



Floods, sedimentation and tidal exchanges in the Keurbooms Estuary, South Africa

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Abstract

The relatively small Keurbooms/Bitou estuarine system on the south coast of South Africa forms a typical bar-built estuary, with a back-barrier lagoon and a barrier dune almost 4-km long. The lagoon is only about 500-m wide, while the barrier dune is not anchored to any substrate and consequently the position of the tidal inlet, or mouth, varies over the whole length of the barrier dune. This study analyses the sedimentary morphology over the years 2006–2019, during which time, three flood events caused substantial changes in the position of the mouth and the structure of the flood-tidal deltas and flow channels. It is found that after each flood the tidal exchanges reached a maximum, decreasing as sand entered the estuary again. The floods caused considerable infrastructural damage, and the sedimentary changes affected the tourism industry which is dependent on stable tourism attractions in the area. With no management changes, it is surmised that future floods will continue the process of dramatic changes in morphology of the estuary, though climate change may exacerbate these effects.

Introduction

Estuaries are the meeting place of rivers and the sea and the processes that occur at the tidal inlet, or mouth, determine the functioning of the estuary as a whole (Cooper et al. 1999). These processes involve in particular ocean waves, tides and the rivers themselves (Dyer 1997) and include the geological history of the region.

The wide range of these criteria occurring along the coastlines of the world means that there are a correspondingly wide range of estuary types. Of particular importance here are microtidal coasts (variation between high and low tides less than 2 m) and the sedimentation resulting from generally low river flows but high waves.

Bar-built estuaries occur when sandbars or barrier beaches are built up by ocean waves and currents along coastal areas fed by one or more rivers (Nardin and Fagherazzi 2012). Sediment availability determines whether an estuary has such a barrier or not, generally springing from a sharp change in

shoreline orientation and then extending parallel to the coast before reattaching to the mainland (Silvester and Hsu 1993). For rivers with low flow volumes, lagoons typically form in the area between the coast and the barrier beaches.

While average conditions can define the type of estuary being considered, it is the extreme events which have major impacts on the structure of an estuary. In particular, floods will wash accumulated sediment out of the estuary, changing the mouth and sand delta morphology, which may then slowly revert to its previous structures over the ensuing years.

Such coastal lagoons with associated barrier beaches often form prime tourist attractions, and the effect of human influences on the functioning of the estuary/lagoon system can be considerable. Nonetheless, it is also true that extreme events can cause considerable damage to such infrastructure built around a lagoon.

This study forms the final part of an investigation into the mouth structures and sedimentation in the lagoon and barrier dune sections of the Keurbooms Estuary. Several flood events over a period of some 15 years have seen substantial changes in the morphology of the estuary, leading to a better understanding of the processes involved. However, these results have not been transcribed into developing an adequate management strategy for the system.

This article is part of the Topical Collection on *Coastal and marine geology in Southern Africa: alluvial to abyssal and everything in between*

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Physical setting

The Keurbooms Estuary on the south coast of South Africa is formed by the confluence of the Keurbooms and Bitou Rivers (Fig. 1). It is part of a drowned river valley formed during the Pleistocene and earlier marine transgressions (Duvenhage and Morant, 1984) and has a combined catchment area given by Heydorn and Tinley (1980) as 1188 km², while Reddering (1981) estimated the catchments of the two rivers as 859 km² and 237 km², respectively (together 1096 km²).

Rainfall occurs throughout the year, with small peaks in autumn and spring (Heydorn and Tinley 1980). It is a relatively small system and Reddering (1981) estimated the annual discharge at around 72×10^6 m³, while Duvenhage and Morant (1984) determined the mean annual run-off over a 10-year period to be 64×10^6 m³.

