RESERVOIR SEDIMENTATION AND POTENTIAL IMPACT OF THE PROPOSED SMITHFIELD DAM ON THE UMKHOMAZI RIVER ON THE COASTAL SEDIMENT BUDGET AND SHORELINE STABILITY

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RESERVOIR SEDIMENTATION AND POTENTIAL IMPACT OF THE PROPOSED SMITHFIELD DAM ON THE UMKHOMAZI RIVER ON THE COASTAL SEDIMENT BUDGET AND SHORELINE STABILITY

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ABSTRACT

The proposed Smithfield Dam is located 187 km upstream of the river mouth and the estimated total sediment load trapped in the reservoir is 1.27 million t/a, of which the sand fraction is about 10%. Reservoir sedimentation prediction of the proposed Smithfield Reservoir was carried out by using a two dimensional hydrodynamic model for a 100 year period which predicted 66% loss in storage capacity.

The coastal impact of the dam is due to the decrease in sand load at the river mouth (coarse sediment) and the simulated net effect of the proposed dam is a 46 000 m^3/a sand reduction. The proposed Smithfield Dam will have a significant and long-term effect on the coastal sediment budget from just south of the uMkhomazi River mouth northwards to Durban. If major dam developments on the uMkhomazi River are inevitable, then the potential impacts in terms of reduced fluvial sand supply to the coast could be mitigated by limiting the current sand mining in the river. Coarse sediment bypassing of the Smithfield Reservoir by bypass tunnel (5km) and weir in the upper reservoir is also possible to limit the impacts of the dam on the downstream fluvial morphology and on the sediment loads at the river mouth.

1. INTRODUCTION

The main objectives of this investigation were to:

a) review the sediment yield and to carry out a hydrodynamic modelling study of the reservoir sedimentation of the proposed Smithfield Reservoir.

b) evaluate how the change in the fluvial sediment (sand) yield at the uMkhomazi River mouth due to the proposed Smithfield Dam, could impact the coastal sediment budget and shoreline stability.

2. SEDIMENT YIELD

The sediment yield was reviewed and compared with observed sediment yields in the region. Sensitivity testing was also carried out by using the WRC (2012) method by considering the accuracy of the 10 year flood. The catchment area at the dam site is 2 058 km^2. Based on the relatively high observed sediment yields in the region, it is recommended that a 95% confidence sediment yield is used of 617 t/km^2.a for the proposed dam, which gives a mean annual sediment load of 1.27 million t/a for the current development scenario.

A possible future sediment yield of double the current yield due to land use change, land degradation and climate change impacts was also considered in the reservoir sedimentation analysis.

3. RESERVOIR SEDIMENTATION

Reservoir sedimentation simulations of the proposed Smithfield Reservoir was carried out by using a two dimensional hydrodynamic model. The new Smithfield Dam Full Supply storage Capacity (FSC) of 253 million m^3 and the Full Supply Level (FSL) water depth at the dam is 75 m. The new reservoir sediment trap efficiency is 97% and therefore only colloidal (very fine) sediment will not be deposited in the reservoir.

The inflow record used in the reservoir sedimentation modelling is shown in **Figure 1**, while the reservoir water levels are shown in **Figure 2**.

A sediment load-discharge rating for cohesive sediment was compiled at the dam site from river data. The total load sediment time series from 1960 to 2014, based on hourly calculated data, has mean and maximum concentrations of 374 mg/l and 35 941 mg/l respectively (**Figure 3**). The largest flood in the record is estimated to be close to a 100 year annual recurrence interval flood. The non-cohesive sediment load was estimated to be 10 % of the total load.

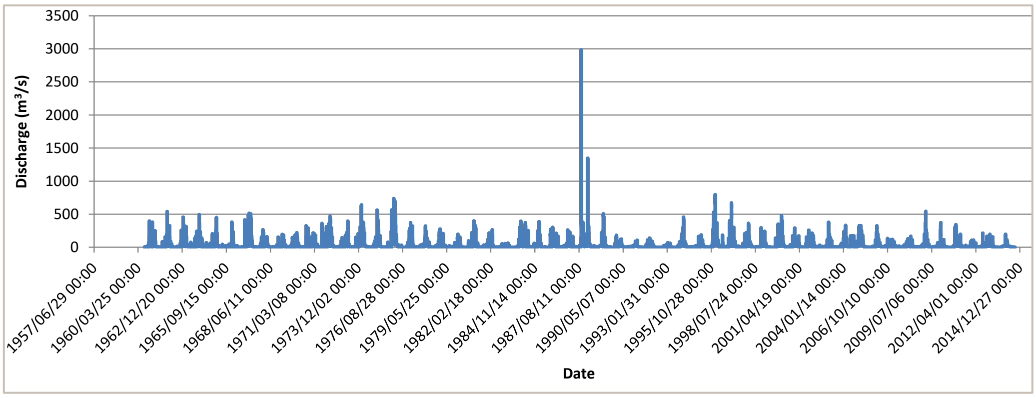

Figure 1: Observed flow record at gauging station U1H005 used as inflow record for Smithfield Reservoir (hourly data)

