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Modifications to the Shoalhaven estuary and the coastal sediment budget over the past 40 years

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The Shoalhaven River is one of the few rivers in NSW to supply significant quantities of sand to the coast at the present time. The bulk of sediment delivery does not occur continuously but rather in pulse events driven by storms and floods that breach the beach berm at Shoalhaven Heads, and modify the estuary and adjacent nearshore. Analysis of aerial photographs and Landsat imagery revealed that the river mouth at Shoalhaven Heads was open in 1961, 1974-1980, 1988-1994, 1998-1999, 2013-2014 and 2015-2016. This work presents a series of surveys that started in the 1980's and included repeated echo-sounding, sediment analyses, Light Detection and Ranging (LiDAR) and Real-Time Kinematic GPS (RTK-GPS) data to assess the volumetric change after the reduction of fluvial input imposed by the construction of Tallowa Dam in 1976. Results showed that the surficial sediments of the Shoalhaven estuary are composed of a complex general pattern characterized by a decrease in grain size from coarse sand in the upper estuary to medium sand at both Shoalhaven and Crookhaven Heads, and muddy areas where mean grain size reached 6 phi. Comparison of interpolated depths showed gradual deposition in the Shoalhaven Heads channel and erosion of the Crookhaven channel, with considerable changes in the estuarine and offshore volume over the years. Modification in the estuary between 1981 and 2006 accounted for a net deposition of ~400,000 m3 of sediment despite the loss of ~1,600,000 m3 at the lower end. During the same period, comparison of bathymetric data in the nearshore indicated a delivery of at least 1,065,000 m3 of sediment to the coast. These values seem to be in agreement with the average sediment yield of ~528,000 m3/y for the catchment upstream of Tallowa Dam and the delivery of ~90,000 m3/y to the estuary, downstream of the dam, over the past 40 years.

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Modifications to the Shoalhaven estuary and the coastal sediment budget over the past 40 years

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Abstract
The Shoalhaven River is one of the few rivers in NSW to supply significant quantities of sand to the coast at the present time. The bulk of sediment delivery does not occur continuously but rather in pulse events driven by storms and floods that breach the beach berm at Shoalhaven Heads, and modify the estuary and adjacent nearshore. Analysis of aerial photographs and Landsat imagery revealed that the river mouth at Shoalhaven Heads was open in 1961, 1974-1980, 1988-1994, 1998-1999, 2013-2014 and 2015-2016. This work presents a series of surveys that started in the 1980's and included repeated echo-sounding, sediment analyses, Light Detection and Ranging (LiDAR) and Real-Time Kinematic GPS (RTK-GPS) data to assess the volumetric change after the reduction of fluvial input imposed by the construction of Tallowa Dam in 1976. Results showed that the surficial sediments of the Shoalhaven estuary are composed of a complex general pattern characterized by a decrease in grain size from coarse sand in the upper estuary to medium sand at both Shoalhaven and Crookhaven Heads, and muddy areas where mean grain size reached 6 phi. Comparison of interpolated depths showed gradual deposition in the Shoalhaven Heads channel and erosion of the Crookhaven channel, with considerable changes in the estuarine and offshore volume over the years. Modification in the estuary between 1981 and 2006 accounted for a net deposition of ~400,000 m^3 of sediment despite the loss of ~1,600,000 m^3 at the lower end. During the same period, comparison of bathymetric data in the nearshore indicated a delivery of at least 1,065,000 m^3 of sediment to the coast. These values seem to be in agreement with the average sediment yield of ~528,000 m^3/y for the catchment upstream of Tallowa Dam and the delivery of ~90,000 m^3/y to the estuary, downstream of the dam, over the past 40 years.

Keywords: catchment yield, sediment transport, estuarine deposition, sediment budget, Shoalhaven River.

1. Introduction

The Shoalhaven estuary is an example of a mature stage wave-dominated barrier estuary [9], which occupies a drowned valley constricted by flood tidal deltas and impounded by a coastal sand barrier. Like many barrier estuaries, the Shoalhaven is characterised by estuarine and fluvial depositional environments, with extensive subaqueous "mud basin" deposits that interdigitate with fluvial deltaic sediments in a landward direction, and with tidal deltaic sand bodies in a seaward direction.