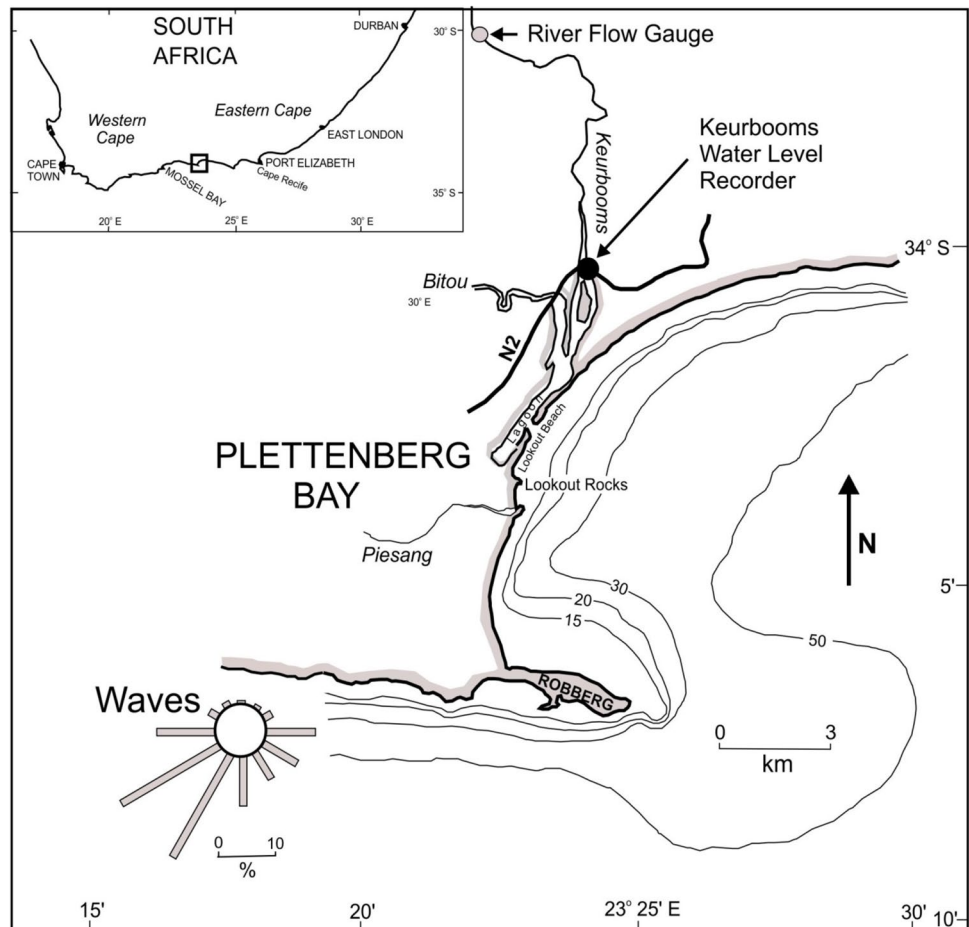
The drainage basin is predominantly underlain by ortho-quartzite of the Table Mountain Group which weathers to acid, well-drained soil. Duvenhage and Morant (1984) determined a sediment yield from the Keurbooms system of about 100,000 m³ pa but with an undefined part retained in the upper stretches of the river caused by infilling of the drowned river valleys.

Reddering (1981) found the sediment yield to be small, with fluvial sand forming only a small part of the estuarine sediment input. Illenberger (2003) inspected available aerial photographs between 1936 and 2003 and also found that river floods flushed insignificant amounts of sediment out of the lower estuary.

The combined Keurbooms and Bitou Rivers flow into a lagoon situated behind a sandy dune bounded in the south by the Lookout Rocks of the Cape Supergroup and in the north by a hard core of carbonate cemented beach/dune sand (B W Flemming, pers. comm.). This narrow back-barrier lagoon extends over a distance of almost 4 km and is only around 500-m wide. Fromme (1985) found that most sand grain sizes at the Lookout Beach fell into the range of fine to medium sand, while Reddering and Esterhuysen (1983) reported a 70% quartz and 30% carbonate content.

There are historical reports giving the position of the Keurbooms tidal inlet or mouth at various times, and Reddering (1981) reports that floodwaters from a severe storm in 1915 breached the barrier dune at its northern end. Thereafter there was a general migration of the mouth southwards, though with substantial fluctuations, and Fig. 2 depicts the mouth positions over the years 1936–2019.

Fig. 1 Site of the Keurbooms Estuary on the south coast of South Africa—indicated by the square. The annual wave directional distribution rose is shown (Rossouw, 1984), as well as the positions of the estuary water level recorder and river flow gauge. Isobaths in m from SAN123



The coast has a tidal variation that at times just reaches 2 m at spring tides and thus falls into the microtidal category. However, the small low-pressure atmospheric systems propagating from west to east along the coast can generate substantial coastal trapped waves with periods of days, and these cause variations in the background sea level of 0.5 m and more (Schumann 2013).

To the south, waves generated in the vast expanses of the Southern Ocean come primarily from the south-west (Fig. 1). The directional distribution for the area is shown in Fig. 1 (Rossouw 1984), while Joubert and van Niekerk (2013) found that more than 70% of waves had amplitudes greater than 2 m with a peak period greater than 10 s. Such waves, approaching the coastline at an angle, will serve to move available sediment eastwards along the coast, and at Mossel Bay to the west the longshore transport has been estimated to be between 5000 and 15,000 m³/year (Brew and Jones 2015).

The Robberg Peninsula (Cape Seal) serves as an obstacle to this eastward, wave-driven longshore sand transport, and a large sediment spit-bar has developed at the eastern end (Martin and Flemming 1986). In such situations deep-water waves will be refracted around the spit, and subsequent dynamics will depend on the angle at which they then strike the western coast of the Bay.

Reddering (1981) concluded that the longshore sand transport at the Lookout Beach was towards the northeast. This was confirmed later by Reddering and Esterhuysen (1983), and Reddering (1983) described the processes whereby the mouth moved southward against the prevalent sand transport. Fromme (1985) analysed the longshore wave transport at the centre of the Keurbooms Estuary barrier dune and concluded that it was north-eastward more than 80% of the time.

Sand that is being transported north-eastward at the coast needs to be replaced at the beaches to the south, and Silvester

and Hsu (1993) have shown that refracted waves can move sand across such a bay. Flemming and Martin (2018) have speculated that there are sediment compartments along this coast where sand is essentially recirculated, one such compartment being at Plettenberg Bay and the next farther east. While volumes are likely to be relatively small, at this stage the volume of sand moving out of the system is not known.

