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The Vulnerability of Walvis Bay to Rising Sea Levels

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ABSTRACT

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The potential impacts of rising sea levels on the harbour town of Walvis Bay on the Namibian coast are considered. Walvis Bay is an arid, semi-desert environment with most of the town lying 2 m above mean sea level. The town is sheltered by a large sandy spit from the prevailing wave climate, which, on the open coast, can be quite severe. The area has an exceedingly dynamic sediment budget and is completely reliant on a small coastal aquifer for freshwater. This paper demonstrates the vulnerability of semi-sheltered environments to sea level rise and the need for accurate sediment budgeting in any Potential Impact Assessment. Four categories of potential impact are considered; increased coastal erosion, flooding and inundation, increased saline intrusion and raised water-tables and lastly reduced protection from extreme events. The effect of increased coastal erosion is found to have limited impact on the town but the remaining three potential impacts could have serious consequences, especially the threat from extreme events. Nine years of hourly tide gauge data were analysed using the Joint Probabilities Method and water level return frequency curves were drawn. A 20 cm rise in sea level was found to be sufficient to raise the annual occurrence water level to above that of a current 1 in 100 year event. A future 1 in 10 year storm, after a 20 cm rise, would attain a higher water level than that which could be reached by a 1 in 1,000 year event now. This Potential Impact Assessment provides an analogue for other environments which may be sheltered from the effects of coastal erosion such as low lying tidal inlets and estuaries.

ADDITIONAL INDEX WORDS: *Sea-level rise, Walvis Bay, Bruun Rule, extreme water levels, joint probabilities method.*

INTRODUCTION

Southern African sea levels are rising at rates comparable with estimates of global sea level rise (HUGHES *et al.*, 1991). It is reasonable therefore to accept future predictions of sea level rise as being applicable to Southern Africa and consequently coastal management procedures must be able to cope with these rising sea levels and climatic changes. However in order to understand the effects of sea level rise in any environment it is helpful to study the processes and impacts in a location where they are of first order magnitude. Such an environment is Walvis Bay and this paper outlines the likely impacts of sea level rise at Walvis Bay, using present climatic conditions. It is intended to illustrate the relative importance of these impacts both locally and in other similarly sheltered environments and to provide guidelines for coastal managers in Walvis Bay.

Walvis Bay is a low lying harbour town of strategic importance to South Africa and Namibia with average relief of between 1 m and 3 m above mean sea level (MSL). It has no detailed topographic maps, is located in an extremely arid and dynamic sedimentary environment and is completely reliant on a coastal aquifer for fresh water supplies. The adjacent saltmarsh areas are also of major ecological significance.

Impacts due to increased erosion, flooding, elevated water tables and salt pollution and extreme storm events are considered for sea levels elevated 20 cm, 50 cm and 100 cm above present levels. Time scales for these levels are taken 35 years, 90 years and 110 years, representing a most likely response (IPCC, 1991) over near and mid-term and a worst case response over long term.

SITE DESCRIPTION

Walvis Bay is a small enclave of some 970 km^2 situated midway between the northern and southern borders of Namibia at latitude and longitude 22°55′S, 14°30′E (Figure 1). It is the only deep water port on the Namibian coastline and handles approximately 900 vessels and 1 million tonnes of cargo per annum, delivery of Namibia's crude oil requirements (COUNTRY PROFILE, 1989) and

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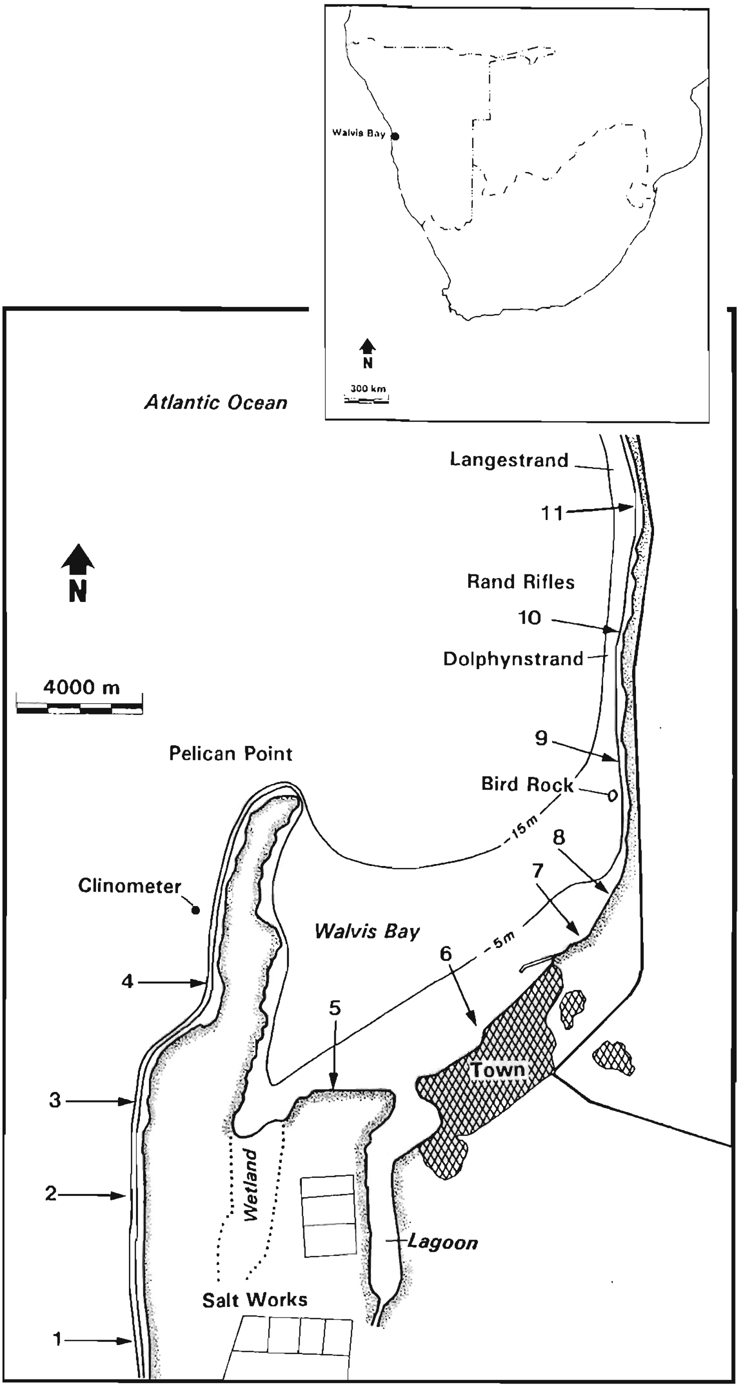

Figure 1. Location of Walvis Bay.

