Coastal Erosion at Keta Lagoon, Ghana
- Large Scale Solution to a Large Scale Problem

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Abstract

This paper describes the development of a solution to a large scale, long term erosion process along the Atlantic coast of eastern Ghana in West Africa. The understanding of the erosion process was developed through a combination of geomorphic investigations and numerical and physical modeling of coastal processes. Key aspects of the investigations are described in this paper. The performance of the adopted sea defence system, consisting of rubblemound structures and beach nourishment, was evaluated using the GENESIS and COSMOS numerical models of shoreline change. The numerical models were also used to modify the sea defence system such that an acceptable level of downdrift impact was confined within the study area.

Introduction

This paper describes the development of a solution to address a large scale erosion problem along the Atlantic Coast of Ghana, West Africa. A background of the problem is presented followed by a summary of some of the more important design investigations. Finally, the various components of the sea defence system are described. The overall project also includes an 8.5 km causeway across Keta Lagoon for the coastal highway, a flood relief system to address lagoon flooding and land reclamation. The sea defence system is the focus of this paper.

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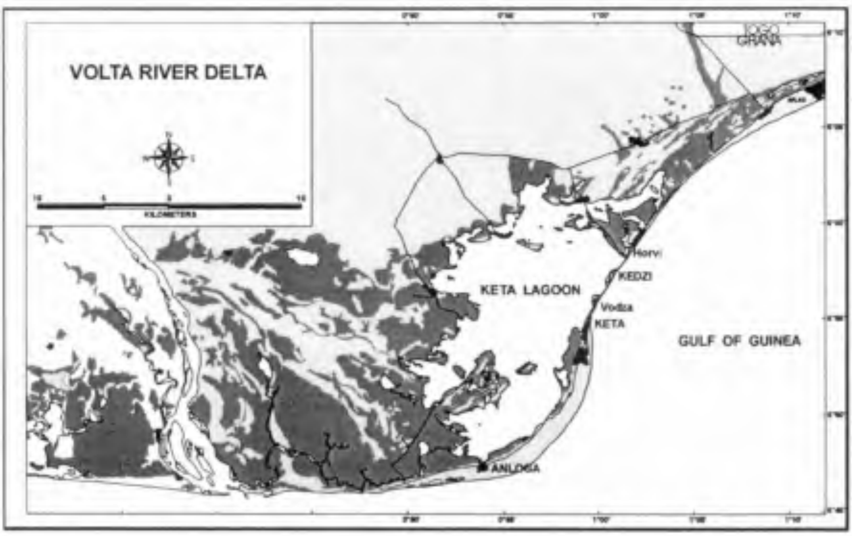
This paper presents a brief summary of some of the key aspects of the Keta Sea Defence Project. Full details are presented in the Final Report on the technical aspects of the Keta Sea Defence Project (Great Lakes Dredge & Dock and Baird & Associates, 1997).

Background

Keta Lagoon is located immediately east of the Volta River mouth along the east coast of Ghana in West Africa (refer to Figure 1). The Volta River historically carried large quantities of sediment, including coarse-grained sand, to the sea and this sediment was deposited at the river mouth, forming the modern (Holocene) delta. Several thousand years ago, at a lower sea level stage, and when the river mouth was located further to the east, another large delta lobe was formed. This old delta is now a large offshore shoal in depths of 10 to 20 m below sea level.

Figure 1 – Regional Study Area – The Volta Delta



Wave action from the South Atlantic is incessant along this section of the West African coast and invariably originates from the south to southwest sectors resulting in continuous eastward directed sand transport with rates in the range of 500,000 to 1,500,000 m^3/yr at most locations. As a result, the shape of the existing delta and the older submerged delta are skewed towards the east. The present eastward migrating delta features a zone of rapid deposition near its eastern leading edge, which is now located immediately southwest of the town of Keta (see Figure 2). This zone is sheltered from wave action by a large depositional protuberance located 20 km east of the river mouth and by the older submerged delta located offshore. As a result, potential sediment transport rates are low.

An apparent repositioning of the river mouth to the west and a decrease in sediment supply, to the area east of Keta, have resulted in erosion and realignment of the delta front east of the present river mouth (see Figure 3). This realignment is thought to be at least partially responsible for the initiation of the depositional protuberance on the delta front.

