

Sediment transport along the Goa–north Karnataka coast, western India

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Abstract

Landsat images, aerial photographs, and topographic maps of the coast of Goa and of north Karnataka were interpreted to delineate sediment-transport sectors. Thirty six sediment-transport sectors were identified from landform indicators and patterns of sediment transport. Although sediment-transport direction is bi-directional, net major sediment transport is southward. The geomorphic study identified possible sediment sources and sinks. Contributions of sources and losses due to sinks are assessed qualitatively as significant, moderate, marginal or unknown. The sediment balance is positive overall, and is reflected in large spits in the southern part of the study area.

1. Introduction

Littoral (beach) and longshore (nearshore) sediment transport have net vectors parallel to the coast. The overall direction of these transport mechanisms determines the areas of coastal erosion and accumulation, and influences the shapes and orientations of coastal landforms of an evolving coast. A coastal budget permits correlation between changes in landforms and supply of materials by different processes in space and time (Shuisky and Schwartz, 1983). Information on sediment-transport patterns is useful for regional and local coastal planning; management of the coastal zone for fish resources; engineering and growth management for sensitive marine-shoreline areas.

A growing literature (Finkelstein, 1982; Schwartz et al., 1985; Schwartz and Anderson, 1986; Wallace, 1988; Taggart, 1989) outlines the advantages of geomorphic drift indicators, compared to short-term tracer studies or sediment traps

or computed wave orthogonals, in determination of net alongshore direction of sediment transport. Earlier studies (Kunte and Wagle, 1993a,b; Kunte, in press) have demonstrated the capability of satellite remote sensing which provides periodic, integrated, and synoptic views, for determination of net direction of alongshore sediment-transport correctly, economically, and quickly.

The present study attempts to understand sediment-transport patterns on the coasts of Goa and the northern sector of Karnataka (north Karnataka), along the west coast of India (Fig. 1), from remotely sensed landform drift indicators. Possible sediment sources and sinks are identified, and the sediment balance along these coasts is assessed.

2. Materials and methods

Landsat 5 images and Multi-spectral Scanner (MSS) digital data, in four spectral bands, cover-

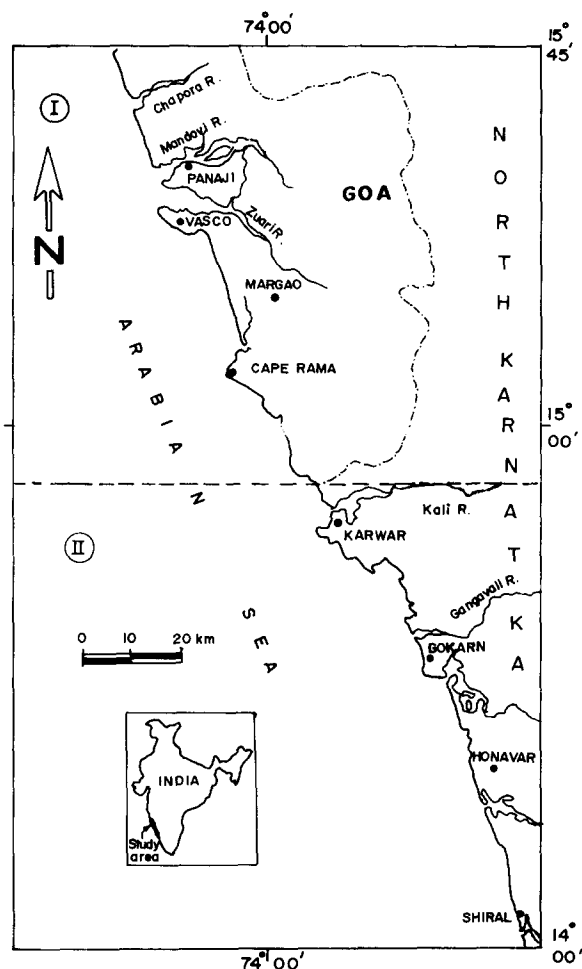


Fig. 1. Map showing location of the study area.

ing the Goa and north Karnataka coasts (Path 50, Row 146, dated 26/10/1986) (Fig. 2) were studied. Though these data provided adequate information on coastal features, little details were available for the nearshore region. Consequently, principal-component transformation was performed by digital processing of spectral bands, from which new principal-component images were generated. The first principal-component image (PC1) enhances coastal features, whereas the second principal-component image (PC2) is most suitable for studying patterns of nearshore turbidity.

