# Klein River Estuary (South Africa): 2D numerical modelling of estuary breaching

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## Abstract

2D numerical modelling of the breaching process of the Klein River Estuary in South Africa was carried out. The model was calibrated on field data and performs reasonably well, and is able to simulate the ebb and flood channels that form upstream of the mouth. The focus of the simulations was to determine the effectiveness of flushing of sediments during breaching, by investigating the breaching process at different water levels in the estuary, as well as at two different areas along the berm. Breaching at higher water levels increases the effectiveness of flushing as the discharge through the mouth increases significantly at higher water levels. Flushing towards the middle or south-east side of the berm is much more effective than towards the north-west side.

**Keywords**: estuary, breaching, Klein River, sediment flushing, numerical modelling

## Introduction

Many estuaries in South Africa are only temporarily open to the sea due to factors such as the low tidal variation. The quality of the environment of these estuaries is largely determined by the frequency, duration and timing of open mouth conditions. Unfortunately many estuaries are at present often closed more frequently and for longer periods than in the past due to reduced river flow such as the Klein River or the Bot River estuaries (CSIR, 1999; Van Niekerk et al., 2005).

Open-mouth conditions at small estuaries are principally maintained by river flow and especially by baseflow. A reduction in minimum baseflow therefore commonly results in an increase in closed mouth conditions. The Groot Brak Estuary, for example, needs only about 0.5 $m^3/s$ to keep it open during neap tides, and it stays open during spring tides (CSIR, 2000). However, the Wolwedans Dam which was built in the 1990s just 2 km upstream of the estuary has reduced the mean annual runoff (MAR) and has led to increased closure of the estuary mouth. In response to that, 1 x $10^6$ $m^3$ is reserved annually for release to the estuary (Huizinga, 1994).

The ever-increasing reports of sedimentation problems in South African estuaries due to increased sediment yields from the catchment, lead to calls for increased flushing of these estuaries and mouth breachings, both natural and mechanical, in order to remove the sediment. However, artificial breachings have often occurred at water levels in the estuary that are too low, which has a negative effect on the flushing efficiency (CSIR, 1999 and 2003). In the case of the Groot Brak Estuary it was found that by using the annual release to breach the mouth at higher levels, more sediment is flushed out during breachings and that the state of sedimentation in the lower estuary is similar to what it was before the dam was built (Schumann, 2003).

This problem is not confined to South-Africa. The tidal prism and the rate and size of river flows through the Murray River Estuary, Australia, have been significantly reduced (Harvey, 1996). In 1981 an artificial channel had to be excavated to re-open the mouth. A first attempt to open the mouth was not successful, but the second channel in a different location managed to re-open the mouth, but also caused rapid erosion of the adjacent peninsula. The restriction to flow by the barrages has also been responsible for rapid deposition of mud in the lower reaches over the past 60 years (Bourman and Barnett, 1995).

Artificial breachings have also been undertaken at the Russian River Estuary, United States, since the late 1960s, in order to lower water levels, restore tidal circulation, and flushing of pollutants, nutrients, fish, and other biological resources into the ocean, rather than to remove accumulated sediment (Goodwin and Cuffe, 1993; Martini-Lamb et al., 2006).

A study was undertaken between 2001 and 2004 to investigate the sedimentation problems in South African estuaries (Beck et al., 2004). Part of this study involved fieldwork at the Klein River Estuary, mainly to obtain data to calibrate and verify numerical as well as physical models. These models were then used to investigate the factors affecting the efficiency of breaching at Klein River. This article only discusses the numerical modelling results at the Klein River Estuary.

## Klein River Estuary

The Klein River Estuary at Hermanus, South Africa, is a micro-tidal estuary that temporarily experiences closed mouth conditions. Perceived sedimentation and reduced river inflow have been cited as the reasons for the more frequent and longer periods of closed mouth conditions at the Klein River Estuary. The estuary has to be breached artificially once or twice a year (Figs. 1 and 2), mainly to prevent flooding of the low-lying properties. Since many of these properties are situated as low as +2 m above mean sea level (MSL), the result has been that breachings have taken place at very low water levels, whereas

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***Figure 1***
*Start of breaching at Klein River Estuary (September 2001)*

***Figure 2***
*During breaching at Klein River Estuary (September 2001)*

natural breachings would have taken place between +2.5 and +3 m MSL (CSIR, 1999). The effect has been that very little sediment has been flushed out of the mouth regions as well as from upstream in the estuary. This in turn means that the mouth closes more quickly. No consensus has been reached about what would be an ideal water level to breach at or even where along the berm the breaching should take place.