Figure 2 – Project Area and Recession Rates

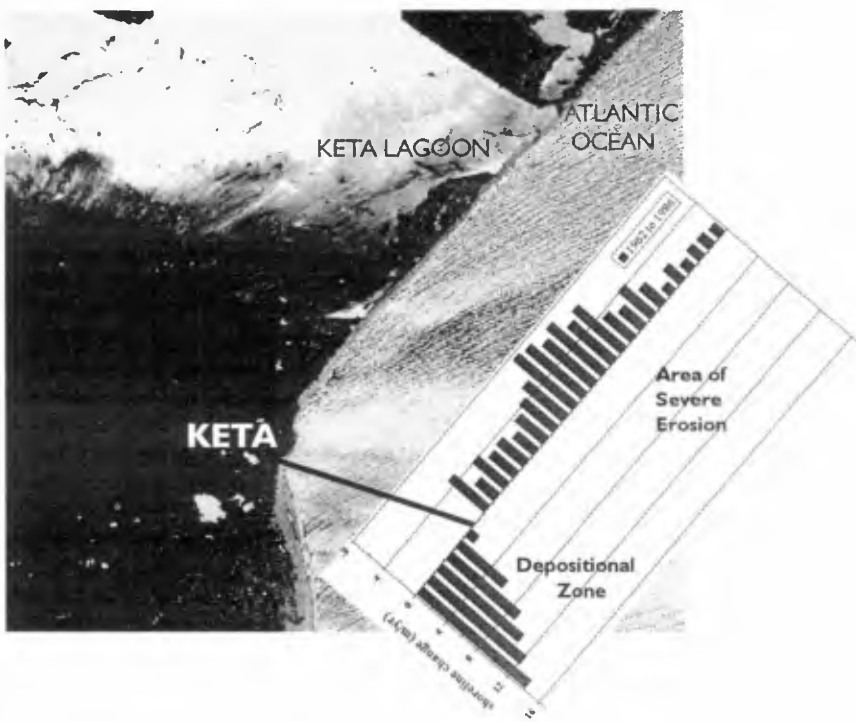
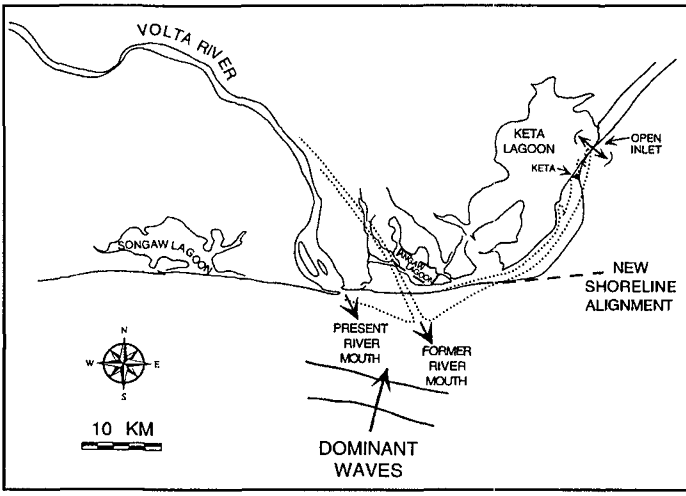


Figure 3 –Proposed changes of the Volta River Delta shoreline as a result of river mouth switching and shoreline realignment.



This large scale, long term process of sediment deposition on the deltaic protuberance is directly responsible for the shoreline recession in the study area, which is located immediately downdrift of the protuberance. The study area consists of a narrow 7 km long washover terrace separating Keta Lagoon from the sea (see Figures 4a and b). The terrace sits on lagoonal sediments, which are presently being transgressed. Annual average recession rates along the narrow section of beach range from 8 m/yr at the southwest end to less than 2 m/yr at the northeast end (refer to Figure 2). In addition, the coastline features migrating sand waves from 10 m long beach cusps to 300 m long tongues of sand. The migration of these features results in fluctuations in shoreline position of 50 m or more over a period of several weeks. These large sand waves appear to be generated by the creation and release of sand spits at beach bends along the leading edge of the delta front protuberance. Small changes in wave direction may initiate the break away of the spits to form migrating sand waves.