Tides at the coast are semidiurnal with a mean range of 1.2 m (spring range of 1.8 m) and their influence extends ~20 km upstream until Burrier. The tidal prism of the estuary is ~23 x 10^6 m^3 during spring tide, which exceeds the base flow by 18 times, but represents only 20% of the extreme flood discharge volume [12].

Although the Shoalhaven River mouth is breached during floods, most of the time the normal flow is diverted through an artificially dug 200-m long canal, constructed in 1822 (Berrys Canal) forming Comerong Island, and only reaches the ocean at Crookhaven Heads [10]. Since then, Berrys Canal continues to widen [8 and 11] and directs the flow of the Shoalhaven River to exit at Crookhaven Heads.

The former mouth of the river at Shoalhaven Heads has been impounded by the deposition of a sandy berm. Following major floods, the outlet is breached temporarily while the river flows naturally to the Tasman Sea, with the beach berm gradually re-establishing over time. Remote sensing analyses [3] revealed that the river mouth at Shoalhaven Heads was open in 1961, 1974-1980, 1988-1994, 1998-1999, 2013-2014 and 2015-2016.

The construction of Tallowa Dam, upstream of Nowra, in 1976, represents another major modification to the catchment, forming Lake Yarrunga from which water is transferred to Sydney. The reservoir has a maximum operational capacity of 35 GL, smoothing the flash flooding of the river considerably, increasing the salinity (~3ppt) in the middle estuary [7] and reducing the sediment delivery [2].

The limited accommodation space for sediment deposition within the estuary favours transfer of sediments to the shoreface during flood events and therefore, sediment transport to the coast is not regular, but rather occurs in pulses. During low flow stage conditions, the entrance at Shoalhaven Heads is closed and the tidal effects transport marine sediments up the estuary through

Crookhaven Heads and therefore, no sediments are discharged to the coast. When the freshwater flow increases but Shoalhaven Heads is not breached, it is likely that sediments are discharged to the nearshore through Crookhaven Heads. During storm events when Shoalhaven Heads is breached, not only sediments that were recently transported from the catchment, but also sediments eroded from the estuarine banks are transferred to the coast through both entrances. After the breaching event, gradual shoreward return of the sand deposit constricts the outlet and re-establishes the beach across the entrance.

This work looks at sedimentological analyses and compares Digital Elevation Models (DEMs) from a series of surveys that started in the 1980's and included repeated echo-sounding, RTK-GPS and LiDAR data to assess the volumetric change after the shortage of fluvial sediment input imposed by the construction of Tallowa Dam in 1976.

2. Methods

Estuarine bathymetry was collected between Shoalhaven Heads and Crookhaven Heads in 2015, in order to compare to previous bathymetric surveys. Approximately 63,500 survey points were collected using the CEEDUCER PRO. Fieldwork was carried out between 18/12/2014 and 03/08/2015 and soundings were corrected using local tide gauges. Previous bathymetric surveys covering Shoalhaven Heads and the entire Shoalhaven estuary in 1989 and 2006, respectively, were provided by OEH.

Approximately 10,500 survey points were digitised from the 1981 PWD's Shoalhaven River hydrographic survey plans that covered most of the estuary and the nearshore between Shoalhaven Heads and Crookhaven Heads. The plans were georeferenced, digitised and spatially adjusted using survey marks identified in the plans to account for the offset in the horizontal coordinates. Specific offshore bathymetric surveys spanning parts of the study area during different years were provided by OEH.

A comprehensive suite of estuarine surficial sediments (n=123) was collected using a square pipe dredge. Samples on the upper/middle estuary were collected in September 2013, whereas samples from the lower estuary were collected in December 2013. In the laboratory, samples were washed for salt extraction, subsampled and dried.

To determine size fractions. ~150 g of sample was dry sieved at 0.5 phi intervals. Size fractions finer than 0 phi were determined by laser scanning using a Malvern Mastersizer 2000. Grain size statistics have been calculated using Folk and Ward [5] formulae. Individual sample results were obtained by running the grain size distribution and statistic software GRADISTAT [1]. Sample results were appended to georeferenced points, and maps of estuarine, and nearshore/offshore surficial sediments were created by Inverse Distance Weighted (IDW) interpolation.