Numerical modelling was identified as a possible tool to aid in the decision-making process.

## Model setup and calibration

### Background of numerical model

For the numerical modelling, the two-dimensional model MIKE 21, developed by the Danish Hydraulics Institute, was used. MIKE 21 is a software package for simulating free-surface flows, water quality, sediment transport and waves in rivers, lakes, estuaries, bays, coastal seas and other water bodies. In particular MIKE 21C, a special module developed to simulate river morphology, was used. MIKE 21C is based on a curvilinear grid, and hydrodynamics, sediment transport and river morphology can be simulated. The modules can run interactively, incorporating feedback from variations in the alluvial resistance, bed topography and bank line geometry to the hydrodynamics and sediment transport.

MIKE 21C has been used extensively by the authors to model river morphology and this study was as much a test to determine whether MIKE 21C could be used to model the breaching process, as it was to investigate the actual breaching process.

### Model setup

A curvilinear grid with 114 grid cells in the flow direction and 101 grid cells across (Fig. 3) was used for the hydrodynamic and morphological simulations, with a cell size of approximately 28 m x 15 m in the berm region. The model bathymetry (Fig. 4) was based on the June 1998 survey of the lower estuary of the Klein River (CSIR, 1999), as the area surveyed was extensive. The crest of the berm was around +2.8 m MSL at the time. In the region around the berm the grid spacing in the flow direction was half of that in the deeper area of the upper estuary, as it was thought that very few morphological changes would take place in the upper estuary.

At the upstream boundary a small inflow of 2 $m^3/s$ (based on gauged average baseflow conditions) was specified. A water level time series with 10 min time steps, representing the tidal variation in the sea, was specified at the downstream boundary.

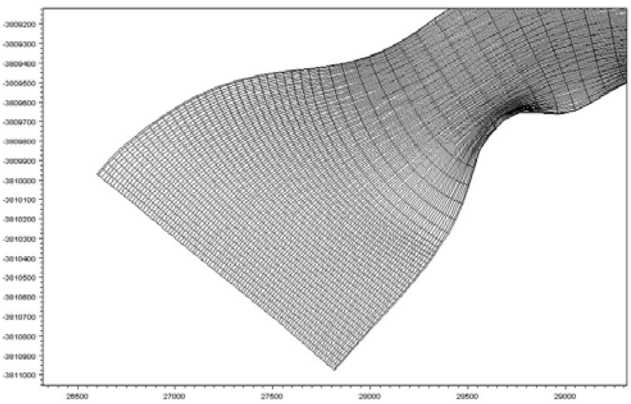

***Figure 3***
*Klein Estuary model grid*

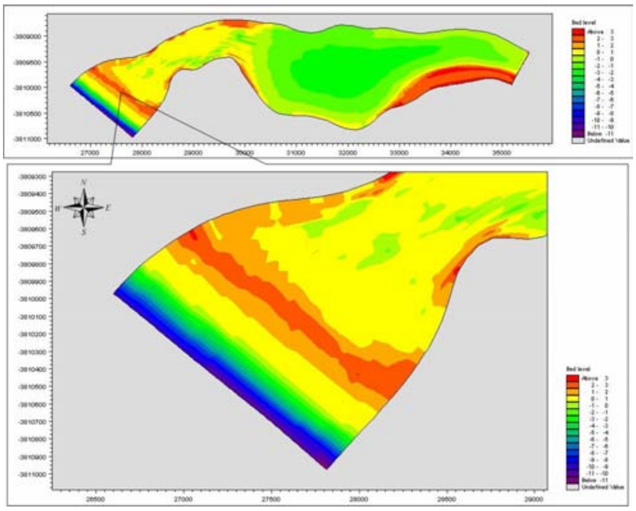

***Figure 4***
*Klein Estuary bathymetry (relative to MSL)*

A uniform sediment size of 0.21 mm was specified throughout the whole model, which was based on bed sediment samples taken in the field. The resistance was kept constant throughout. Initially it was thought to increase the resistance in the berm region. However, the resistance did not prove to affect the simulation results to a great degree, and so the resistance was kept constant throughout the whole region.

