

Variability in Wave Refraction & Resultant Nearshore Current Patterns: Exposed versus Sheltered Beaches along North Karnataka, West Coast of India

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For predominant waves approaching from directions varying between SW and WNW and periods varying from 6 to 11 sec, the refraction function (K_0) shows amplification of wave heights resulting in concentration of wave energy on headlands and reduction of wave heights in headland-bays and at river mouths. Certain stretches of open ocean beaches located on either side of the Kali river and the headland-bay beaches south of Karwar Head experience relatively higher wave heights for W and WSW waves, the latter being more prone to higher wave heights for waves from SW. The higher wave energy zones shift towards the central-northern sectors of the beaches, as the direction of wave approach changes from WNW to SW. The northern and southern stretches of headland-bay beaches receive partial shelter from the headlands for predominant waves approaching from northerly and southerly quadrants respectively. The Karwar port as well as a greater stretch of the Karwar-Kodibag beach being on the lee side of Karwar Head, receives good shelter for WSW and SW waves and only the extreme northern part of the Karwar beach is affected by these waves. Southerly flowing longshore currents are generated along the coastline for WNW waves, except for the presence of converging currents along Karwar beach and in the southern parts of headland-bay beaches. The southerly longshore current reverses to northerly flow along Karwar beach, and zones of converging currents prevail along Ramnath-Sadashivgad beach in the north and at the Kali river mouth for W and WSW waves; for SW waves, converging currents prevail along the headland-bay beaches. The converging currents observed for W and WSW waves along these open ocean beaches are similar to those identified along similar beaches reported elsewhere on the west coast of India.

Ocean wave refraction phenomenon is very important in understanding the shoreline dynamics, sedimentation problems in the vicinity of tidal inlets and harbours, and dispersal of pollutants in the nearshore environs. This paper presents variability of wave refraction patterns along exposed versus sheltered/or bay-head beaches of north Karnataka shoreline on the west coast of India. The changes in incident wave height and propagation direction due to refraction have been utilized in inferring the resulting nearshore current patterns and the associated sediment transport along these shoreline sectors. This study assumes importance because this stretch of the west coast differs from the adjoining SW coast¹⁻³, where barrier beaches backed by lagoons dominate and also from the Goa sector of the central west coast of India^{1,4}, where long and wide beaches bounded by headlands far apart from each other occur.

Reddy and Varadachari⁵ have described broadly the sediment transport phenomena along the west coast of India between Cape Comorin and Vengurla through wave refraction study. Gouveia *et al.*⁶ have studied the wave refraction and sediment transport processes along the coast north of Sadashivgad with

special reference to Loliem Point. Recently, Nayak⁷ has dealt with the morphology, sedimentology and mineralogy of the beaches at some selected locations along this coast.

Study Area

The area under investigation extends from Arge to Loliem Point and seaward up to ~ 100 m depth contour (Fig. 1). In general, the coast is characterised by headlands, headland-bay/bay-head/crescent beaches and drowned river mouths^{8,9}. The coast is oriented NNW-SSE south of Karwar Head, while it trends north between Karwar and Sadashivgad with a concave shape at its southeastern part. The coast is protected by a seawall between port entrance and south of storm Signal Station (Fig. 1). The Kali, a major river in the north Karnataka debouches into the Arabian Sea between Kodibag and Sadashivgad developing prominent shoals on either side of its mouth, the shoal in the south being wider and bigger in areal extent. On the other hand, the shoal in the north off Sadashivgad is welded into a recurved spit with a convex shape at its south-western part. A little north of Sadashivgad, this spit sandwiched between the mainland in the east and

