Assessing the impacts of development on the coastline of Table Bay, South Africa: an empirically-driven student learning experience

Evaluación de impactos derivados del desarrollo costero en la bahía de Table Bay, África del Sur: una experiencia de aprendizaje empírico para estudiantes

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Abstract

A group of 14 post-graduate oceanography and marine science students plus 3 academic staff undertook a coastal zone project in Cape Town, South Africa in order to maximize their understanding of the research process whilst adhering to the principles of bona fides science. The appropriate vehicle for this learning environment was a local field excursion, however the full work programme involved the discussion of working hypotheses, project planning, sample collection, data acquisition, laboratory analyses, data interpretation, report writing and assessment. The area of study was the increasingly developed coastal environment on the eastern shore of Table Bay, South Africa. Field observations were made of the surf zone, beach stability, state of the backing dune barrier and the flow and water quality of the adjacent Diep River. Each of these areas of study gave cause for concern. The river was found to deliver 0.40 and 0.43 tonnes of nitrogen and phosphorus per day respectively into coastal waters. Similarly to many coastal embayments subject to anthropogenic pressure, Table Bay is considered likely to be sensitive to any future increases in plant nutrient input leading to the seasonal occurrence of eutrophication, harmful algal blooms and a gradual deterioration in ecosystem health. Flooding of the area behind the protective dune barrier is expected from extreme rain events in the catchment with damage to the commuter network. A breach of the dune barrier by extreme waves during a severe storm will result in regular winter flooding by the sea and severe damage to the road infrastructure. Recommendations as to the actions needed to guard against these negative future scenarios include the minimising of nutrient inputs, maintaining an open river flow and an intensive dune rehabilitation programme.

Key words: *coastal zone, surf zone, beach stability, dune barrier, water quality, excursions, students*

Resumen

Un grupo de estudiantes de posgrado en oceanografía y ciencias del mar realizó un proyecto en la zona costera de la Ciudad del Cabo, África del Sur. El objetivo fue que los estudiantes participantes maximizaran su comprensión del proceso de investigación y de los auténticos principios científicos. El método apropiado para este ambiente de aprendizaje fue una excursión de campo que involucró los siguientes pasos: discusión de hipótesis de trabajo, diseño del plan de trabajo, recolección de muestras, toma de datos, análisis de laboratorio e interpretación de datos. Además, se preparó y evaluó un informe científico con las principales conclusiones del estudio. El área de estudio correspondió a la costa occidental de la bahía Table Bay, una zona de creciente desarrollo en África del Sur. Durante la excursión de campo, se observó la zona de rompimiento de olas, la estabilidad de la playa, el estado de la barrera de dunas, así como el flujo y calidad del agua del río adyacente. Se encontró que el río entrega 0.40 y 0.43 toneladas de nitrógeno y fósforo por día a las aguas costeras, respectivamente. Se considera altamente probable que la bahía de "Table Bay" sea sensible a los siguientes factores: incremento en el aporte de nutrientes vegetales conducentes a la ocurrencia estacional de eutroficación, ocurrencia de floraciones de algas nocivas y degradación gradual en la salud del ecosistema. Se espera que eventos de lluvias extremas resulten en inundaciones más allá de la barrera de dunas protectoras, ocasionando daño a la red ferroviaria. La destrucción de la barrera de dunas por acción de oleaje derivado de tormentas extremas resultará en inundaciones invernales regulares y daño severo a la infraestructura vial. Algunas de las recomendaciones necesarias para resguardar el sistema contra estos potenciales escenarios futuros son: minimizar el aporte de nutrientes, mantener un flujo ribereño abierto y establecer un programa intensivo de rehabilitación de dunas.

