22-06-2016			0.95	154.70	6.06	0.09	27.85	7.06	LTT
29-06-2016			2.10	170.20	7.02	0.06	79.50	22.39	DIS
14-09-2016			1.27	170.20	6.45	0.08	40.56	10.50	RBB
25-09-2016			1.33	143.44	5.66	0.09	37.07	11.58	RBB
	12-10-2016 (GE)	-2	**1.12**	**167.58**	**7.03**	**0.08**	**39.40**	**8.76**	**TBR**
14-10-2016			1.13	156.09	8.96	0.07	54.90	9.09	TBR
	18-02-2017 (PL)		**0.64**		**5.85**	**0.11**	**16.87**	**3.84**	**LTT**

3.3 Nearshore morphology and surf parameters computation

The change in morphological state is driven by a change in the surf scaling parameter (ε) described by (Guza and Inman, 1975)

$$\varepsilon = \frac{a_b \omega^2}{g tan^2 \beta} \quad (1)$$

where, a_b is the breaker amplitude ($H_b/2$), ω is the radian frequency of the incident waves (2π/T, T = wave period), g is acceleration due to gravity and tanβ is the gradient of the beach/surf zone. The beach slope (β) has been estimated using the formula by (Sunamura, 1984)

$$\tan \beta = 0.12 g^{0.25} {H_b}^{-0.5} T^{0.5} d_{50}^{0.25} \quad (2)$$

here, $H_b = H_o \times K_s \times K_r$ is the breaker height, K_s and K_r are the shoaling and refraction coefficients. The value for d50 has been considered as 0.6 mm (Arun Kumar and Prasad, 2014) for RK Beach.

As wave energy decreases following a storm, the beach changes from dissipative (ε>20) to reflective (ε<2.5) by passing through each of four intermediate states: longshore bar-trough, rhythmic bar-beach, transverse bar and rip and low tide terrace (2.5> ε<20) (Table 2). Each of these intermediate states is characterized (to varying degrees) by the presence of accretion rips. As the shore face evolves, there is an increase in the rip current velocity as the cross-sectional rip channel area decreases and the ability of the bar system to block return flows increases (Brander, 1999), until the innermost bar completely welds to the beach face. These rips do not have the characteristic form and may be difficult to identify from the perspective of a beach user. Further, they persist through both storm and non-storm conditions.

The surf zone width is an important parameter that decides the strength of the rip current. It has been computed using

$$W = H_b/(0.43 * \tan \beta) \quad (3)$$

It has been observed that larger the surf zone width, stronger is the rip current.

Table 2: The surf scaling parameter, beach type, rip current probability and the strength as defined by Wright and Short (Wright & Short, 1984)

ε	Beach type	Rip current formation probability	Rip current strength
< 2.5	Reflective	No	Nil
2.5 – 7.5	Ridge runnel (RR) or low tide terrace (LTT)	Yes	Moderate
7.5 – 10	Transverse bar and rip (TBR)	Yes	Very Strong
10 – 15	Rhythmic bar and beach (RBB)	Yes	Strong
15 – 20	Longshore bar trough (LBT)	Yes	Weak
>20	Dissipative	No	Nil

