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Classification of tidal inlets along the central west coast of India

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Abstract

Tidal inlets along the Maharashtra coast on the central west coast of India were classified according to three methods available in the literature. Two classification methods viz., (i) Hydrodynamic classification (Hayes, 1979) and (ii) Classification based on dimensionless parameters (Vu, 2013) used for the classification are compared with the morphological classification of de Vriend et al., (1999). The hydrodynamic classification of Tidal inlets along Maharashtra coast is carried out considering mean annual significant wave height. The classification is also extended considering significant wave heights obtained for South-West monsoon, North-East monsoon and Fair Weather seasons. It has been observed that 74% of the inlets are tide dominated as per morphological classification whereas considering annual mean wave heights in Vu (2013) method, 67% of the inlets are wave dominated.

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1. Introduction

Davis and Fitzgerald (2004) defined tidal inlet as an opening in the shoreline through which water enters the hinterland, thereby providing a connection between the ocean and bays, lagoons, and estuaries. These inlets provide a tidal connection between back barrier bays, lagoons, marsh and tidal creeks, and the coastal ocean and are kept open by tidal currents. Tidal inlets significantly impact the local coastal environment. They play an important role in near shore processes and exchange of water, sediments, nutrients, larvae, planktonic organisms and pollutants. Tidal basins, including tidal lagoons and estuaries with their associated coastal inlets, interrupt a significant part of the world's shorelines (Stive and Wang, 2003). The main channel of a tidal inlet is maintained by the tidal currents

propagating back and forth between the lagoon and the sea resulting from the rise and fall of the tides (Davis and Fitzgerald, 2004). Due to the fact that coastal inlets interrupt the continuity of the shorelines and near shore processes, they play a vital role in sediment budgets and coastal erosion (Weishar and Aubrey, 1988).

The morphology of tidal inlets is controlled by the interaction of hydrologic, geologic, meteorological, oceanographic, and topographic features. The complexity of inlet processes show diversity in hydraulic signature, sediment transport patterns, and morphology. The frequency and interactions of tide, wave and freshwater flow, together with topographic and geologic controls, are responsible for wide range in tidal settings (FitzGerald, 1988, 2005; Stive et al. 2006).

2. Study area

Study area considered in this work is the Maharashtra coast along the west coast of India adjoining Arabian Sea. Maharashtra coast starts from Vahindra River on its North to Terekhol River to its South. It lies between $20^{\circ} 7'42.88''$ – $15^{\circ}43'16.83''$ North latitudes and $72^{\circ}44'18.81''$ – $73^{\circ}41'23.10''$ East longitudes (Figure 1). The indented length of the coastline is 720 km and is oriented along the NNW–SSE direction. A total of 65 inlets are identified from Google Earth®. The inlets with width less than 5m are not considered in this study and the names given to these inlets are the names of the nearest visible places at the inlets on Google Earth®. Table 1 shows the tidal inlets identified along the Maharashtra coast.



Fig 1. Locations of inlets considered in study area

Table 1. Tidal inlets identified and geomorphological classification along the Maharashtra coast

No.	Name	LONG	LAT	Cls.
1	Zai	72.7386	20.1286	TD
2	Gholvad	72.7263	20.0821	TD
3	Dahanu	72.7260	19.9694	TD
4	Navapur	72.6965	19.7923	WD
5	Dudh river	72.7186	19.7299	WD
6	Darapada	72.7291	19.6205	TD
7	Kelwa	72.7598	19.5983	TD
8	Bhadve	72.7946	19.4933	TD
9	Rajodi	72.7615	19.4172	TD
10	Bhuigaon Kh.	72.7677	19.3930	TD
11	Vasai	72.8033	19.3170	TD
12	Malad	72.8005	19.1981	TD
13	Versova	72.8341	19.1445	TD
14	Revas	72.8833	18.8954	TD
15	Mandve	72.9593	18.8359	TD
16	Awas	72.8645	18.7696	TD
17	Surekhar	72.8671	18.7575	WD
18	Navgaon	72.8633	18.7012	WD
19	Navapada	72.8669	18.6687	WD
20	Akshi	72.8888	18.6384	TD
21	Bagmala	72.9250	18.5784	TD
22	Revdanda	72.9328	18.5384	TD
23	Wandeli	72.9105	18.5034	WD
24	Surulpeth	72.9297	18.3733	TD
25	Eakdara	72.9731	18.3201	TD
26	Rajapuri	72.9802	18.2814	TD
27	Velas Agar	72.9886	18.1957	TD
28	Diveagar	73.0002	18.1591	TD
29	Walavati kh.	73.0167	18.0723	TD