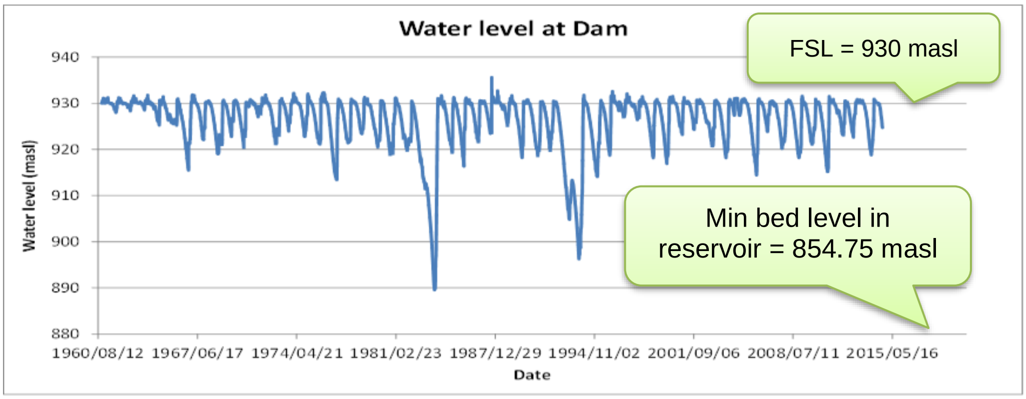

Figure 2: Simulated water level time series at the proposed dam for the period 1960 to 2014

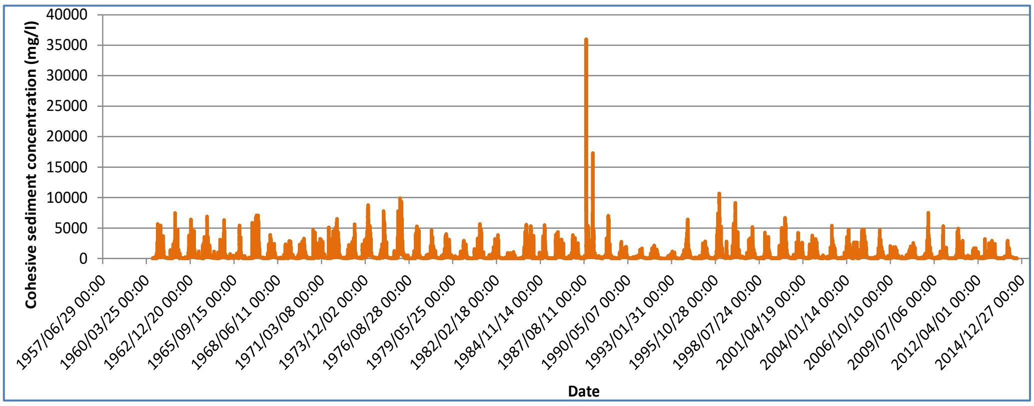

Figure 3: Calculated Smithfield Reservoir inflow cohesive sediment concentrations

The hydrodynamic model bathymetry is shown in **Figure 4**. **Figure 5** shows the simulated longitudinal sedimentation profiles in the reservoir. At the current sediment yield and future possible higher sediment yield over a 100-year period, the FSC could be 163 and 87 million m^3, a decrease of 36% and 66% in the original FSC, respectively.