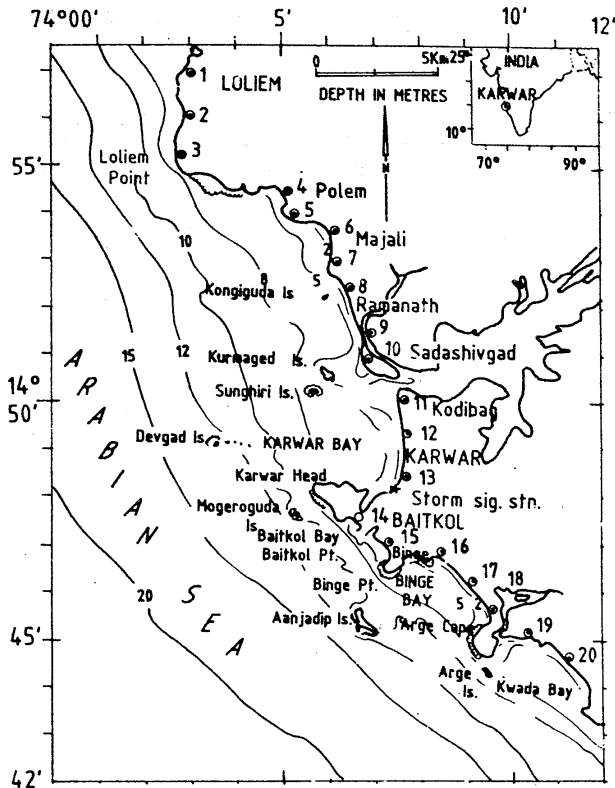


Fig. 1—Location of study area showing the geography of north Karnataka coastline and sts 1-20 selected for determination of refraction parameters

the sea in the west, apparently maintains its delicate geomorphic equilibrium on this part of the coast. North of Sadashivgad the coast trends NNW up to Loliem Point. Small but prominent headland-bay/bay-head beaches oriented NNW-SSE occur at Arge, Binge and Baitkol in the south whereas more or less crescent shaped beaches form a part of the coastline in the north (Majali, Polem). However, between Polem and Loliem Point the coast is virtually rocky. Almost all these beaches are backed by sand dunes with heights ranging from < 1 to ~ 3 m and serve as natural shore protective measures. The nearshore sea bottom is relatively steep off the headlands as compared to that in the bays and in the vicinity of the river mouths as is evident from the submarine contours (Fig. 1).

Methods

For the construction of wave refraction diagrams, bathymetry of the region extending seaward to a depth of one-half the wavelength of incoming deep water wave has been used from the available hydrographic charts. Initial wave parameters including wave height, period and frequency of occurrence are required for each significant approach direction.

Since long-term recorded wave data for the region under study are lacking, the already available data on wave characteristics¹⁰⁻¹² off west coast of India derived from the Indian Daily Weather Reports for the grid 13° - 18° N as well as the recorded wave data¹³ for the nearby locality, viz. Mangalore (~ 200 km south of Karwar) have been assumed to hold good for the present study area and are used.

After taking into consideration the orientation of the shoreline, and an examination of wave data¹⁰⁻¹³ for predominant direction of wave approach and the significant wave periods, wave refraction diagrams have been constructed for waves of periods 6, 8 and 11 sec approaching from WNW, W, WSW and SW. The refraction diagrams have been prepared following the orthogonal methods^{14,15}. Twenty arbitrary stations starting from the north have been chosen around the 2 fm (3.65 m) contour to cover the various geomorphic regions of the study area (Fig. 1). Typical refraction diagrams for 8 sec period waves approaching from WNW, W, WSW and SW direction are presented in Figs 2a to 2d. From the original refraction diagrams, refraction parameters—refraction coefficient (K_d) and direction function (θ) have been evaluated. Figs 3a to 3d depict the probable nearshore current patterns derived from the values of direction function.

Results and Discussion

Topography and Sediments

Beach profile observations⁷ have revealed that the beaches along the north Karnataka coast undergo cyclic seasonal changes in their morphology and sedimentological characteristics in response to the changing wind and wave climates off the west coast of India. They are characterised by a well developed summer berm by about April. The beaches experience erosion from May onwards due to short period, high and steep waves associated with the on set of the southwest monsoon and erosion continues till about August. They accrete soon after the cessation of the SW monsoon under the influence of low and long period swell waves and almost attain premonsoonal configuration by about April.

Grain-size data⁷ reveal that Sadashivgad-Ramanath and Kodibag-Karwar beaches located north and south of the Kali river creek mouth respectively are composed of medium to fine sands ($M_z = 1.32$ - 2.96ϕ ; 1.12 - 2.88ϕ), the sediments at Kodibag and Sadashivgad being relatively coarser. The crescent beach at Majali in the north and the headland-bay beach at Shankurbag in the south are characterised by fine to very fine sands ($M_z = 2.34$ - 3.16ϕ ; 2.58 - 3.14ϕ). The beaches at extreme ends of the study

area are composed of medium to very fine sands (Polem: $Mz = 1.08-3.13 \phi$; Arge: $Mz = 1.86-3.08 \phi$). These results suggest that, in general, the mean grain-size of the sediments of the open ocean beaches decreases from the mouth of the Kali river to either side. Further, the beaches during the period

of SW monsoon erosion are characterised by relatively coarser particles than in accretion phase.