From enlarged *Landsat* images, major geomorphic features like rivers, creeks, estuaries (dark

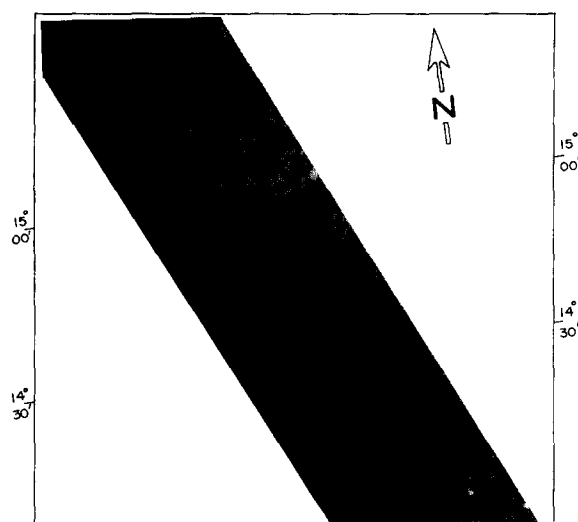


Fig. 2. Section of *Landsat* 5 image covering the Goa and north Karnataka coast.

tone) and islands, spits and beaches (bright tone) and other coastal landforms including shore line (gray tone) were located. Stereopairs of vertical aerial photographs of the Goa coast (1960, 1:15,000 approximate scale and 1973, 1:25,000 approximate scale) were studied to understand location, orientation, and the association of geomorphic landforms with other landforms and to prepare a map (Fig. 3). For convenience of discussion, the study area is divided into two sectors (Fig. 1).

2.1. Physiographic setting of the study area

The area under study is a coastal strip of 275 km long, in the Goa state and the northern sector of Karnataka state. It lies between 14°N and 15°45'N. Overall, the shoreline trends NNW–SSE. From north to south, it shows a series of dextral shifts to the east. The shoreline is crenulated and segmented, with alternating headlands, estuaries, beaches, cliffs, bays, creeks, and spits.

The Goa coast is underlain by rocks of the Goa Group, belonging to the Dharwar Supergroup of Archaean Proterozoic age, mainly metavolcanics, metagraywacke, and metabasalt (Gokul et al., 1981). The northern Karnataka coast is dominated by younger parts of the Precambrian Dharwar