LiDAR data acquired by NSW Land and Property Information (LPI) between December/2010 and April/2011, as well as elevation points collected by Shoalhaven City Council between June/2013 and October/2015, using a RTK-GPS at the beach-berm that separates the estuary from the nearshore at Shoalhaven Heads, were used to assess the volumes exchanged between the beach-berm and the shoreface, and determine how fast recovery occurs from an event of the magnitude of the 2013 storm. Surveyed dates with restricted or poor coverage of the area were discarded. Elevation points were interpolated using IDW to create monthly DEMs of the beach-berm.

3. Results and Discussion

Depth modification between 1981 and 2006 showed that ~400,000 m^3 of sediment was deposited throughout most of the estuary (from Long Reach to both Shoalhaven Heads and Crookhaven Heads entrances) over the 25-year period. However, dividing the area in two, just upstream of O'Keefes Point, it was observed that the upper part accreted ~2,000,000 m^3, whereas the lower part eroded ~1,600,000 m^3, showing that a lot of fluvial deposition occurred upstream of O'Keefes Point, and that erosion heavily dominated between the two entrances.

The first survey, carried out in 1981, registered a maximum depth of 21.6 m, 0.2 m deeper than the maximum depth recorded in the 2006 survey. The map on the left of Figure 1 shows the areas where deposition and erosion occurred between 1981 and 2006. Areas of substantial deposition greater than 4 m, represented by dark blue, were located mostly upstream from Nowra, but areas with vertical deposition of up to 2 m were found throughout the estuary. Areas of erosion mostly occurred along the estuarine channel, especially on the north of Pig and Numbaa Islands, as well as at some pools upstream from Nowra (dark red). Downstream from Numbaa Island, the estuarine thalweg migrated towards the right margin, as indicated by the light red channel.

An area of ~200,000 m^2 located on the southwest of Pig Island was excavated for sand mining and depth increased 7.5 m at some points. A volume of ~620,000 m^3 was extracted between the two surveys. When this value is added to the 2,000,000 m^3 calculated previously, a total estuarine deposition of 1,020,000 m^3 (2,620,000

m^3 - 1,600,000 m^3) is inferred between 1981 and 2006.

The difference in depths between DEMs derived from 1981, 1989, 2006 and 2015 surveys, in the lower part of the estuary between Shoalhaven Heads and Crookhaven Heads, is shown on the right side of Figure 1. The survey carried out in 1989 only covered the downstream part of the natural channel that leads to Shoalhaven Heads.

At Shoalhaven Heads, a loss of ~160,000 m^3 of sediments was observed in most of the area between 1981 and 1989, driven by the breaching event that happened in July/1988 and flushed sediments to the nearshore.

Between 1989 and 2006, erosion occurred to form the new channel observed in 2006 and deposition was observed along most of the remaining area, reaching up to 3.4 m of accretion near the river mouth. A comparison of the interpolated data gave an estimate of ~285,000 m^3 of sand accumulated over the 17-year interval, implying an average rate of 16,760 m^3/y. This accumulation rate is limited by three facts: i) Shoalhaven Heads was closing in 1989 from the breaching event that happened in middle 1988; ii) another major event opened up Shoalhaven Heads in the middle of 1990, taking 3.5 years to close; and iii) much weaker breaching events that occurred in 1989-1999.

A lot of deposition occurred near Old Man Island and towards Shoalhaven Heads between 1981 and 2006. However, erosion was predominant on the majority of Crookhaven channel, from O'Keefes Point to Crookhaven Heads. Heavy scouring took place along the entire Berrys Canal, several parts of Comerong Island and further downstream.

The bathymetric campaign carried out specifically for this project in 2015 showed a very similar pattern as in 2006, with minor changes in the morphology but considerable changes in volume of sediments. Regarding the entire area surveyed in 2015, a net volume loss of ~1,095,000 m^3 occurred between 2006 and 2015, which corresponds to an average loss of 122,000 m^3/y. However, not everywhere behaved the same way.