Wave Refraction Pattern

Open ocean beaches—Ramnath-Sadashivgad beach (sts 8 to 10), except for the presence of Kangi-

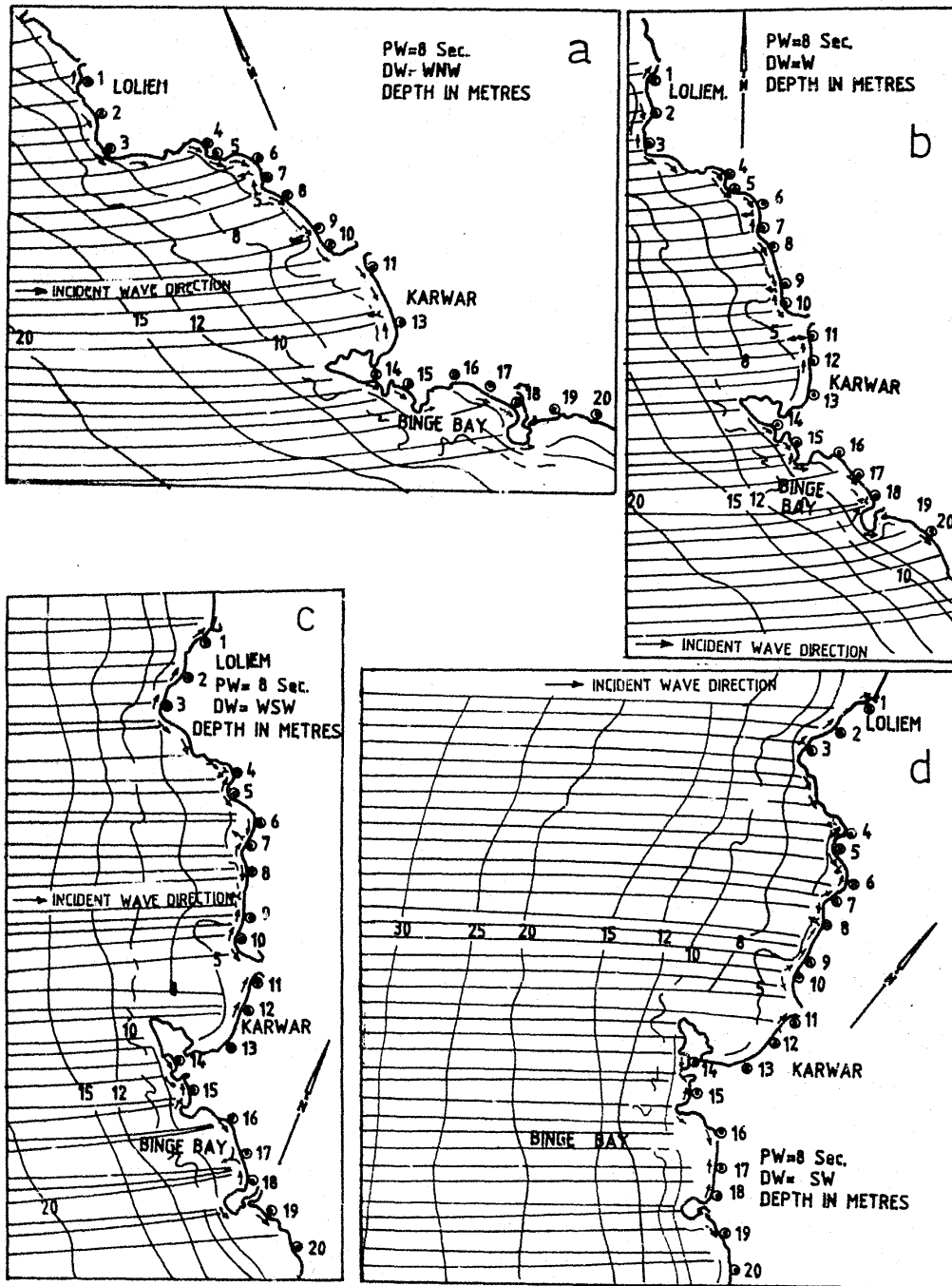


Fig. 2.—Typical wave refraction diagrams for 8 sec. Period waves from (a) WNW, (b) W, (c) WSW and (d) SW [→ Wave induced flow direction]

guda island in the northwest and Kurmagad island in the southwest between 6.5 and 7 m water depths offshore, is an open ocean environment. The refraction function values show that the beach experiences low wave heights for all waves approaching from WNW; but as the direction of wave approach changes considerable amplification in wave height occurs mostly for waves approaching from W and WSW, maximum amplification being observed for 8 sec period waves approaching from WSW. This beach generally experiences higher wave heights in south for waves approaching from southerly quadrants. However, the zone of higher wave heights shifts towards the central region and to further north as the direction of deep-water wave approach changes from W to WSW, which is more conspicuously seen for 8 sec period waves (Table 1). The refraction function shows reduction in wave height at the northern sector for waves approaching from SW while amplification in wave height occurs in the south at Sadashivgad for 8 sec and lower period waves approaching from SW.