40% by weight of Namibia's total foreign trade (MOORSOM, 1984). Sovereignty of the area is claimed by South Africa.

The bay is bounded on the west by a large dynamic sandy spit known as Pelican Point and the town and harbour are located on the south eastern shore adjacent to the mouth of the ephemeral Kuiseb River which forms the Walvis Bay lagoon (Figure 1). The study area is located in a harsh desert environment characterized by summer rainfall of less than 50 mm/yr (STENGEL, 1964). Within the river catchment, rainfall is of the order of 50 mm to 100 mm per annum (STENGEL, 1964) and is generally insufficient to make the river flow as far as Walvis Bay except during floods. Even then the flow has not always reached the Atlantic (over the period 1837 to 1963 the river has only reached the sea 15 times). As a result of this extremely low rainfall, storm water drainage is unnecessary in Walvis Bay and consequently no detailed topographic plans of the town are available. Most of the town, harbour and adjacent coastline is exceedingly flat and low lying with elevation of the order of between 1 m and 3 m above land levelling datum.

Tides are semi-diurnal and have a mean spring range of 1.42 m with mean sea level (MSL), mean high water springs (MHWS) and highest astronomical tide (HAT) being at 0 m, 0.71 m and 1.02 m elevation respectively, relative to land levelling datum (ANON., 1991). Tide gauge or chart datum is fixed 0.913 m below land levelling datum. The dominant wind direction is southwesterly and this has been shown to create a clockwise flow of surface water within the bay (FDC, 1974). There is a strong diurnal variation in wind direction at Walvis Bay with light morning northeasterly and easterly land breezes being dominated by strong southwesterlies in the afternoon. The main driving force for these winds is the pressure gradient formed by the South Atlantic High. The whole coastline is essentially soft, sandy and erodible, save for a few rocky outcrops.

Figure 2 is a Landsat image of the region. The Kuiseb forms the northern boundary of the Namib Sand Sea which can be clearly seen to the south of the river, truncating the longitudinal dunes which encroach from the south. To the north, the Namib forms an extensive gravel deflation surface. Huge volumes of sand are available and rates of aeolian transport have been estimated to be approximately 150 $m^3/m/yr$ northwards (CSIR, 1989). Periodic floods remove these encroaching dunes and redeposit the sand in the area to the south of the spit. These intermittent and irregular pulses of additional sediment input, which occur on average with about decadal frequency, probably account for the irregular shape of the seaward side of the spit. The sand to the southwest (upwind) of the salt works (Figure 1) and northern part of the lagoon is reasonably well stabilized by fences but some aeolian sedimentation is taking place in the southern portion of the lagoon (CSIR, 1989). This lagoon provides a significant saltmarsh habitat for migratory birds and has been described by WILLIAMS (1988) as being the most important system in Southern Africa and the second most important in Africa with respect to the total number of birds it supports.

Examination of wave roses from data collected from the Pelican Point clinometer shows the dominant wave direction to be from between 225° to 270° with effectively no waves from other directions (FDC, 1974). Other sources (CSIR, 1989) indicate a more southerly component over a narrow range of directions although the measurements were taken over a shorter period. Design wave specification for an approximate 1 in 10 year significant wave height in 50 m of open water outside the bay can be taken as 5 m (ROUSSOUW, 1989). The presence of Pelican Point effectively shelters Walvis Bay harbour area from any direct wave action but due to wave diffraction and refraction some wave energy, though much reduced, does enter the bay (Figure 3). As a result of the differential set up within the shadow zone caused when these waves break on the shore, a southwards longshore current is propagated (FDC, 1974).

At the edge of the shadow zone the waves are virtually undiffracted and break almost parallel to the coast. Little or no longshore current is generated as there is no longshore gradient in wave energy. However, to the north the waves become oblique to the coast line and a longshore current is generated in a direction opposite to the angle of incidence, *i.e.* northwards. This change over between northwards and southwards directed current appears to occur in an area between Dolphynstrand and Bird Rock (Figure 3).

Sediment Dynamics

As a result of wave and wind action, the net sediment transport directions can be taken as northwards along the exposed coast, Pelican Point