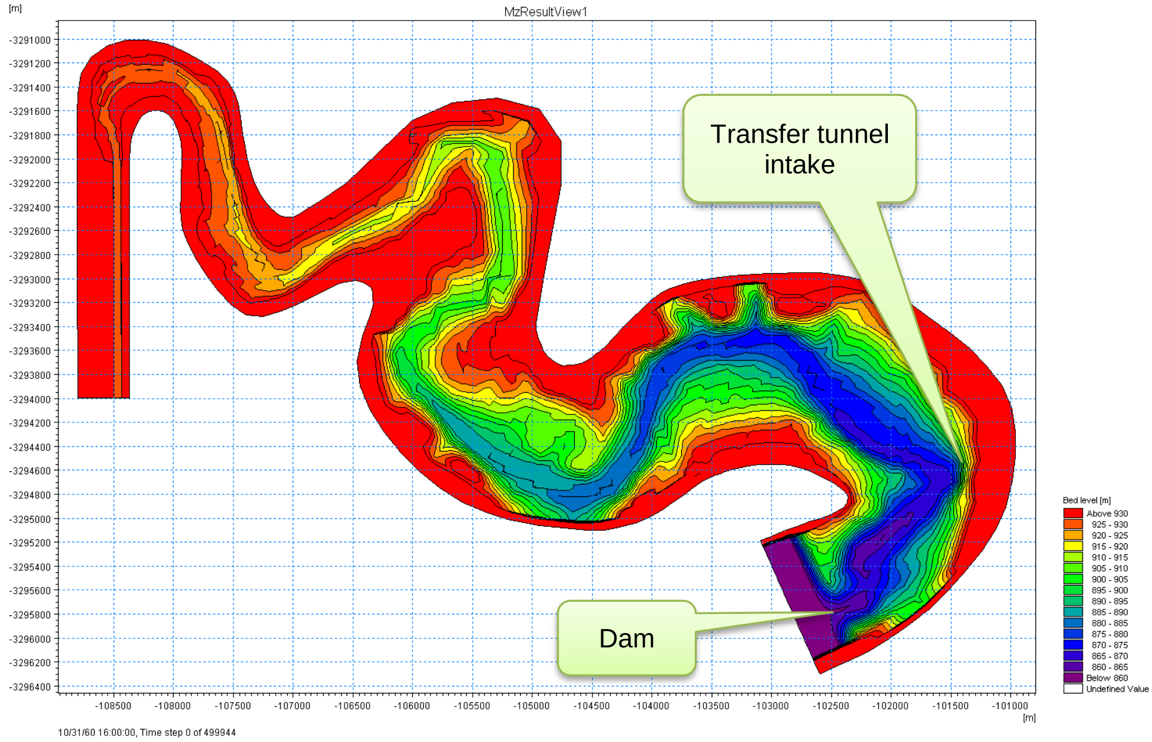

Figure 4: Reservoir hydrodynamic model bathymetry used in the simulations (elevations masl)

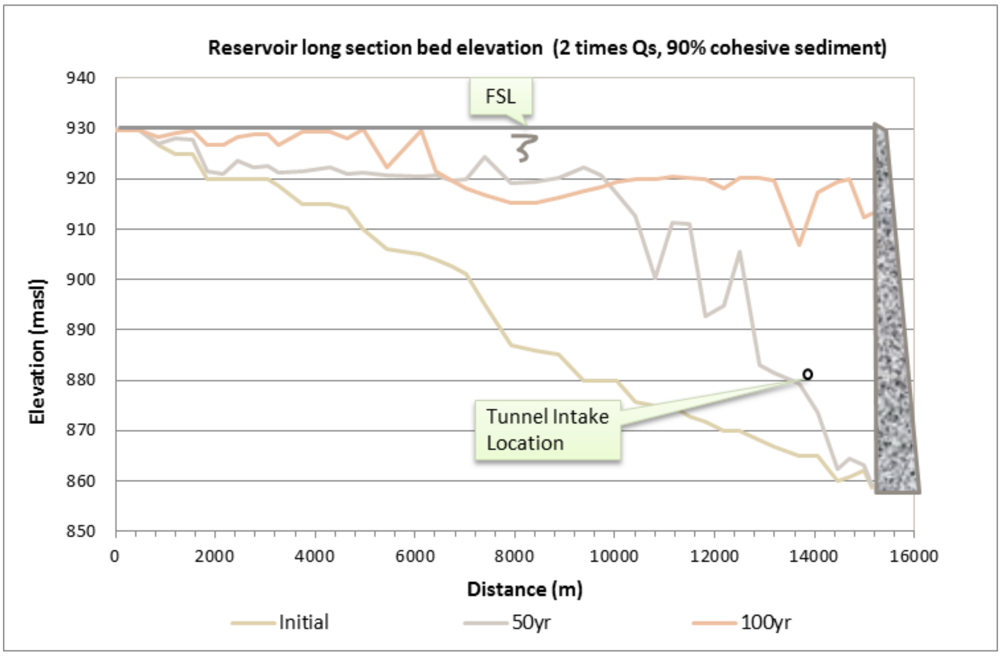

Figure 5: Longitudinal profile of the deepest reservoir bed levels simulated over a 100 year period for a scenario with the sediment yield double the current yield

4. ROUTING OF SEDIMENT LOADS DOWNSTREAM OF THE DAM SITE TO THE OCEAN

A one dimensional fully hydrodynamic model of the river was set up, from the Smithfield Dam site to the river mouth, to simulate the pre-dam and post-dam sediment transport downstream of the dam site. For the pre-dam scenario the upstream boundary of the model was based on a DWS flow record using hourly flows as indicated in **Figure 6**.

Post dam inflows were determined by simulating the full mass balance of the Smithfield Dam using a one-dimensional (1D) hydrodynamic model. For this model the inflows were observed, and the diversion tunnel flows, evaporation and rainfall on the reservoir data was obtained from the *Water Resources Yield Assessment Report* (AECOM, et al., 2015). A dam spillway was built into the model at the FSL. The output of the model was reservoir water levels and spillage flows. The post-dam spillage flows are shown in **Figure 6** which indicates the reduction of the flood peaks and the number of floods locally downstream of the dam.