Kodibag-Karwar coastal strip (sts 11 to 13) is a long, straight open beach except for Devgad group of islands which are situated around 13 m water depths and at about 7 km away from the shore in the offshore region. Refraction patterns show that a major part of the beach is exposed to waves from WNW and W, while its southern sector receives shelter from Karwar Head for waves approaching from WSW and SW. However, refraction function values show reduction in wave height for WNW waves, except for 11 sec period waves approaching the northern sector wherein K_d values show appreciable amplification in wave heights. Amplification in K_d values also occurs for waves approaching from W, WSW, and for waves of 11 sec period from SW. As at Ramnath-Sadashivgad, it also experiences higher wave heights for deep-water waves approaching from W. One conspicuous feature is the fanning away of orthogonals at Kali river mouth, for WSW waves (Fig. 2c) and focussing of orthogonals on either side, probably due to marked change in bathymetry off the river mouth and the presence of shoals, thus resulting in reduction in wave heights (Table 1) at the river mouth and appreciable increase in wave heights on either side.

Sheltered beaches: Headland-bay/crescent beaches—Binge and Baitkol beaches (sts 14 and 15) indicate interesting wave refraction patterns. The former is marked by amplification in wave heights for higher period waves whereas reduction in wave height occurs for lower period waves. Amplification is prominent for waves approaching from WNW and W. At Baitkol also similar amplification in wave

height occurs for WNW and WSW waves of higher periods.

Binge bay (sts 16 to 18): Because of NNW orientated shoreline and the presence of prominent headland-Binge Pt., jetting into the sea on the north, the northern part of the beach do not receive directly refracted wave energy for waves approaching from WNW. Further K_d values for waves approaching from this quadrant show marked reduction in wave height in the southern sector of this beach (Table 1). As the incident wave direction changes from W to WSW, the zone of higher wave heights shifts towards the north characterised by well defined focussing of wave rays (Fig. 2c) and almost 2/3 of the bay mainly the north-central sector experiences higher wave heights for low period waves. On the other hand, slight reduction in K_d values occurs for higher period waves at the southern sector (st 18). Nevertheless, wave refraction patterns reveal concentration of wave rays to either side of the central part of the bay (st 17) suggesting appreciable amplification in wave heights at the shoreline for WSW waves.

Arge (Kwada bay) sts 19 and 20: Wave refraction patterns show that the entire beach is protected by Arge cape from WNW waves while the central and southern parts only receive waves from the west that too with considerable reduction in their heights. K_d values show that waves from WSW are amplified in the northern sector whereas they are apparently reduced in their heights in the southern sector. The northern sector experiences low wave heights for SW waves while the southern part receives little refracted wave energy due to the presence of headland in the south.

Polem (st 4): The beach is protected by the Loliem promontory in its north from deep-water waves approaching from WNW. K_d values show appreciable amplification in wave heights for deep-water waves approaching from W and SW, maximum amplification being observed for waves from the west. However, slight reduction in wave height occurs for WSW waves.

Majali (sts 6 and 7): The crescent shaped beach at Majali, unlike the beach at Polem, is subjected to refraction effects considerably. K_d values show amplification in wave heights for lower period waves from WNW and WSW along the curved part of the coastline in the north and again along the straight part for lower period waves from W and SW, but K_d values show reduction in wave heights for higher period waves.

In general, K_d values along the coastline north of Polem show appreciable amplification for deep-water waves approaching from W and WSW, amplification for the westerly waves being more prominent.

Table 1—Computed Values of Refraction Parameters (RP) at the Station Locations Shown in Fig. 1