With limited river discharge, a high wave energy climate, and microtidal conditions, the Keurbooms Estuary forms a good example of a bar-built estuary. The sandy barrier dune is not anchored in any substrate resistant to erosion, and as such the mouth is not constrained to any particular section of the barrier dune; there is also no record of the mouth having closed at any time.

As is typical of such estuaries, the Keurbooms has a mobile subtidal sandy barrier that extends across the mouth (Cooper 2001). This produces an asymmetric flood-tidal signal in the estuary, where the flood tide flows for a shorter time than the ebb tide (Schumann et al. 1999). Consequently the flood-tidal currents are stronger than the ebb-tidal currents and more sand will enter the estuary mouth on the flood tide than exits on the ebb (Reddering and Schumann 2003). This is augmented by waves which penetrate farther into an estuary mouth during flood tide, and sand which is raised into suspension is then also carried farther. This results in flood-tidal sand deltas being established within the lagoon area, while small ebb-tidal deltas also occur at the exit of the estuary mouth.

Lookout Beach and the Keurbooms Lagoon form important components of the tourist attractions of Plettenberg Bay (Fig. 1). However, the dynamic and variable nature of the mouth has had substantial consequences for managing the infrastructure and facilities built around the beach and estuary. Not only has substantial damage been caused to roads, parking areas and buildings by floods, but the fact that the beach itself was washed away and inaccessible for a number of years also affected tourism.

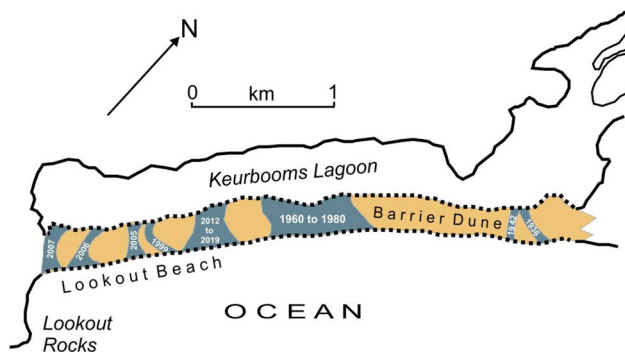


Fig. 2 The Keurbooms Lagoon and associated Barrier Dune. The approximate positions of the mouth over the given years are shown by the dark blue areas on the barrier dune (Duvenhage and Morant 1984; Illenberger 2003; Schumann 2015)

Methods

GPS surveys were carried out when possible from December, 2005, to December, 2018, with a total of 35 surveys completed. These were executed by running/walking along the water's edge on the beach and in the estuary, while marking out the route with a GPS; waypoints were taken at suitable locations. This was done at low and high tides and more specifically at spring low and high. These two surveys then give a qualitative spatial representation of the intertidal sediment distribution.

In general, the distances covered along the water's edge in such surveys varied between about 3 (at high tide) and 10 km (at low tide) and could be completed in not much more than

1–1.5 h. It is acknowledged that there is a certain amount of subjectivity involved in this process, particularly on the beach face, since the waves present at the time will have influenced the assessment of what constitutes the water's edge. Nonetheless, the technique gives a good representation of the estuary's sedimentary morphology, primarily because the changes recorded have been large and small deviations do not affect the conclusions in any substantial manner.

The surveys were initially done using a *Garmin 12* GPS and later a *Garmin 60CSx* GPS; the accuracy of the GPS instruments is given as better than 10 m. Fixed reference points were identified so that all the surveys could be georeferenced. Conversion scales for latitude and longitude were obtained from 1:50,000 SAN charts and programmes were written to plot the results onto scale maps of 1:10 000. *Google Earth* maps on the same scale were used to include all the adjacent features such as roads, buildings and bush.

Sea level is measured by the South African Naval Hydrographer (SANH) at various ports along the coast. The tide at Mossel Bay to the east leads that at Plettenberg Bay by less than 15 min, and the hourly data from this port were therefore used to represent the sea level offshore of the Keurbooms Estuary.

The site of the Department of Water and Sanitation (DWS) water level recorder is at the N2 bridge over the Keurbooms Estuary (Fig. 1). Hourly values in metres were provided from January, 2006, to December, 2019, though there was a break in the recordings from August to December, 2013. The values have not been adjusted to chart datum.

The position of a flow gauge operated by the DWS on the Keurbooms River is also shown in Fig. 1, and hourly values of flow in m^3/s were provided for the period January, 2006 to October, 2017. Unfortunately the gauge could only measure a maximum flow of $133.5 \text{ m}^3/\text{s}$, with the result that peak flows during the flood periods could not be measured or compared.

Daily rainfall data for the Plettenberg Bay weather station were provided by the South African Weather Services (SAWS).

Results

Even with the shortcoming of the flow gauge on the Keurbooms River in not being able to measure flows greater than $133.5 \text{ m}^3/\text{s}$, the time series shown in Fig. 3 identifies the maximum flood events over the 14 years from 2006 to 2019. The analysis details the effects of these floods and the sedimentation processes in the estuary over this time.