30	Shrivardhan	73.0420	18.0264	TD
31	Bankot	73.0500	17.9832	TD
32	Sakhari	73.0689	17.9318	TD
33	Koliwada	73.0910	17.8904	TD
No.	Name	LONG	LAT	Cls.
34	Juikar	73.0916	17.8421	TD
35	Dabhol	73.1769	17.5798	TD
36	Mouje	73.1976	17.5152	WD
37	Palshet	73.2210	17.4378	TD
38	Musloni	73.2270	17.3545	TD
39	Jaigad	73.2403	17.2924	TD
40	Bhandrawada	73.2619	17.1995	TD
41	Bhandarpule	73.2748	17.1585	WD
42	Kajitbhati	73.2883	17.1001	WD
43	Sadye	73.2928	17.0780	TD
44	Sadamirya	73.2844	17.0381	TD
45	Karle	73.3006	16.9859	TD
46	Bhathiwadi	73.3166	16.8910	TD
47	Khsheli	73.3273	16.8065	TD
48	Wadativare	73.3573	16.6872	TD
49	Vijayadurg	73.3300	16.5707	TD
50	Phanase	73.3725	16.4434	WD
51	Padavne	73.3864	16.3929	WD
52	Taramumbari	73.4113	16.3601	TD
53	Morve	73.4342	16.2745	WD
54	Pirawadi	73.4629	16.2011	TD
55	Sariekot	73.4658	16.0880	WD
56	Malvan	73.4907	16.0710	TD
57	Kalethar	73.5038	16.0102	TD
58	Bhogwa	73.5340	15.9670	WD
59	Shriramwadi	73.5675	15.9382	TD
60	Khalchiwadi	73.5864	15.9191	TD
61	Kelus 1	73.5967	15.9105	TD
62	Kelus 2	73.6113	15.8951	CD
63	Dabholi	73.6534	15.8658	WD
64	Tank	73.6637	15.7938	WD
65	Khalchikar	73.6897	15.7535	TD

where, Cls-Geomorphological Classification; WD-Wave Dominated; TD-Tide dominated; CD- Closed

3. Methods

The diversity is the result of the simultaneous occurrence of all coastal system determining factors in a nearly infinite number of combinations. That is why there exists no truly unique classification system of coastal ocean systems; and that is why one encounters a large variety of classification systems in literature. The decision of which classification scheme to be followed depends on the perception and concern of managers or researchers. Here, Geomorphological classification (de Vriend, 1999), Hydrodynamic classification (Hayes, 1979) and classification based on dimensionless parameters (Vu, 2013) are done. Other methods of classification based on the longshore sediment transport rates (LSTR) and tidal prism (e.g., Bruun, 1978) is not attempted here as enough information on the LSTR is not available at present.

3.1 Hydrodynamic classification:

Hayes (1979) and Davis and Hayes (1984) characterized inlet planform morphology according to the relative strength of tide and waves with tidal range serving as a substitute for tidal prism or tidal current (which moves the sediment) and also the Hayes' classification is concerned not only with the morphologic behavior of a tidal inlet, but also with the frequency of occurrence and number of inlets along a barrier coastline. The nature of tidal inlets and characteristics around the inlets is dependent on relative influence of average significant wave height and average tidal range.

Table 2. Shoreline classification based on tidal range.