| Sl No. | RP | Period, sec | | | | | | | | | | | |
|--------|----|--------------|-------|------|----------|------|-------|--------------|------|------|-----------|------|------|
| | | 6 | 8 | 11 | 6 | 8 | 11 | 6 | 8 | 11 | 6 | 8 | 11 |
| | | 292.5° (WNW) | | | 270° (W) | | | 247.5° (WSW) | | | 225° (SW) | | |
| 1 | K | 0.91 | 0.66 | 0.69 | 0.93 | 0.83 | 3.00 | 0.92 | 0.63 | 1.43 | 0.87 | 0.60 | 0.83 |
| | θ | + 35 | + 30 | + 34 | + 44 | + 48 | + 47 | + 62 | x | + 58 | + 83 | + 82 | + 72 |
| 2 | K | 0.63 | 0.63 | 0.63 | 1.04 | 1.43 | 0.38 | 1.11 | 0.93 | 0.38 | 0.64 | 0.64 | 0.83 |
| | θ | - 19 | - 32 | - 23 | - 10 | - 7 | - 6.5 | + 7 | + 8 | x | + 27 | + 22 | + 16 |
| 3 | K | 0.86 | 0.81 | 1.32 | 1.00 | 1.25 | 0.38 | 1.00 | 0.74 | 3.58 | 1.00 | 0.86 | 1.19 |
| | θ | - 10 | - 16 | - 5 | + 9 | + 7 | + 13 | + 25 | + 27 | + 22 | + 45 | + 41 | + 39 |
| 4 | K | x | x | x | 1.00 | 1.25 | 1.40 | 0.83 | 0.69 | 0.85 | 1.04 | 1.04 | 0.83 |
| | θ | x | - 43 | - 35 | - 28 | - 19 | - 19 | - 12 | - 9 | - 17 | + 8 | + 7 | - 3 |
| 5 | K | 0.83 | 0.64 | 0.81 | 0.89 | 0.71 | 1.06 | 1.00 | 0.71 | 1.14 | 0.89 | 0.94 | 0.77 |
| | θ | - 62 | - 57 | - 48 | - 36 | - 31 | - 32 | - 24 | - 21 | - 25 | + 2 | - 7 | - 13 |
| 6 | K | 1.56 | 0.64 | 1.09 | 1.00 | 0.90 | 0.53 | 1.25 | 5.00 | 0.69 | 0.83 | 0.64 | 0.83 |
| | θ | - 32 | - 31 | - 20 | - 12 | - 8 | - 6.5 | + 4 | + 1 | 0.00 | + 20 | + 18 | + 19 |
| 7 | K | 0.73 | 0.92 | 0.63 | 1.14 | 0.72 | 0.53 | 1.04 | 0.63 | 0.45 | 0.96 | 1.25 | 0.94 |
| | θ | + 10 | + 14 | + 8 | + 23 | + 20 | + 22 | + 32 | + 33 | x | + 51 | + 46 | + 45 |
| 8 | K | 0.56 | 0.59 | 0.50 | 0.79 | 0.76 | 0.63 | 1.47 | 1.67 | 1.66 | 0.90 | 0.53 | 0.63 |
| | θ | - 29 | - 34 | - 29 | - 17 | - 18 | - 14 | - 8 | - 7 | - 9 | + 11 | x | + 5 |
| 9 | K | 0.71 | 0.55 | 0.63 | 1.00 | 0.86 | 1.60 | 1.09 | 1.79 | 0.71 | 0.78 | 1.43 | 0.56 |
| | θ | - 22 | - 26 | - 20 | - 8 | - 9 | - 2 | + 3 | + 8 | 0.00 | + 22 | + 22 | + 12 |
| 10 | K | 0.96 | 0.55 | 1.00 | 1.19 | 1.52 | 0.81 | 1.00 | 0.91 | 0.71 | 1.19 | 1.04 | 0.56 |
| | θ | - 20 | - 20 | - 17 | + 1 | - 2 | 0.00 | + 10 | + 18 | + 8 | + 27 | + 30 | + 22 |
| 11 | K | 0.71 | 0.78 | 1.34 | 1.25 | 1.04 | 0.73 | 1.02 | 0.42 | 1.00 | x | 0.67 | 1.11 |
| | θ | - 20 | - 21 | - 16 | 0.00 | 0.00 | 0.00 | + 16 | + 14 | + 8 | + 32 | + 29 | + 30 |
| 12 | K | 0.75 | 0.63 | 0.51 | 0.88 | 1.25 | 3.13 | 0.77 | x | x | x | x | x |
| | θ | - 14 | - 11 | - 11 | + 11 | + 5 | + 15 | + 18 | + 22 | + 18 | x | x | x |
| 13 | K | 0.53 | x | 0.89 | x | x | x | x | x | x | x | x | x |
| | θ | + 6 | + 6.5 | + 7 | + 25 | x | x | x | x | x | x | x | x |