The period prior to 2006 was characterised by a movement southward by the estuary mouth (Illenberger 2006), eroding away the barrier dune and backwater sedimentation that had become established over many decades. Reddering (1981) estimated that the mouth would reach the Lookout Rocks by 2025; however, Fromme (1985) indicated that 'it appears impossible that the massive 4 to 6 m high and densely vegetated dune ridge on the south-western sand spit could be eroded to such an extent that Lookout Beach would disappear'.

Nonetheless, the flood of August, 2006, removed about 200 m of the barrier dune, in the process destroying a toilet/shower building. Figure 3 shows that the flood of November, 2007, had flows of more than $50 \text{ m}^3/\text{s}$ for 6 days, damaging the recorder which could not measure the high water level. In the process the last section of the barrier dune north of the Lookout Rocks was washed out, with this sand being deposited in a subtidal sand bank farther out to sea. The new mouth of the estuary was then adjacent to the Lookout Rocks (Schumann 2015).

March, 2008, to October, 2011

Figure 4 shows the physiographic elements along the barrier dune as well as within the Keurbooms Estuary itself. After the devastating flood in December, 2007, Fig. 4a shows that by March, 2008, the position of the barrier dune had been re-established, but with a limited area of sand. It is likely that most of this sand originated from the barrier dune deposited offshore by the 2007 flood.

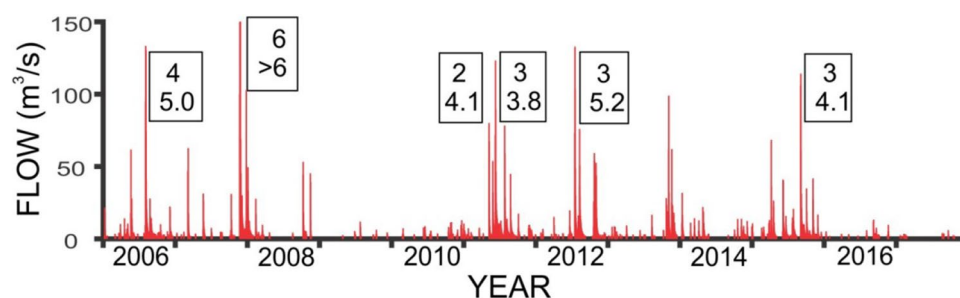


Fig. 3 River flow measured at the flow gauge in the Keurbooms catchment—for this representation the hourly values have been averaged over each day. The six largest flood events are identified and the

corresponding boxes have the number of days with a flow greater than $50 \text{ m}^3/\text{s}$ and the highest water level (in m) measured at the Keurbooms Estuary water level recorder

Fig. 4 Low tide surveys made in the Keurbooms Estuary in March, 2008 (S07) and both low and high tide surveys made in October, 2011 (S15). The spokes on the sand bodies show areas measured up to the line X-X and the associated areas in ha

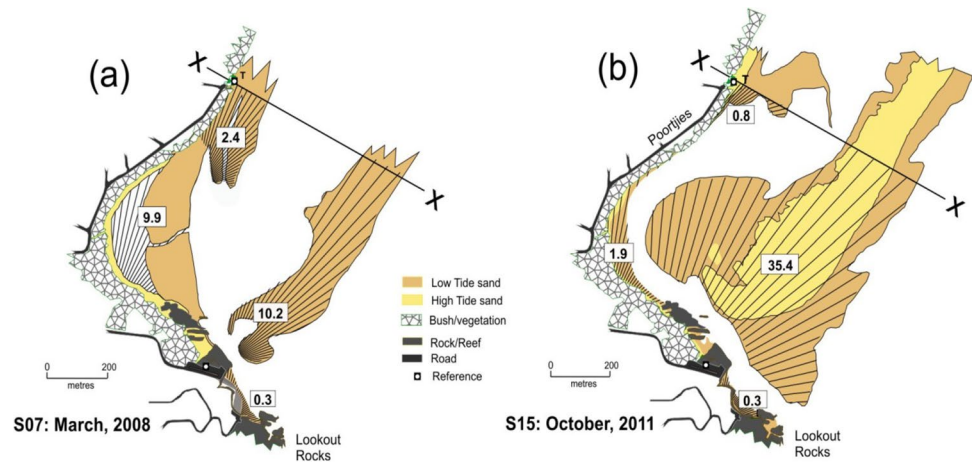


Figure 3 shows that there were two substantial floods in May and June, 2011, causing the water level at the recorder to rise to 4.1 and 3.8 m, respectively. However, comparison with survey 13 in December, 2010, shows that neither flood had any substantial impact on the estuary: survey 14 in July, 2011, and survey 15 in October, 2011 (Fig. 4b) essentially portray the same structures, and the two floods would merely have served to interrupt the sedimentation processes.

From Fig. 4b, substantial changes occurred in the back-barrier lagoon of the estuary over the years from 2008 to October 2011 before the next flood in July, 2012. In particular, both the tidal flood and ebb flows served to erode away the outer side of the south-west bend; this consolidated mud and sand bank had been established over more than 90 years since the mouth was last at the Lookout Rocks. At the same time on the inner boundary of the channel, a substantial spit of new sand was built up.

The erosion of the sandbank at Poortjies also affected bushes and other vegetation, and there were concerns about the road and other infrastructure adjacent to the estuary. Plans were made to establish bank protection measures in the area, but as it was the next flood altered the situation again.

