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A Review and Re-assessment of Sediment Transport along The Goa Coast, India

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ABSTRACT

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Although, a variety of methods have been employed to determine sediment transport along Goa coast, the results differ in some sections. Fifteen studies have been reviewed, compared, re-assessed and a corrected shore drift map of the Goa coast is prepared and presented. Advantages and limitations of these methods are discussed. The present review and re-assessment confirms that, though sediment transport is bi-directional, the long-term net shore drift direction along Calangute and Colva beaches is southward. The overall net shore drift direction along Goa coast is also towards south. It is qualitatively determined that except for 3 short drift cells, shore zone has long-term stability. Finally, it is concluded that landform indicator study using remote sensing can be an effective method for determining long-term net shore drift along the coast.

ADDITIONAL INDEX WORDS: *Sediment transport, Geomorphic indicators, Remote Sensing, West coast, alongshore drift, India.*

INTRODUCTION

Goa, though one of the smallest states of India, is an important destination for National and International tourists. As a result, complexes supporting tourism occupy most of the coastline of 105 km. Homes, large hotels, and resort complexes are still being erected along the coast. In addition, the shore zone is vulnerable to changes due to the global sea-level rise, intense monsoon storms and human interference. Geomorphologists, engineers, and oceanographers have been trying, each with their own methods, to understand the dynamics and factors influencing shore zone changes. However, only partial success has been achieved.

Sediment transport (shore drift) plays an important role in determining the areas of coastal erosion and sediment accumulation. A coastal sediment budget study provides mechanism for correlating changes in landforms and supply of materials by different processes in space and time. Hence, understanding the net shore drift and sediment balance along the shoreline is a pre-requisite for projects focused on coastal protection, design and development of ports, pollution control, land reclamation, *etc.*

Along the Goa coast, a variety of methods have been used to determine sediment transport in general and littoral drift in particular. The results have differed along some sections of the coast. Hence, to improve understanding of littoral transport patterns and mechanism, these studies are examined by reviewing relevant literature. Considering the advantages and limitations of different methods, the results are compared and reassessed to obtain corrected description of littoral drift along the Goa coast.

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Study Area

The coast of Goa (Figure 1) extends approximately from Terekhol (15°43′30″N and 73°42′10″E) in the north to Kali river (14°55′N and 73°03′10″E) in the South and it forms part of the central West Coast of India. The Goa State is bordered by the Western escarpment on the east and by the Arabian Sea on the west. The shoreline is crenulated and segmented, with alternating headlands, estuaries, beaches, cliffs, bays, creeks, and spits. The region lies in the tropics, and has a warm, equable, humid climate. Monsoons are seasonal reversals of wind. On the western coast the monsoon cycle is composed of warm, wet storms from the southwest and west during SW monsoon season and dry, cool, mild winds from north during NE monsoon season. The SW monsoon has the most profound effect on the coastal environment by supplying 90% of the annual rainfall (about 300 cm/year), and generating the largest wind and strongest waves of the year. The mean wind speed varies from 5 to 10 knots with the maximum during the southwest monsoon period. The region experiences mixed semidiurnal tides with a 2.3 m range (VEERAYYA *et al.,* 1981a).

State-of-the-Art

Since 1972, scientists have investigated Goa Coast to understand sediment transportation and distribution in, alongshore, cross-shore and near shore regions. These studies are examined and a brief review is presented below.