Contd

Table 1—Computed Values of Refraction Parameters (RP) at the Station Locations Shown in Fig. 1—*Contd*

| Sl No. | RP | Period, sec | | | | | | | | | | | |
|--------|----------|--------------|------|------|----------|------|------|--------------|------|------|-----------|------|------|
| | | 6 | 8 | 11 | 6 | 8 | 11 | 6 | 8 | 11 | 6 | 8 | 11 |
| | | 292.5° (WNW) | | | 270° (W) | | | 247.5° (WSW) | | | 225° (SW) | | |
| 14 | K | 0.88 | 1.16 | 0.63 | 1.00 | 0.59 | 0.55 | 0.96 | 1.14 | 3.30 | 1.00 | 0.71 | 0.93 |
| | θ | - 57 | - 66 | x | - 43 | - 43 | x | - 32 | - 22 | - 32 | 0.00 | - 6 | - 11 |
| 15 | K | 0.61 | 1.43 | 2.5 | 0.89 | 1.11 | 1.25 | 0.83 | 0.77 | 0.55 | 0.83 | 0.64 | 1.53 |
| | θ | - 51 | - 53 | - 42 | - 34 | - 30 | - 29 | - 15 | - 16 | x | + 4 | + 7 | - 4 |
| 16 | K | x | x | x | 1.14 | 0.96 | 0.60 | 0.88 | x | x | 1.04 | 1.25 | 0.96 |
| | θ | x | x | x | x | x | - 51 | - 49 | - 38 | - 55 | - 30 | - 26 | - 33 |
| 17 | K | x | x | 0.74 | 0.71 | 0.48 | 0.36 | 1.04 | 0.38 | 0.73 | 1.04 | 1.02 | 0.92 |
| | θ | - 43 | - 47 | - 30 | - 25 | - 22 | x | - 13 | x | - 17 | + 7 | + 12 | + 6 |
| 18 | K | 0.63 | 0.53 | 0.66 | 0.88 | 1.19 | 0.36 | 0.81 | 0.50 | x | 0.98 | 0.63 | 0.82 |
| | θ | - 27 | - 29 | - 16 | - 12 | 0.00 | 0.00 | + 9 | + 14 | + 6 | + 27 | + 30 | + 25 |
| 19 | K | x | x | x | x | 0.66 | 0.96 | 1.79 | x | x | 1.00 | 0.55 | 0.89 |
| | θ | x | x | x | x | x | x | - 53 | x | - 60 | - 35 | - 32 | - 35 |
| 20 | K | x | x | x | x | 0.71 | x | 0.66 | x | 0.63 | x | x | x |
| | θ | - 45 | - 55 | x | - 39 | - 20 | - 28 | - 17 | x | - 18 | + 4 | x | x |

K = refraction coefficient, θ = direction function
 + indicates northerly flow, - indicates southerly flow
 x = parameter values not evaluated as the refracted waves do not reach these stations

Wave Induced Longshore Current Pattern

The wave induced longshore current patterns for deep water waves approaching from WNW (Fig. 3a) reveal that the current is predominantly southerly along the open ocean beach north of Karwar (st 12), except for the presence of a convergent zone along the curved part of the crescent beach at Majali (sts 6-7). It is known that the longshore currents on the sides of a headland are always directed shoreward. In general, at the side of the wave approach, a nodal point is formed where the normal longshore current generated by the impinging waves on the headland meets the longshore current caused by the surf along the beach on the upcoast side of the headland,

leading to opposing longshore flows at the ends of the beaches. Therefore, for WNW waves, the current patterns at the southern parts of the headland-bay beaches are characterised by converging currents which have been clearly identified off Karwar (between sts 12 and 13) and along Binge-bay beach (st 18). Except these, the general current south of Karwar Head is towards the south which is more prominent along the shores of Binge and Kwada bays.

The current patterns for deep water waves approaching from W is northerly along the open ocean beach at Karwar. The zone of convergent current pattern identified along this beach between sts 13-