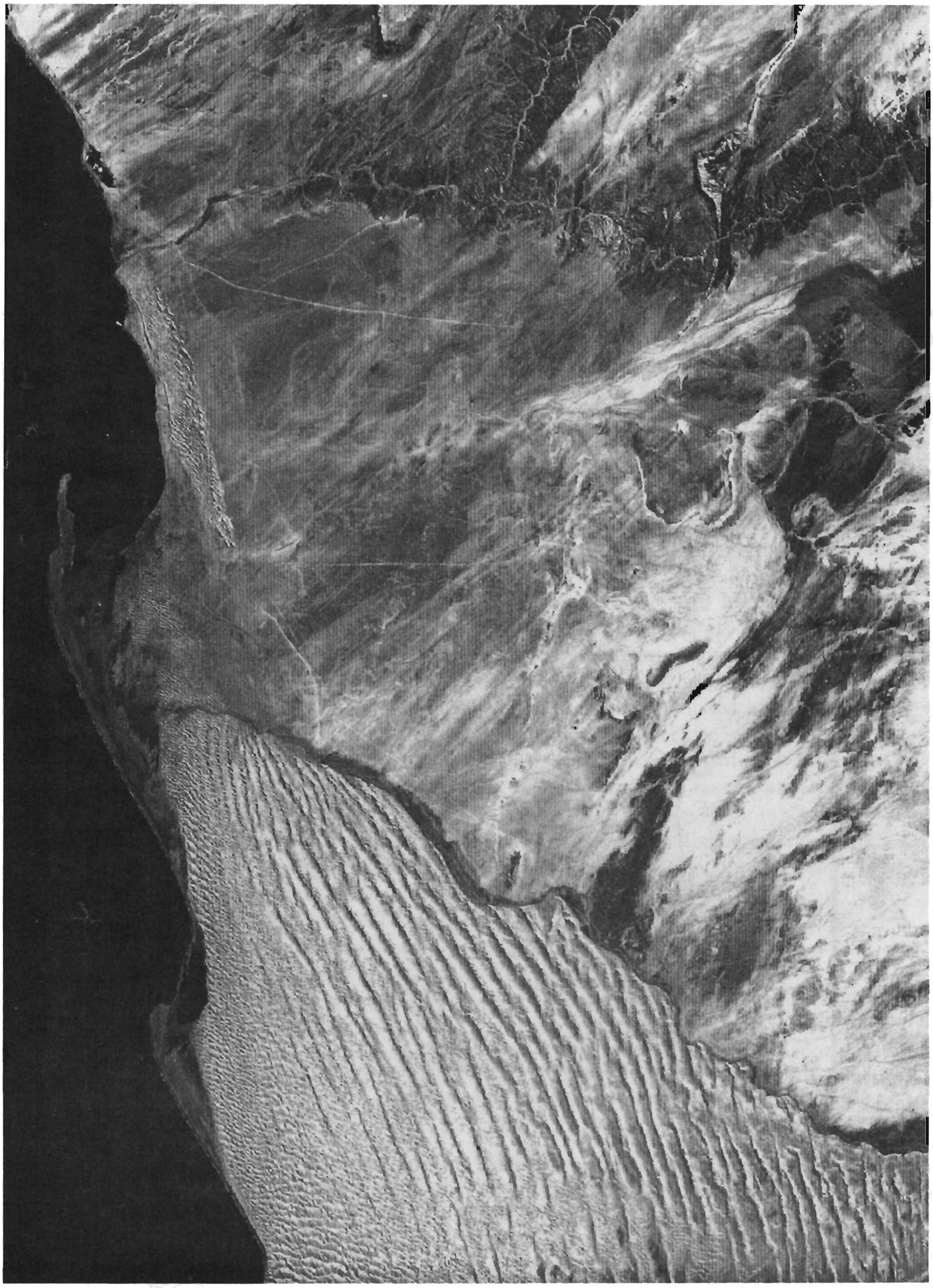

Figure 2. Landsat image of the Walvis Bay area, the Kuiseb River and the northern section of the Namib desert (after SHEFFIELD, 1981).

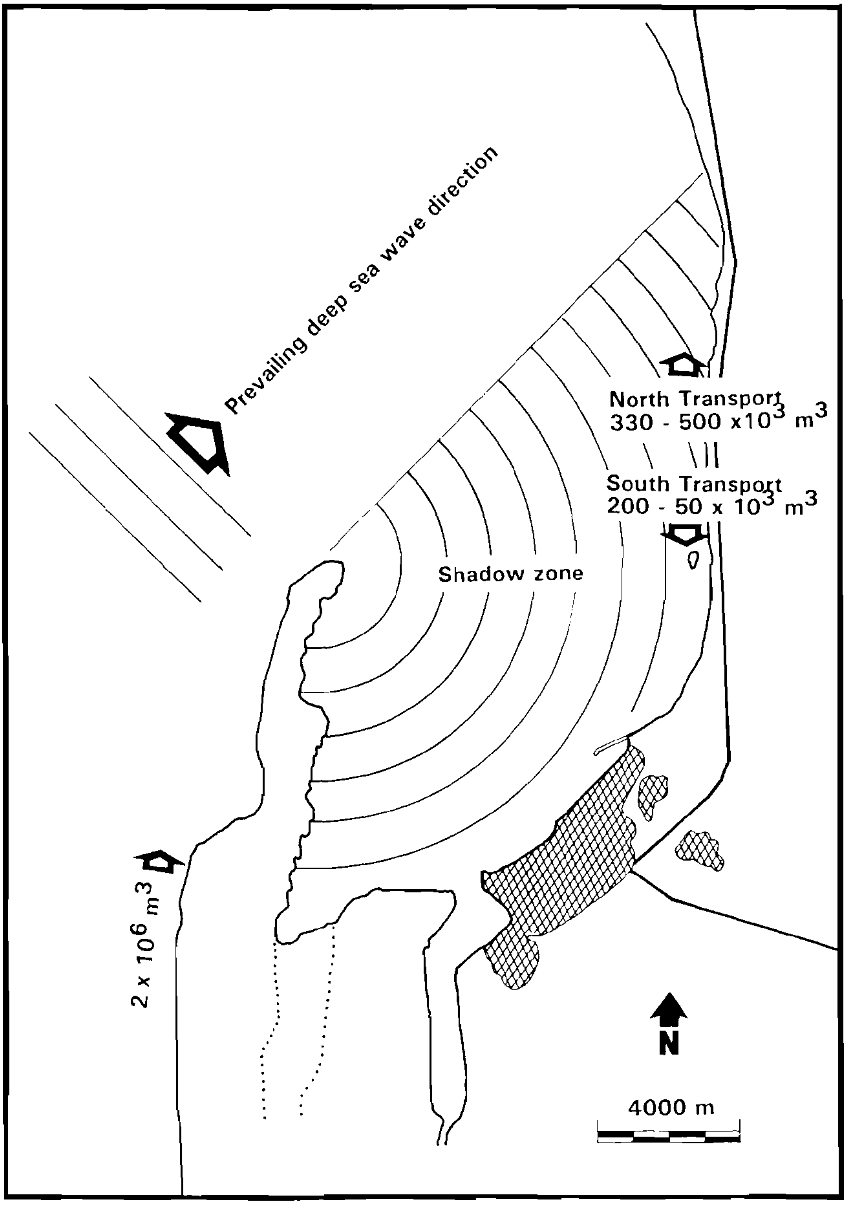

Figure 3. Summary of net sediment transport rates and wave orthogonals.

and Dolphynstrand, and southwards from Bird Rock (CSIR, 1989; FCS, 1974; CSIR, 1984; CSIR, 1985). Figure 3 summarizes the volumes of net sediment transport. Measurements taken from old maps and aerial photographs have shown that Pelican Point has developed northwards at a rate of 17 m/yr over the last 200 years and the coastline to the south of the Point is prograding westwards at a rate of between 5 m and 10 m/yr (CSIR, 1984). Net transport rates are of the order of 2×10^6 m^3/yr (CSIR, 1985). South of Dolphynstrand the net southwards longshore transport rate is uncertain but sand tracer tests have confirmed the net direction between Bird Rock and the harbour breakwater (FDC, 1974). Rates are believed to be between 200,000 m^3/yr and 50,000 m^3/yr (decreasing southwards) indicating a significant amount of deposition in this area (CSIR, 1989).

Figure 1 shows where the 5 m isobath veers away sharply from the coast, north of the breakwater (near Profile 7). Grain size analysis and tracer experiments indicate that recent deposition is responsible for this change in slope (FDC, 1974). This area of deposition is probably migrating northwards at a rate comparable to the growth of Pelican Point (FDC, 1974).

Maintenance dredging in the two channels in the harbour is intermittent and accurate records of depths dredged are not kept (T. RAW, *personal communication,* 1990). Dredge spoils are dumped on either side of the channels suggesting that current velocities are (optimistically) considered by the dredger operators to be too low to support major sediment transport and that the majority of deposition has already occurred upstream or north of the breakwater channel. In the long term, a combination of the migration of Pelican Point, aeolian deposition in the saltmarsh and lagoon and marine deposition in the harbour and breakwater area is likely to cause the southern end of the bay to silt up and migrate northwards. Sea level rise may be expected to slow this process.