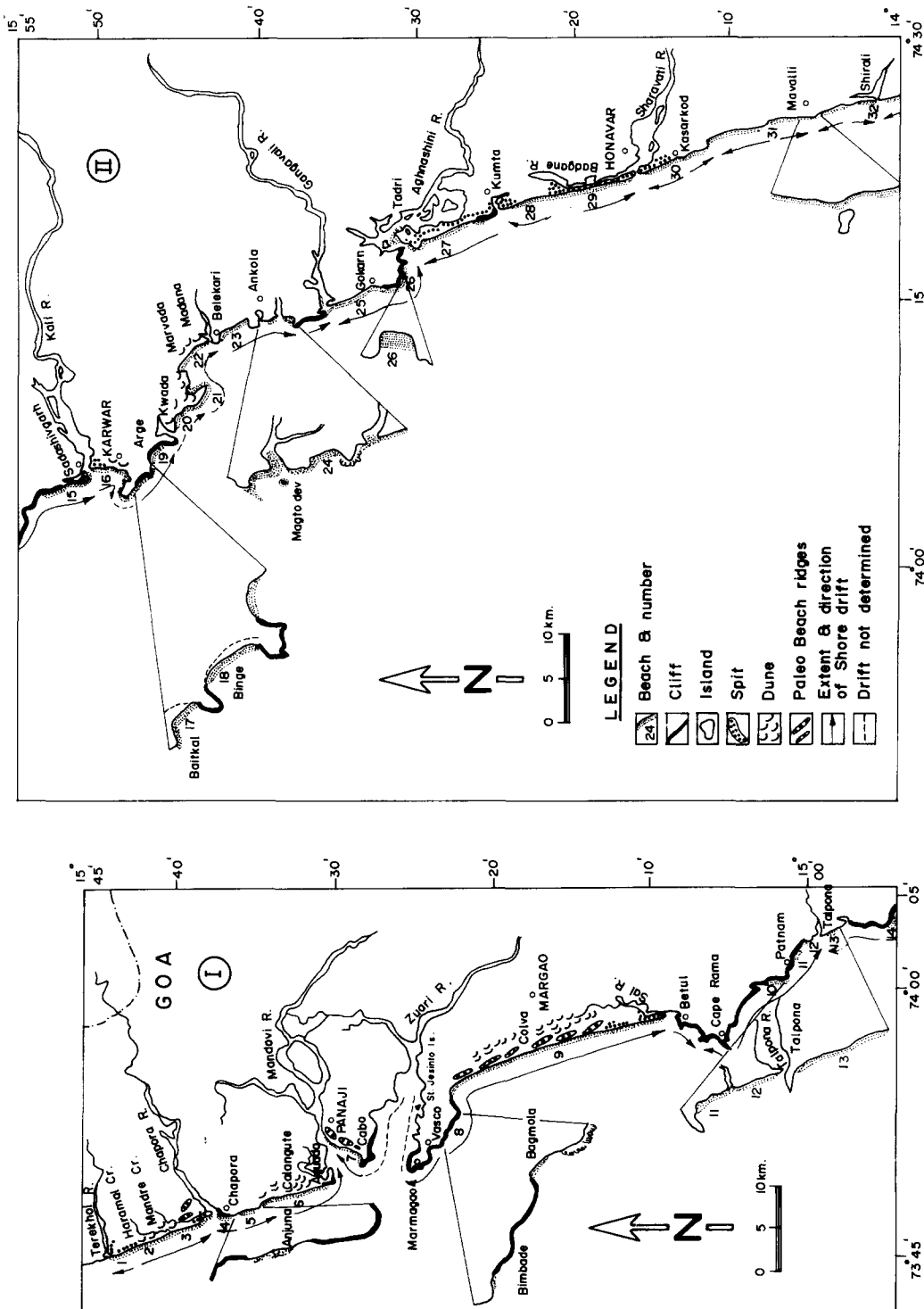


Fig. 3. Map showing extents and directions of drift cells and geomorphic landforms in the study area.

Group, mainly dolerites and granitic gneisses. Alluvium and coastal sands with laterites form a superficial cover concealing these varied basement rocks.

The region lies in the tropics, and has a warm, equable, humid climate. The area receives rainfall of about 350 cm/year, mostly during the southwest monsoon season (June to September). The mean wind speed varies from 5 to 10 knots with the maximum during the southwest monsoon period (Gune, 1979). The region experiences mixed semi-diurnal tides (range, 2.3 m) in the meso-tidal range (Veerayya et al., 1981).

3. Determination of sediment transport direction

The patterns of net alongshore sediment transport can be determined by finding littoral-drift sectors based on the variations in coastal configurations and nearby oceanographic conditions. A littoral-drift sector is a shoreline segment containing three elements: (1) an erosional shoreline or other sediment source; (2) an accretional beach where sand and sediments are deposited; and (3) a neutral transport shoreline or driftway along which sediments move between erosional sources and accretional beaches.

Drift-direction indicators are reported in the literature (Jacobsen and Schwartz, 1981; Taggart and Schwartz, 1988; Kunte and Wagle, 1993a,b). Of these, indicators like stream-mouth diversion, direction of spit growth, active recession of cliffs, relative beach width, beach location and orientation, orientation of tombolos, progradational beach ridges, and patterns of offshore turbidity that can be mapped readily from remote-sensing and field studies, were used. The indicators and their utilization are described below.