Palabras clave: *zona costera, zona de rompimiento de olas, estabilidad de la playa, barrera de dunas, calidad del agua, excursiones, estudiantes.*

INTRODUCTION

In August 2004, under the guidance of three academic staff, a group of 13 students, comprising the University of Cape Town Oceanography Honours' class and members of the Applied Marine Science taught Masters' course, undertook a research-in-action project to investigate the coastal environment on the eastern shore of Table Bay. This project formed part of a module which introduced students to various aspects of coastal and shelf oceanography such as; waves and beaches, beach ecology, water quality, shelf currents, satellite oceanography and shelf ecosystems. The project itself involved an integrated study of the wave climate, beach and dune morphology and river water quality in the area, in respect of its present state and its possible future configuration. It was the academic staff's wish to provide an effective learning environment for the students that would help to underpin their future research endeavours. The first step in this process was to convene a planning meeting with the students during which a suite of objectives was set which incorporated a number of working hypotheses. A research plan was formulated which included the identification of relevant field sites, methods of sample collection and data acquisition. The students were given training in the use of instrumentation and appropriate laboratory techniques for the determination of certain water quality variables. A plan was also put in place for the interpretation of data and the writing of a scientific paper. This phase would take the form of a "data interpretation workshop" and "theme groups" that would write sub-sections of the paper in a tutored environment. Each individual student was required to produce a report on the particular "theme" they were allocated. The portfolio for the course required that the students' work as a team in identifying the major hypotheses, defining the objectives and identifying the methods to be used in acquiring the necessary data. Each student was then assessed individually on their initiative and contributions within the group in addition to their conduct in; the field, the laboratory, data analysis and report writing. The students' work during the project would be formally assessed as part of their portfolio for the course. Once the individual reports were assessed, the groups reconvened in order to co-author their sub-sections. The outcome of this process is presented below.

The construction of new and extension of existing coastal harbours may alter the distribution of wave energy in their vicinity, so that the equilibrium state of nearby beaches is disrupted and long-term coastal erosion is initiated. Many beaches are backed by sand dunes, which provide a physical barrier between the sea and the land. When the dunes are damaged by erosion, either through the removal of the binding vegetation or in combination with a more extreme wave climate, the consequences can be severe, not only for the dune barrier, but also for any residential and industrial infrastructure behind the dune barrier.

This is the case with Cape Town harbour. Its gradual extension in the twentieth century led to persistent erosion on the eastern shore of Table Bay. Between 1944 and 1958, severe erosion close to the harbour resulted in the loss of the seafront marine drive leading from the harbour (CSIR, 1972). The coastline along the eastern shore receded by an estimated 80m between 1900 and 1980 (CSIR, 1983), whilst erosion by a further 40m was expected to occur as a continued response to this harbour development (CSIR, 1986). Future additions to the harbour could well exacerbate the erosion problem over an even longer time period.

On this eastern shore (figure 1), Milnerton Beach and its backing dunes form a relatively thin band between the ocean and the lower reaches of the Diep River. The dunes protect a small up-market housing development, Woodbridge Island, and an 18-hole golf course, with access across the river provided by a small road bridge. On the landward side of the river is the R27 Otto du Plessis arterial commuter highway, with residential properties on its inland side. The Diep river (Beaumont and Heydenrych, 1980; CSIR, 1988) drains the extensive Rietvlei wetland system, whilst its upper catchment supports a large agricultural area. The river acts as a conduit to the adjacent coastal zone delivering nitrogen and phosphorus to the sea. Due to anthropogenic activity in the catchment it is important to establish the extent of nutrient delivery since it may pose a eutrophication threat. The estuary of the Diep river has been dredged on several occasions in the past to maintain its depth and to assist the rather sluggish through-flow of river water. Recent river flow conditions and human intervention determine whether the river mouth is open or closed.

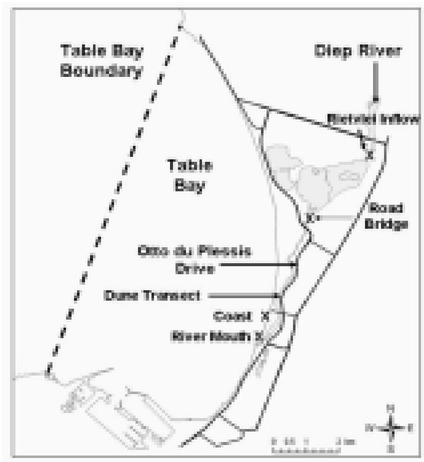

Figure 1. Study area. Water sampling sites are marked X. The outer boundary of Table Bay is delineated with a dashed line. The location of the dune transect is located with an arrow.