Groundwater

Walvis Bay is entirely dependent on a small coastal aquifer for its fresh water supply. This aquifer may best be described as a "lemon-wedge" shaped lens of fresh water of maximum depth 60 m and hydraulic gradient 0.6×10^{-3} fed by a narrow aquifer underlying the Kuiseb River bed. Figure 4 shows the outline of the aquifer, its approximate area below 1 m elevation, the location of the main extraction wells and the position of the salt wedge. Should uncontrolled extraction take place, the area for potential saline pollution below MHWS is obvious. Although extraction wells are not currently in operation in the deep "wedge" part of the aquifer, their commission is intended to take place in the near future (R. BUSH, *personal communication,* 1990) and rising sea levels will exacerbate potential salt pollution problems. Fresh water flow to the sea is intermittent but a mean value of 0.5 m^3/m/d and hydraulic conductivity of the order of 40 m^3/d is acceptable (R. BUSH, *personal communication,* 1990).

Figure 5 shows the inferred elevation of the top of the piezometric surface and the surface topography. Underneath the whole area of the town the saline water table is known to be within 0.7 m and 0.9 m of the ground surface (F.F. LANGE, *personal communication,* 1990).

METHOD

Increased coastal erosion as a result of rising sea levels is modelled with the Bruun Rule (1962) using the following extension to account for changes in rates of longshore transport (dq/dx):

$$R = \frac{LS + dq/dx\, \Delta t}{h + B}$$

The berm height (B) is generally taken conservatively as between 1 m and 5 m estimated from the most recent topographic maps, orthophotos and from personal communications. The maximum depth (h) for shore-normal sediment transport is taken as 18 m and distance (L) to this depth is taken from the 1990 South African Navy Chart SAN 1001. "Average" profiles were constructed from these sources and Figure 1 shows their locations. All points on the profiles were found to conform to the form $h = Ax^{2/3}$ with 95% confidence (DEAN and MAURMEYER, 1983). The effects of inundation are modelled by assuming those areas of land adjacent to the coast below 0.9 m, 1.2 m and 1.7 m elevation with direct access to the sea will be flooded at MHWS under each respective sea level rise scenario.

Salt water intrusion into the aquifer as a result of rising sea levels is modelled using the relationship between surface slope (s), sea level increase (S) and shoreward displacement of the interface (Δx) and assumes a currently stable wedge position:

$$\Delta x = S/s$$

The elevation of the water table is assumed to increase at the same rate as the rising sea level and the maximum elevation of the (saline) water table under the town and harbour is taken as MHWS. It is noteworthy that excavations currently carried out in parts of the town make use of the tide tables to calculate the optimal working time.

After averaging out the effect of waves, an observed sea level consists of three components; a mean sea level, an astronomical tide component and a meteorologically induced surge component. An approximation of the probability of a particular water level occurring may be considered as the sum of the probability of all possible combi-

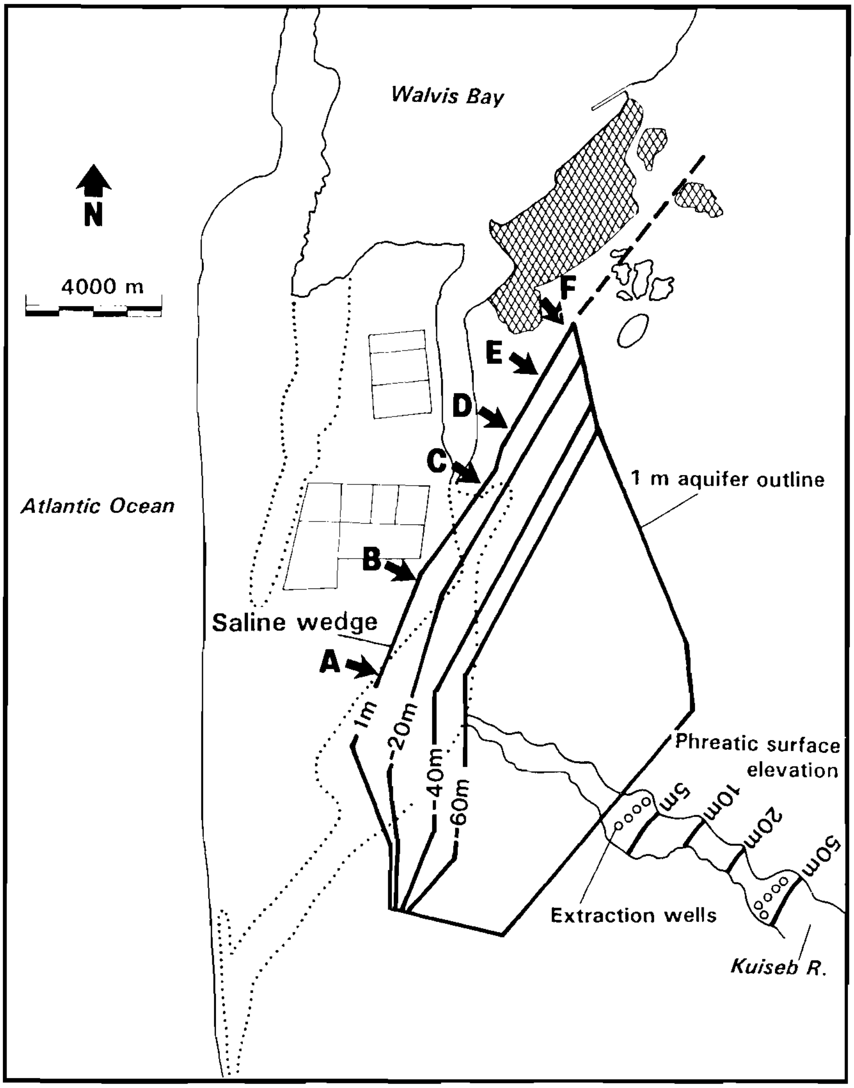

Figure 4. Outline of the Walvis Bay Aquifer, showing the position of the saline wedge and freshwater drawpoints and hydrological profiles A to F.

nations of tide and surge that could make up that level. This is the Joint Probabilities Method (PUGH and VASSIE, 1978) and can be used to provide a probability or return period curve for sea level.