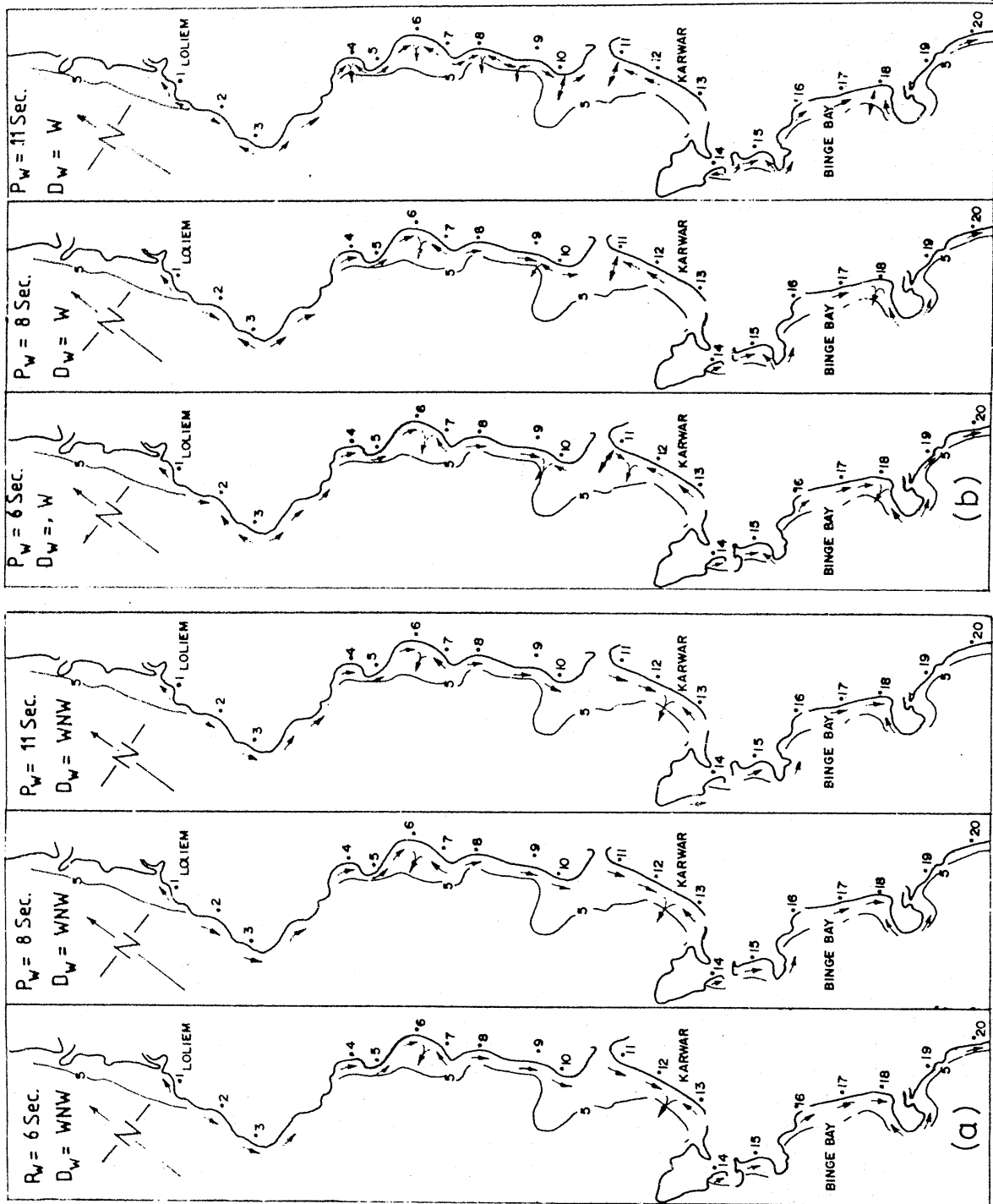


Fig. 3 a & b - Wave induced littoral current pattern inferred from wave refraction study for 6, 8 and 11 sec period waves approaching from (a) WNW and (b) W [- Wave induced flow direction]