The channel that existed in 2006 at Shoalhaven Heads, was still observed in 2015, but was encountered further away from the beach. Deposition continued and an extra volume of ~61,000 m^3 of sediments accumulated over the 9-year interval, an average rate of 6,780 m^3/y, using the polygonal area of the 1989 survey. This lower accretion rate than the one estimated between 1989 and 2006 may be partly explained by the fact that Shoalhaven Heads remained open for eight months after the breaching event in June/2013, and some of the sediments deposited before the artificial opening are likely to have been transported offshore.

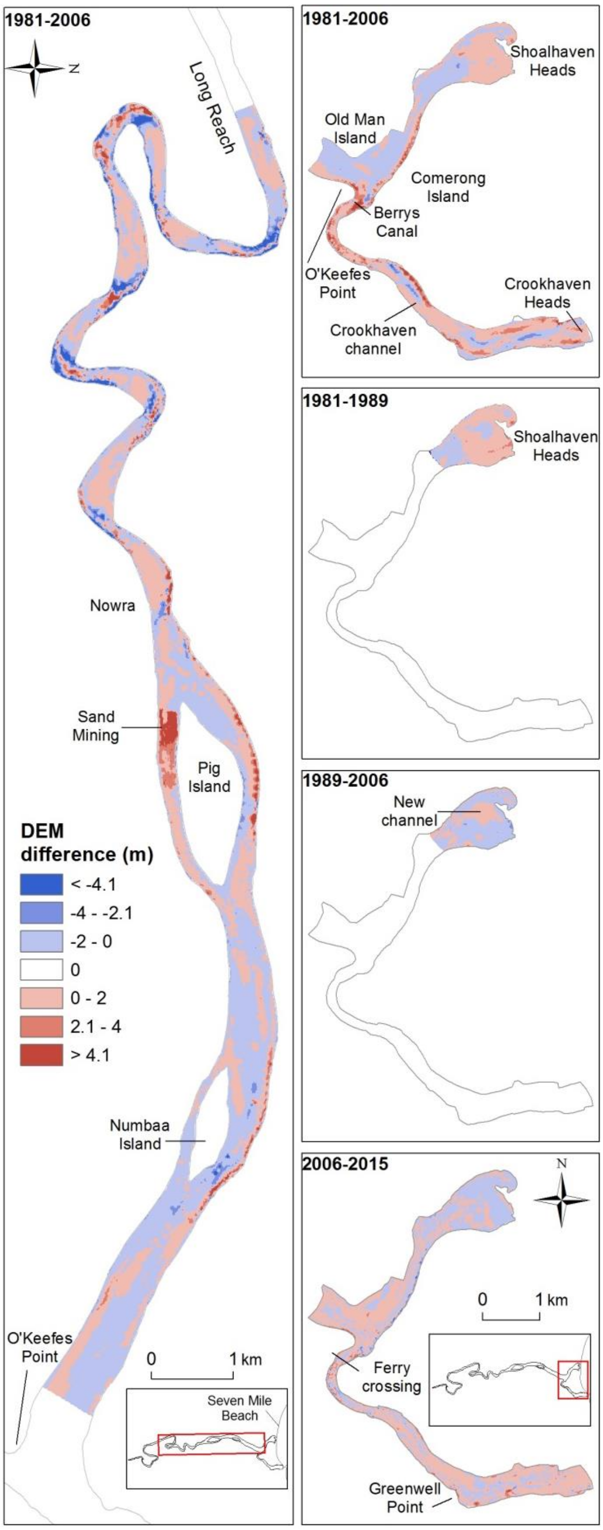

Figure 1 Bathymetric variation in the Shoalhaven estuary. The left map shows the area between Long Reach and O'Keefes Point in 1981 and 2006, whereas right maps show the area at the lower end of the estuary between Shoalhaven Heads and Crookhaven Heads during different periods. Red shading indicates areas

where erosion occurred whereas blue shading indicates areas of accretion over time.