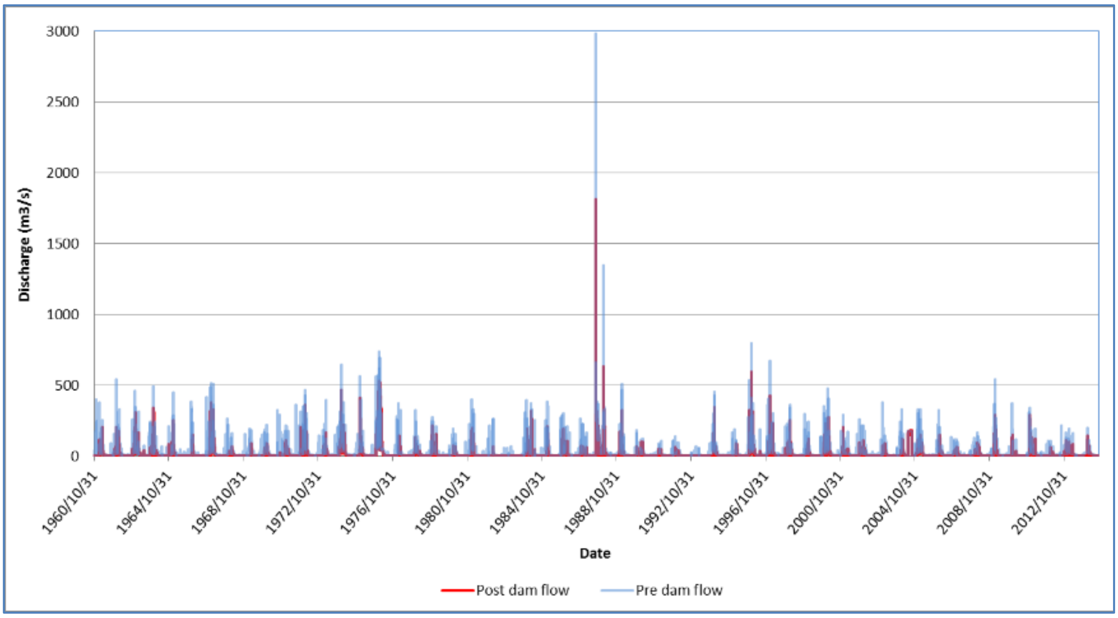

Figure 6: Pre- and post-dam simulated spillage flow record at the dam site

The bed sediment grading specified in the 1D-hydrodynamic model, from the dam site to the ocean, was obtained from sediment samples collected in the field. Sediment sizes of 0.14 mm (72%), 1.17 mm (22%) and 7.28 mm (6%) were used in the model setup of the initial bed grading.

Two tributaries were included in the hydrodynamic model between the dam and the river mouth. The inflow time series of these tributaries were such that the pre-dam MAR of 1 078 million m^3/a was obtained for the total catchment. The total catchment area for the river at the mouth is 4 287 km^2.

The Mike 11 model (DHI Group) was used to simulate the sediment transport, deposition and erosion processes in the river from the dam site to the mouth. Since post-dam narrowing of the river will occur due to reduced flood peaks and number of floods spilling at the dam, the main channel of the river was narrowed for the post-dam scenario, based on empirical data for South Africa. The river channel adjusts to a new post-dam equilibrium due to a smaller dominant flood and decreased non-cohesive sediment transport capacity. The largest impact on the river channel would also be closest to the dam, upstream of a major tributary. Typically, it takes about 7 years of dam operation for the new river equilibrium to be established (Beck and Basson, 2003). Near the dam site, reduction of post-dam top width of the main channel of 24 % was calculated, and at the river mouth the main channel top width is 18% narrower than under pre-dam conditions. The relative width change from upstream to downstream is not much because the river length downstream of the dam is relatively short (187 km).

The simulated coarse sediment loads for the period 1960 to 2014 is shown in **Figure 7**, with the simulated data summed to annual values. Coarse non-cohesive sediment transport is based on the local hydraulic conditions and sediment transport capacity of the stream. Post-dam the inflow into the river is the spillage from the dam with attenuated floods and fewer floods, and no coarse sediment could be transported through the reservoir. Inflows and sediment input from tributaries downstream of the dam pre- and post-dam are the same. The land use upstream of the dam does not play a role because all the coarse sediment is trapped in the proposed reservoir.

The simulated mean long term sediment loads at the mouth are indicated in **Table 1.** The long term average reduction in coarse sediment by the proposed Smithfield Dam is 74 000 t/a.

Table 1: Long-term mean coarse sediment loads at the river mouth (t/a)