The erosion problem at Keta has been the focus of many investigations dating back to the first published engineering report by Coode (1929). This report concluded that the erosion problem had existed for at least 50 to 60 years prior to 1929 and relocation was proposed as the only practical solution. A series of reports by Batley between 1947 and 1950 suggested that the erosion problem at Keta was diminishing and that changes in erosion trends in the Keta area are related to dynamics of the Volta River mouth (including long term changes in the position of the mouth). Halcrow (1954) investigated the potential impact of the Akosombo Dam (which resulted in the creation of Lake Volta) on the coastal erosion at Keta. That study concluded that the regulated flow conditions would result in a reduction of the rate of depostion in the vicinity of Cape St. Paul, and therefore, alleviation of the erosion problem at Keta. Freedman (1955) disagreed with Batley's conclusion that the erosion problem at Keta was coming to an end. Emphasis was placed on seepage from the lagoon through the beach face during low tide conditions as an important factor in the erosion process. Groynes were rejected as a viable solution while the construction of a continuous seawall was endorsed as a practical but costly solution, relocation was proposed for further consideration. In 1960 a recommendation in a report by the Hydrological Branch of the Public Works Department of Ghana resulted in the construction of 1600 m long steel sheet pile wall at Keta (the remains of this can be seen offshore of Keta in Figure 4a). Following construction of the wall serious erosion occurred at the northeast (downdrift) end of the wall. NEDECO (1964, 1976 and 1980) and Delft Hydraulics (1993) have prepared several reports on the flooding and erosion problem at Keta. These reports agree with the view that the erosion problem is slowly shifting northeastwards. In the 1980 report a series of groynes was proposed to protect the shoreline between Keta and Horvi. Most recently, Anthonio and Valentine (1995) developed a numerical nearshore wave transformation model to describe the variability in alongshore transport passing Keta depending on the direction of wave attack.

Figure 4a - A view of Keta and the delta protuberance looking southwest

Figure 4b - A view of the washover terrace looking northeast from above Keta at Vodza in the foreground and Kedzi in the background

Design Investigations

Geomorphic investigations consisted of air photo and satellite imagery analysis, mapping historic beach ridges; hydrographic surveys; subsurface investigations including vibracores, augers, boreholes, sediment sampling, seismic profiling and radiocarbon dating; and monitoring of 10 permanent beach profile stations (some of which have been monitored since the early 1970's). The key findings of these investigations are listed below:

- Earlier during the present Holocene high-stand of sea level, the mouth of the Volta River was located further to the east and the leading edge of the delta probably consisted of spits curving into an open bay which is now the enclosed Keta Lagoon (see Figure 3);
- The northeastward migration of the leading edge of the Volta River delta has been occuring in an episodic manner at the existing location for a period of centuries and will continue to do so (see Figure 5);
- The section of eroding shoreline is a washover terrace consisting of a wedge of sand migrating into the lagoon through overwash processes and through shoreface erosion of underlying lagoonal sediments (see Figure 6).

Figure 5 – Beach –ridge development. (A) Overlay tracing of the beach ridge margins seen on aerial photographs taken in October 1993. (B) Interpretation of episodes of beach-ridge growth (1=oldest; 6=youngest).