A. Shoreline classification by Davies (1964)		B. Refined classification by Hayes (1975) (Medium wave height, H = 0.6 -1.5m)	
Microtidal	0-2.0 m	Microtidal	0-1.0 m
Mesotidal	2.0-4.0 m	Low-mesotidal	1.0-2.0m
Macrotidal	> 4.0 m	High-mesotidal	2.0-3.5m
		Low-macrotidal	3.5 - 5.0m
		Macrotidal	> 5.0m

In the hydrodynamic classification method there are three limiting states viz., Tide Dominated (TD), Wave Dominated (WD) and Mixed Energy (ME) (Figure 2).

3.2 Geomorphological classification:

The inlets were classified based on their shape which is influenced by waves, tide and river flow (de Vriend et al, 1999). With reference to this classification, the inlets are visually examined in Google Earth® and the dominance of wave or tide or river is decided based on the inlet morphology. The inlet cannot be perpetually classified as wave or tide dominated because the wave and tide forces modify the inlet discharge and corresponding sediment transport and morphology for tidal dominated system and wave dominated system.

3.3 Classification based on dimensionless parameters:

Among those numerous methods to classify coastal systems; the most preferred and used classification is based on the hydro-morphological perspective related to ecological parameters. The literature review revealed that none of the previous methods consider quantitatively the three main driving agents that govern inlet morphodynamics. A new method of classification was introduced by Vu (2013) based on dimensionless parameters which represent the relative strength of the three main forcing agents, viz., tide, river flow and waves. The non-dimensional parameters are introduced in which tidal forcing is quantified in terms of the peak tidal discharge and wave forcing represented

in terms of sediment transport capacity. Along New South Wales coast of Australia, 178 inlets are classified based on this new classification system, which revealed a clear peculiarity of three main groups (Table 3).

Table 3. Classification of Coastal systems based on dimensionless parameters (Vu, 2013)

S. No	Description	Type of Coast
1	$\frac{Q_{tide}}{\sqrt{gH}} < 7.5$	Wave dominated
2	$\frac{Q_{tide}}{\sqrt{gH}} > 7.5$	Tide dominated
3	$\frac{Q_f}{\sqrt{gH}} > 2$	River dominated

4. Results & Discussion

The results of the inlet classification based on three different methods are as follows. Figure 2 shows the classification of inlets as per Hayes (1949) which is hydrodynamic classification method. Classification is carried out considering the seasonal variation of wave height for North East monsoon, South West monsoon and Fair Weather season. This classification clearly shows the seasonal influence on the inlets. It is observed that the type of dominance over some inlets varies seasonally. This is because of the variation in wave height during different seasons. An inlet which is classified as mixed energy wave dominated (B in Fig. 2) considering the SW monsoon waves becomes as Tide dominated inlet (E category) during NW monsoon wave conditions.

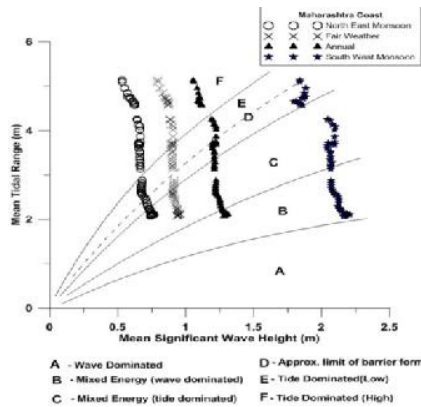


Fig 2. Hydrodynamic based classification of tidal inlet morphology (After Hayes, 1979)

The geomorphological classification is given in Table 1 which shows that 48 inlets (74%) are tide dominated and 16 are dominated by waves while 1 inlet is found to be perpetually closed. Classification based on non-dimensional parameters as per Vu(2013) including Q_{tide} and wave heights is carried out for all inlets to establish the dominance of waves or tides (as per Table 3) and the results are shown in Table 4. Based on the Vu(2013) classification method and considering annual mean wave height, 68% of inlets are observed to be wave dominated whereas 32% are tide dominated. Since Q_f is available for four inlets and the classification involving waves, tides and river discharge is carried out for these 4 inlets which shows that inlets are tide dominated (Figs. 3 & 4) and during SW monsoon two of these inlets fall under wave dominated ICOLLS.