Pre-dam scenario	Post-dam scenario	%-difference
352 000	278 000	21%/a

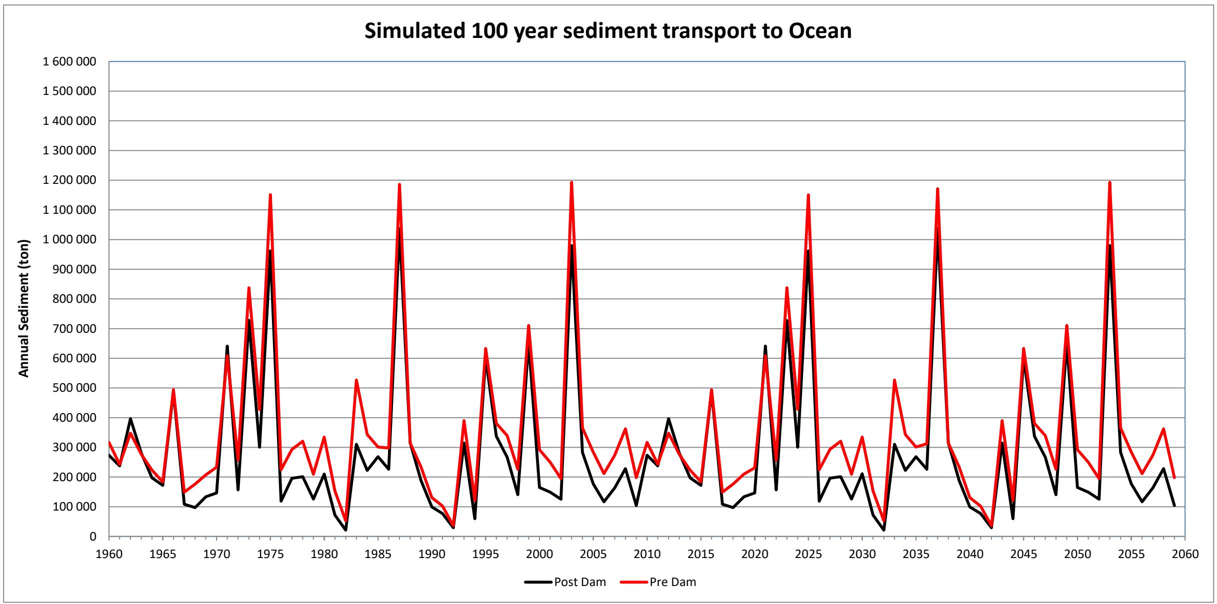

Figure 7: Simulated annual coarse sediment loads at the uMkhomazi River mouth

5. POTENTIAL IMPACT OF SMITHFIELD DAM ON COASTAL SEDIMENT BUDGET AND SHORELINE STABILITY

5.1 uMkhomazi River Sand Yield Reductions in the Context of the Coastal Sediment Budget

The main focus of this component was on the shoreline stretching from just south of the uMkhomazi River mouth northwards to Durban. The proposed Smithfield Dam is located 187 km upstream of the river mouth and the estimated total sediment yield trapped in the reservoir is 1.27 million t/a. The coastal impact of the dam is due to the decrease in sand load at the river mouth (coarse sediment) caused by sediment trapping in the reservoir and also due to the decreased sediment transport capacity downstream of the dam with the attenuated flood peaks and fewer floods spilling at the dam. The simulated net effect of the proposed dam is a 46 000 m^3/a reduction in sand load at the mouth. The pre-dam mean sand load at the river mouth was calculated as 352 000 t/a, while the post dam sand load is calculated to be 287 000 t/a, with an estimated reduction of sand load of 74 000 t/a (a 21% reduction in sand yield on this river). This reduction in sand yield represents a reduction of 18% of all the current inland sand load of all the rivers (from the river mouth to Durban), and a 10 % reduction in total load at Durban (river and longshore inputs combined). These values are based on interpretation of previous studies into the central Kwazulu-Natal coastal sediment budget (Theron et al, 2008), and present understanding and quantification of the Durban regional sediment budget including dams, coastal dredging and fluvial sand mining (as discussed in Basson and Theron, 2015). It should be noted that the sediment yield has increased significantly over the past 100 years on this river due to land use changes. The sand fraction of the yield is however not increased because it is related to the sediment transport capacity based on local hydraulic conditions. What has changed is mainly the fine cohesive sediment load (clay and silt) which is now much higher, but the fine sediment load does not contribute to the coastal sand budget, for example, to limit coastal erosion (Basson and Theron, 2015).

Unfortunately, in addition to the above potential impact to the sand yield of the uMkhomazi River, this important source of sand has also already been impacted on by sand mining (as is the case with many of the other central KZN rivers and some rivers in southern and northern KZN). Much of the sand mining operations extract sand directly from the main river channel and active/dynamic sand banks along the main channel, as can clearly been seen in the example shown in **Figure 8**. In the 2008 study (Theron et al, 2008), it was estimated that the sand mining rate from the uMkhomazi River is at least 42 000 m^3/a. It is possible that present sand mining volumes could be higher than the 2008 value, but this has to be confirmed by the local authorities. The 2008 study for Ethekwini estimated that the total sand mining rate from all 18 ''Ethekwini rivers'' was at least 400 000 m^3/a. Based on the 2015 estimate of fluvial sand yield of the uMkhomazi River, the sand mining (2008 volume) constitutes a loss of about 19% of the "natural" sand yield. Thus, the sand trapping in the proposed dam and the sand mining would have about equal impact on the sand yield from this river, and in total would reduce the sand yield of the uMkhomazi River by as much as about 18+19 = 37%. (The 2008 study, which contributed significantly to the present investigation, was reviewed, and the findings were then strongly backed by DWAF, DEA and Ethekwini municipality.)