Nine years of hourly tide gauge records for Walvis Bay were obtained from the Hydrographic Office of the South African Navy. These records were checked for errors both visually and by two Lagrangian methods (LENNON, 1965). A Doodson Tide Filter (DOODSON and WARBURG, 1941) was then applied to separate the tidal signal from the surge component. The Joint Probabilities Method was applied and an extreme water level return period curve was drawn. To this curve a 0.2 m and 0.5 m increase in the mean sea level was added to obtain a first order insight into the effects of sea level rise on extreme water levels.

RESULTS

Application of the Bruun Rule (1962) to the 11 profiles (Figure 1) provides the results shown in Table 1 for the three scenarios. Rates of longshore

Table 1. *Coastal recession in metres for Walvis Bay as indicated by application of the Bruun Rule.*

	Erosion			
Profile	0.2 m Rise	0.5 m Rise	1.0 m Rise	dQ/dx (m^3/m)
1	4	10	21	0
2	4	11	22	0
3	4	10	21	0
4	18	45	90	0
5	95	236	473	0
6	86	219	432	0
7A	24	57	202	50,000/2,000
7B	−20	−55	·65	100,000/2,000
8	85	215	371	50,000/3,000
9	28	70	142	0
10A	117	300	400	330,000/5,000
10B	168	408	561	500,000/5,000
11A	136	350	467	330,000/5,000
11B	418	502	654	500,000/5,000

Negative values imply progradation

Table 2. *Saline intrusion for sea level rise in Walvis Bay Aquifer.*

	Increased Saline Intrusion (m)		
Profile	0.2 m Rise	0.5 m Rise	1.0 m Rise
A	95	238	476
B	55	139	278
C	15	37	75
D	15	37	75
E	333	348	373
F	105	262	450

sediment transport are uncertain and have been bracketed in their use and consequently use of the Bruun Rule in this environment provides only a first order estimate for the increased coastal erosion. Negative values indicate deposition.

Profile 7 is in an area of net deposition and two different deposition rates have been used (*i.e.* 50,000 m^3/yr/2,000 m and 100,000 m^3/yr/2,000 m) to illustrate the need for a more accurate understanding of the dynamics of this area. The lower deposition rate indicates net erosion of the shoreline and the higher indicates net progradation. Profile 6 assumes as equilibrium profile in absence of the harbour wall. Profile 9 is located in an area of rocky outcrop and maximum direct wave attack. Although this area is probably one of maximum potential onshore/offshore sediment movement it is felt that the effect of outcrops and shore-normal wave orthogonals limits any longshore component and the Bruun Rule is used in its simplest form. Profiles 10 and 11 also use two erosion rates (330,000 m^3/yr/5,000 m and 500,000 m^3/yr/5,000 m) the lower indicating an "average" erosion rate and the higher indicating an upper limit of erosion (CSIR, 1985).

Table 2 shows the anticipated increased saline wedge intrusion under current extraction rates for the three sea level rise scenarios for profiles A to F indicated in Figure 4. The calculations assume a simplified topography and uniform hydraulic conductivity. The results show that the amount of increased intrusion is much less than the maximum possible should fresh water flow rates be reduced.

Application of the Ghyben-Herzberg relationship using a shore to interface toe distance of 6,500 m, an average toe depth of 50 m and a hydraulic conductivity of 40 m^3/d shows that the rate of seaward fresh water flow may be calculated to be 0.2 m^3/m/d. This value is likely to be more representative of fresh water flow, especially in the northern part of the aquifer. If the width of the aquifer is approximately 20 km, the total seaward flow may be calculated to be of the order of 4,000 m^3/d. Extraction of fresh water at rates greater than 4,000 m^3/d (or 170 m^3/hr) within the Kuiseb aquifer will therefore cause the saline wedge to migrate landwards, reducing the volume of useable aquifer in the wedge section. Any over extraction will obviously exacerbate the impacts of sea level rise.

Figure 5 shows the elevation of the water table surface and the approximate topography. Any change in sea level will be accompanied by a similar change in water table elevation. Virtually the whole town lies below 2 m elevation (F.F. LANGE, *personal communication,* 1990) and a few locations are very low lying such as the local sports stadium (1.0 m), cemetery, sewage works (1.0 m) and the local senior and junior schools and hospital (0.4 m). Any rise in the water table from its present position at about MHWS (0.71 m elevation) will have serious consequences for the whole town. A 0.2 m rise would probably cause the Voelparadys vlei to expand slightly and areas below 0.9 m, such as near the hospital and schools, would flood. A 0.5 m rise would further enlarge the vlei, flood a greater area of the town and harbour and probably cause engineering and pollution problems in areas such as the cemetery and sewage works. A 1.0 m rise in water tables would be likely to flood the majority of the town below about 1.7 m elevation. These water levels will not be af-

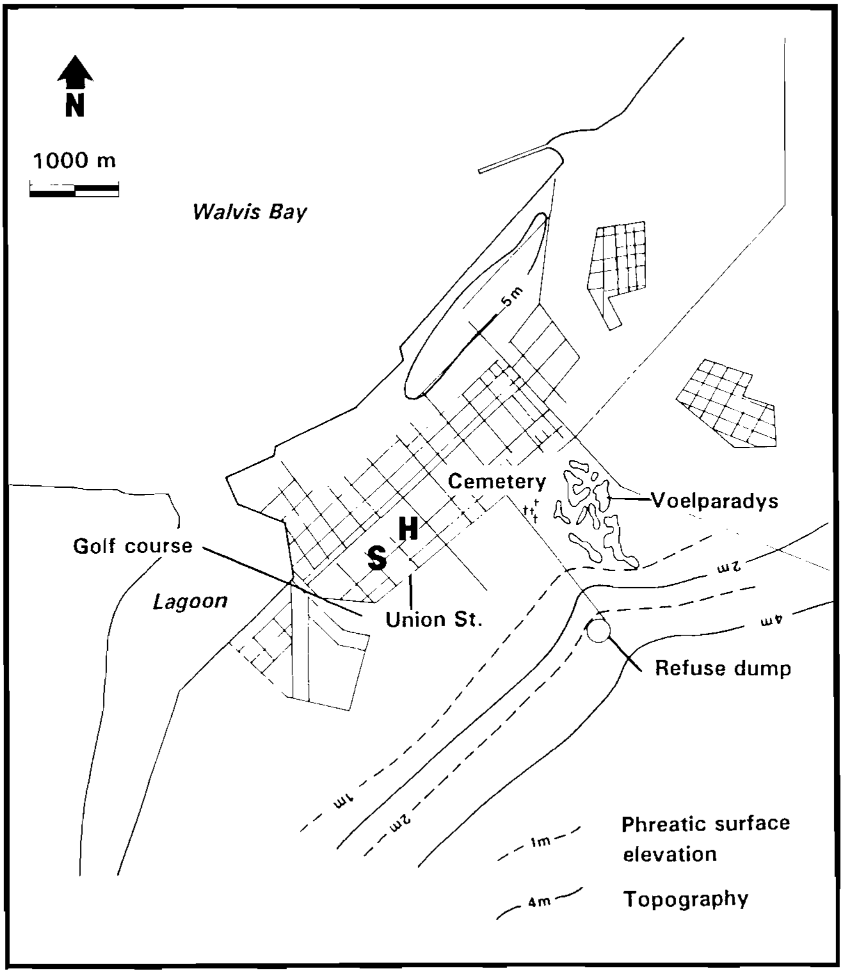

Figure 5. Approximate phreatic surface and topography elevations.

fected by freshwater extraction rates as the ground-water under the town is saline.