3.1. Stream-mouth diversion

If the volume of sediment accumulating on the updrift side of the stream mouth exceeds the stream's capacity to remove it, the stream will become progressively offset in the other direction (Jacobsen and Schwartz, 1981). Accordingly, southward diversion of rivers Chapora, Sal,

Badgane, and the creeks near Mandre and Haramal (Fig. 2) suggests sediment-transport direction toward the south. Other rivers like Sharavati and Aghnashini demonstrate that the alongshore sediment-transport direction is north. Lithologically and structurally diverted rivers like the Terekhol, Mandovi, Zuari, Talpona, Kali, and Gangavali are probably not representative of alongshore sediment-transport direction.

3.2. Direction of spit growth

Along the coast, sixteen spits having lengths exceeding one km were plotted from enlarged satellite images and topographic maps. Detailed descriptions in Table 1 show that most of the spits are simple, narrow, and long, and that some have pointed distal downdrift ends. The distal ends of 10 of 16 spits point south. In different areas of spit formation alongshore drift is toward both north and south.

3.3. Active recession of cliffs

The retreat of wave-cut cliffs typically is more pronounced in areas exposed to the direct attack of powerful waves on the cliff face (Wagle, 1987). The direction of active retreat of a cliff clearly indicates the direction of wave attack and, thereby, the direction of alongshore sediment transport (Kunte and Wagle, 1993b).

Many cliffs are evident on the aerial photographs of the study area. The cliffs that developed on the north or northwest sides of headlands are less steep, and lack appreciable undermining. The waves at most sites have created small notches at the bases of cliffs. In contrast, cliffs facing south and southwest exhibit more pronounced erosion that produced caves, overhangs, and notches. This asymmetry of headland cliffs is pronounced near Chapora (Fig. 4), and Anjuna, Aguada, Marmagao, Cape Rama, South of Talpona and Karwar and Gokarn (Fig. 3). This evidence shows that the cliffy coast of the study area is under constant attack of waves, primarily those from the south.

Table 1
Locations and descriptions of spits

Sample no.	Spit name	Location latitudes (°N)	Total length (km)	Distal end		Description	Pointing	Deflection of river			Spit type
				Length (km)	Width (km)			Name of river	Towards	Distance	
1	Keri	15°42'15"–15°43'10"	1.75	0.50	0.50	Wide, blunt	N	Terekhol	N	0.50	Composite
2	Haramal	15°55'00"–15°41'30"	3.75	1.00	0.30	Narrow, blunt	S	Haramal creek	S	1.50	Simple
3	Mandre	15°39'40"–15°39'00"	1.50	0.75	0.20	Narrow, pointed	S	Mandre creek	S	1.25	Simple
4	Morji	15°37'35"–15°36'40"	2.00	0.50	0.50	Wide, blunt	S	Chapora	S	1.00	Composite
5	Betul	15°11'10"–15°08'30"	5.00	3.00	0.75	Triangular					recurved type
6	Talpona	14°59'40"–14°59'00"	1.25	0.50	0.10	Narrow, pointed	S	Sal	S	3.00	Simple
7	Galgibag	14°57'40"–14°57'25"	0.75	0.50	0.40	Narrow, pointed	S	Talpona	S	0.40	Simple
8	Sadashivgarh	14°52'00"–14°50'30"	3.75	2.50	0.10	Long, curved	S	Galgibag Creek	S	0.50	Simple
9	Karwar	14°49'10"–14°50'25"	2.00	0.50	0.20	Wide, blunt	N	Kali	N	2.50	Simple, curved
10	Belekeri	14°43'10"–14°42'40"	1.00	0.40	0.20	Pointed, narrow	S	Madana	S	0.50	Composite
11	Gangavali	14°35'00"–14°35'45"	1.50	0.75	0.30	Wide, blunt	N	Gangavali	S	0.40	Simple
12	Tadri	14°26'30"–14°31'30"	9.50	7.50	1.00	Broad, squarish	N	Aghnashini	N	0.75	Composite, curved
13	Kumta	14°23'10"–14°25'30"	5.55	3.00	0.50	Broad, squarish	N	Creek	N	7.50	Composite
14	Honavar	14°17'05"–14°23'00"	9.50	7.50	0.50	Wide, blunt	S	Badgane	S	2.00	Simple
15	Kasarkod	14°15'00"–14°16'30"	4.00	2.00	0.40	Pointed, narrow	N	Sharavati	N	6.50	Composite
16	Shirali	14°01'15"–14°03'15"	3.75	1.00	0.30	Pointed, narrow	S	Creek	S	3.00	Composite, curved