## Calibration

The model was calibrated on the field data (including water level measurements in the estuary, water levels and flow measurements in the river, cross-section surveys before and after breaching, and mouth scouring over time) obtained during and after the breaching of September 2001. The berm was at approximately the same height in September 2001 as in June 1998, when the data for the bathymetry was obtained. The mouth was breached at a level of +2.8 m MSL with initial excavated channel 15 m wide (one grid cell) and 0.5 m deep. The model parameters are shown in Table 1.

**TABLE 1**
**Calibrated model parameters**

| Parameter | Value |
|---|---|
| Hydrodynamic time step | 4 [s] |
| Morphological time step | 8 [s] |
| Flooding depth | 0.02 [m] |
| Drying depth | 0.01 [m] |
| Manning *M* (1/*n*) | 20 [$m^{0.33}$/s] |
| Median grain diameter | 0.21 [mm] |
| Sediment transport formula | Engelund and Fredsøe |
| Eddy viscosity | 0.2 [$m^2$/s] |
| Mass density of sediment | 2650 [$kg/m^3$] |
| Porosity | 0.35 |
| Transverse slope coefficient | 0.005 |
| Transverse slope power | 0.5 |
| Longitudinal slope coefficient | 5 |

The model performed reasonably well, except for the fact that the breach did not develop rapidly enough. The storage volume of the estuary is quite significant and it takes a few hours for the breach to develop from the initial excavated channel and for the water level in the estuary to drop, which has been observed during actual breachings in the field. However, the model responds slower than in the field, which led to the result that the tide would move into the estuary again before the breach could fully develop. The solution to this problem was to provide a wide shallow initial channel width. This means the breaching is started with a channel that is closer to its final form, thereby reducing the time it takes to develop a stable width. A 45 m wide initial channel was therefore specified, as part of the calibration based on field data.

The model simulated the final breach to be 75 m wide (see Fig. 5), which corresponds well with the field data. A survey of the area after the breaching showed the bed level in the mouth to be just below -2 m MSL. During breaching the maximum scour was up to 5 m (maximum 3 m below MSL), but as the tide moves into the estuary again, some sand is deposited in the mouth, so that within a short period of time the mouth becomes somewhat shallower. Some sediment is deposited just inside the mouth, and two ebb channels form upstream of the mouth. The velocity vectors in Fig. 6 clearly show that the flow is more confined in the two channels during the ebb tide, while during the flood tide the flow is initially more evenly spread out, but as sediment starts to deposit upstream of the mouth, the flow during the flood tide is diverted somewhat.

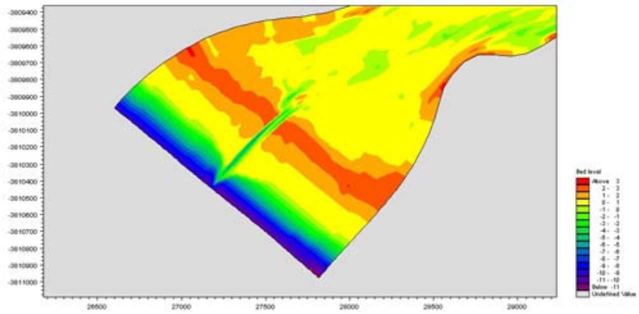

***Figure 5***
*Simulated breach 1 week after breaching (Initial water level in the estuary at +2.8 m MSL and 7 d of normal tidal action)*