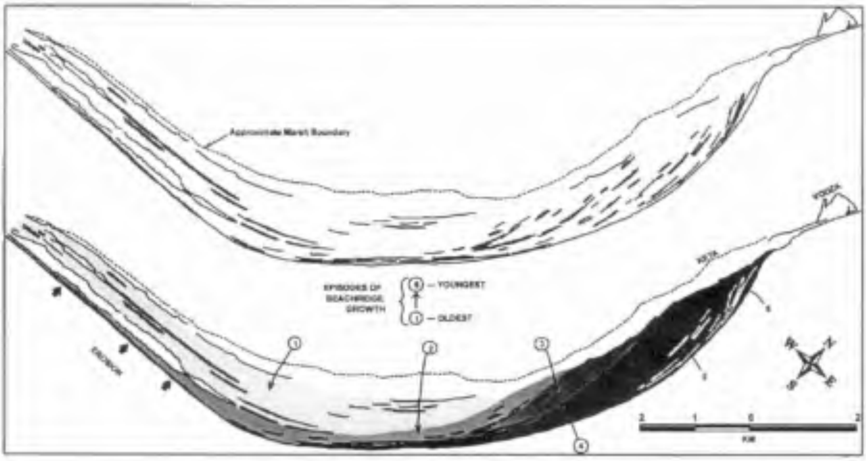
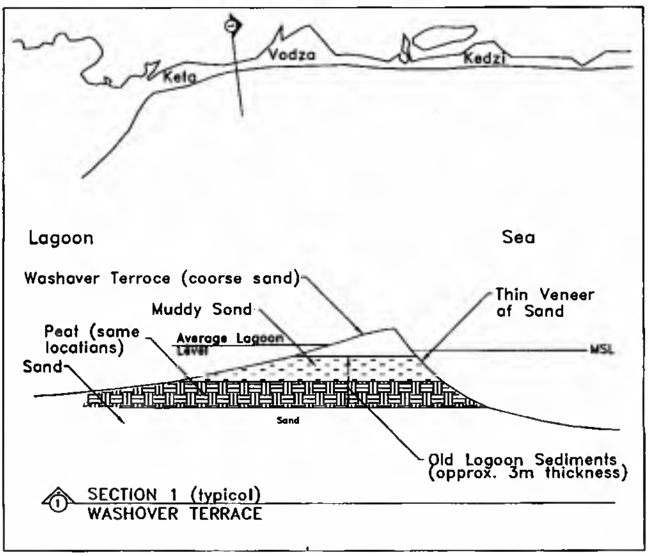


Figure 6 – Section of Washover Terrace



The findings of the geomorphic investigations were corroborated or refined based on the coastal engineering analyses described below.

Coastal process investigations included prediction of the deepwater wave conditions with the U.K Global Wave Model calibrated by satellite data by Oceanor (1997) and verified against wave measurements with pressure sensors deployed by Baird. Nearshore wave transformation was completed using the Nearshore Spectral Wave model of the MIKE21 package developed by DHI. The nearshore wave transformation results showed that the degree of sheltering at Keta varies significantly with only a small change in incident wave angle. For a typical 12 s wave period, the wave height in the vicinity of Keta is reduced to 20% of the incident wave height for SW incident wave attack, 50% for SSW wave attack and 70% for S wave attack.

An overtopping analysis was completed to simulate serious flooding events that occurred during the course of the design investigations. The findings of this analysis demonstrated the importance of washover in the retreat of the beach terrace. Samples of the underlying lagoonal sediment (peat and clay) were found to contain little or no beach sand. Therefore, once the underlying lagoonal sediment was exposed in the surfzone, it was readily and irreversibly eroded, with little or no contribution of sand to the littoral system.

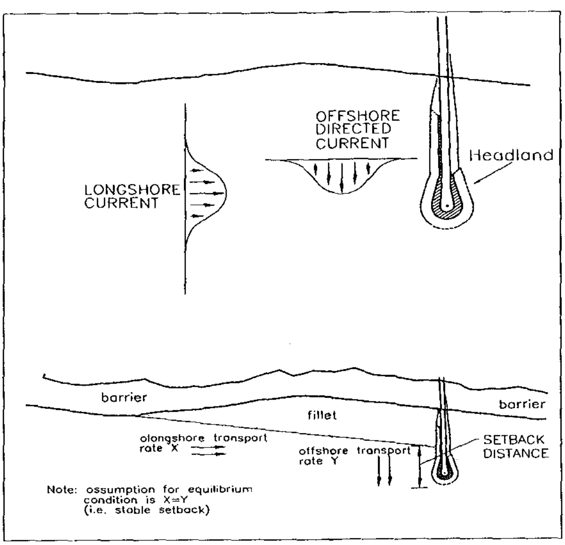
Prediction of longshore and cross-shore currents and sand transport rates (including in the vicinity of the headlands) were completed using the COSMOS model (see Nairn and Southgate, 1993). There were two purposes of these estimates: 1) to quantify the geomorphic findings and specifically to develop a sediment budget to provide the basis for a solution; and 2) to assess the potential performance of the proposed solution.