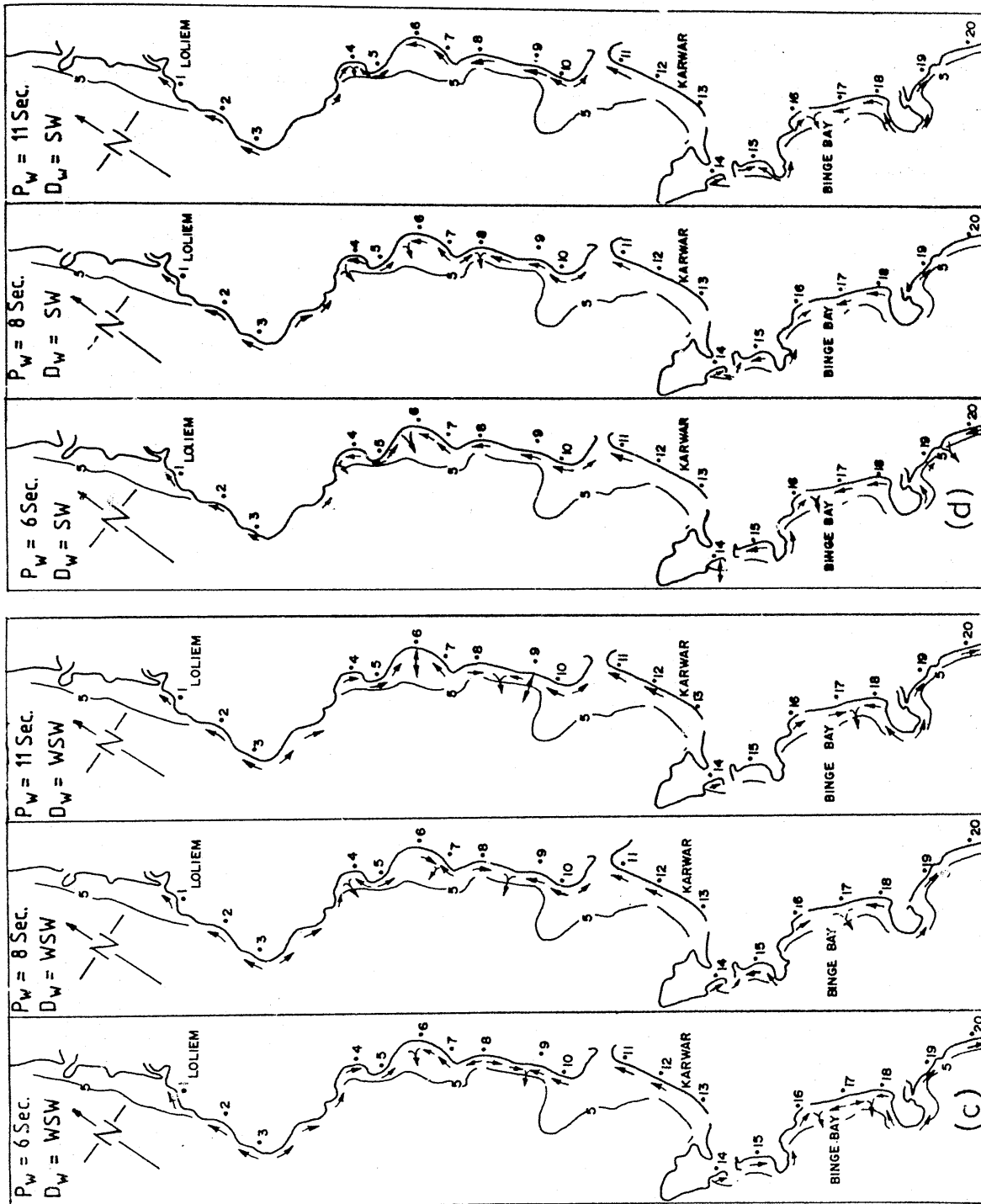


Fig. 3 c & d - Wave induced littoral current pattern inferred from wave refraction study for 6,8 and 11 sec period waves approaching from (c) WSW and (d) SW [- Wave induced flow direction; - - - Wave induced flow direction.]

12 for WNW waves persists for lower period waves from W but its location shifts towards the north between sts 12-11. For higher period waves the refracted wave rays almost reach perpendicular to the shoreline (Fig. 2b, st 11), generating onshore-offshore currents at Kodibag (Fig. 3b, st 11). A zone of opposing longshore currents leading to seaward return flow has been identified at Sadashivgad for 6 sec period waves which again shows a shift towards the north for higher period waves (8 sec). Waves of 11 sec generate 2 circulation cells characterised by opposing alongshore and seaward return flowing rip currents along this open ocean beach (Fig. 3b). South of Karwar Head, the flow pattern is characterised by southerly currents on the down coast side of headland/or upcoast sector of the headland-bay beaches, which in turn, are opposed by the northerly flows on the upcoast side of the headlands, giving rise to seaward return flows mainly at the southern parts of the headland-bay beaches, similar to that identified for WNW waves. A prominent converging current pattern has also been identified at Polem beach.

The northerly current identified along the open ocean beach at Karwar for W waves prevails for WSW waves but is confined to the northern half i.e. between sts 12-11 uptill Kodibag only (Fig. 3c). Further north, the longshore currents along the open ocean beach at Sadashivgad-Ramnath are characterised by either converging/or on-offshore flows. The wave induced currents at the Kali river entrance are found to be directed towards its mouth, because of the fanning away of refracted wave rays (Fig. 2c), leading to sediment deposition (?) at the entrance; but the net deposition/erosion being dependent on flood/ebb flow predominance at the river entrance. The flow pattern along Binge Bay beach is characterised by opposing alongshore flows from either end of the beach towards its centre leading to seaward return flows. This circulation pattern is quite conspicuous along the southern shore of the bay between sts 17-18. Similar flow pattern has been identified at the crescent beach at Majali.

The wave induced currents for SW waves are predominantly northerly along the open ocean beaches at Karwar, Ramnath-Sadashivgad and along greater

parts of the Binge and Arge bay shores (Fig. 3d). However, the headland-bay beaches at Baitkol, Binge and the crescent beach at Majali show opposing longshore currents giving rise to seaward return flow.

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