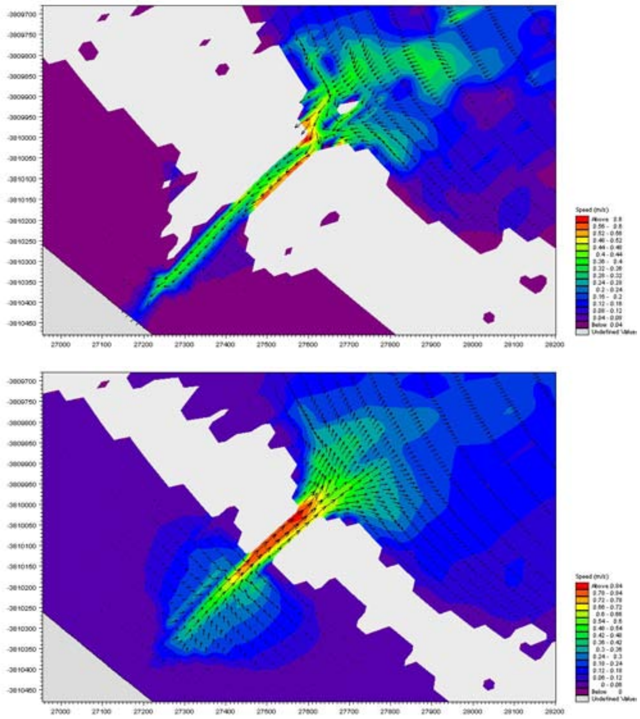

***Figure 6***
*Velocity distribution during ebb (top) and flood (bottom) simulation results*

The scenarios were chosen mainly to investigate the effect of the initial water level at which breaching takes place, but also the location of the breach and the timing. The scenarios included breaching towards the south-east or north-west side of the berm, at spring or neap tide and with different initial upstream water levels.

An initial shallow (0.5 m deep) and 45 m wide breaching channel was provided in all simulations. The simulations were started just before high tide in all scenarios. The simulations have shown that whether breaching takes place at spring or neap tide does not affect this particular estuary due to the large volume of the estuary. However, the initial water level at which breaching takes place, has a very significant effect on the efficiency of the breaching.

Table 2 lists the maximum discharges that occurred during breaching, based on the drop in water level in the estuary. It

| TABLE 2<br>Simulated resultant maximum outflow discharge | |
|---|---|
| **Scenario** | **Maximum discharge ($m^3/s$)** |
| 1. South-east side, spring tide, initial water level at 2 m MSL | 125 |
| 2. South-east side, spring tide, initial water level at 2.8 m MSL | 285 |
| 3. South-east side, neap tide, initial water level at 2 m MSL | 102 |
| 4. South-east side, neap tide, initial water level at 2.8 m MSL | 280 |
| 5. North-west side, spring tide, initial water level at 2 m MSL | 85 |
| 6. North-west side, spring tide, initial water level at 2.8 m MSL | 207 |
| 7. North-west side, neap tide, initial water level at 2 m MSL | 50 |
| 8. North-west side, neap tide, initial water level at 2.8 m MSL | 202 |