In summary, the sediment budget found that between Cape St. Paul and just southwest of Keta, the net eastward transport rate decreases from nearly 1,000,000 m^3/year to less than 50,000 m^3/year. The result is deposition of sand and the migration of the leading edge of the delta. The rate of shoreline progradation is greatest at Keta where the depths of water are shallow (owing to the fact that this area was recently eroded). Northeast of Keta the potential sand transport rate increases from 50,000 to 200,000 m^3/year towards the east at the northeast end of the study area near Horvi. The deficit in the potential transport rate of approximately 150,000 m^3/year compares well to the estimated average annual loss of 164,000 m^3 of sand sized sediment from this reach of coastline (determined from historic recession rates and a consideration of the thickness of sand eroded - accounting for the fact that the washover terrace material is conserved and that the lagoonal muds do not produce sand sized material).

The GENESIS model (Hanson and Kraus, 1989) was used to assess the potential performance of large headlands in protecting the shoreline from erosion and regulating the rate of alongshore transport. Two key aspects of the GENESIS model that required calibration to address specific site and project conditions are: 1) the potential sand transport rate; and 2) the rate of bypassing at each headland (referred to as the permeability of the structure in the GENISIS input). The transport rate was established by the COSMOS model and the sediment budget findings discussed above. The rate of bypassing, or groyne permeability, is a critical factor as it establishes the offset of the shoreline from the tip of the downdrift groin with a groin cell. This setback distance must be determined to assess the required groin or headland spacing to optimize the transport rate through the study area and to avoid flanking erosion on the downdrift side of the headlands. The setback distance was determined for a given alongshore transport rate (i.e. associated with a given shoreline orientation) by finding the position that resulted in equilibrium between alongshore and offshore transport just updrift of the headland (see Figure 7). It was determined that the shoreline must advance to within 50 m of the end of the headland before the offshore transport ratc matches the alongshore transport rate of 150,000 m^3/year. However, for an alongshore transport rate of 50,000 m^3/year, the setback distance increases to 120 m. The prediction of setback distances was corroborated by a review of setback distances for many existing groin and headland structures.

Physical modelling was completed to examine the impact of the headlands on the beach orientation and the bypassing process as well as the stability and constructability of the rubblemound structures. One of thc key findings of the mobile bed modelling was that the advantages of implementing T-head, L-head or angled groins or headlands at this location did not justify the additional cost compared to a straight, shore perpendicular headland. The finding that the T and L head layouts did not add significantly to the length of protected beach (and the required spacing between headlands) may be a function of the narrow window of wave attack at this site (i.e. all significant waves approach from the SW to SSE sectors). The model test results for beach planform compared well to empirical predictions from expressions developed by Hsu et al (1989).

Figure 7 – Estimating bypassing at the headlands



The Sea Defence System

The objectives of the sea defence system are:

- stabilize areas of existing and planned development;
- prevent flooding of the coastal communities;
- minimize disruption to human activities associated with the coastline, particularly seine netting and the launching of fishing canoes; and
- avoid transferring the erosion problem to developed areas downdrift and northeast of the study area.

In order to stabilize the study shoreline and meet the above objectives, it is necessary to address a deficit of approximately 150,000 m^3/yr of sand between the updrift and downdrift limits of the developed area (a distance of 5 km). It is also necessary to protect the erosion susceptible lagoonal sediments underlying the beach.

Prior to developing a solution to the erosion problem, the "do nothing" scenario was considered in detail. Based on the results of the geomorphic investigation, the coastal process modelling and the sediment budget analysis, projeetions of shoreline position for the next 75 years were made (see Figure 8). It is evident that perhaps within 25 years time, erosion will no longer be a threat to the community of Keta. However, the communities of Vodza and Kedzi will suffer severe erosion. Relocation of these communities was not an acceptable option as there are no remaining suitable locations for ocean seine netting – the primary occupation of the communities. In addition, it is possible that the erosion may result in the breach of the narrow washover terrace separating the lagoon from the sea. The introduction of seawater into fresh/brackish water of Keta Lagoon would have disastrous effects on local drinking water, lagoon fishing and irrigation of adjacent agricultural land. Therefore, the "do nothing" option was considered to be unacceptable.