Figure 8: Example of sand mining operations directly in uMkhomazi main river channel (Aerial view generated from Google EarthTM 2008©)

A historical reduction in longshore sand supply to the Durban Bluff has been observed. Long-term dredging records of the sand trap in Cave Rock Bight appear to indicate a declining trend in the annual dredging rate since the 1970's (TNPA and eThekwini data), and as indicated in **Figure 9**.

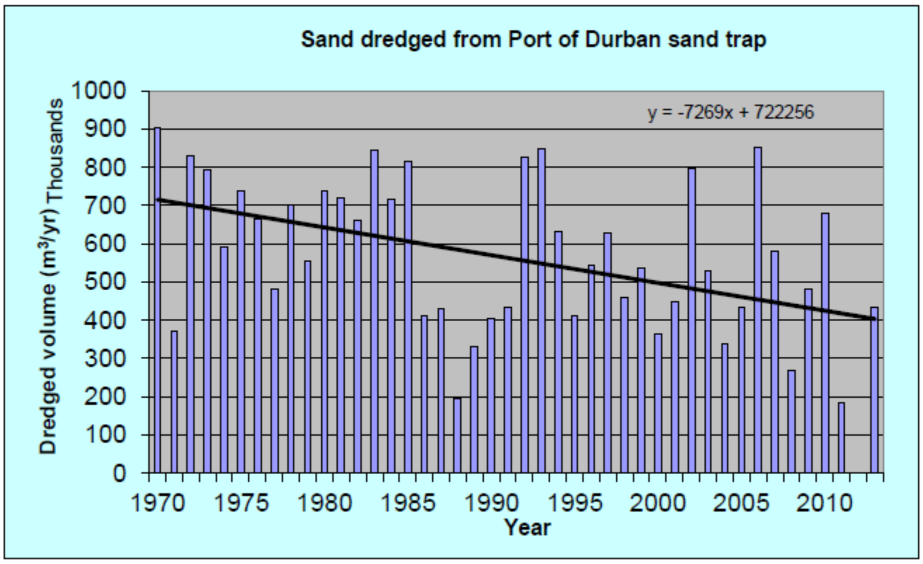

Figure 9: Annual sand volumes dredged from Durban sand trap since 1970 (Theron and Rautenbach, 2014)

In evaluating the potential (future) impact of the proposed dam on coastal stability, it is relevant to consider if the shoreline is currently in a state of dynamic equilibrium, or already subject to erosional trends. From the aerial photographic analyses (**Figure 10**) and the topographic survey results it cannot be clearly ascertained whether there is currently a significant long-term trend in the shoreline location in the vicinity of the uMkhomazi River mouth. Horizontal shoreline variations are naturally relatively large on this exposed high energy coastline and are further subject to the effects of episodic flood derived pulses of sediment input from the larger rivers in the region. Based on the longer-term aerial photographic analyses it appears that if indeed an eroding trend were present, it would have to be quite small (<=0.3 m/a, i.e. <=15 m over 50 years) to remain undetected at this stage. However, along the Durban Bluff coastline, which is located about 31 km northeast of the uMkhomazi Mouth, the historical observed lateral erosion rate is about 1 m/a. This was based on about 30 years of beach survey data and historical aerial photographs (Theron et al, 2008). More recent research (Habets, 2015 pers. com.) has confirmed this rate of recession over the period 1984 to 2012 (**Figure 11**). Although the Durban Bluff area is relatively far from the uMkhomazi Mouth, a long-term reduction in sand supply to the coast at the mouth will eventually affect the coastal sand budget further to the northeast (i.e. in the down-drift direction in terms of longshore transport).

The proposed dam on the uMkhomazi River will probably have a significant and long-term effect on the coastal sediment budget due to the relatively large volume of sediment (sand) that will not reach the river mouth due to sediment deposition in the reservoir and due to the reduced sediment transport capacity downstream of the dam. It is however possible to mitigate and limit the impact of the dam by implementing a combination of measures (see below). The impact in terms of net coastal erosion will be most noticeable in the first 10 km to the north of the mouth of the river, but even in this area it may be a decade or more before the impact is clearly apparent. However, in the long-term the impact (although initially insignificant), will gradually spread further north and is likely to eventually even result in a reduction of the longshore sand supply to the Durban Bluff area. The proposed Smithfield Dam has an estimated 10 % long term impact (reduction) of the total longshore sediment load at Durban (Basson and Theron, 2015), which is likely to increase the current rate of coastal erosion. Numerical shoreline modelling could be employed to quantify potential erosion impacts in the medium-term.