Figure 6 shows the return period curve for the present sea level at Walvis Bay plus the curves for MSL + 0.2 m and + 0.5 m. The current plot shows that Walvis Bay is extremely well sheltered from the effects of direct wave action and associated storm surge by Pelican Point. Extreme levels are very rare and the water levels achieved during an annual event and a 1 in 100 year event fall within a very narrow range of 1.08 m to 1.24 m elevation.

A rise in sea level of 0.2 m would therefore put the annual occurrence water level at 1.28 m—a level greater than the present 1 in 100 year event. During storms, wave action and chop will tend to increase the practical level of the wetted area. However, applying conservatism, it is fair to say that all land adjacent to the sea below this predicted water level will be flooded in the absence of preventative measures.

After a rise in sea level of 0.2 m, all land below 1.36 m adjacent to the coast will be flooded with an expected frequency of once in every 10 years. This level is possibly greater than that achieved if a 1 in 1,000 year event were to happen now. After a rise of 0.5 m, the MHWS will be higher than is probably attainable now during any possible storm and a 1 in 10 year storm will flood all land below 1.66 m elevation.

The effects of a 1 m rise are not practicable to consider for this exercise.

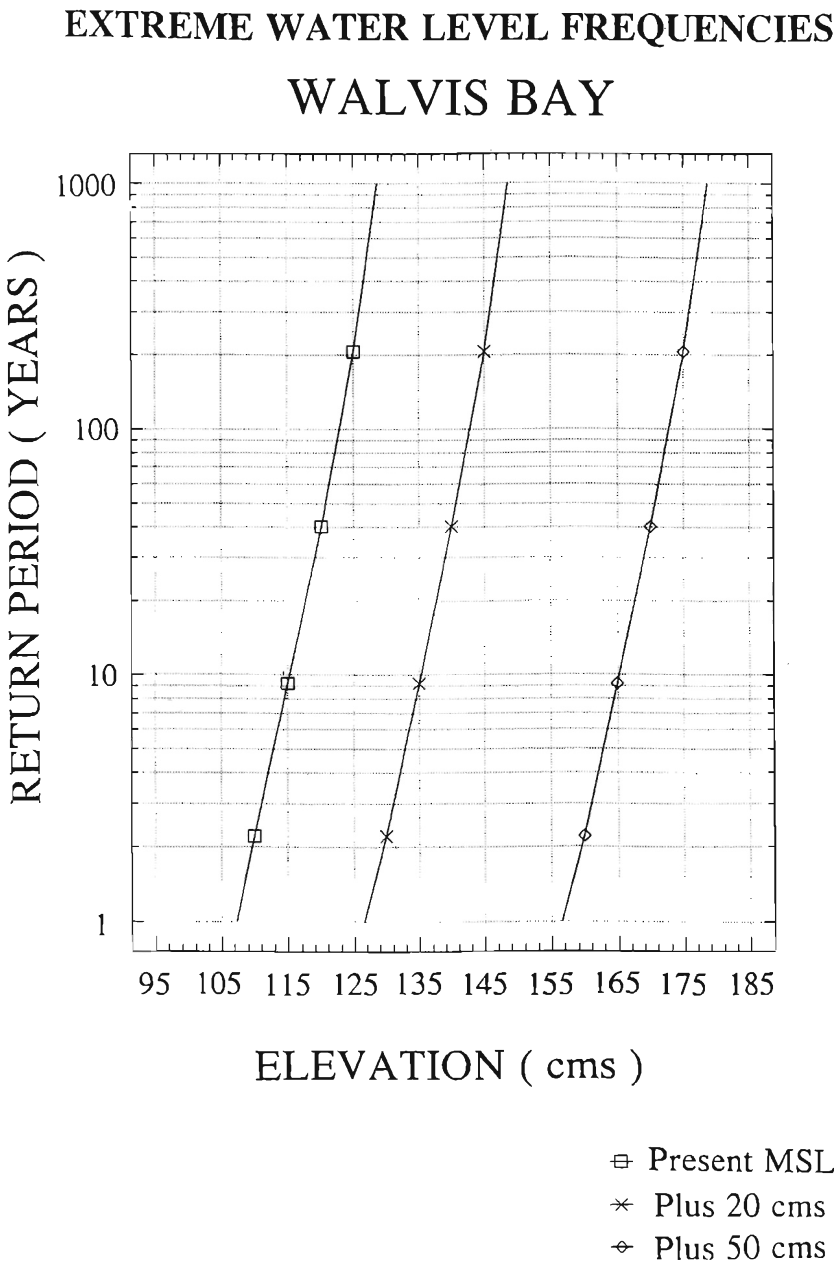

Figure 6. Extreme water level return frequencies for Walvis Bay with increments of 20 cm and 50 cm in sea level (after SEARSON, *in preparation*).

DISCUSSION

Application of the Bruun Rule for the prediction of erosion in such a dynamic sedimentary environment can at best be described as a hazardous occupation—the Rule can provide only a first order estimate. Sediment transport rates are not well known and the rates of progradation of Pelican Point both northwards and westwards will have a cumulative effect on sediment transport rates in other locations in the bay. In addition the effects of present and future dune stabilization on the huge sediment budget is unknown. Only the order of magnitude or range of rates of shoreline change is predictable. In order to improve on these estimates a detailed study of the sediment budget and wave climate in the bay would be necessary. This would be an arduous task in such an environment and the results would be of questionable value when considering all the possible variables. On the other hand there is a short answer which is eminently more practical: The coastal margin is an extremely active and harsh environment where development has in the past been either undesirable or impossible to carry out due to the shoreline's natural variability. Consequently any future shoreline change within the anticipated range is likely to be of limited impact to the local infrastructure. Management procedure would be simply to maintain any development a "respectable" distance from the shoreline, based on historical rates of change and local knowledge.