Towards Berrys Canal, maximum depths slightly increased to 18.1 m, but scouring took place near/downstream from the Ferry crossing. Around Crookhaven Heads, not much change could be observed over the nine-year period, apart from the deepening of the channel itself to 11.3 m on the southern flank near Greenwell Point. Between 2006 and 2015, deposition occurred mainly towards Shoalhaven Heads and consisted of less than 2 m of accretion, while, most of the area between Berrys Canal and Crookhaven Heads was dominated by less than 2 m of erosion. The Comerong Island side of the estuary, primarily towards Shoalhaven Heads, experienced most of the deposition of up to 5 m, whereas most of the deep eroded areas were located between Berrys Canal and Crookhaven Heads.

From the DEM difference maps, it is also inferred that erosion dominated most of the Crookhaven channel in the past 34 years, and that deposition is the major process happening along the Shoalhaven channel including Shoalhaven Heads, despite the gross losses that might occur during breaching events. This trend of erosion and deposition is apparent especially over longer periods such as between 1981 and 2006 and is expected as a result of the diversion of the flow via Berrys Canal and its continuing adjustment to fluvial and tidal scouring since 1822, and the low hydrodynamics experienced in Shoalhaven channel when Shoalhaven Heads is closed.

Some of the volumetric figures, as well as, the spatial extent of such changes over time, need to be addressed with caution as they represent an approximation calculated by the IDW interpolator used to generate the DEM of the bathymetric points. Nevertheless, clear erosional and depositional trends are apparent.

Grain size analysis showed that the mean grain size ranged from -0.4 phi to 6 phi (Figure 2). The general pattern is characterized by a decrease in grain size from coarse sand in the upper estuary to medium sand at both Shoalhaven and Crookhaven Heads. In the upper part of the estuary, very coarse sand occurs in shallow water, whereas finer fractions (medium to very fine sand) prevail in the pools. The most diverse textural part of the river is located between Pig Island and the 10 km upstream of Nowra Bridge. In this part, the river is composed of medium sand intercalated with finer sediments down to medium silt.

Downstream from Pig Island, medium sand prevails and the texture becomes finer near both entrances, with coarse silt just upstream of Shoalhaven Heads and fine sand adjacent to Orient Point. Towards both entrances the mean grain size increases again to medium sand due to the flood tide delta deposit at Crookhaven Heads and the penetration of marine sand transported by waves and wind at Shoalhaven Heads, an area of net upstream transport during low flow stages, as revealed by Wright et al.[12].

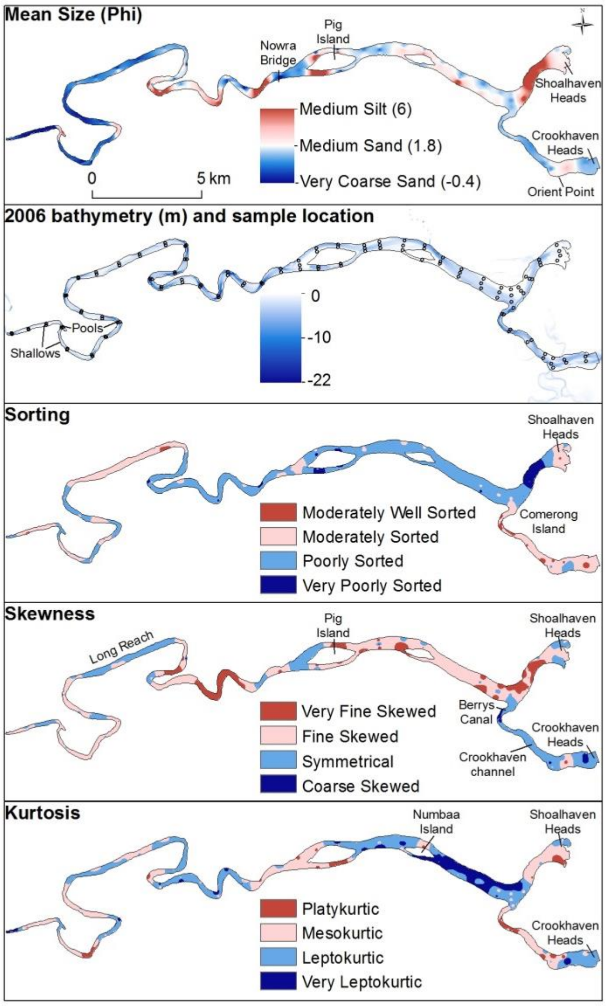

Figure 2 Mean grain size, bathymetry and sample location, sorting, skewness and kurtosis along the Shoalhaven estuary. 2006 Bathymetric data © NSW Government: Office of Environment and Heritage (OEH).