Table 1 provides the total sand areas given in surveys 7 and 15. It was a period of substantial change in the sand bodies in the estuary, and over the 43 months, the low tide sand area increased by 15.6 ha.

December, 2012 to July, 2015

The flood of July, 2012, is described in Schumann (2015). Figure 3 shows that the water level reached 5.2 m at the recorder, and this was enough to cause a breach in the barrier dune about 1.2 km north of the Lookout Rocks; the existence of overwash points on the dune and high wave conditions would have assisted in defining this breach.

This corresponded to massive further changes in the structure of the estuary, as depicted in Fig. 5. Initially there were two mouths, and it was not clear which mouth would stay open and which would close. However, it soon became clear that the new, northern mouth provided a much more direct access to the sea, particularly considering the convoluted channel past Poortjies to get to the mouth at the Lookout Rocks. Effectively, by the middle of 2013, the southern mouth had ceased to function.

The barrier dune also underwent substantial changes as the mouth moved northwards some 400 m, probably as a result of sand provided by the north-eastward longshore drift. New flood and ebb-tidal deltas became established, and an intertidal sand spit extended from the northern side across most of the distance to the western bank of the lagoon. The main channel, for both flood and ebb flows, moved adjacent to the western bank; this had severe repercussions for infrastructure associated with the caravan park as the bank was eroded away.

The southern channel was now a dead end, and consequently sand from the sea, materials generated within the estuary itself and silt and mud from the Keurbooms River started settling out in this area. Essentially these components were in suspension from active flows

Table 1 Areas of sand bodies determined as shown in Figs. 4, 5 and 7. Note that estuary areas considered for S07 and S15 differ from those for S19, S27 and S35

Survey	Date	Area (ha)
S07	March, 2008	22.8
S15	October, 2011	38.4
S19	December, 2012	54.3
S27	July, 2015	54.6
S35	December, 2018	67.9

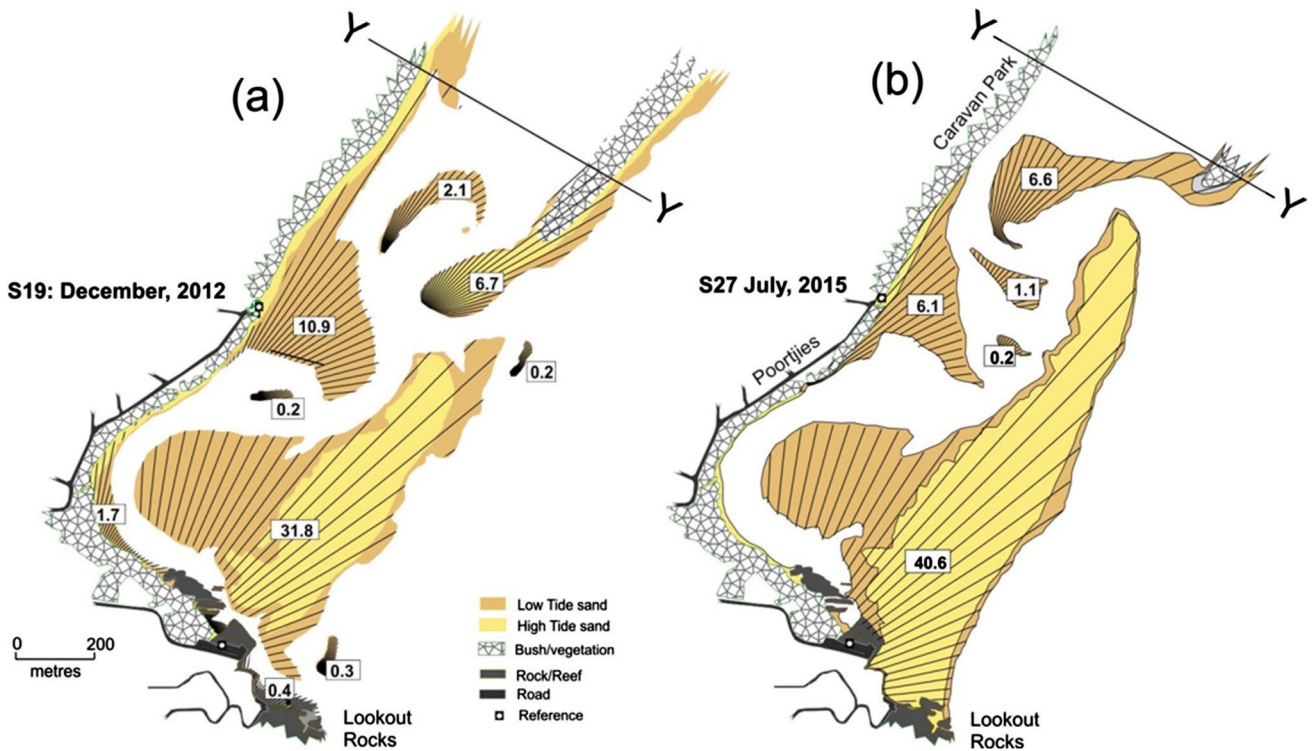


Fig. 5 Low and high tide surveys made in the Keurbooms Estuary in December, 2012 (S19), and July, 2015 (S27). The spokes on the sand bodies show areas measured up to the line Y-Y and the associated area in ha

during flood tides and settled out as currents slowed. Later ebb flows were very slow and not capable of lifting the sediments into suspension again. Consequently the estuary edge at Poortjies slowly started building up again, even as the bank at the caravan park was being eroded away.