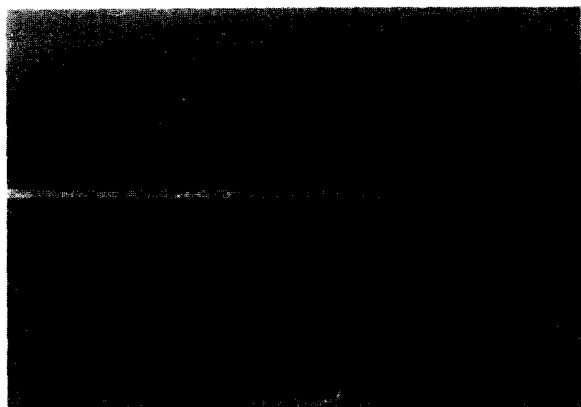


Fig. 4. View of the promontory situated just south of Chapora River. The promontory retreated under the powerful attack of waves from the northwest and southwest side.

3.4. Relative beach width

Thirty two separate beaches with asymmetry were identified on the aerial photographs in the study area. The width, location, and orientation of each beach with respect to other landforms, such as promontories, bays, rivers and estuaries, and to wave approach are very significant predictors of alongshore sediment transport. Generally, beach width increases through a drift cell in the down-drift direction (Taggart and Schwartz, 1988). Thirteen beaches widen toward the south and four protected beaches widen to the southeast, whereas nine beaches widen toward the north and one widens towards the northwest (Table 2). Beaches 6, 12, 13, 30 and 31 have greater widths at both ends, which suggests that the shore drift may be in both directions. Thus, asymmetric beach widths suggest that alongshore sediment transport is bidirectional.

3.5. Beach location and orientation

In the study area, promontories, like Marmagao, Cape Rama, and Karwar, lie almost normal to the shoreline. Beaches 8, 17, 18, 19 and 20 (Table 2) are stretched nearly E–W along the south side of these promontories. This sand accumulation results because northward alongshore sediment transport is partially obstructed by these promontories. Beaches 14, 21 and 24 suggest a local

southward or westward sediment transport direction, opposed to the net direction in that coastal segment, whereas beaches 3, 28 and 32 suggest the other direction.

3.6. Orientation of tombolos

From aerial photos taken at low tide, it is observed that sand accumulates initially in the shadow zone of wave fronts, between an island and the coast, to form cone-shape accumulations where the alongshore drift is obstructed. The cone points in the direction of net alongshore drift. At an advanced stage, this accumulation joins an island with the coast, to form a tombolo. A tombolo is present off Mavalli ($14^{\circ}05'36''N$), where Murdashwar Island has been joined to the coast. Similarly, a tombolo has joined St. Jesinto Island with the coast. Off Ankola ($14^{\circ}39'20''N$), a growing spit (Fig. 2) is likely to join Magtodev Island with the coast.

According to Feio (1956) the present Marmagao headland was also an island now connected with the mainland by a tombolo on which now stands the city of Vasco. Panaji City (Altinho hillock) and Aguada headland have been joined to the mainland by tombolos (Wagle, 1987).

3.7. Progradational beach ridges

Multiple beach ridges form by progradation. Such abandoned beach ridges locally show moderate to major changes in the orientation of successive shorelines. Such changes in trend can be useful in understanding present and past sediment transport directions (Kunte and Wagle, 1993a).

On the aerial photographs the multiple beach ridges appear as light to medium gray speckled areas with medium texture. Such ridges are located behind the modern beaches at Miramar, Caranzalem (near Panaji), Colva, and north of Chapora. Although the spacing between the beach ridges is variable, they are oriented mostly parallel to the present shoreline (Fig. 3). Almost straight beach ridges parallel to the present shoreline indicate that the previous sediment transport was bi-directional (Kunte and Wagle, 1993a,b).