Table 4. Classification based on dimensionless parameters (Vu, 2013)

No	Name	Bay Area (m ²)	Tidal Range (m)	Tidal Prism (m ³)	Qtide (m ³ /S)	H (m)	$\frac{Qtide}{\sqrt{rtgH^5}}$	Classification
1	Zai	40822.22	5.14	209876.83	14.74	1.06	4.11	Wave dominated
2	Gholvad	5225.60	5.09	26609.27	1.86	1.06	0.52	Wave dominated
3	Dahanu	1973969.28	4.96	9796375.26	688.32	1.08	180.40	Tide dominated
4	Navapur	653884.40	4.84	3167089.09	222.52	1.09	56.81	Wave dominated
5	Dudh river	1662026.76	4.77	7918942.56	556.40	1.10	139.85	Tide dominated
6	Darapada	55553.26	4.74	263153.02	18.49	1.10	4.65	Wave dominated
7	Kelwa	633620.28	4.72	2987703.37	209.92	1.10	52.28	Wave dominated
8	Bhadve	32590059.19	4.65	151631442.50	10654.06	1.09	2750.58	Tide dominated
9	Rajodi	7089.45	4.67	33069.66	2.32	1.10	0.59	Wave dominated
10	Bhuigaon Kh.	232398.29	4.65	1080115.21	75.89	1.10	19.17	Wave dominated
11	Vasai	43904492.10	4.62	202857193.40	14253.33	1.11	3502.72	Tide dominated
12	Malad	4652036.14	4.59	21336935.92	1499.19	1.11	367.49	Tide dominated
13	Versova	1283028.80	4.58	5875540.58	412.83	1.12	99.77	Tide dominated
14	Revas	249331458.20	4.25	1058693785.00	74386.85	1.19	15362.78	Tide dominated
15	Mandve	30577769.00	4.25	129837182.30	9122.73	1.19	1884.08	Tide dominated
16	Awas	6261.06	4.23	26482.59	1.86	1.20	0.38	Wave dominated
17	Surekhar	92708.98	3.70	342952.77	24.10	1.21	4.79	Wave dominated
18	Navgaon	46181.18	4.14	191247.81	13.44	1.21	2.68	Wave dominated
19	Navapada	98102.08	4.10	401794.73	28.23	1.22	5.46	Wave dominated
20	Akshi	794766.67	4.02	3194858.69	224.48	1.22	43.34	Wave dominated
21	Bagmala	70494.61	3.74	263950.15	18.55	1.22	3.57	Wave dominated
22	Revdanda	11964373.54	3.69	44127002.49	3100.49	1.22	599.73	Tide dominated
23	Wandeli	96788.46	3.87	374182.25	26.29	1.22	5.06	Wave dominated
24	Surulpeth	129229.89	3.72	480913.53	33.79	1.20	6.85	Wave dominated
25	Eakdara	283118.82	3.67	1039875.61	73.06	1.20	14.89	Wave dominated
26	Rajapuri	56897200.44	3.61	205239581.40	14420.72	1.20	2944.02	Tide dominated
27	Velas Agar	192119.66	3.53	678361.07	47.66	1.21	9.44	Wave dominated
28	Diveagar	59649.73	3.50	208719.18	14.67	1.21	2.92	Wave dominated
29	Walavati kh.	136399.12	3.41	464749.99	32.65	1.21	6.46	Wave dominated
30	Shrivardhan	1398745.51	3.35	4684035.04	329.11	1.21	65.39	Wave dominated
31	Bankot	19776854.19	3.28	64830307.95	4555.16	1.21	894.01	Tide dominated
32	Sakhari	924282.18	3.22	2973452.74	208.92	1.21	41.35	Wave dominated
33	Koliwada	162176.19	3.19	516727.40	36.31	1.21	7.19	Wave dominated
34	Juikar	848256.40	3.13	2656484.57	186.65	1.21	36.95	Wave dominated
35	Dabhol	18361936.31	2.87	52720791.53	3704.31	1.22	717.08	Tide dominated
36	Mouje	109356.50	2.81	307430.65	21.60	1.22	4.18	Wave dominated
37	Palshet	34913.76	2.76	96373.50	6.77	1.22	1.32	Wave dominated
38	Muslondi	37271.69	2.71	100902.44	7.09	1.22	1.39	Wave dominated
39	Jaigad	18327896.14	2.67	48905773.17	3436.26	1.22	666.32	Tide dominated
40	Bhandrawada	298025.69	2.62	779837.27	54.79	1.22	10.67	Wave dominated
41	Bhandarpule	113697.39	2.60	295124.43	20.74	1.22	3.99	Wave dominated
42	Kajitbhati	172901.40	2.57	443605.17	31.17	1.23	5.95	Wave dominated
43	Sadye	324633.56	2.55	828863.82	58.24	1.23	11.03	Wave dominated
44	Sadamirya	2375265.74	2.55	6065362.21	426.17	1.23	80.96	Tide dominated
45	Karle	2940577.62	2.51	7374039.45	518.12	1.24	96.26	Tide dominated
46	Bhatiwadi	2682646.40	2.46	6605558.03	464.13	1.25	84.62	Tide dominated
47	Khsheli	4655405.02	2.42	11276987.76	792.35	1.25	143.72	Tide dominated
48	Wadatavare	299052.68	2.37	708730.63	49.80	1.26	9.00	Wave dominated