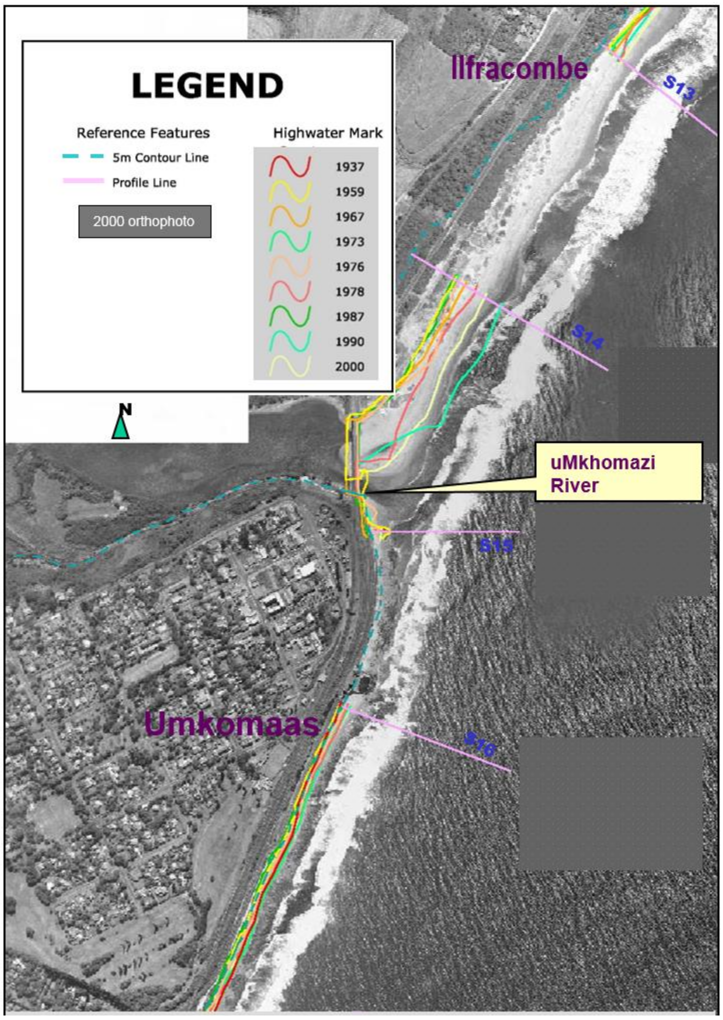

Figure 10. Coastal high-water lines at and south of uMkomazi Mouth

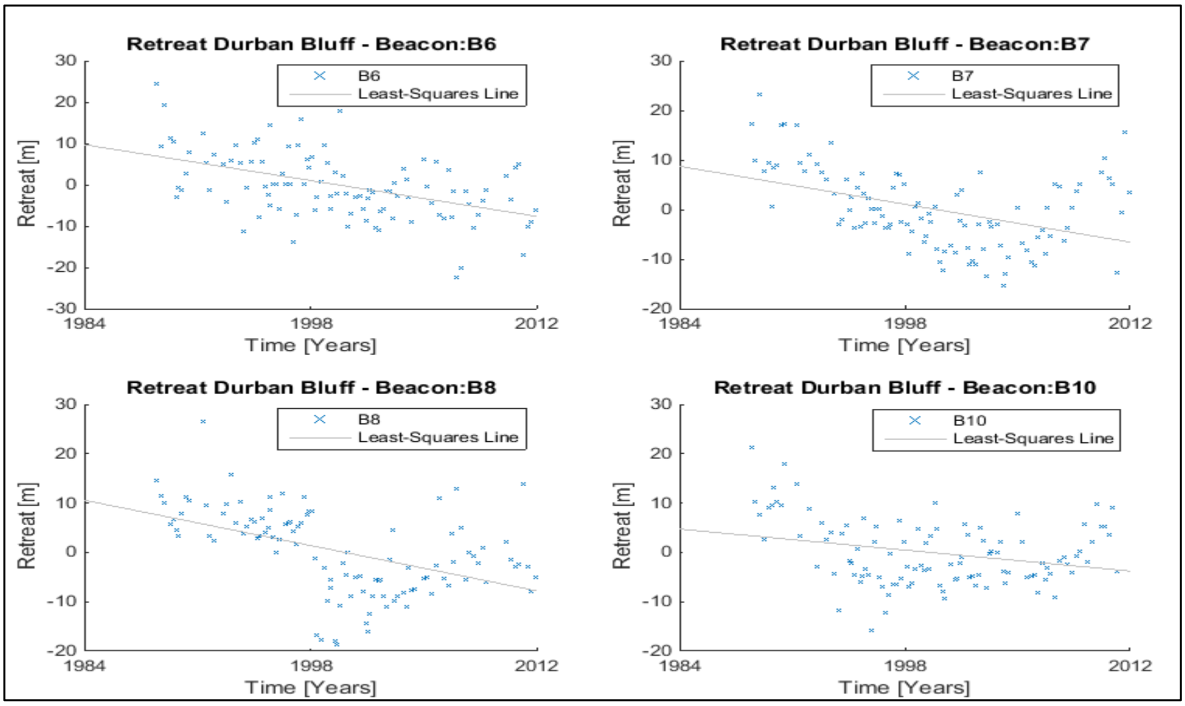

Figure 11. Erosion of Durban Bluff since 1984 from surveyed profiles (adapted from Habets 2015, pers com)