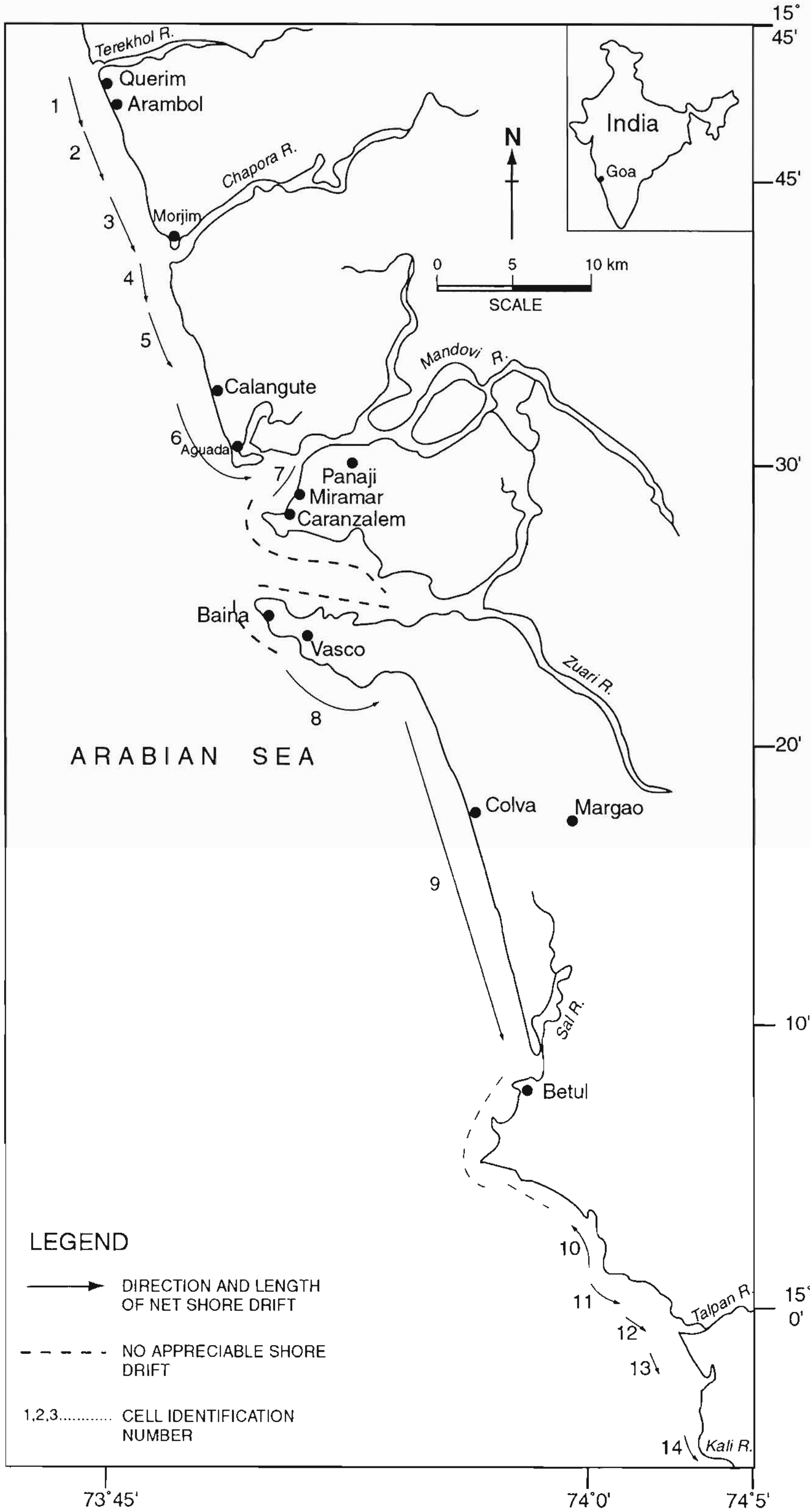

Figure 1. Map showing re-assessed extents and direction of drift cells.

VEERAYYA (1972,78) investigated sediments of Calangute beach by collecting samples monthly, from September 1969 to August 1970, along 5 sections. He studied textural characteristics like mean grain size, sorting, and skewness along with beach topographic changes and inferred transport and distribution directions of sediments along and across the beach. He also determined alongshore current velocities by observing float movements. The measurement varied from a few centimeters/sec to about 80 cm/sec and during NW monsoon season floats moved towards north. During the rest of the year, floats travel partly towards north and also in offshore-onshore directions and at times towards south. Based on grain size variation and float movement, he predicted net littoral transport towards north.

By studying the effect of dumping dredged material from Mormugao Harbor on the Baina beach, based on the changes in beach topographic features, variations in particle size distribution of beach sediments *etc.*, VEERAYYA *et al.* (1973), found that there is very slow littoral movement along the beach. He concluded that material dumped is not influencing the Baina beach. From grain size analysis of thirty-three surface sediment samples, collected from Mormugao Bay, RAO and RAO (1974) detected a patch of coarse material extending from the NW end of the bay in a NW-SE direction into the bay. It indicates that the incoming and outgoing currents follow this path and prevents finer sediments from accumulating and consequently silting up the bay.

Based on grain size statistics, environmental conditions of beach deposits and dune sediments from Calangute beach, VEERAYYA & VARADACHARI (1975) explained sediment transport across the beach. The study reveals the usefulness of grain size parameter not only in differentiating the beach and the dune sediment but also in delineating the beach into foreshore and backshore. The difference in grain size of the sediments in the environmental reflects the transport, erosion and depositional mechanism prevailing in the area of study. ANTONY (1976), from the wave refraction diagram for predominant waves approaching the shore from directions varying between SW and WNW and periods varying from 6 to 12 sec., worked out wave energy distribution, direction of alongshore currents and volume of littoral transport at 4 m depth contour along Calangute beach. He demarcated probable areas of rip currents and estimated that about 9 million m^3 of littoral drift takes place along this beach annually. The net annual drift of 1.9 million m^3 was directed northwards.

VEERAYYA *et al.* (1981a) carried out wave refraction studies for the waves of different periods approaching the Colva beach. Authors observed that littoral flow is towards the north for deep-water waves approaching from SW and towards the south for waves approaching from WNW. They concluded that waves approaching from W and WSW generate inshore-offshore flows and converging and diverging alongshore flows, giving rise to circulation cells in the near shore regions. The studies showed that the sediments of Colva beach mostly get re-circulated between the two promontories, under the influence of the prevailing currents and the associated circulation pattern in the surf zone.

Morphological variations of Calangute and Colva beaches have been found to be cyclic over a period of one year (VEERAYYA *et al.*, 1981b). These beaches accumulate maximum sediment storage during April/May. They are then subjected to rapid rate of erosion with onset of SW monsoon winds and wave conditions, followed by slower rates during the subsequent period of the monsoon. Erosion continues until August, when the beaches have minimum sediment storage. The wave climate during post-monsoon and winter months helps the beaches in recovering gradually after passing through a secondary phase of erosion associated closely with the onset of northeast monsoon during November/December.