The adopted large scale solution consists of constructing one breakwater and 7 rubblemound headlands, prefilled with 2.5 million cubic metres of sand dredged from the lagoon bed. The breakwater (not shown on Figure 8) will protect the town of Keta from erosion until this area is naturally protected by the migrating delta front. One of the reasons a breakwater was preferred to a headland at this location was to minimize the disruption to alongshore transport between the depositional area at the leading edge of the delta and the downdrift erosion area. On average, the headlands are approximately 200 m long and extend out to a depth of 5 m. The average spacing between the headlands is 750 m. The function of the headlands is to extend the longevity of the beach nourishment and to protect the underlying lagoonal sediments from erosion. The purpose of the beach nourishment is to act as a feeder beach to address the potential transport deficit within the study area. Figure 9 illustrates the solution in terms of its performance relative to the sediment budget. It is noted that Figure 9 shows eight headlands, the design was recently modified to eliminate the most northerly headland (reducing the total number to 7).

Figure 8 –Projections of future shoreline change under the 'Do Nothing' scenario

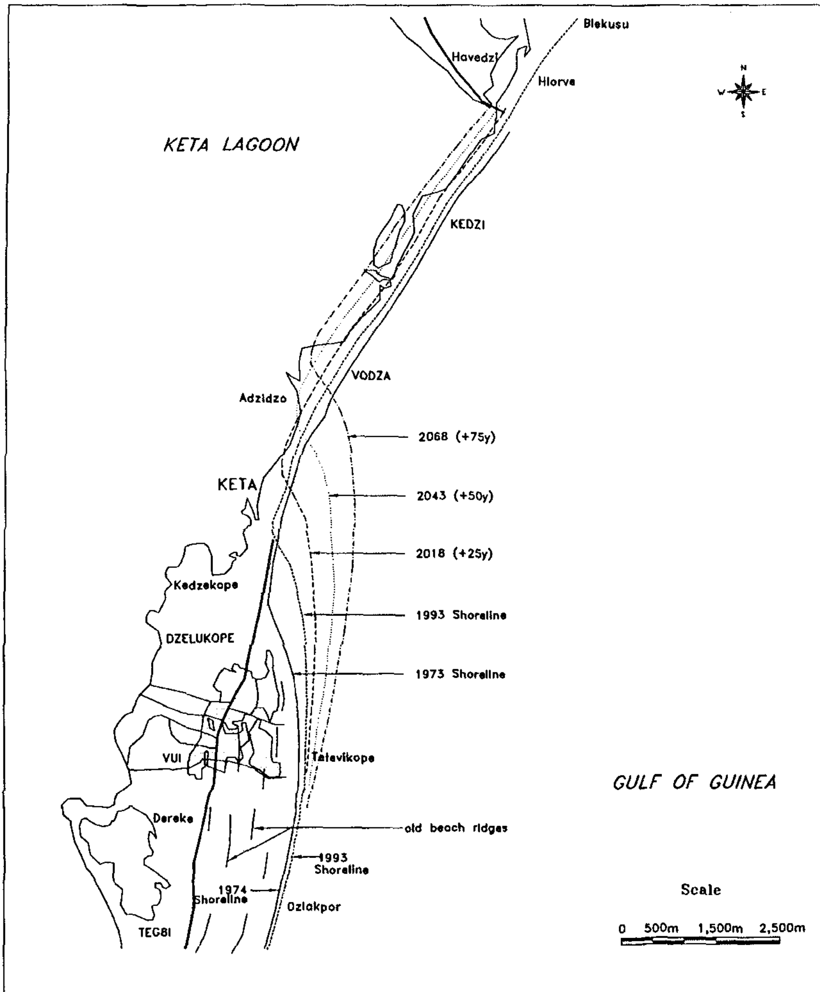
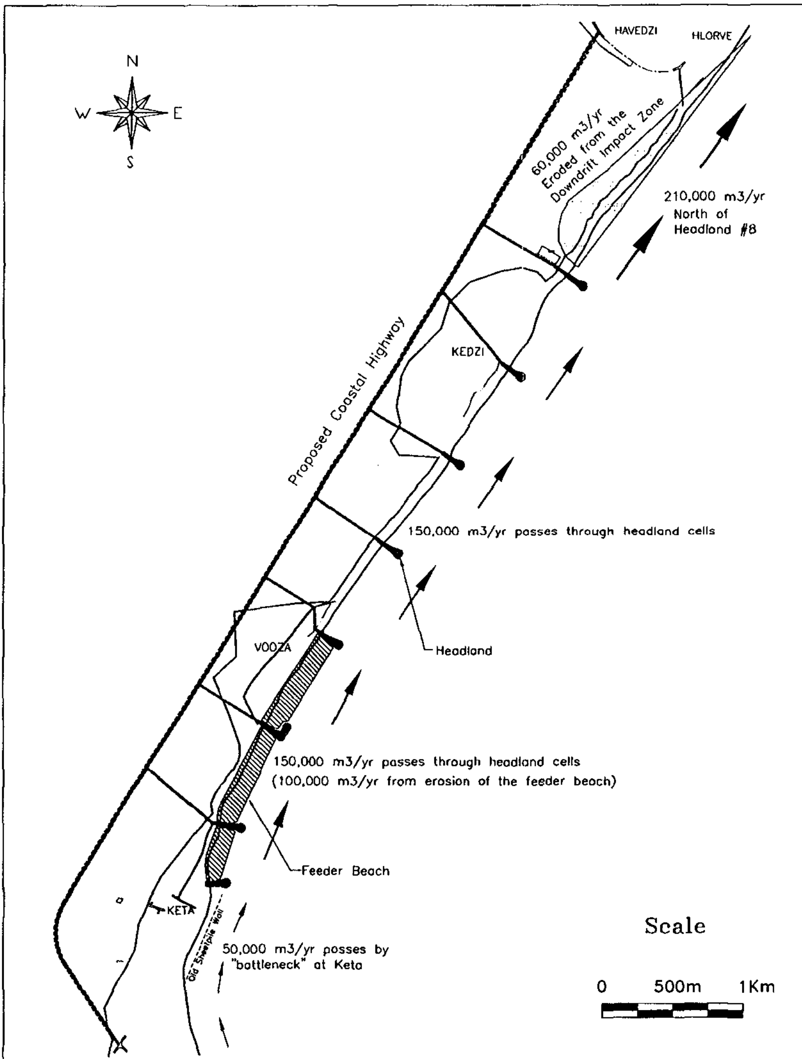