Sorting, skewness and kurtosis indicate how similar the samples are from a normal probability curve and are indicative of important sedimentary processes happening especially in the lower estuary. Environmental interpretation of these statistical parameters for most of the middle-upper estuary has proven to be difficult due to the existence of a complex general pattern of grain size, deep pools, meandering narrow channels, and mixing with material from eroding banks.

The dispersion around the average value, known as standard deviation or sorting, varied from 0.6 phi to 2.8 phi. Sediments were moderately sorted in the upper estuary, mostly poorly sorted upstream of Comerong Island, and moderately sorted to moderately well sorted around both entrances. The very poorly sorted mud sediments just before Shoalhaven Heads can be explained by the restricted hydrodynamic conditions experienced in this area after the gradual closing of the entrance during the months prior to the sampling.

The skewness or asymmetry is determined by the relative importance of the tails of the distribution. The skewness has a positive or negative value when more fine or coarse material is present than in a normal distribution. Sediments in the estuary varied from coarse skewed (-0.24) to very fine skewed (0.55), with most of the samples considered fine skewed. Sediments with symmetrical distribution were observed at Long Reach, around Pig Island, between Berrys Canal and Crookhaven Heads, and in two of the four samples collected at Shoalhaven Heads. The moderately sorted symmetrical samples that predominate along the Crookhaven channel and to a lesser extent near Shoalhaven Heads entrance indicate that marine-derived sands are penetrating the estuary.

Very fine skewed samples were found scattered downstream from Long Reach towards Shoalhaven Heads and also in a sample near Crookhaven Heads. The fact that there are patches of very fine skewed poorly sorted mud sediments just upstream of Shoalhaven Heads, indicates a mix of fluvial and marine material, as strongly skewed samples are generally obtained from zones of environmental mixing [4]. Coarse skewed sediments also occurred between Berrys Canal and Crookhaven Heads.

Kurtosis measures the peakedness of the distribution. If a distribution is flatter than a normal one, it is called Platykurtic; if more peaked, it is called Leptokurtic. Kurtosis in the estuarine sediments varied from Platykurtic (0.73) to very Leptokurtic (2.8). 49 out of 123 samples were normal (Mesokurtic) and found all over the estuary, including near both entrances at Shoalhaven Heads and Crookhaven Heads, and also in the upper and middle estuary, where patches of Mesokurtic surficial sediments alternate with Leptokurtic ones.

Sediments with very peaked distribution curves (Very Leptokurtic) occur especially downstream of Numbaa Island. The occurrence of very Leptokurtic material implies a mix of two different materials (fluvial and marine), suggesting that part of the (marine) sediment achieved its sorting elsewhere in a high-energy environment, and was transported with its size characteristics unmodified into another environment (estuarine), as discussed by Folk and Ward [5].

The dynamics of sand transport during breaching events at Shoalhaven Heads can be better understood by looking at monthly surveys of RTK-GPS elevation data, collected by Shoalhaven City Council, before and after flood events (Figure 3), such as the one that happened at the end of June/2013.

In early 2011, LiDAR data processed for bare ground elevation showed a stretch of ~300 m of beach formed connecting Seven Mile Beach and Comerong Island, after at least 11 years since the last brief opening that occurred in 1999/2000. The remains of the foredune could be identified by the scattered deposits of sand in the north and south, reaching 5 m in elevation (AHD), and a berm crest of 2.2 m high was formed. RTK-GPS data collected in June/2013 showed a slight increase in the berm crest height to 2.5 m and the deposition of sediments behind the berm.