This coastline is under heavy development pressure (Quick & Roberts, 1993), with the construction of high rise beachfront apartments and the municipal services needed to support a rapidly increasing population. Erosion on this coastline continues, with the underlying cause being the coastal instability from the continued expansion of the Cape Town harbour. The need to anticipate future problems, arising from this juxtaposition of hard structures being placed in a soft and dynamic coastal environment, is becoming increasingly important. Sea level rise (Hughes et al., 1993) and changing weather patterns add to the complexity, with the possibility of more frequent extreme weather events exacerbating the situation (Searson & Brundrit, 1995).

The observations of the coastal environment, made on the day of the study, are now reported. This is followed by an assessment of the extreme conditions that might be expected, and the recommended actions needed to mitigate against the worst impacts.

FIELD RESULTS

Surf-zone and Beach.

The field work took place in the late morning on 19 August 2004, at Milnerton beach to the north of the mouth of the Diep river, (figure 1). Observations were taken on the early part of a flood tide, rising from a spring low tide in mid morning (table 1). According to the synoptic weather chart for the day, a high pressure cell was located some distance seawards of the bay resulting in light southerly winds, strengthening in the afternoon, with sunny and mild weather. Light winds implied that the level of the tide was a good indicator of sea level in the bay, with little additional wave action beyond the light swell generated in the deep ocean. Surf and beach characteristics were derived from measurements of the sea state, beach slope and sediment type present, and through the calculation of surf scaling and beach stability parameters (Brown & McLachlan, 1990) (table 1).

At approximately 100 metres from the shore, plunging waves with a significant wave height of 1.5m were observed, suggesting the presence of a subsurface sandbar. Closer inshore, 4 to 5 rows of low spilling breakers were evident over the relatively flat outer beach. The surf scaling parameter relates the breaker type to the measurements of beach slope and wave height at the break point. During the field study, the

Table 1
Tides, wave climate and beach characteristics, 19 august 2004

Time of tide	**Height relative to mean sea level**
High tide at 04h33	0.63 m
Low tide at 10h34	- 0.74 m
High tide at 16h50	0.74 m
Low tide at 23h00	-0.67 m
Observed parameter	**Value**
Beach slope below mean sea level	1:75
Beach slope above mean sea level	1:9
Beach sediment	Medium sand
Maximum wave height at outer breakpoint	2.0 m
Significant wave height at outer breakpoint	1.5 m
Wave period	13 s
Surf beat	130 s: 10 waves
Derived parameter	**Value**
Mid-tide surf scaling parameter	129.4
Spilling breaker surf zone set-up	0.5 m
Beach stability parameter	4

values of the surf scaling parameter confirmed that a spilling breaker environment across the surf zone and lower part of the beach should be expected. After the completion of the field study (high tide), the sea would have reached the steeper part of the beach, inshore of the line of mean sea level, where a surging breaker may have developed. The beach stability parameter describes the inherent beach variability in terms of wave characteristics and sediment particle size. The value calculated suggested a marginally unstable beach environment, with sediment movement that would eventually lead to the shoreward migration of the offshore bar and its associated plunging breakers.

In summary, a low energy sea-state, in the surf and on the beach, was observed during the fieldwork, with low water levels, small waves and light winds. A more robust surf environment is more typical of conditions along this coastline, with the overall beach rating (Brown and McLachlan, 1990) for Milnerton Beach falling into the category of an exposed beach. Whilst this still represents a set of conditions with little impact on coastal structures, the implications of extreme wave events in the same environment can be profound.

Section across the dunes

Previous studies have shown that the narrow band of dunes behind Milnerton Beach is being subjected to erosion. This is manifested in the loss of natural binding structures in the beach zone and a progressive reduction in overall beach and dune area (CSIR, 1988). The adjacent land consists of sandy soil, which requires binding in order to combat erosion from the sea and river. Since the river runs parallel to the beach, the dune barrier is crucial for the protection of all the land behind. If this dune were to be breached by wave action, it would lead to an inundation of sea water onto the golf course and up to the main coast road.