Equally difficult to predict in such a mobile environment are the areas likely to be inundated at high tide. Rising sea levels will tend to increase the tidal volume of the lagoon, but will the current rate of sedimentation be sufficient to keep pace with rising sea levels? Taking the area of land surrounding the saltworks wetted at high spring tides to be of the order of 30.5×10^6 m^2, sedimentation rates of 1.7×10^5 m^3 pa, 1.7×10^5 m^3 pa and 2.8×10^5 m^3 pa will be required under the three sea level rise scenarios in order for this whole area to keep pace with the rising water. Although these volumes of sediment are possibly available, their distribution will be uneven due to the stabilization of sections of the dunes up-wind and variable wind conditions. In addition, growth of Pelican Point will encourage migration of the shoreline in its lee and the land will probably continue to prograde from the southwest, squeezing the western saltmarsh against the saltworks and eventually squeezing the lagoon against the town. The ecological consequences of this are difficult to predict as a shift in wetland habitat does not necessarily imply a loss of habitat. The mobility of these areas and lack of accurate knowledge of sedimentation rates precludes a realistic delineation of those areas at risk except to say that land below 0.9 m, 1.2 m and 1.7 m elevation, if unprotected, will be inundated under the three scenarios. This will affect production in the salt works south of the town as the base level of the pans is at approximately 1 m elevation. Much of the town is at 1 m elevation and it is suggested that unless protected, inundation could take place through the lagoon mouth and onto the golf course and Union St. Certain low lying areas within the harbour area may also be vulnerable to some flooding.

Of greater consequence to Walvis Bay are the changes in saline groundwater levels under the town which will probably match changes in sea level. As a result, those low lying areas vulnerable to inundation will be vulnerable to waterlogging even if shore protection work is carried out. Lowering of the water table by extraction within artificial water compartments is likely to be prohibitively expensive. The exact definition of these low lying areas in the town is not possible due to the absence of detailed topographic plans.

If the current understanding of the Kuiseb aquifer dimensions and the freshwater extraction rates are indicative of a relatively stable saline intrusion, it is unlikely that rising sea levels and the associated increased saline intrusion will create major saline pollution problems. Rates of freshwater extraction are more likely to be the controlling influence on the position of the salt wedge and if these rates exceed 4,000 m^3/d then the wedge will tend to intrude further into the deep "wedge" part of the aquifer. Although all the extraction wells currently in use are outside the area for potential pollution (Figure 4) there are plans for extraction wells within this area (R. Bush, *personal communication,* 1990) and these may become vulnerable. A large portion of the Walvis Bay economy centres around its fish processing factories which have a high freshwater demand. Consequently aquifer over-exploitation is more likely to exacerbate saline intrusion than any changes in sea level. Proper aquifer management, essential to the welfare of the local community, can mitigate the effects of sea level intrusion.

By far the most serious consequence of rising sea levels for Walvis Bay is that of higher, storm induced, coastal water levels. As a result of the extremely effective sheltering of Walvis Bay by Pelican Point, the range of storm levels is very small. Development has therefore taken place using a narrow safety margin above "normal" water levels and the likelihood of an extraordinary event occurring is taken as "part of the risk". A change in water level shifts the range of "acceptable" levels and the norm quickly moves into a category of intolerable risk to present development with only a small change in mean sea level. For such a low lying town the effects could be devastating. Unfortunately there are a number of problems and assumptions used in the determination of extreme water levels in this example which may detract from the accuracy of the results. They must therefore rather be used as a good first model to provide an insight into the potential for storm damage.

When analysing tide gauge data for trends it is preferable to have a long record or at least a full nodal cycle (of 18.6 years) generated from identified tidal constituents. Unfortunately this is not available for hourly data in this instance and the results of the return period analysis must be considered an approximation. However, from experience with other South African data is was felt that 9 years of hourly data were sufficiently representative for these purposes. The 9 years of data used contain a 7 month period of anomalously high background sea levels from October 1983 to April 1984. Maximum positive anomalies of up to 7 cm were recorded (SHANNON *et al.*, 1986). This data set therefore may not be representative of the "Walvis Bay environment" and this may be expected to influence the water level return period distribution. Preliminary findings of ongoing research suggest that the influence of this so-called Benguela Niño on the statistical distribution is minimal and for all practical purposes can be ignored. In addition the Joint Probabilities Method (PUGH and VASSIE, 1978) assumes that surges are individual and non-sequential events and is limited in its ability to model the upper tail of the surge distribution.

Nevertheless it is clear that a rise of 0.2 m will have a more devastating impact than a 1 in 100 year storm at present levels and a rise of 0.5 m will be more dramatic than any storm currently possible. The effects of a relatively small or frequently occurring storm combined with a small increase in sea level (which could occur in the very near future) could therefore be disastrous.

In order for the town to survive, these impacts of sea level rise must be managed. The most important impacts have been identified and a first step towards managing them would be to flag those areas most vulnerable to the most serious hazards—*i.e.* inundation, waterlogging and storm damage. A moderately detailed survey of the area is the most logical route to follow, after which a more thorough plan of action for coastal defences or retreat may be drawn up.

CONCLUSION

The extremely dynamic sediment budget of the area makes the effects of increased coastal erosion on Walvis Bay of limited importance to existing infrastructure and these impacts may be carefully managed. Put simply, development has not taken place in the most dynamic and vulnerable parts of the coastline because these areas have traditionally been recognised as unstable and undesirable. Similarly, the increased intrusion of the saline wedge into the Kuiseb aquifer is something that can be managed and accommodated by judicious freshwater extraction. Sea level induced intrusion is secondary to freshwater demand.

Of greater consequence is the possibility of inundation, waterlogging and flooding of Walvis Bay. In many respects the town provides an analogy for the corollary of these impacts on low lying estuaries and tidal inlets. A rise of 0.2 m, in the absence of any coastal protection work being carried out, has potential to inundate all areas adjacent to the coast below 0.9 m elevation at MHWS. Likewise all areas of the town below 0.9 m elevation have potential for waterlogging and all areas below 1.36 m may be flooded with a frequency of once in every 10 years. The annual event storm water level would be greater than that achieved during a 1 in 1,000 storm at present.

A rise of 0.5 m has potential to inundate and waterlog the town and land below 1.2 m at MHWS and flood land below 1.66 m once in every 10 years. The extent of these vulnerable areas is not yet possible to measure accurately but is extensive.

A rise of 1.0 m would completely inundate and waterlog land below 1.7 m elevation. The effects of extreme events on what would be left of the town are not worth considering at this stage.