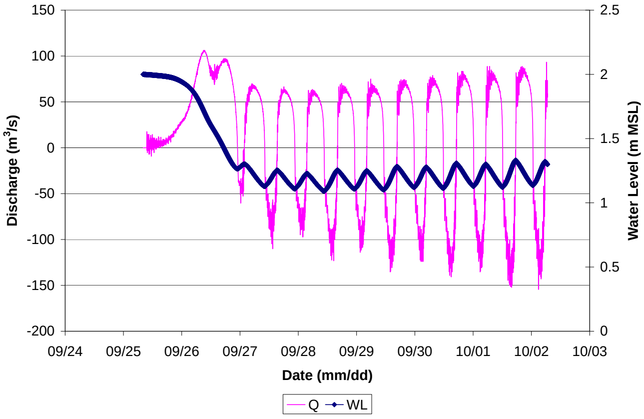


***Figure 7***
*Scenario 3 – simulated discharge and water level*

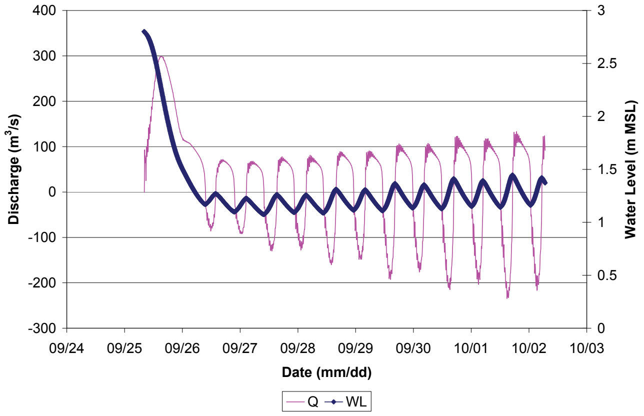


***Figure 8***
*Scenario 4 – simulated discharge and water level*

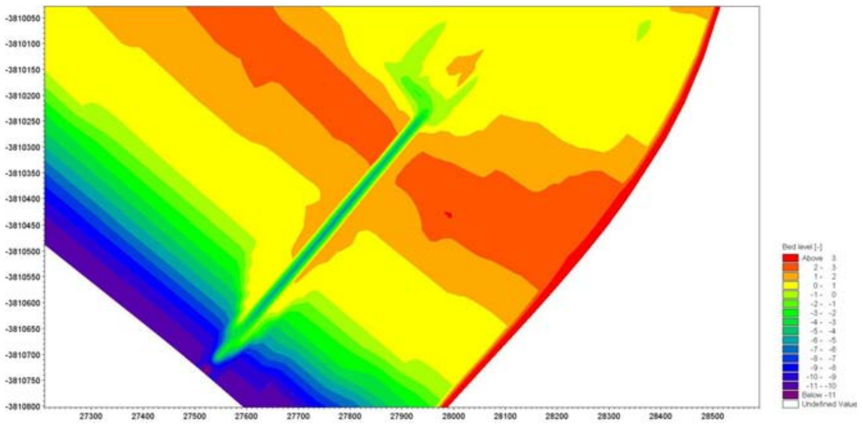

***Figure 9***
*Scenario 1 – breaching channel towards the south-east after 7 d (+2 m MSL)*

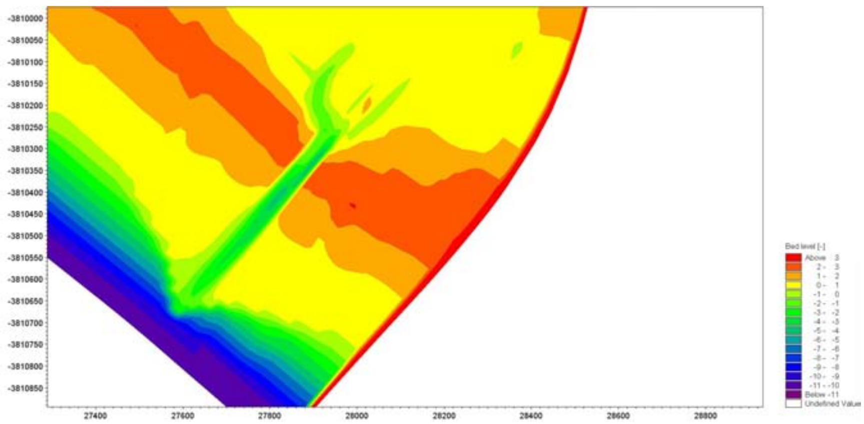

***Figure 10***
*Scenario 2 – breaching channel towards the south-east after 7 d (+2.8 m MSL)*

shows that higher discharges occurred when breaching occurred at a higher water level, and towards the south-east side. Slightly higher discharges were also obtained during spring tide compared to neap tide, but the difference is small.

Figures 7 and 8 show the water levels and associated discharges for Scenarios 3 and 4 (see Table 2). It can be seen that the maximum discharge during breaching in the first instance is not much more than the normal tidal discharge, whereas with the higher initial water level, the breaching discharge is more than three times the magnitude of the tidal discharge. The fact that the subsequent tidal discharges are higher for Scenario 4 than for Scenario 3 also indicate that flushing was more efficient during Scenario 4, and that a greater tidal exchange is possible, which means that the mouth will have a better chance of staying open for longer than Scenario 3.