The narrowest and most vulnerable point in the dune barrier is situated about 200m north of the lighthouse on Woodbridge Island. A vertical section (figure 1), from the beach, across the dunes and golf-course to the river and road, was surveyed using a Racal Landstar MkIV DGPS Receiver. The heights were recorded with reference to the WGS84 best-fit spheroid, and the measurements were differentially corrected to a reading above the local geoid, using a nearby base station. The first reading was taken at the limit of the beach swash zone which, at the prevailing wave set up and tidal level, corresponded to a height of 0.5 metres above the predicted mean sea level. Thus, it was established that the height readings were accurate to within 0.1m, and fell within the standard deviation for the DGPS measurements in the vertical. Heights above mean sea level and horizontal positions were measured at the base of the dune, the top of the dune, at the lagoon and at the road level. A schematic of the section is given in figure 2.

River water quality

In the Diep river, hydrochemical measurements along its lower reaches were made, with the objective of estimating its delivery of nitrogen and phosphorous into adjacent coastal waters. Surface samples were taken at four sites (figure 1):

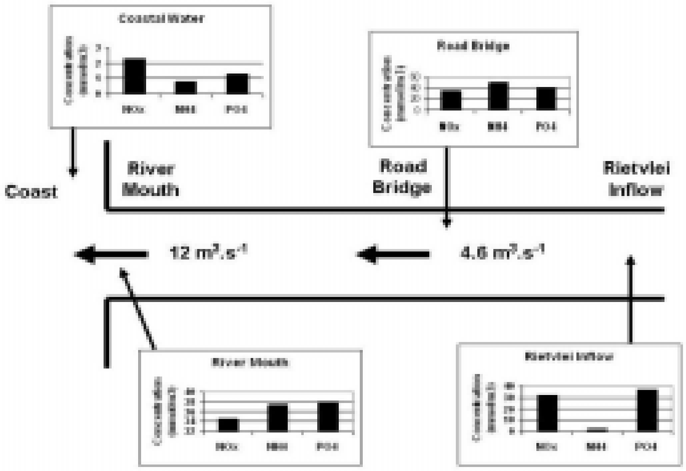

Figure 2. Cross section of dune transect showing height (m) above mean sea level.

- Table Bay shoreline (~300m north of the river mouth).
- The mouth of the Diep River.
- The river next to the Otto du Plessis Drive road bridge.
- Upriver at the inflow to the Rietvlei wetland.

Current speed and cross-sectional area were measured at the river mouth and road bridge sites. All sites were sampled and analysed for nitrate plus nitrite nitrogen (NO^-_x-N), ammonium nitrogen (NH_4^+-N) and phosphate phosphorus (PO^{-3}_4-P) according to Grasshoff *et al.* (1983), scaled to a 5ml sample size. Results are given schematically in figure 3.

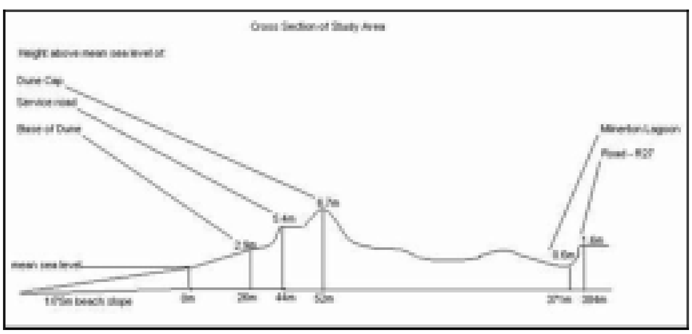

Figure 3. Concentrations of NOx—N, NH_4^+-N and PO^{-3}_4-P (mmol.m^{-3}) at the four sampling sites plus volume fluxes (m^3.s^{-1}) of the Diep River.

The Diep River nutrient concentrations were higher than in the coastal water, generally speaking the increase being by factors of ten. The exception to this was the low ammonium concentration measured at the Rietvlei inflow site. This suggests that the source of ammonium is an influx into the river between the Rietvlei inflow site and the road bridge that as yet remains unidentified.

The volume fluxes of water estimated at the river mouth and road bridge were found to be 12 m^{3}s^{-1} and 4.6 m^{3}s^{-1} respectively. Tidal action may act as the largest input into this increase in water volume, as sea water enters the estuary during higher sea levels when the river mouth is open. For this reason, the volume flux measured at the river mouth during a low tidal level probably represents a maximum discharge. The average flux over the tidal cycle is probably best represented by the measurement at the road bridge site, away from the tidal influence.