The field observations made by MURTY & VEERAYYA (1985), on the alongshore currents at Calangute and Colva beaches over a span of five years revealed high variability in their direction and speed. Wave refraction diagrams for these regions indicated the close cellular patterns of flows for waves of near normal incidence. The sediments of this zone are brought into suspension through turbulence generated by wave breaking processes and get re-circulated in the area. These currents and associated circulation of water help in maintaining the shoals in the vicinity of river mouths. SHENOI *et al.* (1987) quantitatively compared changes in the profile configuration of the beaches at Calangute and Colva by means of Empirical Orthogonal Function (EOF) analysis. The analysis suggests that, for the period of study, the beaches are stable as revealed by the temporal dependence of the first Eigen function. The second function reveals the significant erosional/accretional phases with a well-defined cyclicity of one year associated with monsoon wind and wave climate. Unprotected beaches showed higher magnitudes of variability.

REDDY & SASTRY (1988) computed aeolian sand transport for Miramar-Caranzalem beach (Figure 1) utilizing the relation among the rate of sediment transport, the sediment and the wind characteristics. They analyzed winds recorded at Panaji for the period 1969–1973 and discussed the directional transport of sand from the beach face. During fair weather months, the diurnal, inland, aeolian transport has been found to be nearly 180 m^3 per km. length of the beach subjected to 10 m/sec. winds lasting for periods of approximately 8 hr. a day. The resulting transport and its effects on the stability of this beach were discussed.

The large embayment at the entrance of the Mandovi Estuary, Aguada Bay has resulted in very complex flow patterns of the tidal flow. According to PURANDARE (1989), the main mechanism causing siltation in the channel is littoral drift. He suggested that a jetty on the southern side would reduce siltation due to littoral drift and river borne sand to great extent. CHANDRAMOHAN & NAYAK (1989, 92), developed an empirical sediment transport model based on alongshore energy flux equation and studied entire shoreline of India. In that, they also mentioned alongshore sediment transport rate along Goa coast as 0.530×10^6 m^3/yr towards north, and 0.820×10^6 m^3/yr towards south.

Above studies carried out during 1972–1990 along Goa coast, covered single or two beaches or localities. Geomorphologic and wave refraction approaches were mostly used for studying sediment transport along and/or across the beach or bay; probably keeping limited objectives in mind. Though, these studies cover short stretch of the state's coast, studies provided useful information on sediment distribution, grain size variation, locations of rip currents, direction of local currents and littoral drift. However, no integrated attempt was made to synthesize all data for Goa state. From 1990 onwards, five studies covering Goa State as one unit, were published. The concept, methods, and results of each method are briefed below.

Sediment Transport Study

Littoral drift represents sediment transport parallel to the coast as a result of the alongshore current generated by oblique breaking of waves. The alongshore drift, thus, depends on the wave climate (wave height, period direction), bathymetry of the seabed, and sediment properties (size and density). As wave condition vary frequently, the estimation of magnitude and direction of seasonal or annual drift require observations on the frequency of occurrence of waves in area.

Study 1: Empirical Orthogonal Function Analysis Study

In 1991, ANAND *et al.* presented the results of the field observations and theoretical studies on the coastal processes along the entire Goa coast. Monthly beach profiles, monthly alongshore current, daily littoral environmental observation, monthly beach sediment size distribution etc. were measured in the field. Field observations were carried out from May 1989 to April 1990 along 5 base stations located at Harambol, Calangute, Miramar, Colva, and Majali (Figure 1). They determined monthly beach levels, breaking wave characteristics, alongshore currents, grain size distribution, and calculated alongshore sediment transport. Authors reported that variation in beach level is attributed to seasonal pattern viz. fair weather monsoon; southwest monsoon and northeast monsoon and beaches are in equilibrium as beaches recover their original profiles during the year. They determined sediment transport rate along Calangute and Colva beach. ANAND *et al.*, (1991) have estimated that at Calangute, the sediment transport was towards north in September, October, November and December. The rate was relatively high about 0.39×10^5 m^3/month in July and August and it was less than 0.04×10^5 m^3/month during rest of the months. At Colva beach the sediment transport has been towards north throughout the year. The transport rate was high about 0.43×10^5 m^3/month in August and it was less than 0.07×10^5 m^3/month in January to April, July and September. The net annual transport was 0.89×10^5 m^3/year towards south at Calangute beach and 1.59×10^5 m^3/year towards north at Colva beach.

Study 2: Wave Refraction Diagram Study

Using bathymetry and wave parameters from wave atlas DHOLAKIA *et al.*, (1995), constructed wave refraction diagrams graphically by wave front method. The wave refraction pattern constructed for waves of 5 sec and 14 sec periods approaching from WNW, W, WSW and SW directions do not show predominant convergence or divergence along the Goa Coast. The spits extending to the north (at Querim) as well as south of Morjim and Betul beaches indicate the prevalence of alongshore sediment transport in both the directions. According to him, because there were no net erosion or deposition of sediments, the beaches are almost stable.