Much of the town of Walvis Bay lies below 2 m elevation. When considering the impacts of even a small rise combined with moderate size storms—the ability of the town to survive may be reduced long before the modelled rise takes place. Detailed surveys of the town and environs do not exist; their completion is essential to the first step in managing these impacts.

ACKNOWLEDGEMENTS

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□ RÉSUMÉ □

On examine les différents impacts potentiels d'une hausse du niveau de la mer à Walvis Bay, sur la côte de Namibie. Le milieu de Walvis Bay est aride semi-désertique, la majeure partie de la ville se situe à 2 m au dessus du niveau de la mer. Elle est abritée du régime des houles par une large flèche sableuse, qui, sur cette côte ouverte, est sévère. La région a un budget sédimentaire excédentaire qui dépend tout à fait d'une petite nappe d'eau douce. Cet article démontre la vulnérabilité d'environnements semi-abrités aux élévations du niveau de la mer et le besoin impérieux d'une gestion du bilan sédimentaire dans toute évaluation de l'impact sédimentaire. On a considéré quatre catégories d'impacts potentiels: accroissement de l'érosion littorale, inondation, accroissement de l'intrusion saline et surélévation des nappes phréatiques, et enfin, protection réduite contre les événements extrêmes. L'accroissement de l'érosion a un impact limité sur la ville mais les trois autres impacts potentiels peuvent avoir de sérieuses conséquences, surtout la menace d'événements extrêmes. On a analysé neuf années d'enregistrements de marégraphe et dressé une courbe des fréqences du retour d'un niveau de l'eau. On a montré qu'une élévation de 20 cm du niveau de l'eau était suffisante pour amener le niveau de l'eau d'occurence centenaire à une occurence annuelle. Dans le futur, une tempête se produisant tous les 10 ans, après une élévation de 20 cm du niveau de l'eau atteindrait un niveau d'eau plus haut que le niveau atteint tous les 100 ans. Cet impact potentiel permet la comparaison avec d'autres environnements en position d'abri par rapport aux effets de l'érosion littorale, comme les goulets de marée et les estuaires.—*Catherine Bousquet-Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ ZUSAMMENFASSUNG □

In diesem Aufsatz werden die möglichen Auswirkungen eines steigenden Meeresspiegels auf die Hafenstadt Walfischbai an der Küste von Namibia erörtert. Die größte Teil der Stadt Walfischbai, welche in einer ariden, halbwüstenartigen Landschaft angesiedelt ist, liegt ca. 2 Meter über dem mittleren Meeresspiegel. Vor der vorherrschenden Wellenrichtung ist die Stadt durch einen ausgedehnten Nehrungshaken geschützt. An der ungeschützten Küste sind dagegen Ausmaß und Wirkung der Wellen nicht unbeträchtlich. Das Gebiet hat einen äußerst dynamischen Sedimenthaushalt und ist in seiner Süßwasserzufuhr vollständig von einem schmalen Frischwasseraquifer entlang der Küste. In dem Aufsatz wird die Verwundbarkeit einer nur teilweise vor Meeresspiegelanstieg geschützten (Küsten-) Landschaft aufgezeigt und auf die Notwendigkeit einer exakten Erfassung des Sedimenthaushaltes bei jedweder Bewertung und Einschätzung möglicher Auswirkungen hingewiesen. Es wird vorgeschlagen, zwischen vier Kategorien möglicher Auswirkungen eines Meeresspiegelanstiegs zu unterscheiden: Zunahme der Küstenerosion, Überflutung bzw. Überschwemmung, stärkeres Eindringen von Salzwasser und Anstieg des Grundwasserspiegels sowie ein verringerter Schutz vor extremen Naturereignissen. Es wurde herausgefunden, daß ein Anstieg der Küstenerosion nur einen begrenzten Einfluß auf die Stadt haben würde. Die in den verbleibenden drei Kategorien zusammenfaßten Einflüsse könnten aber ernsthafte Gefahren darstellen, insbesondere die Bedrohung infolge von Extremereignissen. Auf der Basis neunjähriger stündlicher Tidenmessungen wurde mittels der einer statistischen Methode (Joint Probabilities Method) berechnet, daß bereits ein Anstieg des Meeresspiegels von 20 cm mehr als ein Jahrhundertereignis hervorrufen würde. Nach einem Anstieg des Meeresspiegels von 20 cm hätte ein zukünftiges Sturmereignis, welches dann mit einer Wahrscheinlichkeit von einmal in zehn Jahren auftreten würde, einen höheren Wasserspiegel zur Folge als ein aktuelles Jahrtausendereignis (d.h. ein Sturm in 1,000 Jahren). Die Methode zur Bewertung und Einschätzung der möglichen Auswirkungen des Meeresspiegelanstiegs kann auch für andere gefährdete Küstenlandschaften Anwendung finden.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, Germany.*

□ RESUMEN □

En este trabajo se consideran los potenciales impactos, sobre la ciudad portuaria de Walvis Bay, a causa de los ascensos del nivel del mar. Walvis Bay, es un ambiente semidesértico, árido, con gran parte de la ciudad situada 2 m por encima del nivel medio del mar. La ciudad está protegida, del régimen de olas dominantes el cual puede ser bastante severo, por una larga espiga arenosa. El área posee una importante dinámica sedimentaria la cual es dependiente de un pequeño acuífero costero de agua dulce. Este trabajo demuestra la vulnerabilidad de los ambientes semiprotegidos ante una elevación del nivel del mar y la necesidad de establecer balances de sedimentos precisos en cualquier intento de Establecimiento Potencial de Impacto. Se han considerado cuatro categorías de impactos potenciales: el incremento de la erosión costera, las inundaciones, el aumento de la intrusión salina y el ascenso de las napas freáticas y finalmente, la reducida protección a los eventos extremos. El efecto del incremento de la erosión costera posee un efecto limitado sobre la ciudad pero los tres impactos remanentes pueden tener serias consecuencias, especialmente ante la amenaza de eventos extremos. Nueve años de datos de alturas horarias de la marea fueron analizados, utilizando el Método de Probabilidad Conjunta y graficando las curvas de la frecuencia de retorno del nivel del agua. Hallando que una elevación del nivel del agua de 20 cm era suficiente para elevar la ocurrencia anual del nivel del agua por encima de un evento corriente de una probabilidad de 1 en 100 años. Una tormenta de un evento futuro 1 en 10 años, después un ascenso de 20 cm, se podría alcanzar un nivel de agua más alto que los que podrían haber alcanzado actual de 1 en 1,000 años.

Este Establecimiento Potencial de Impactos provee una analogía para otros ambientes los cuales pueden ser alterados a partir de los efectos de la erosión costera tales como en estuarios y pasos con mareas.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*