Table 2
Locations and characteristics of beaches of study area

Sample no.	Location (Central)	Locality	Catagory	Local drift	Length	Width	Remark
1	15°43'30"N	Keri	Spit beach	N	2.0 km	more to N	Spit on the north side
2	15°42'00"N	Haramal	Spit beach	S	7.5 km	more to S	Straight open shore
3	15°38'00"N	Morji	Spit beach	S	2.5 km	more to N	Spit towards south
4	15°36'10"N	Chapora	Pocket beach	N	1.0 km	more to N	Headland on north
5	15°34'30"N	Anjuna	Open beach	S	2.0 km	more to S	Between two headlands
6	15°32'15"N	Calangute	Open beach	S	7.5 km	more to N and S	Straight shoreline
7	15°28'30"N	Miramar	Bay beach	N	4.0 km	more to N	Protected from the south
8	15°22'12"N	Bagmola	Pocket beach	S	0.5 km	more to SE	Well protected
9	15°15'00"N	Colva	Spit beach	S	27.0 km	more to S	Straight open shore beach
10	15°02'30"N	Agonda	Spit beach	S	3.0 km	more to S	Protected from either side
11	15°01'30"N	Patnam	Spit beach	S	1.0 km	more to S	Headland on the north
12	14°59'50"N	Piplibag	Pocket beach	S	1.0 km	more to N and S	Well protected, along beach
13	14°58'25"N	Talpona	Spit beach	S	3.0 km	more to N and S	Protected from the north
14	14°55'25"N	Polem	Pocket beach	N	0.7 km	more to N	Protected from the north
15	14°52'30"N	Sadashivgarh	Spit beach	S	8.0 km	more to S	River to the south
16	14°49'40"N	Karwar	Bay beach	S	4.0 km	more to S	Spit on north, protected
17	14°47'48"N	Baitkal	Pocket beach	S	0.7 km	more to SE	Protected from the north
18	14°47'00"N	Binge	Pocket beach	S	1.6 km	more to SE	Protected by two headlands
19	14°45'32"N	Arge	Bay beach	S	3.0 km	more to NW	Beach in shadow zone
20	14°44'32"N	Kwada	Bay beach	S	3.0 km	more to SE	Spit projection to the north
21	14°44'15"N	Ambai	Headland beach	–	0.4 km	more to S	Concave protected
22	14°44'00"N	Marvada	Bay beach	S	3.5 km	more to S	Straight, protected
23	14°42'25"N	Belekari	Bay beach	S	4.5 km	more to S	Protected by headland
24	14°38'22"N	Ankola	Bay beach	S	3.0 km	more to N	Well protected from the south
25	14°32'30"N	Gokarn	Open beach	N	6.5 km	more to N	Straight shore line
26	14°31'40"N	Kundle	Pocket beach	N	0.7 km	more to N	Wedge shape beach
27	14°27'00"N	Tadri	Spit beach	N	8.0 km	more to N	Straight shore line
28	14°24'00"N	Kumta	Spit beach	N	15.0 km	more to S	Straight shoreline
29	14°16'45"N	Honavar	Spit beach	S	7.0 km	more to S	Straight shoreline
30	14°10'57"N	Kasarkod	Open beach	N and S	6.0 km	more to N and S	Straight shoreline
31	14°07'30"N	Mavalli	Spit beach	N and S	4.5 km	more to N and S	Forming tombolo to the south
32	14°02'20"N	Shirali	Spit beach	N and S	8.0 km	more to S	Concave seaward

3.8. Patterns of offshore turbidity

Satellite images provide a synoptic view of discrete turbid water masses in the nearshore region. Although dependent on the type of particulate matter, stratification of the water masses, depth of settling, and bottom conditions, the turbid waters tend to be more reflective than clear water and appear in different tones of gray. On the satellite images, the sharp contrast between various sediment-laden waters is clear and mappable. Tonal variation is considered a measure of sediment concentration. Texture and pattern in the

images help to determine the distribution and direction of movement of turbid water masses.