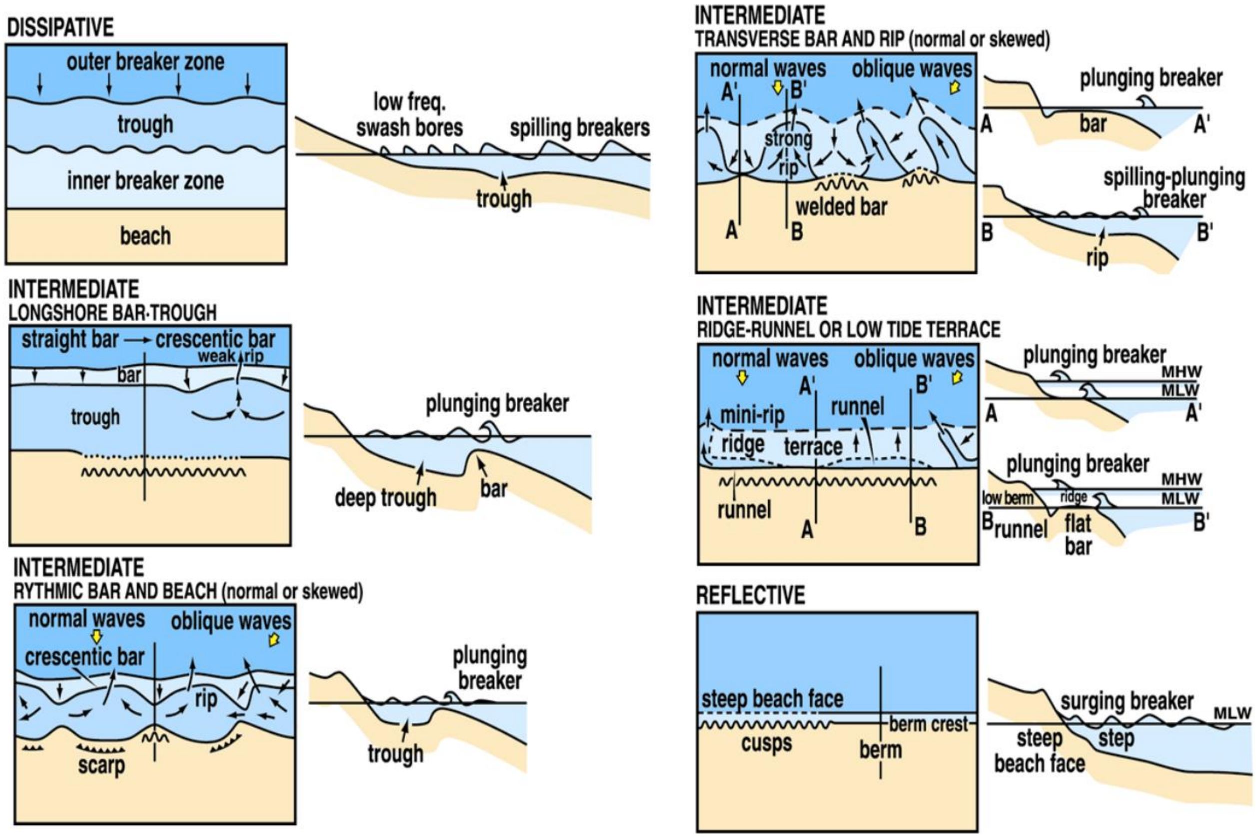

Figure 2: Configuration of the six major beach types. Modified from Wright and Short (Wright & Short, 1984).

4. Results and discussion

Nearshore bars migrate offshore in response to, and onshore in recovery from the storms. Migration offshore is caused by breaking waves affecting the bar crest which creates an offshore-directed current (Ruessink et al., 1998; Plant et al., 2001). In this section, we have explained the application of satellite remote sensing to observe the transition of a beach from dissipative (high wave energy) to the reflective type (calm sea) and discussed the morphology and migration of nearshore bars affect circulation and formation of rips.

4.1 Beach type analysis from satellite imageries

In general, nearshore bars migrate onshore during calm conditions and offshore during high-energy conditions. Rip currents develop as the bar migrates landward. If a reset event occurs, the bar will migrate offshore and rip channel formations will be lost until the bar migrates landward again, restarting the sequence of stages in the bar cycle. This cycle has been examined from a series of high resolution satellite imageries to infer the rip current hazard for different beach stages. In the absence of on-site observations and measurements, the satellite images can be used to classify various beach states as mentioned below, by following the classification descriptions suggested by (Wright and Short, 1984).

Accordingly, the beach is classified into three stages Dissipative, Intermediate and Reflective. The Intermediate stage is further classified into four stages Longshore bar-trough (LBT), Rhythmic bar and beach (RBB), Transverse bar and rip (TBR) and Low-Tide Terrace (LTT) or Ridge Runnel (RR) (Figure 2).

4.1.1 Dissipative

This type of beach occurs generally during stormy condition and monsoons, where the surf zone is full of breaking waves (Figure 3a). High sea-state attract fewer people to venture in to the surf during this time. No rips are possible during this stage. However, due to high energy waves, there are chances of drowning due to wave attack.