Figures 9 to 12 show the final bed levels of Scenarios 1, 2, 5 and 6. It can be seen that the breach width is only about 30 m when breaching takes place at 2 m MSL, while the channel is more than twice that size when breaching takes place at 2.8 m MSL. It is also interesting to note that the breaching channel on the south-east side of the berm is larger than on the north-west side, where the flow is more confined



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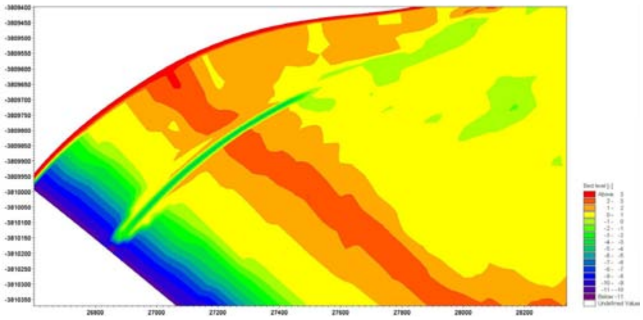

***Figure 11***
*Scenario 5 – breaching channel towards the north-west after 7 d (+2 m MSL)*

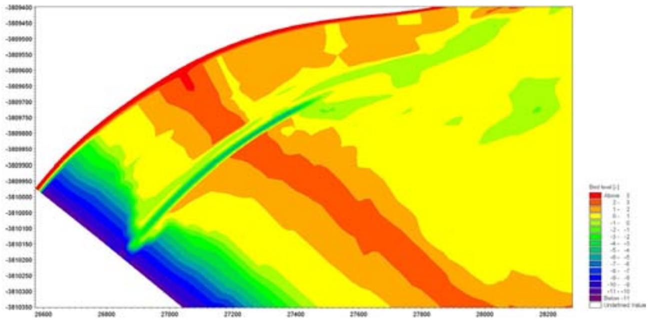

***Figure 12***
*Scenario 6 – breaching channel towards the north-west after 7 d (+2.8 m MSL)*

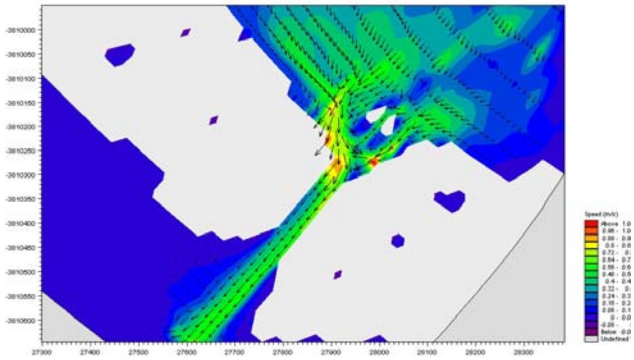

***Figure 13***
*Scenario 2 – ebb tide velocity distribution*

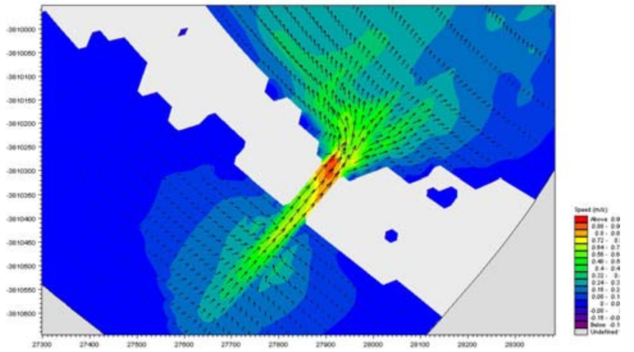

***Figure 14***
*Scenario 2 – flood tide velocity distribution*

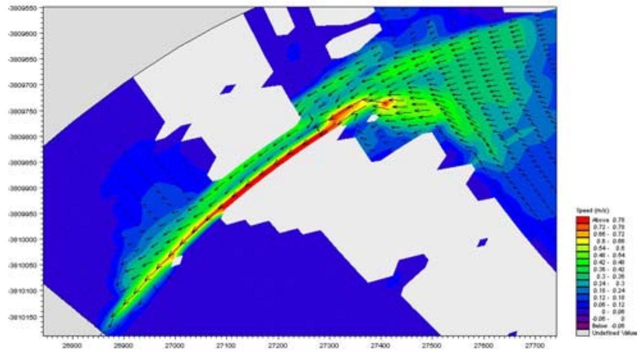

***Figure 15***
*Scenario 6 – ebb tide velocity distribution*

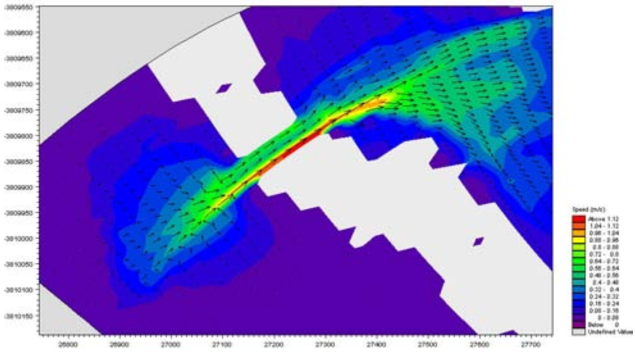

***Figure 16***
*Scenario 6 – flood tide velocity distribution*

towards the left bank of the breaching channel.

It is also interesting to see that when breaching takes place towards the south-east side of the berm, the flushing channel splits into two channels upstream (see Figs 9 and 10). In the field ebb and flood channels develop in much the same way, when breaching takes place more to the south-east side of the berm. The velocity vectors in Figs. 13 and 14 show that the ebb velocities are much stronger in the channels, whereas the flood velocities are more uniform. On the other hand, when breaching takes place at the north-west side of the berm, the ebb and flood channels interfere (Figs. 15 and 16).

The volume of sediment removed at the higher water level is in some cases more than twice than what was flushed at the lower level (Table 3). During breaching sediment is almost exclusively removed from upstream of the berm, but within a day or so the point where most of the sediment is removed moves downstream, so that little or no sediment transport takes place upstream, and more and more sediment is removed from downstream of the berm. It is important that the sediment is also removed or at least dispersed downstream of the berm, because if it is allowed to accumulate in front of the mouth, it may eventually block the mouth. During spring tide it seems that this process is more efficient than during neap tide.

## Summary and conclusions

The numerical modelling of the breaching process at the Klein River estuary indicates similar results as have been observed during numerous breachings in the field, i.e. that breaching at higher water levels and towards the south-east side are more effective (judging from the larger breaching channel, individually defined ebb and flood channels, and increased sediment removal).