Study 3: Landform Indicator Study from Remotely Sensed Data

KUNTE and WAGLE (1993) used remote sensing techniques to determine sediment transport and sediment budget based on concept of drift cells and drift directions. Net shore-drift patterns define the direction in which the majority of sediments move over many years, regardless of seasonal variations. Long-term sediment transport (net shore-drift) direction may change from one coastal sector to the next due to variation in coastal orientation and wave climate. Each coastal segment with a particular net shore-drift direction forms a discrete unit called a drift cell. A drift cell consists of three regimes 1) an area of erosion, 2) an area of transport and 3) an area of deposition.

Because net shore-drift direction is a resultant of all shore drift directions, it is necessary to understand the behavior of shore drift within each drift cell. Since the shore drift varies with respect to direction, time, place, duration and amount, and coastal landforms respond to all the variables of shore drift during their course of formation, hence these landforms are considered to be the most reliable and long-term shore-drift indicators. Shape, size, form, pattern, development, location, orientation of landforms and their association with other landform are important to study while determining shore drift.

KUNTE (1994b) analyzed Landsat images, aerial photographs, and topographic maps of the Goa coast to examine direction, amount and behavior of long-shore drift and its contribution towards deciding areas vulnerable to coastal erosion and accretion along the coast. Out of drift-direction indicator reported in literature, he mapped and used indicators like spit growth, active recession of cliffs, relative beach width, beach location & orientation, orientation of tombolos, progradational beach ridges *etc.* He determined 14 sediment-transport sectors using these landform indicators (Figure 2). Of these, 10 cells show sediment transport to the south and 4 cells to the north. From his landform indicators study, he suggested that during the southwest monsoon period, strong southerly currents are eroding protruded sectors and are depositing eroded material, along varying sectors, whereas, during the rest of the year, under the influence of a northerly current, accretion is taking place along retreating sectors. He inferred that although sediment-transport is bi-directional, net major sediment transport is southward. His geomorphic study identified possible sediment sources and sinks. He assessed contributions of sources and losses due to sinks qualitatively as significant, moderate, marginal or unknown and concluded that overall sediment balance is positive.

Study 4: Sediment Plume Study Using Satellite Images

KUNTE and WAGLE (1994a) studied dynamics of sediment plumes from satellite images and determined sediment trans-

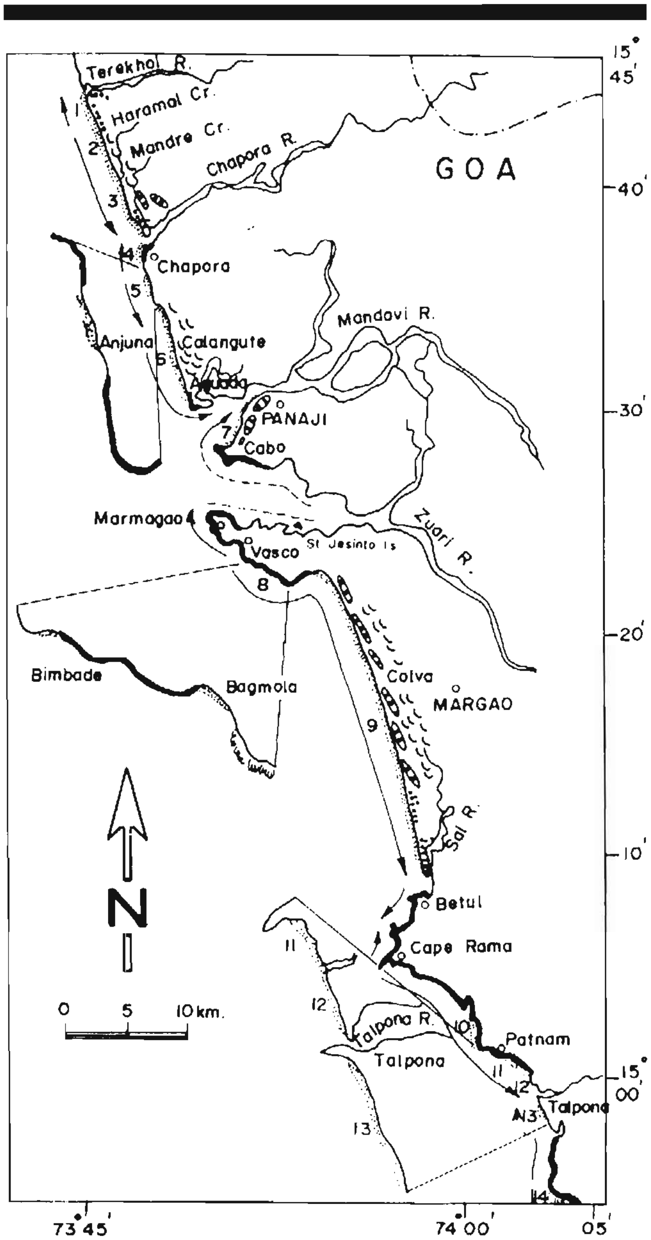

Figure 2. Map showing extents and direction of drift cells and geomorphic landforms in the study area (After Kunte, 1994).

port. Multi-spectral Sensor (MSS) data pertaining to the scene of Landsat 5 (Path 49, Row 142, dated 17th March, 1985) were used. Principal-component transformation was performed by digital processing of spectral bands, from which new principal-component images were generated. The second principal-component image (PC2) was used for studying near shore turbidity pattern. Tonal variation has been used as a measure of turbidity. Texture and pattern helped in monitoring the distribution and movement.