The delivery of nitrogen and phosphorous into Table Bay by the Diep River was calculated using the average flux in combination with the hydrochemical concentrations to give an average contribution for the prevailing conditions. Molar quantities of carbon (C), nitrogen (N) and phosphorus (P) have been converted to mass by multiplying by 12, 14 and 31 respectively.

Average N (NO^-_3+NH_4^+).

4.6 m^{3}s^{-1} * 71.9 mmol. m^{-3} = 330.7 mmol. s^{-1} = 0.40 tonnes of N per day.

Average P.

4.6 m^{3}s^{-1} * 37.8 mmol. m^{-3} = 173.9 mmol. s^{-1} = 0.43 tonnes of P per day.

This daily input of N and P into Table Bay seems substantial.

Extreme event scenarios

The aims of this section are to examine extreme events in the river and along this stretch of coastline.

The volume flux in the Diep river shows a seasonal cycle typical of the winter rainfall region. The only appreciable flows occur during the middle months of any year, with a mean monthly run-off of 10^6 m^3 or a sustained discharge rate of 4 m^3 s^{-1} being typical of winter (CSIR, 1988). Peak discharge rates, achieved after heavy rain in the river catchment, are accompanied by flooding of low-lying land bordering the river. On 13 June 1974, the peak discharge rate reached 56m^3 s^{-1}, the river covered much of the golf course and the water level reached the road level, 2.1 m above mean sea level, along the R27 Otto du Plessis Drive. Two months later on 21 August 1974, the peak discharge reached 87 m^3 s^{-1}, but the water level only reached 1.8 m above mean sea level as the river mouth was wide open after the earlier flood event. The magnitude of the anticipated 50 year peak discharge in the Diep river was estimated as 210 m^3 s^{-1} from synthetic flow analysis (CSIR, 1983).

As far as extreme wave events along the coast are concerned, a fifty year storm event, which occurred on 16 May 1984, is well documented (Hughes *et al.*, 1993) in respect of wave conditions and the accompanying erosion. This event can be used to give confidence to the approach. A prediction of the conditions to be expected from the typical strongest storm to occur on an annual basis can then be realised.

During the storm of 16 May 1984, wave records were available from the CSIR wave recorder, then situated 7 km offshore of Slangkop Lighthouse at a point 20 km to the south of Table Bay, and the wave recorder for the Koeberg Nuclear Power Station, just north of the study site. At the deep sea Slangkop recorder on the day of the storm, the significant wave height reached 10m, with a maximum individual wave height of 16m. The corresponding recordings from the Koeberg wave recorder were a significant wave height of 6 m, with a maximum wave height of 10 m. This loss of wave energy is consistent with the dissipation due to white-capping and bottom interaction, and to refraction of the south-westerly wave field as it turned into Table Bay.

Assuming that the maximum wave experienced at the Milnerton study site on that day was also 10 m in height, the wave set-up from the spilling breakers in the surf zone can be estimated to be 2.5 m. The occurrence of a spring high tide, reaching 0.75 m above mean sea level on that day, meant that the sea level associated with the maximum wave would have reached 3.25 m above mean sea level. The surf zone would have extended well onto the steeper section of the beach onshore of the line of mean sea level, where the spilling breaker would have been transformed into surging breakers. The wave height at this line of mean sea level can be estimated to be 80% of the water depth at this point, at a value of 2.6 m. The much more vigorous character of the surging breakers would have led to a wave set up of double the initial surging breaker wave height, reaching 5.2 m. Again with the addition of the spring high tide, the peak water level at the beach associated with the maximum wave was estimated to reach 5.95 m above mean sea level.

The dune face would be severely eroded by the surging breakers and overtopping of the dune would be possible. This was indeed recorded (CSIR, 1986; Hughes *et al*., 1993), with a recession of the coastline by 30m. The service road atop the dune was damaged beyond repair and later abandoned, whilst severe erosion and loss of unprotected land occurred at neighbouring beachfront properties. This agreement gives credence to the approach adopted in this section.