Overall it seems that breaching at a higher initial water level increases the flushing efficiency. Not only is the flushing channel wider and reaches further upstream, but a greater volume of

| TABLE 3<br>Scoured sediment volumes | |
|---|---|
| **Scenario** | **Volume removed ($m^3$)*** |
| 1. South-east side, spring tide, initial water level at 2 m MSL | 37 652 |
| 2. South-east side, spring tide, initial water level at 2.8 m MSL | 58 172 (55%) |
| 3. South-east side, neap tide, initial water level at 2 m MSL | 22 927 |
| 4. South-east side, neap tide, initial water level at 2.8 m MSL | 54 577 (138%) |
| 5. North-west side, spring tide, initial water level at 2 m MSL | 38 636 |
| 6. North-west side, spring tide, initial water level at 2.8 m MSL | 71 268 (85%) |
| 7. North-west side, neap tide, initial water level at 2 m MSL | 27 770 |
| 8. North-west side, neap tide, initial water level at 2.8 m MSL | 64 018 (131%) |

** Value in parenthesis indicates the extra percentage sediment removed at the 2.8 m MSL water level compared with the same situation at the 2 m MSL water level*

sediment is removed from the estuary as well as downstream of the berm. Breaching further to the south-east also allows for a wider breach, although slightly less sediment is scoured than further to the north-west where the berm is wider and more sand is available because no recent breaching occurred in the north-west.

2D numerical models such as the one described in this paper can be used to simulate the complex flow patterns and sediment dynamics of the sand bank breaching (natural or artificial), in order to optimize the breaching effectiveness for sediment flushing considering the initial estuary water level, initial ocean water level, volume of the estuary, breaching location and tidal flow following the breaching. Models such as these, however, always need practical data to calibrate against further, which will significantly increase the confidence with which these models can be used. Essential data includes field measurements of water levels, erosion rates, flow rates and bathymetric surveys during and after breaching events.

Since field measurements are often time-consuming and expensive, models such as these can be very valuable tools in management decision-making, as they enable the user to identify and analyse the impact and effectiveness of various breaching options, and present these to stakeholders. The use of these models does not need to be limited to the breaching process, but can be applied in many aspects of estuarine management, such as Reserve determinations (Beck et al., 2004).

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