On the satellite image, the sediment transport direction is inferred towards south as sediment-laden plumes are elongated and pointed southwards. They noted movement of plumes towards south all along the coast during March and towards north during October. The plumes are seen dispersed if obstructed by headlands or at river mouth. The results of the two approaches were found comparable. And so, they concluded that shore-drift direction, which can be determined effectively by remote sensing, is season-dependent and plays a significant role in deciding the areas of coastal erosion and accretion. WAGLE (1985) has also determined southward net shore drift while studying sediment plumes along West Coast of India.

Study 5: Site-Specific Sedimentological Field Study

Subsequently in 1997, ORZECH carried out detailed field study to locate distinct geomorphic and sedimentologic field evidences to define drift cell boundaries and to determine net shore-drift on the Goa coast. His study relies on the same concept as was adopted in landform indicator studies (KUNTE, 1994b) only difference is that he studied various landform indicators that reveal long-term net shore directions by field study. Indicators used were spit growth direction, stream mouth diversion, and presence of identifiable sediment, obstacles that interrupt drift, beach width changes, bluff morphology, and seawall stability and sediment size gradation. He determined 32 drift cells, out of which, 24 cells reveal distinct geomorphic evidence of south net shore drift. 8 cells indicated northward shore drift (Figure 3). The north drift cells comprise only 16 km of the total 68 km of drift cells. He concluded that an overall net shore drift direction towards south, predominates on the Goa coast.

RE-ASSESSMENT

The review of last five studies conducted from 1991 onwards along Goa Coast indicates that in each of these studies, different approaches have been used to explain littoral drift. However, these studies have provided differing results for certain coastal stretches. To re-assess correctly, the results of these studies are compared with each other and with other studies carried out earlier.

The third (KUNTE & WAGLE, 1993) and fifth (ORZECH, 1997) studies are based on similar concept and methodology except that 3rd is conducted using remote sensing techniques and 5th is conducted by actual field study. In both studies, drift cells, drift direction within each drift cell, and net shore drift is determined. The results of the two studies are compared in detail and displayed in Table 1. It may be noted that in 3rd study, due to lower resolution of satellite data, the drift cells delineated are lesser in number and are of larger extent. Whereas in 5th study, due to closer look at the field, more number of sub-drift cells are identified within some larger drift cells of 3rd study. Extent of drift cell boundaries in 3rd study is fairly analogous with collective extent of sub-drift cells of 5th study. Similarly, drift directions within drift cells of these two studies are matching except along few drift cells like 4th, 7th and 10th, of 3rd study, but these drift cells are shorter in extent.

From both the studies along such sectors, landform indicators and site-specific geomorphologic indicators have been again closely examined. Drift cells and a drift direction with-