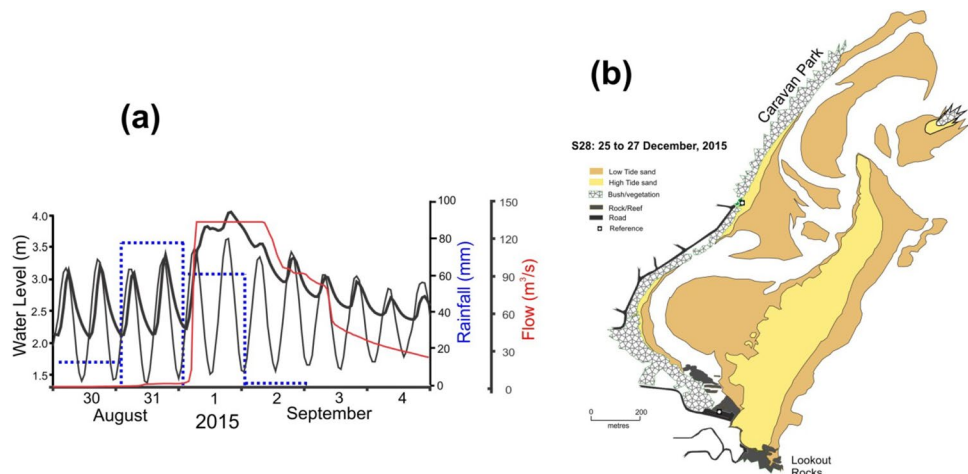
Table 1 shows that over all these changes the effective low tide sand surface area in the estuary and adjacent coast varied very little.

The flood of August/September, 2015

The next flood to have a substantial effect on the Keurbooms Estuary occurred over 30 August to 1 September, 2015, when a total of 153 mm rain was recorded at the Plettenberg Bay weather station. It is likely that rainfall in the mountainous catchment areas would have been considerably higher.

Figure 6(a) shows the effect of the floodwaters at the water level recorder in the Keurbooms Estuary. The increase

Fig. 6 (a) Water levels measured by the tide recorder at Mossel Bay (light black line – level adjusted) and the recorder in the Keurbooms Estuary (dark black line). Daily rainfall measured in Plettenberg Bay is shown by the blue dotted line and the river flow by the red line. (b) Low and high tide surveys made over 25 to 27 December, 2015 (S28)



in flow in the river and water level in the estuary were first registered in the morning of 1 September, increasing to a maximum over the next day or two. Thereafter it decreased fairly rapidly but still flowed strongly for a number of days.

The effects of these floodwaters can be seen in Fig. 6(b), about 4 months after the event. The main consequence was the removal of the subtidal sand spit that was extending westwards from the northern side of the mouth, as well as the establishment of a substantial sand body parallel to the western side of the back-barrier lagoon. It is not clear which were the main channels at that time, since removal of the spit enabled a more direct access to the upstream estuary, while observations showed that the western channel was still a major flow conduit. Moreover, erosion of the bank at the caravan park continued.

2016–2020

Subsequent surveys showed that by December, 2018, the subtidal sand spit off the northern side of the mouth had not been re-established, though the sand bank parallel to the western side of the lagoon at the caravan park consolidated—see Fig. 7. Overall, this survey shows a further substantial increase in surface area of the intertidal and sub-erial sand bodies in the back-barrier lagoon. Table 1 gives this increase as about 13.3 ha.

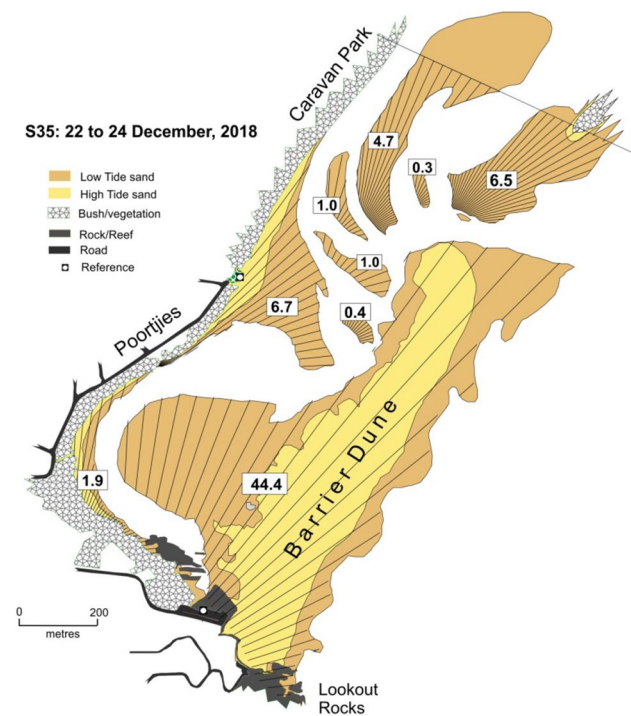


Fig. 7 Low and high tide surveys made over 22–24 December, 2015, in the last survey (S35)



Fig. 8 Google Earth image from 2020/09/03

However, the Google Earth image of September, 2020, in Fig. 8 shows further ingress of sand into the estuary and in particular that the sand spit was again present and welded to the northern bank of the mouth. Unfortunately it was not possible to determine whether this was an intertidal sand bank allowing flows at high tides or whether the flood and ebb tides were now confined to the western channel; the extent of the sand spit to the south indicates it was about mid-tide.