The effects of the strongest storm to be expected on an annual basis can now be investigated. The wave climatology established for the Slangkop wave recorder over a period of forty years gives a 1% significant wave height of 5.4 m and a maximum wave of 9 m (Rossouw & Rossouw, 1999). Again reducing the expected wave heights at Milnerton, the 1% significant wave height can be expected to be 3.2 m, with a maximum wave of 5.4 m. According to an investigation into extreme sea levels around the coast of southern Africa (Searson and Brundrit, 1995), it is the combination of storm surge and spring high tides which give rise to extreme sea levels. Assuming spring high tide conditions and the maximum wave, the spilling breaker wave set up on top of the tide will give rise to a maximum sea level of 2.1 m above mean sea level. This will again bring the surf zone onto the steeper section of the beach and transform the breakers into surging breakers inshore of the line of mean sea level. At this line, the wave height of the initial surging breaker will be 1.7 m. The surging breaker set up will reach 3.4 m and, with the addition of the spring high tide of 0.75 m, the maximum water level will reach 4.15 m above mean sea level.

Thus the strongest winter storm to be expected on three days in each year (the 1% wave climate), if it coincides with spring high tide, will reach past the base of the dune at 2.9 m above mean sea level and begin to erode the dune face. Even a neap high tide will produce some erosion in these annual storm conditions. Erosion of the dune barrier is likely to be an annual occurrence, with severe erosion from the fifty year storms.

DISCUSSION

Typical field observations made at the study site on the eastern shore of Table Bay, on the beach, along the river and across the dune barrier separating the river from the beach, have revealed the normal environmental loading at the study site. From this, the key elements of potential vulnerability to this coastal and estuarine system can be investigated further. Three threats to the health and stability of the coastal environment are now discussed:

- The gradual eutrophication of coastal waters in Table Bay through increased nutrient input from the river,
- Flooding of the golf course and the R27 road from the river, and
- The complete erosion of the protective dune barrier and the exposure of roads and housing to regular inundation from the sea.

Eutrophication in Table Bay

An attempt can be made to put the average rates of nutrient input into Table Bay into context by assuming its total assimilation by phytoplankton and expressing this in terms of carbon fixed by primary production. In this respect, either the N or P input can be converted to carbon (not both). It was decided to use N input for the calculation of primary production. The Redfield ratio between C and N in the marine environment is 106:16. In order to provide a conservative estimate of potential primary production due to Diep River N and P, the average rate of river flux (4.6 m^3s^{-1}) was used.

Primary production due to N input:

4.6 m^3s^{-1} * 71.9 mmol.N. m^{-3} * 6.6 = 2182.9 mmol.C.s^{-1}
2182.9 mmol.C. s^{-1} * 12 = 26194.8 mg.C. s^{-1} = 2.3*10^9 mg.C.d^{-1}

Table Bay was given an outer boundary line between Green Point and Bloubergstrand, (figure 1) giving a surface area of 72.25*10^6 m^2. The per unit area contribution of the Diep River to Table Bay was then calculated as 31.8 mg.C.m^{-2}.d^{-1} (or 0.03 g.C.m^{-2}.d^{-1}). This calculation assumes an even distribution of nutrient input over Table Bay although it is likely that there is a northward long-shore drift.

Spring and summer primary production rates have been found to vary between 1.5 and 3.7 g.C. m^{-2}.d^{-1} in the southern Benguela (Waldron, 1995). The contribution of the Diep River, under the prevailing conditions, was therefore found to contribute (potentially) between 0.9 and 2% of ambient Spring and Summer primary production rates (not insignificant for a small river system feeding into a major upwelling system).

From this integrated snapshot study the following conclusion can be drawn. Water quality in Table Bay is likely to be sensitive to any future increase in nutrient input from the Diep river. Failure to address this issue may lead to the seasonal occurrence of eutrophication, harmful algal blooms and a gradual deterioration in ecosystem health. This means that the source of ammonium in the river needs to be established and measures taken to ensure that the concentration levels are kept to a minimum.