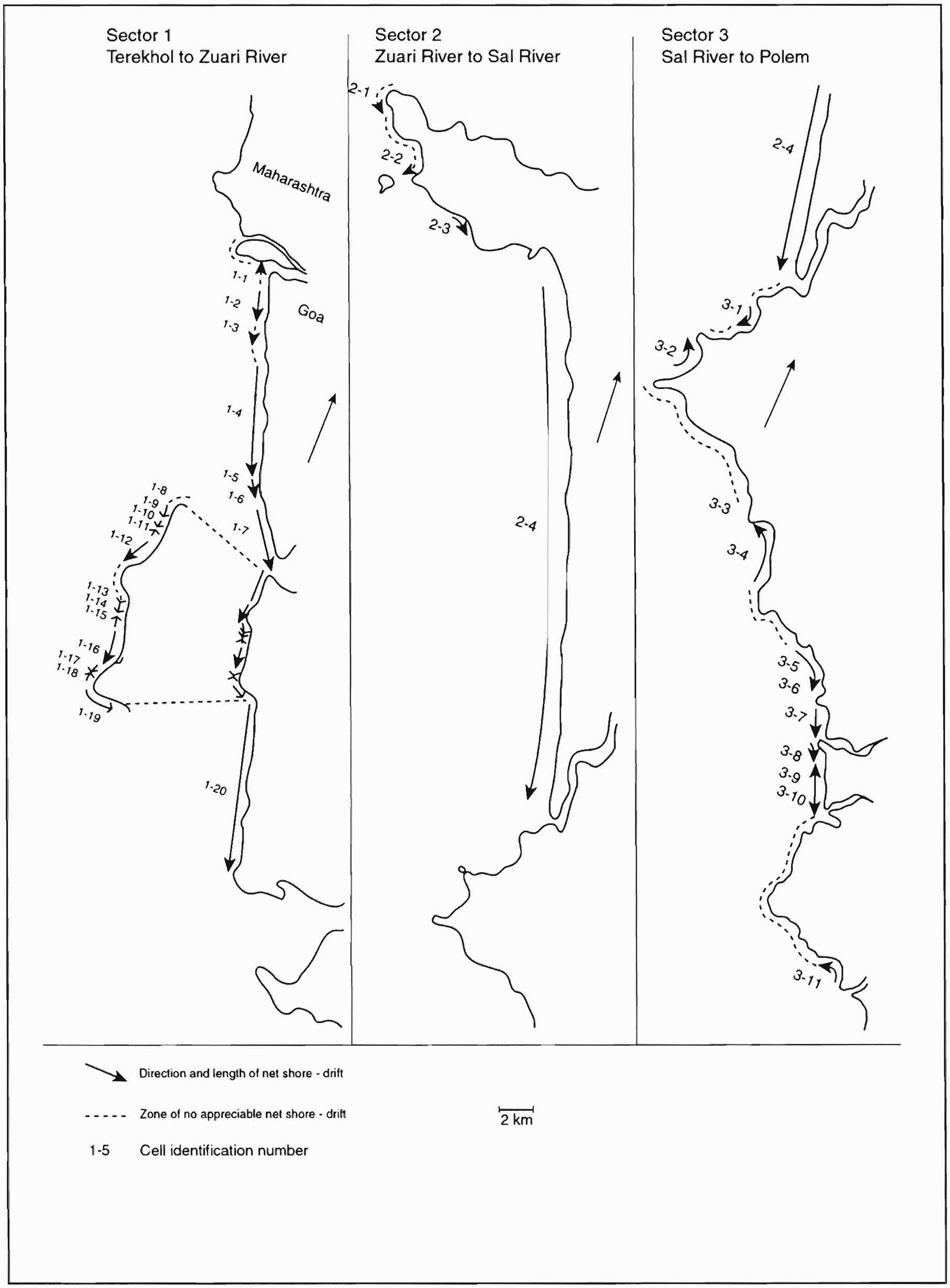

Figure 3. Map showing extents and direction of drift cells determined by field study. (Modified after Orzech, 1997).

Table 1. *Showing corrected Drift cells and Drift directions after re-assessment.*

Result of 3rd Study by Kunte (1994)		Result of 5th Study By Orzech (1997)				Corrected Drifts Cells After Re-Assessment				
						Remote Sensing		Field Study		
Drift Cell No.	Drift Direction (towards)	Drift Cell No.	Drift Direction (towards)	Drift Length (km)	Name of the Locality	Drift Cells	Drift Direction	Drift Cells	Drift Direction	Indicators Used for Re-Assessment
1	N	1-1	N	0.7	N. Keri	1	N	1	N	Growing spit, northward diversion of river
2	S	1-2	S	0.7	S. Keri	2	S	2	S	Stream diversion, widening of beach
		1-3	S	0.3	Pocket beach			3	S	Widening of beach, erosion of bluff, beach steepness
		1-4	S	7.5	Arambol			4	S	Spits pointing south, river diversion, sediment size
3	S	1-5	S	0.7	Pocket beach	3	S	5	S	Eroding bluff to the north, eroding south face
		1-6	Nansd	1.0	Madrem			6	Nansd	Cliffy coast—paucity of sediments
		1-7	S	2.5	Morjim			7	S	Southward widening of beach, diversion of river
4	N	1-8	Nansd	0.2	Pocket beach	4	S	8	Nansd	Cliffy coast—paucity of sediments
		1-9	S	0.5	N. Vagator			9	S	Widening of beach, sediment accumulation, eroding bluff
		1-10	S	0.1	S. Vagator			10	S	Eroding bluff, Widening of beach, Decreasing grain size
		1-11	N	0.1	S. Vagator			11	N	Fining of sediments north wards
		1-12	S	1.0	S. Vagator			12	S	Decreasing grain size, Eroding bluff, Widening of beach
5	S	1-13	S	0.1	N. of Anjuna	5	S	13	S	Bluff decrease to south, fining of grains southwards, beach width
		1-14	S	0.3	N. of Anjuna			14	S	Sediments from graval to sand southwards
		1-15	N	0.1	N. of Anjuna			15	N	Fetch to SW, decreasing grain size
		1-16	S	2.0	Anjuna			16	S	Beach widening, sediment accumulation
		1-17	S	0.1	Tombolla beach			17	S	Fining grains, beach width, increasing spits
		1-18	N	0.1	Tombolla beach			18	N	Tombolla formation, spit growth direction
		1-19	S	0.1	Pocket beach			19	S	Accumulation of sediments on north
6	S	1-20	S	7.5	Calungut	6	S	20	S	Eroding north bluff, river divergence, widening of beach
7	N	—	—	—	—	7	S	21	—	Decrease in Grain size & Tidal influence
8	S	2-1	S	0.1	Pocket beach	8	S	22	S	Protected from North, 2, 11
		2-2	S	1.0	Vasco de Gama			23	S	Protected from N, sediment accumulation, Eroding bluff
		2-3	S	0.5	Bogmalo			24	S	Eroding bluff, widening of beach, protected form north
9	S	2-4	S	27.0	Colva	9	S	25	S	River divergence, widening of beach, growing spit toward south
—	—	3-1	S	0.2	Canaguinium	—	—	26	S	Sediment accumulation, diversion of stream, decreasing grain size
		3-2	N	3.2	Cabo de Rama			27	N	Widening of beach, diversion of stream, protected from north.
10	S	3-3	?	0.2	Saleri	10	N	28	Nansd	Cliffy coast—paucity of sediments
		3-4	N	3.0	Agonda			29	N	Spit growth, diversion of stream, protected from north
11	S	3-5	S	3.0	Palolem	11	S	30	S	Beach widening to south, erosion of north bluff
		3-6	S	1.0	Patnem			31	S	Widening of beach to the south
		3-7	S	2.5	Sandy beach			32	S	Southward diversion of river, spit points south, beach narrow south
12	S	3-8	S	1.5	Talpoona	12	S	33	S	Narrowing beach towards south, north eroding bluff
		3-9	N	1.0	Galgaibag			34	N	Widening of beach to the north
		3-10	S	1.0	Galgaibag			35	S	Southward river diversion, southward progradation of spit
13	S	—	—	—	—	13	S	36	—	Not accessible
14	S	3-11	N	0.7	Polem	14	S	37	—	Not accessible
		= 35		= 71.5						