4.1.2 Intermediate

Longshore bar-trough (LBT)

A longshore bar-trough (LBT) morphology is characterized by a straight or crescentic nearshore bar with a trough on its landward edge and a shoreline that may be straight or have cusps. If there is any discontinuity in the bar, a weak rip is expected. In figure 3b, a significant bar along with the beach cusps can be clearly seen. After a few days of the storm, this bar starts coming closer to the shore.

Rhythmic bar and beach (RBB)

The rhythmic bar and beach (RBB) morphology presents a crescentic bar with horns migrating more landward and aligning with mega cusp horns alongshore (Figure 3c). Rip currents may form at the bay sections of the crescentic bar. However, their signatures may not be clear from the beach view.

Transverse bar and rip (TBR)

The transverse bar and rip state (TBR) develops during an accretionary sequence when the horns of the crescentic bar welds with the beach face. Rip currents are created when water flows seaward through the topographic channels created from the partial welding of the nearshore bar (Wright and Short, 1984; Sonu, 1972) producing the strongest rip current circulation. The cusped shoreline of the RBB beach state is softened by the partial welding of the bars and creates a more undulating shoreline profile (Figure 3d). This beach type will have the strongest rip current and pose danger to the swimmers often occurs in pre and post monsoon.

Figure 3a: Dissipative beach type classification with satellite image on 22-05-2016

Figure 3b: Longshore bar-trough beach type classification with satellite image on 17-10-2014

Figure 3c: Rhythmic bar and beach type classification with satellite image on 14-05-2015

Figure 3d: Transverse bar and rip beach type classification with satellite image on 29-05-2015

Figure 3e: Ridge-runnel (RR) or low-tide terrace (LTT) beach type classification with satellite image on 18-02-2017

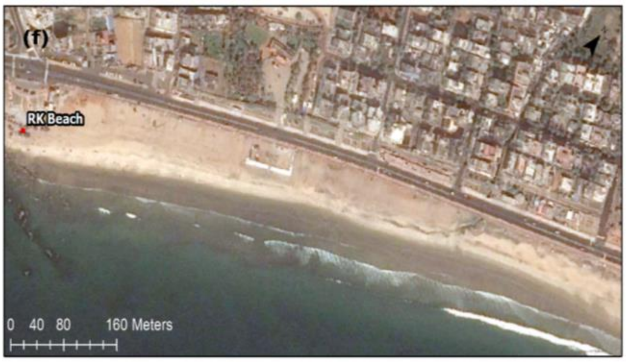

Figure 3f: Reflective beach type classification with satellite image on 17-01-2016

Ridge-runnel (RR) or low-tide terrace (LTT)

The low tide terrace or ridge and runnel beach state (LTT) is formed as the bar welds almost entirely onto the beach face creating a terrace at low tide. Small rip currents may be present during this stage but are more dominant during the TBR and RBB beach states (Figure 3e). This type of beach generally occurs during January and February.

4.1.3 Reflective

If calm conditions continue, the bar will continue to attach to the shore and rip channels will disappear (Ruessink and Kroon, 1994; Houser and Greenwood, 2005; Aagaard et al., 2004). The beach has a steep face and does not pose danger to the general public. Figure 3f shows a typical reflective type of beach in the study region. This type of beach often occurs during January or February.

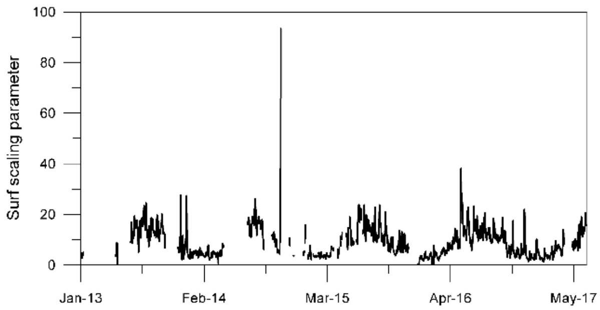

Figure 4: Variation in the Surf scaling parameter

4.2 Rip current hazard variability

From the previous section, it has been observed that the rip current probability and its strength can be easily interpreted from the satellite imageries based on its classification stage. If the wave data is available, the beach stage can be computed using the equation (1) and therefore rip current can be predicted with or without any other supporting data. The surf similarity parameter is a proxy for the rip current formation. It is observed that the values are high during the monsoon season (June to September) and low during January – March (Figure 4). From Table 2, it is clear that stronger rip currents form when the ε ranges between 7.5 and 15. However, the rip formation probability is seen for ε = 2.5 to 20.