More sand reaching higher into the estuary also led to a spit developing north-east of the caravan park and shows the meandering nature of the flood and ebb-tidal flows. In the bend in the south-west corner of the back-barrier lagoon, the estuary bank was accreting, with sand coming through the estuary mouth from the ocean and with finer silts and muds from the river flow.

Tidal exchanges

In an estuary the exchange of water over a tidal cycle refers to the water entering the estuary on the flood and exiting on the ebb, while the volume is the tidal prism (Dyer 1997); according to Reddering (1983) the spring tidal prism of the Keurbooms Estuary is about $1.8 \times 10^6 \text{ m}^3$. It is therefore of interest to determine the manner in which the sedimentary changes in the lower Keurbooms Estuary affect the tidal

exchanges throughout the Bitou and Keurbooms estuary system.

During a single-tidal period, the measure of the highest water level in an estuary compared with the lowest water level gives a relative measure of the tidal exchange. It does not give the actual exchange, neither does it give any indication of the salinity structure of the water or of mixing or any other processes, but comparisons over time of the difference between the highest and lowest water levels will show how the tidal exchange varies.

This will be affected by the spring/neap tidal variation, with the neap tide having a smaller exchange than the spring tide. Consequently, in order to eliminate the spring/neap effect, only spring tides were considered in the following analysis. The longer-period sea level variations discussed earlier are weather-dependent and therefore too random to be eliminated.

The high and low water levels at spring tide were therefore extracted from the time series of water levels from the Keurbooms Estuary water level recorder over the years from 2006 to 2019. These occur 24 or 25 times per year, and these results are shown in Fig. 7.

The effects of the three flood events in 2007, 2012 and 2015 are clearly evident. Each of the floods flushed out a substantial volume of sand that had accumulated in the estuary and thus enabled a more efficient tidal exchange and therefore a greater difference between high and low tide water levels.

However, in the following years, sediment again entered the estuary, closing some of the channels that had been opened up thereby reducing the tidal exchange. In Fig. 9 linear regression lines have been fitted to this decrease in the tidal differences, though it is very unlikely that this would necessarily have been such a linear decrease. Nonetheless, the sequence of floods opening the channels and then a subsequent decrease in the tidal exchange is very clear.

The bottom low tide line in Fig. 9 shows no particular trend over the whole period. This means that, during the ebb tide, draining of the sea water that entered the estuary

Table 2 Linear tidal difference values at start and end of the three sections shown in Fig. 9

Section	Start tidal difference	End tidal difference	Months	Rate of decrease
A	1.03 m	0.69 m	55	0.62 cm/month
B	1.05 m	0.79 m	38	0.68 cm/month
C	1.06 m	0.98 m	52	0.15 cm/month

during the flood tide remained effectively constant over the whole period.

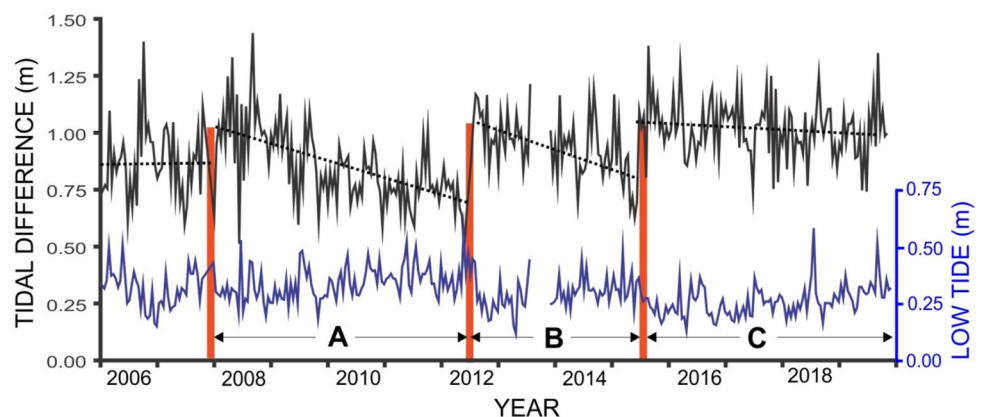
Table 2 shows the decrease in the spring tide tidal difference during the different sections shown in Fig. 7. Although the accuracies are probably overstated, the similarities between sections A and B are remarkable. The very limited decrease in section C is possibly due to the fact that the relatively new channel past the caravan park was sufficiently large and open to cater for the tidal exchanges, while other sections of the estuary silted up.

Of particular interest is the fact that after each flood, the tidal difference reverted to precisely the same level, i.e. just over 1 m. The implication of this result is that this is the maximum tidal exchange that can occur, no matter how large the estuary mouth through the barrier dune. Further limitations to the tidal exchange higher up in the estuary will then dictate the volume of water which can flow through those areas.