in each drift cell have been re-assessed and presented in the Table 1. Re-assessed extent and direction of drift cells and geomorphic landforms mapped by remote sensing are shown in Figure 1. Indicators, based on which drifts size or direction has been decided, are mentioned in last column of the Table 1. Of 37 re-assessed drift cells, 27 cells reveal distinct geomorphic evidence of southward shore drifts, 7 cells indicate northward shore drift and 3 drift cells have showed no appreciable shore drift. The north drift cells comprise only 9 km of the total 70 km of re-assessed drift cells. Re-assessed results also show that the shore drift is bi-directional and an overall south net shore-drift direction predominates on the Goa coast.

From the satellite images and aerial photos (4^{th} study), the sediment transport direction is inferred southwards as sediment-laden plumes are elongated and pointed towards south all along shore and near shore region. This approach adopted by KUNTE and WAGLE (1994a,b) supports above result and confirms the southward shore drift.

According to 2[nd] study (DHOLAKIA *et al.,* 1995), the wave induced alongshore currents for WNW and W directions flow northerly for both the periods whereas those for WSW direction flow southerly as well as northerly and for SW flow southerly. Only conclusion that shore drift is bi-directional along Goa coast matches well with other studies. Their alongshore drift direction determination is based on wind speed and wind direction and has not considered sediment properties, lithology, shoreline characteristics, field investigation, etc. Thus the other conclusions seems to be less reliable as they are based on inadequate data and limited observations.

VEERAYYA, *et al.* (1981a) determined that waves from the SW winds drove drift north and WNW winds drove drift south. W and WSW winds created onshore and offshore flows and generate circulation cells and rip currents and thus direct shore-drift towards north and south in as many as 6 temporary drift cells. Whereas, ANAND *et al.* (1991), has estimated that at Colva beach, the sediment transport has been towards north through out the year. The transport rate was high about 0.43×10^5 m^3/month in August and it was less than 0.07×10^5 m^3/month in January to April, July and September. The annual transport was 1.59×10^5 m^3/year towards north at Colva beach. However, along Colva beach, KUNTE (1994) and ORZECH (1997) have determined shore drift and net shore drift direction towards south, based on landform indicators and sedimentological evidences respectively, which is contradictory.

Twenty-seven km. long & straight Colva beach is situated between two promontories and hence winds striking almost orthogonal have been generating circulation cells and rip currents under low energy conditions. Based on distinct, physical and long term landform indicators, like the 3 km long spit situated at the south beach terminus, the southward diversion of the Sal river around spit, the fining of grains to the south, a narrow beach at the far north and an eroding under cut north headland, the long term sediment transport direction has been re-assessed as towards south.

ANAND *et al.* (1991) has estimated that at Calangute, the sediment transport was towards north in September, October, November and December. The rate was relatively high about 0.39×10^5 m^3/month in July and August and it was less that 0.04×10^5 m^3/month during rest of the months. ANTONY (1976), along Calangute beach, demarcated probable areas of rip currents and estimated that about 9 million m^3 of littoral drift takes place along this beach annually. The net annual drift of 1.9 million m^3 was directed towards north. Float measurement (VEERAYYA, 1972) along Calangute beach varied from a few centimeters to about 80 cm/sec and predicted littoral transport towards north.

The above studies are based on estimation of alongshore component of wave energy flux and used empirical relationship between the alongshore energy flux and littoral drift. Conversions and diversions of wave refraction rays determine drift cells, directions and locations of rip currents, erosion, and sedimentation. The approach (ANAND *et al.,* 1991, VERRAYYA *et al.,* 1981) addresses wind, wave and beach dynamics together, unlike the other shore drift methods. Direct correlation between wind, wave and shore drift directions is revealed. However, the data are collected for short duration and seasonal and hence no long-term drift evidence can be determined. Long-term (for more than 100 years) data on wave energy, wave period, and wave height for specific beaches are not available. Therefore, in a bi-directional drift regime such as Calangute, long-term drift changes cannot be determined with this method.

Total reliance on short-term engineering methods such as artificial tracers, sediment traps, floats (VEERAYYA, 1972), and the calculations of wave heights based on wind data, is fraught with hazards. None of these methods takes into account all the variables of drift, especially the possibility that the predominant movement of sediment may be caused by extreme events, which are rare. These methods, when used, may determine only seasonal drift, not net shore drift (SCHWARTZ *et al.,* 1985). The more complicated the shoreline, such as Goa, the less likely that these methods will accurately predict net shore drift direction.