Careful observations of the fourth and fifth spectral bands and PC2 images of the study area show gradation from high to low sediment concentrations in turbid water masses from north to south and from the coast seaward. On the satellite images, the current directions are indicated where the sediment-laden plumes become elongate and point in the direction of flow. The shapes of most of the plumes are elongated and point southward. At river mouths and wherever the plumes are obstructed by headlands, they are dispersed and

deflected seaward. Based on tonal gradation and current direction, the suspended-sediment transport direction is to the south.

4. Sediment budget

A sediment budget is a volumetric accounting of the material eroded and deposited in a given stretch of coast (Stapor, 1973). It is based on quantification of sediment transport, erosion, and deposition for a given coastal segment. The sediment usually discussed is sand, and the controlling processes are either alongshore drift or those caused by humans. Any process that increases the quantity of sand available downdrift in a given coastal segment is a source, whereas any process that decreases the quantity of sand available downdrift is a sink. The coastal sector, for which sediment budget is to be calculated, would have shore-parallel boundaries landward of the line of expected erosion and at or beyond the seaward limit of significant transport (CERC, 1977).

Offshore bathymetry, studied from Indian Naval Hydrographic Chart No. 257 (Naval Hydrographic Office, India, 1979), shows no submarine canyons along the coast under study, so their role as a sink is unlikely. The continental shelf received deposits of sandy sediments as a consequence of postglacial transgression (Nair and Pylee, 1968). Therefore, it is likely that substantial quantities of sediments have been derived from offshore and added to the littoral zone under conditions of rising sea level (Murty et al., 1976). Under constant attack of strong waves, cliffs and headlands are eroding rapidly (Fig. 4). Rock fractures, which are parallel to the coast, accelerate wave erosion. Sand fractions contributed by major rivers like the Mandovi and Zuari are a minor factor. These sands are trapped in estuaries and in turn nourish the bay beaches (Nair and Hashimi, 1986). Kali River is nourishing beaches situated to the south of it (Nayak and Chavadi, 1989). The Gangavali, Aghnashini and Sharavati rivers are contributing sediments to local spits.

The processes of transport of sand are presented in Fig. 5. From these, an estimate of sediment balance can be made. Wave erosion of shores and cliffs, dune and backshore erosion by waves, winds,

and streams, landward transfer from offshore by storm waves, and carbonate production by organisms (Wagle, 1987) are identified as sources. Sediment trapped in inlets, estuaries, bays, and dunes, or transferred to offshore slopes, plus carbonate loss, and mining and dredging are identified as sinks. Within the study area, the contributions of sources and losses due to sinks are assessed qualitatively as significant, moderate, marginal, and unknown (Fig. 5).

5. Discussion and conclusion

The present study of landform indicators and turbidity patterns identified thirty four sectors of alongshore sediment transport. Of these, eighteen sectors show sediment transport to the south and twelve sectors, to the north. The sediment-transport direction in four sectors is not clearly defined. Though nearly half of the alongshore-drift sectors have a northward drift direction, those sectors with a southward drift direction are much longer. Therefore, it is likely that net sediment-transport direction overall is toward the south.

A heavy-mineral study (Nayak and Chavadi, 1989) revealed that the Kali River is the source for the sediments of beaches at Karwar, Baitkal, Binge, Arge and Kwada, situated south of the Kali River. Sediment-transport direction, determined from landform drift indicators along the coasts north and south of the study area (Kunte and Wagle, 1991, 1993a) are also to the south.

The Arabian sea as a whole is dominated by a reversal of winds during the two monsoon seasons. As a consequence, along the west coast of India, during the southwestern monsoon, winds blow southwards from May to September and attain a northerly direction during the northeastern monsoon, with a transitional period between. Thus, the seasonally reversing wind pattern influences southward drift during the southwestern monsoon while northward drift occurs during the northeastern monsoon. Therefore, the sediment-transport direction within each littoral-drift sector can be either north or south, coincident with the dominant seasonal winds.