Figure 9 – Proposed Sea Defence Scheme



(Note: The proposed breakwater is located along the alignment of the old sheet pile wall and the most northerly headland has been removed from the latest design revision.)

Another important aspect of the sea defence system is the 2 km section of unprotected shoreline at the downdrift end of the project. This undeveloped area will erode to make up the remaining 60,000 m^3/yr deficit between the transport through the project area and the potential rate downdrift of the sea defence system.

Based on the COSMOS and GENESIS numerical modeling, it was determined that the feeder beach area will have to be renourished every 10 to 15 years. Model simulations showed that failure to renourish the feeder beach would result in flanking erosion at the base of the headlands and accelerated downdrift erosion, to the extent that downdrift communities may eventually be affected.

A range of other possible solutions was considered in detail. These included the use of rubblemound structures without beach nourishment, and beach nourishment without structures. In the former case it was determined that twelve headlands would be required and that five more headlands would have to be added every 10 to 15 years to address downdrift erosion. This solution would simply transfer the problem downdrift. One alternative that consisted exclusively of beachfill was a "sand bridge" extending from updrift of Keta to Vodza. The purpose of the sand bridge was to link updrift and downdrift locations with similar potential transport rates (eliminating some of the deposition updrift and alleviating the downdrift supply deficit). The net present value of this solution was similar to the adopted solution of the feeder beach and headlands, however, it was not selected owing to the higher risk associated with estimating the performance of the sand bridge.

Conclusions

The combined investigation of coastal processes, geology and geomorphology was utilized to develop an understanding of the coastal morphodynamics across a wide range of temporal and spatial scales. This understanding was used to predict future shoreline change in order to develop a coastal management solution to the ongoing impact of the shoreline recession on the coastal communities in the study area. The solution addresses the erosion problem within the limits of the study area and avoids the downdrift transfer of the problem.

Construction is planned to commence in early 1999. An extensive monitoring program through the four year construction period will assess the waves, shoreline change, scour and stability of structures in addition to environmental conditions as part of the environmental impact assessment requirements.

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