5.2 Possible Mitigation Measures to Limit Potential Coastal Erosion

If major dam developments on the uMkhomazi River are inevitable, then the potential impacts in terms of reduced fluvial sand supply to the coast could be mitigated by:

- Increase the fluvial sand load at the mouth by adding a sand bypass tunnel and weir (sand trap) in the upper reservoir of the proposed Smithfield Dam, similar to international designs used in Switzerland and Japan. A 5.1 km concrete lined tunnel length is required. Flushing of sediment will be carried out during floods under gravity and the firm yield of the dam could decrease slightly due to the flushing operation. The bypass would have the additional benefit of also resulting in less sediment accumulating in the dam, thus increasing the long-term useful capacity of the dam. Coarse sediment bypassing of the Smithfield Reservoir by bypass tunnel is possible to mitigate the impacts of the dam on the downstream river morphology and on the sediment loads at the river mouth. A 5.1 km tunnel is required with diameter of 7.0 m to 8.3 m (if concrete lined), to bypass the frequent floods such as the 2 year and 5 year floods, respectively. At the tunnel intake a weir is required in the upper reservoir, with a height of about 12 m.

- The current impact of sand mining on the uMkhomazi River is as large as the impact on the sand yield of the proposed Smithfield Dam. It is recommended to establish the status quo of sand mining in the uMkhomazi catchment, including illegal/unpermitted mining to quantify the extent of the problem. It is proposed that firstly existing illegal sand mining south of Durban should be prevented. In general, future legal sand mining south of Durban should also be limited. As an alternative to the current sources of alluvial river bed sediment, suitable sand sources at the coast could be identified, such as historical beach zones (geologic deposits) currently located inland near the coast, possible quarries, from the Smithfield Reservoir or upstream of the dam site on the river (but this is relatively far from the coast), and possibly from alluvial river floodplains from above the 200 year flood levels,

- Control and management of the catchment and coastal development could possibly be improved to limit erosion (by not removing or damaging coastal dunes, etc.).

- A beach nourishment programme (i.e. sand pumping) is possible, but requires a suitable off-shore source of coarse sand and dredging cost will be expensive. Critical zones along the beach could be targeted or general dredge disposal could be done to increase the available sediment budget (for longshore transport or resilience to erosion).

6. CONCLUSIONS AND RECOMMENDATIONS

The following are key findings and recommendations:

- The current development sediment yield (95% confidence) is estimated at 617 t/km^2.a for the proposed dam, which gives a mean annual sediment load of 1.27 million t/a. A possible future sediment yield of double the current yield due to land use change, land degradation and climate change impacts was also considered in the reservoir sedimentation analysis.

- Reservoir sedimentation modelling by 2D hydrodynamic model indicated that at the current sediment yield and future possible higher sediment yield over a 100 year period, the FSC could be 163 and 87 million m^3, a decrease of 36% and 66% of the original FSC, respectively.

- The Pre- and post-Smithfield Dam sediment dynamics downstream of the dam site to the ocean was investigated by 1D hydrodynamic model. The dam attenuates flood, the river main channel post dam will narrow and all the non-cohesive sediment is trapped by the dam. The long term average reduction in coarse sediment by the proposed Smithfield Dam at the river mouth is 74 000 t/a.

- The reduction in sand yield represents a reduction of 18% of all the inland sand load of all the rivers (from the river mouth to Durban), and a 10 % reduction in total load at Durban (river and longshore inputs combined). It is clear that the proposed dam on the uMkhomazi River will possibly have a significant and long-term effect on the coastal sediment budget due to the relatively large volume of sediment (sand) that will not reach the river mouth due to sediment deposition in the reservoir and due to the reduced sediment transport capacity downstream of the dam. The impact in terms of net coastal erosion will be most noticeable in the first 10 km to the north of the mouth of the river, but even in this area it may be a decade or more before the impact is clearly apparent. However, in the long-term the impact (although initially insignificant), will gradually spread further north and is likely to eventually even result in a reduction of the longshore sand supply to the Durban Bluff area.

- It is however possible to mitigate and limit the impact of the dam by implementing a combination of measures (see section 5.2). A 5.1 km long sediment flushing bypass tunnel and 12m high weir (sand trap) at the upper Smithfield Reservoir is a possible mitigation measure (although expensive), identified during the feasibility study, and is similar to international designs used in Switzerland and Japan (Basson and Theron, 2015), in conjunction with control of sand mining on the river, improved land care in the catchment and management of coastal erosion. Some of the key outcomes of an authorities meeting held during 2016 as part of the EIA, include: "targets to be established in terms of the volume of sediment that should be made available from the system and requires further input from the relevant stakeholders and specialists; further investigations must include a detailed understanding of the current state of the sediment regime of the river as well as establishing a monitoring programme; and most likely a host of interventions will need to be explored by the mandated authorities (including DEA, DWS, KZN DEDTEA, EKZNW, DMR, eThekwini Municipality, etc.)".

7. ACKNOWLEDGEMENTS

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