It is interestingly observed that: (1) prograding

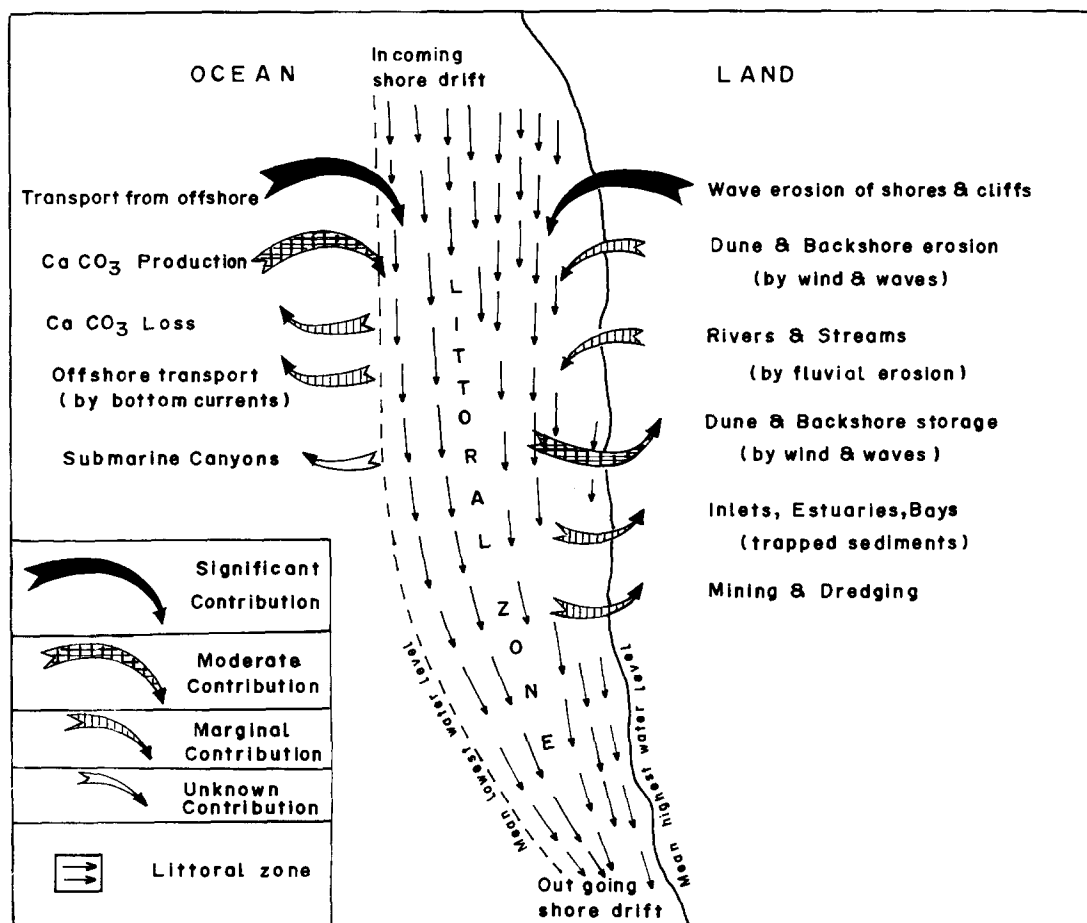


Fig. 5. A schematic drawing of sediment balance along the Goa-north Karnataka coast.

coastal sectors represented by features like beaches, dunes, abandoned beach ridges, and abandoned cliffs, and retreating coastal sectors, represented by features like nearshore islands, wave-cut terraces, cliffs, caves, and overhangs are situated alternately throughout the coastal tract; and (2) each occupies subequal parts of the coast. These observations suggest that every retreating coastal sector is supplying sediments to shore drift and that these sediments are transported a short distance and deposited along an adjacent prograding sector.

Adequate amounts of sediments are available for the bi-directional longshore currents. This has resulted in annual stability and straightness of beaches. Sand dunes backing the beaches reveal shoreward transport of surplus beach sediments.

The discussion reveals that: (1) though sediment transport is bi-directional, the overall net sediment transport direction is toward the south; and (2) a positive sediment balance is reflected in development of large spits in the southern part of study area. Finally, the study of geomorphic landforms with remotely sensed data can determine sediment-transport direction and sediment balance along coasts.

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