49	Vijayadurg	18997595.28	2.30	43710465.12	3071.22	1.26	554.03	Tide dominated
50	Phanase	335757.57	2.26	757461.69	53.22	1.27	9.43	Wave dominated
51	Padavne	7921668.34	2.24	17722950.54	1245.27	1.27	219.02	Tide dominated
52	Taramumbari	1284779.60	2.22	2847307.99	200.06	1.27	34.97	Wave dominated
53	Morve	931059.72	2.19	2036681.03	143.10	1.27	24.90	Wave dominated
54	Pirawadi	1563059.12	2.16	3372221.90	236.94	1.28	40.46	Wave dominated
55	Sariekot	6939686.12	2.13	14812003.60	1040.73	1.30	173.28	Tide dominated
56	Malvan	248313.22	2.13	528606.45	37.14	1.30	6.15	Wave dominated
57	Kalethar	11688.69	2.11	24683.75	1.73	1.31	0.28	Wave dominated
58	Bhogwa	5507266.63	2.11	11594200.61	814.64	1.31	132.16	Tide dominated
59	Shriramwadi	140353.62	2.10	294806.60	20.71	1.29	3.48	Wave dominated
60	Khalchiwadi	46345.03	2.10	97187.01	6.83	1.29	1.14	Wave dominated
61	Kelus 1	177248.43	2.10	371421.60	26.10	1.29	4.42	Wave dominated
62	Kelus 2	38102.21	2.09	79771.28	5.60	1.29	0.95	Wave dominated
63	Dabholi	111712.46	2.09	233324.32	16.39	1.29	2.79	Wave dominated
64	Tank	632315.22	2.08	1314355.71	92.35	1.28	15.85	Wave dominated
65	Khalchikar	654420.81	2.07	1357450.69	95.38	1.28	16.44	Wave dominated