River flooding

The 50 year peak discharge in the river was estimated at 210 m^3 s^{-1}, well above the flow rate of 56 m^3 s^{-1} which accompanied the widespread flooding in june 1974. Two important factors need to be taken into consideration before it is assumed that more serious flooding should be expected in the future. Both refer to conditions within the river itself. Since the synthetic flow analysis was carried out to give the estimates of the 50 year peak discharge rates, there has been much construction of dams for agricultural purposes within the upper catchment area. This will lead to a greater impoundment of flood waters and a lowering of the expected 50 year peak discharge rate. On the other hand, whether or not a high discharge rate necessarily means flooding of low-lying land depends on the accompanying water levels. Despite the greater discharge rate in august 1974 compared to june 1974, the flooding was less on the later event. Sediment build-up in the river, especially at the bridges and at the river mouth can seriously impede the flow and exacerbate the potential for damage from flooding. Ensuring that the water course is kept as open as possible and, if necessary, artificially opening the river mouth will be the most effective measures to be taken to avoid flood damage from the river.

Inundation from the sea

In the event of a dune breach during extreme wave conditions, sea water will flood onto the golf course behind the dune barrier and into the river. The ebb tide will widen the breach and mean that this route will remain available at each successive high tide for the sea to flood into the area behind the dune. The river will then change its course and use the newly opened short cut as a shorter and faster outlet to the sea.

At each high tide, access by the sea through the breach in the dune barrier and into the new lagoon area will occur. Spilling breakers will move through the breach and across the very flat (slope of approximately 1:500) ground behind the dunes, reaching right up to the R27 commuter route, a vital artery in Cape Town's road network. The annual maximum expected sea level of 2.1 m in a spilling wave environment, will be well above the present river water level of 0.6 m above mean sea level, and even the road level at 1.6 m. The R27 road will be vulnerable to flooding from the sea every winter. The 50 year maximum expected sea level of 3.25 m will be well above road level and cause substantial damage to property on the landward side of the road. If the river were to come down in flood as a result of the high rainfall associated with winter storms the situation would be compounded resulting in even higher water levels and greater flooding of the road.

The dunes are evidently under threat and, although it is difficult to estimate to what extent and when they will be completely eroded by wave action, it seems inevitable that preventative measures will need to be taken to prevent a situation where the R27 road is being flooded every winter. The simplest way to achieve this is to provide additional stabilisation of the dune barrier. Further south towards the estuary, dune stabilisation measures have been taken to protect private property. After brick walls, beams and concrete slabs all proved to be ineffective, a formidable bank of expensive rounded ceramic blocks now seems to be working. Closer to Cape Town harbour, protection of the coastal road was achieved with hard engineering in the form of a heavily armoured sea wall. However, this was accompanied by the complete loss of the beach. Until a permanent solution is found, an immediate and intensive dune rehabilitation programme is recommended, including artificially increasing the height of the dune to a recommended 10 m above mean sea level (CSIR, 1986), and planting plenty of indigenous vegetation. This should keep the sea out under normal conditions but will not be sufficient protection against significant sea level rise.

Pedagogic value

It was felt by students and academic staff that the project-based work reported here provided a highly successful learning environment for recent post-graduates. The students were part of the research process and took part in the setting of objectives, assignment of roles and responsibilities and, ultimately, provided an outcome that was meaningful to them and others as well as being assessable as part of the education process.

Specifically, the students acquired the following skills as a result of the learning process:

- Surf zone and beach measurements required the understanding and observation of local meteorology, tidal forcing, wave generation, sea state, beach slope and sediment type and the interactions occurring therein.
- Dune profiling resulted in the students learning how to use sophisticated Differential Global Positioning System instrumentation and understanding the relevance of the WGS84 best-fit spheroid and the local geoid.
- Water Quality measurements introduced the students to the methods of sampling and laboratory analysis for a range of hydrochemical variables.
- Having acquired the foregoing expertises, an exercise in extrapolation permitted the students to predict the consequences for the system under "extreme event" scenarios.

Having undertaken this work and, as their research careers advance, the students will have a fuller understanding of the processes involved in conducting an empirical research project and using such results in an interpretative way so as to provide information useful to (*inter alia*) environmental managers.

CONCLUSIONS

In the event of increased nutrient delivery by the river system, the coastal zone may be subject to the future threat of eutrophication and increased frequency of red tide.

Sediment build-up in the river system should be carefully monitored so as to avoid increased likelihood of flooding.

The dune height should be artificially increased to a height of 10m above mean sea level as part of an intensive dune re-habilitation programme.

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