The wave height, wave period, the computed surf zone width and the beach slope are shown in figure 5. A significant seasonal cycle can be observed in all the parameters (excluding wave period, wave direction – not shown). The variation of beach slope is inversely related to wave height. It is evident that the higher sea state erodes the beach face and thereby decreases its slope.

The dependency of wave height (or breaker wave height), surf zone width and the beach slope have been examined in figure 6. It is observed that the surf scaling parameter is high for higher wave heights, larger surf zone widths but smaller beach slopes.

4.3 Rip current drowning analysis

It has been observed that the rip current formation and its strength are strongly related to the surf scaling parameter, which in turn depends on the surf zone width, beach slope and wave height. In order to prove this, the actual drowning cases reported at RK Beach during 2013-2017 have been examined in this section. During this period, around 14 cases have been reported due to rip currents. However, there are no actual observations at the time of the event. Using the method described in the above section, surf zone and nearshore morphological parameters have been calculated for the drowning events. As anticipated, none of the events reported during dissipative and reflective stages. All the events happened during the intermediate stage. Out of all, most of the rip current related drownings reported in the LTT beach stage. It is expected that more people venture into the sea following the storm due to the calm sea state. However, due to alongshore irregularities in the bar, rip current pose danger and lead to drowning.

The beach stage obtained from the wave data for the rip current cases have been compared with the satellite imageries. Due to lack of coincident high-resolution satellite data at the time of the event, the scene within 15 days of the event has been considered for this comparison. Surprisingly, the computations from the wave data are perfectly representing the beach stage on the satellite imagery during the event. On 14-03-2014, LTT type of beach was present and the same type has been obtained from the wave data. In another case, a rip current drowning was reported on 14-10-2016, where the beach stage was TBR as obtained from the wave data. There is no coincident satellite image to verify on that day. However, the same TBR stage was obtained from the satellite image two days prior (12-10-2016). It is often understood that TBR stage will remain at least 2-7 days unless a reset event occurs.

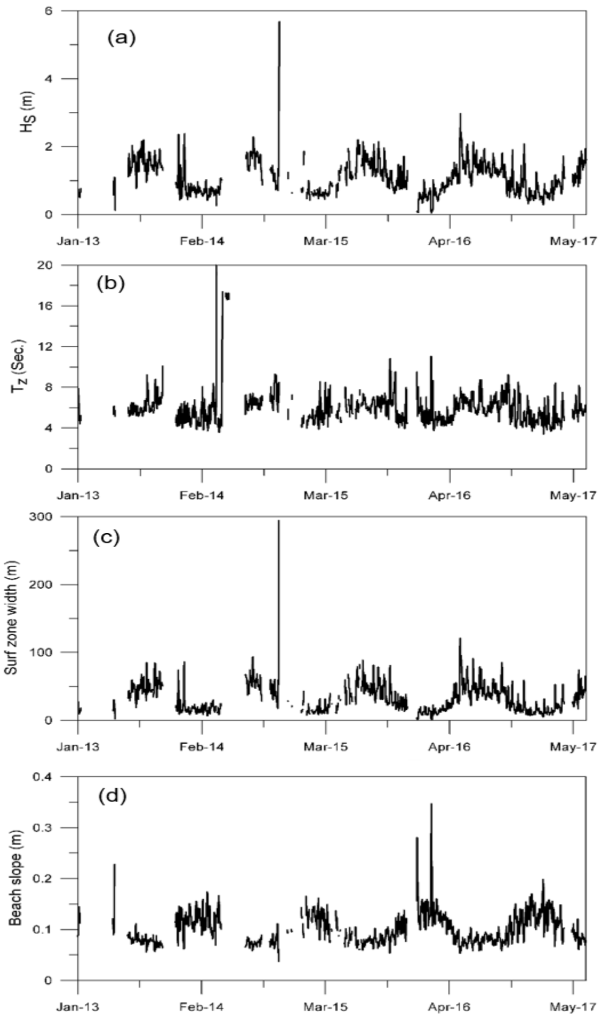

Figure 5: Time series of wave height, wave period, computed surf zone width and beach slope.