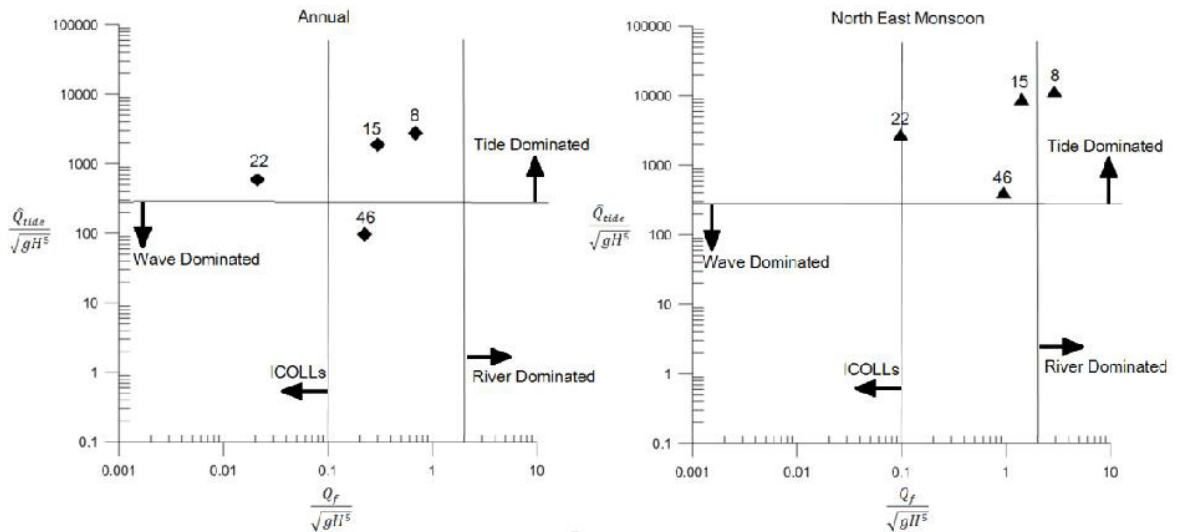


Fig 3. Classification based on dimensionless parameters for annual and NEM wave heights

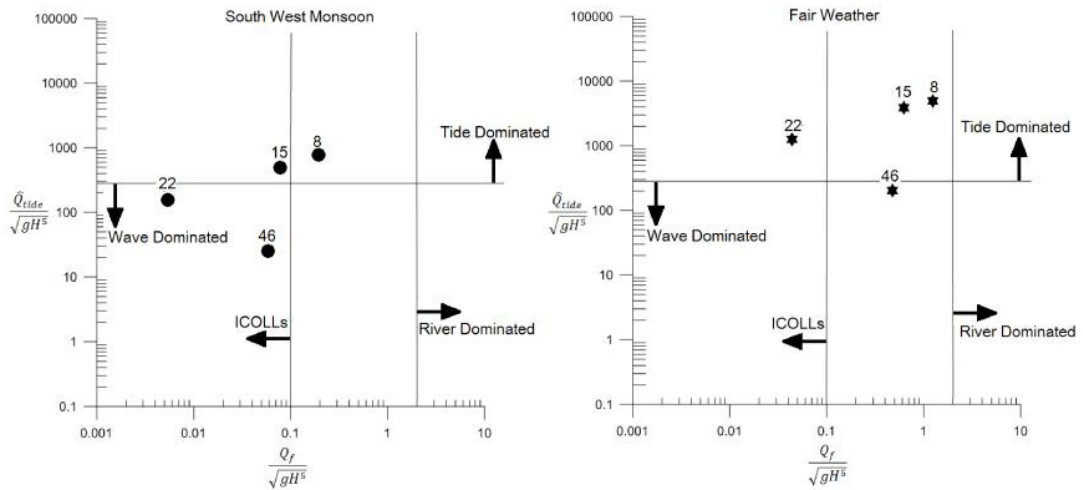


Fig 4. Classification based on dimensionless parameters for different wave climate during (a) South West Monsoon and (b) Fair Weather.

5. Conclusions

- Tidal inlets along Maharashtra coast are classified by three methods. Under geomorphological classification, 48 inlets (74%) are dominated by tide and 16 are wave dominated while 1 remained perpetually closed.
- The hydrodynamic classification compares well with geomorphological classification. It can also be observed that the dominance over the inlets changes with seasonal variation in wave heights.
- The classification based on dimensionless parameters is expected to (a) reduce discrepancy between the other two methods (b) allow better long-term prediction of inlet morphodynamics, enabling effective coastal zone management. Based on this method of classification considering annual mean wave height, the 68% of inlets are observed to be wave dominated whereas 32% are tide dominated.
- Further, dimensionless classification based on Q_r is needed to get a better idea of the classification system.

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