In case of two studies (ANTONY, 1976 and VEERAYYA, 1972), estimation of the high net shore drift towards north along Calangute beach requires explanation, because, if this continues, the beach should run short of material and would get eroded completely in due course of time. But the fact is the Calangute beach is more or less in a stable equilibrium. For this, ANTONY (1976) suggested that the material transported along the beach towards north, returns to the beach through the cellular structures of circulation pattern. Whereas, along Calangute beach, 3[rd], 4[th], and 5[th] studies have determined long-term shore drift direction towards southward. The shore drift is evidenced by an eroding north bluff, southward stream mouth divergence, sediment accumulation on the north side of beach structures and widening of the beach to the far south, steep and narrow beach to the south. These physical indicators are studied by remote sensing and are confirmed in the field. And hence, shore drift along Calangute beach is to the south.

In above studies, the amount and direction of sediment transported along the shoreline in either direction is estimated and re-assessed. However, bulk cross-shore sediment transport, as is visible along the Goa coast, is not given enough consideration in estimation. Sand dunes backing the beaches (Figure 1) reveal shoreward transport of surplus beach sediments (KUNTE, 1994b). These sediments are transported across beaches (REDDY & SASTRY, 1988) and deposited as dunes. Similarly, large volume of sand in front of conifer trees along Calangute and Colva beaches suggest that the onshore transport of sediments is large (ORZECH, 1997). Morphological variations along beaches have been found to be cyclic over a period of one-year (VEERAYYA *et al.,* 1981, SHENOI *et al.,* 1987) and attend beach stability. This cross-shore sediment transport plays important role in estimation of sediment transport.

With remote sensing study, considering geomorphologic features, geology of the area, lineament pattern, shore drift dynamics *etc.* corrected drift cells (Figure 1 and Table 1, 3[rd] column) were qualitatively examined for their long-term shore zone stability and are designated as significant, moderate and marginal. It is estimated qualitatively that drift cells 1,3,8 are marginally stable; drift cells 2,4,5,7,12,13,14 are moderately stable, whereas, 6,9,10,11 are significantly stable.

DISCUSSION AND CONCLUSION

Along the West Coast, the monsoon cycle is composed of warm, wet storm from the southwest and west during the summer season and dry, cool, mild winds from the north (northeast monsoon) during winter season. Thus, the seasonally reversing wind pattern influences southward drift during southwest monsoon while northward drift occurs during NE monsoon. Therefore, the sediment transport direction within each littoral-drift sector can be either north or south, coincident with the dominant seasonal winds (KUNTE, 1994). The consistency of south directed drift cells suggests that a regional trend of wave and wind pattern is responsible for net shore-drift. Along the coast, the strongest winds arrive from the southwest and west. However, the strong west winds are nearly twice as frequent as the southwest winds. Winds approaching from the northwest commonly exceed 11 knots during summer. Although less frequent than west winds, northwest winds approach the shore at a more efficient angle for littoral transport—near 45°. Thus, ORZECH (1997) confirmed that the summer winds from the west and northwest are the dominant mechanism driving net shore-drift south along Goa.

KUNTE (1994b) noted that prograding and retrograding coastal sectors are situated alternately throughout the coastal tract and each occupies sub-equal parts of the coast. It means retreating coastal sectors are supplying sediments to shore drift and these sediments are transported to a short distance and deposited along prograding sectors. Stability and straightness of beaches indicate that adequate amount of sediments are available for the bi-directional alongshore currents. Results of two (3rd and 5th) studies differed marginally due to limitations of these approaches as mentioned below.

Site-specific sedimentological evidences are studied well in the field and allow determining shorter drift cells as well. The evidence for drift is concrete and can be easily monitored and checked. The field approach allows for a wide range of perspectives in determining drift—from sediment to beach-scale features. Sediment samples for indicator like grain size can be collected and studied in laboratory condition while adopting this approach. The field approach adopted in study 5th is laborious and time consuming but valuable as less expensive. However, the approach is limited to accessible regions of a coast. A full view of a larger drift-cell is needed to determine drift which field approach may not provide.

In 3rd study, the remote sensing method allows comprehensive view of coastal features including fluvial, marine, aeolian, vegetation, structural and near shore features over large regions at a glance. Beach width, spit growth, bluff morphology, and stream mouth divergence indicators are viewed using aerial images with often-superior accuracy to the field approach. Aerial images reveal the submerged near shore beach regardless of the tidal flux. Submerged extend of spits are also seen easily on aerial images. Much of the southern Goa shoreline is difficult to access by road, for inaccessible coastlines, the remote sensing method greatly reduces difficulty. However, the low spatial resolution of aerial images disallows sedimentologic indicators to be used as drift evidence.

From present study, it is confirmed that the long-term net shore drift direction along Calangute and Colva beaches is southward and though sediment transport is bi-directional, overall net shore drift direction is also towards south. It is qualitatively determined that except three short drift cells; shore zone has long-term stability. From on-going discussion, it can be said that landform indicator study using remote sensing is most effective method for determining long term net shore drift along coasts.

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