Whereas in the case of 10-05-2016 event, the beach stage was LTT, the nearest available satellite image was on 22-05-2016. But by that time the sea state was entirely changed to the dissipative domain. Hence, cannot be compared. From this analysis, it is very clear that the rip current events can be well predicted just by observing the beach stage classification. However, the interpretation is very subjective and requires skills and experience. Also, high resolution satellite imageries are expensive and sometimes covered with clouds. Whereas, the same job can be easily done using wave data if obtained from a nearby buoy or from an accurate model forecast. The early detection of a change in beach stage can be very much helpful in saving valuable lives in the beaches.

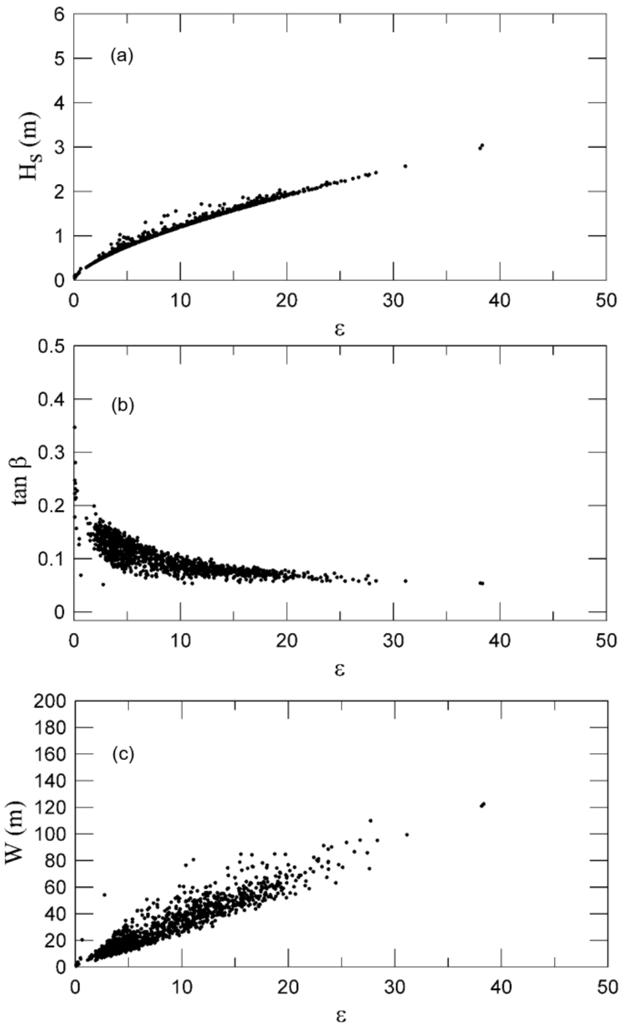

Figure 6: Relationship between H_s, beach slope, and surf zone width with surf scaling parameter

5. Conclusion

High resolution optical satellite imageries have been used to analyse different beach stages along RK Beach, Visakhapatnam where a record drowning reported. The satellite data is supported by the in-situ wave data from a nearby buoy in the shallow waters. Surf scaling parameter - a proxy to the rip current formation was computed from the wave data. It has been observed that the surf scaling parameter has strong seasonal variability and related well with the surf zone width, beach slope and wave height. Based on the drowning data for the period 2013 – 2017, we have observed that most of the drownings happened at low-tide terrace beach type (LTT) and occur during pre and post monsoon seasons. The method proposed in this paper can be used to detect the beach stage and thereby the rip current probability and its strength. The method will be used to examine other beaches along the Indian coast in future.

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