Discussion

The data presented here emphasise the variability in the physiographic elements in the Keurbooms Estuary and in particular the narrow back-barrier lagoon. Over the 14 years from 2006 to 2019, three flood events served to dramatically change the morphology of this section of the estuary, and this analysis identifies some of the processes involved.

Fig. 9 Water level difference between high tide and low tide at spring tide, measured at the Keurbooms Estuary water level recorder. The three main flood events discussed in the text are shown by vertical brown lines, namely December, 2007; July, 2012 and August/September, 2015. Linear regression lines are shown dotted over the inter-flood periods A, B and C. The lower blue line shows the corresponding spring low tide water level



As already described, the fluvial sediment discharge of the Keurbooms/Bitou system is small. The dominant sediment exchanges then occur with the ocean, primarily through ingress of sand through the mouth and then subsequent ejection by floods. The measurements presented do not allow a direct assessment of volumes of sand involved since essentially only areas were determined, but comparisons can be made.

Reddering (1983) estimated that the long-term sediment input through the mouth was about $15 \times 10^3 \text{ m}^3/\text{yr}$, while overwash contributed $10 \times 10^3 \text{ m}^3/\text{yr}$, giving a total of $25 \times 10^3 \text{ m}^3/\text{yr}$. The areas comprising the sand bank buildup over the 9.75 years given in Table 1 correspond to about $300 \times 10^3 \text{ m}^2/\text{yr}$.

Most of the surveys were made at or near spring tides, which means that the difference in sand height over the intertidal areas was probably at least 1.5 m; however, most of the additional area was nearer the low tide level. As such, to determine a volume should not involve a height of more than 0.5 m, but even this gives a sand volume input of around $0.15 \times 10^6 \text{ m}^3/\text{yr}$, which is considerably higher than Reddering's (1983) estimate.

However, it is important to recognise when the surveys were made. Thus the floods of 2007 and 2012 served to wash large sections of the barrier dune offshore, forming large sand banks in the nearshore. This sand would have been rapidly brought onshore again by ocean waves and onto the re-established barrier dune, leading to an abnormally high rate of increase in the accumulated surface area. This was the case after both the 2007 and 2012 floods when new mouths were established. By comparison, in the 32 months up to the 2015 flood, the rate of increase was only $1.13 \times 10^3 \text{ m}^2/\text{yr}$.

Consequently it is important to recognise that sand accumulation in the lagoon area is a variable process. Figure 9 has shown that there is a decrease in the tidal exchange over time as more sediment enters the estuary, and Fig. 8 demonstrates that the movement of this sediment higher up the estuary is a slow process: effectively 5 years after the 2015 flood sand entering the estuary mouth had not moved much more than 200 m farther into the estuary, though the sandbanks near the mouth had consolidated.

The importation of sand cannot continue indefinitely, and at some stage a morphodynamic equilibrium should be reached between the import and export of sand by tidal currents. At that stage the tidal exchange would also have reduced to a steady value, and it is likely that the structure of flood-tidal deltas will not change appreciably after reaching equilibrium. However, it is not known whether this stage will ever be reached since it is likely that subsequent floods will again wash out the sand.

Management

Recreation on Lookout Beach and in the estuary itself is part of the tourism industry of Plettenberg Bay. However, in order to attract tourists, it is necessary to be able to offer known attractions, and the removal of Lookout Beach in 2007 was a major blow to this industry. Moreover, the sand entering the lower estuary from the sea causes shoaling and the establishment of new sand banks with consequent navigational problems for pleasure craft.

As identified earlier, there is a migration southward of the mouth of the Keurbooms Estuary, against the general wave-driven longshore drift northwards. However, it is apparent from this analysis that floods can disrupt such a migration and open a new mouth at any suitable breaching point. The effects of such floods will be dependent on a number of factors at the time, namely:

- a) The volume flow and nature of the flood waters, in particular the rate of increase of the flow and the level of the floodwaters at the head of the estuary
- b) Sea level at the time, i.e. spring or neap tide, high or low tide, and any other variations caused by ocean waves and weather-related effects
- c) The nature of the channels and sand banks/flood-tidal deltas in the estuary
- d) Any weaknesses in the barrier dune caused for example, by overwash fans

Reddering and Esterhuysen (1983) addressed the management issues in terms of the sediment in the estuary, finding that the position of the mouth was central to the problem. Nonetheless, dredging of sediment was also recognised as one of the consequences of management. In the analysis of Illenberger (2003), options such as fixing the mouth position, artificial breaching of the barrier dune and the zero option of doing nothing were considered; this latter option has held sway.

Any management plans will need to take into account the effects of climate change (Zietsman (2011)). The Keurbooms will be particularly sensitive to increases in sea level, but changes in wind, waves and rainfall will also affect the morphology and processes defining the structure of the whole estuarine system.

On a shorter time scale, there is no doubt that further floods will occur. The inherent variability of the estuary and dependence on conditions at the time make management difficult, but as it is there will be removal of sediment from the estuary and possible damage to infrastructure.

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Declarations

Conflict of interest The author declares that there is no conflict of interest with third parties.

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