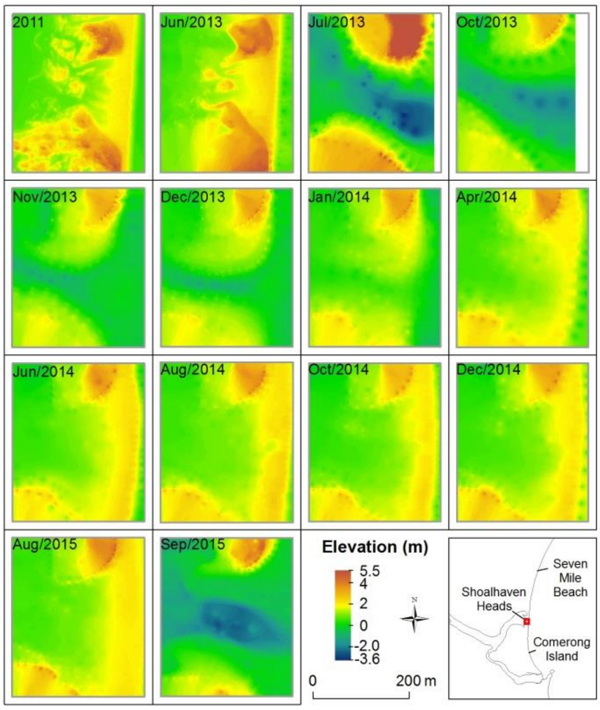

Figure 3 Shoalhaven Heads dynamics before and after the mechanical opening by Shoalhaven City Council to mitigate the floods during the 2013 and 2015 East Coast Lows. Map sequence shows the gradual closing of the channel after the breaching event that happened in July/2013, and the reopening after the complete closing of the estuary in September/2015. Elevation data (m AHD) collected using a RTK-GPS, except 2011 map derived from LiDAR.

During the passage of the East Coast Low at the end of June/2013, Shoalhaven City Council bulldozed Shoalhaven Heads, through the dry notch, allowing fresh water discharge into the ocean. This process resulted in the scouring of the beach transporting sand offshore and the formation of a 140 m wide channel 3.5 m deep.

The following months show the gradual closing of the channel and the return of most of the lost sand by April/2014, when the beach was reformed across the entrance.

From April/2014 to August/2015 the beach accreted both in width and height, prograding seawards, and in the following month, another East Coast Low event, forced the Shoalhaven City Council to mechanically open up Shoalhaven Heads one more time.

The 2013 breaching event has resulted in a loss of ~200,000 m^3 of sand as the volume decreased from 485,000 m^3 in June/2013 to 284,000 m^3 in July/2013 in the sand volume above a depth corresponding to 3.65 m below AHD. A loss of ~165,000 m^3 happened during the 2015 event, when the total volume decreased from 459,000 m^3 in August/2015 to 294,000 m^3 in September/2015.

The breaching dynamics at Shoalhaven Heads demonstrates not only the volumes exchanged between the beach-berm and the shoreface, but also how fast the recovery from an event of the magnitude of the 2013 storm occurs.

The bathymetric change experienced off Shoalhaven Heads (Figure 4) has helped to understand the volume of sediment transported to the nearshore over time. In 1981, Shoalhaven Heads was closed, but in 1980 the area was still closing from the opening that happened during the 1970's, and therefore, a large amount of sediment was deposited in the nearshore down to 18 m deep.

Between 1981 and middle 1988, the entrance remained closed, and only opened again in the second half of 1988. It is expected that during this time much of the sediment deposited in the nearshore adjacent to Shoalhaven Heads had been reworked and redistributed alongshore by wave action and part of it moved across-shore to the beach berm and also back into the estuary by wind processes. Gordon [6] estimated that 400,000 m^3 of sand was involved in the re-formation of the entrance from 1981 to 1985.

The survey carried out in April/1989 after the breaching event in 1988, covered a much more restricted area than the survey of 1981. Once again, a large volume of sediment was deposited in the nearshore, but this time the convex form deposited was located slightly more to the south. This time, ~440,000 m^3 of sediment was deposited in the nearshore when compared to the same area in the 1981 survey.

By 2006, a considerable amount of sand previously observed in the nearshore adjacent to Shoalhaven Heads had been moved away. This time a loss of ~1,640,000 m^3 occurred from the same area mapped in 1989. Shore-parallel isobaths down to 8 m of depth suggest that the sediment was transported from shallow water by wave action, whereas non-parallel deeper isobaths suggested that remains of the nearshore deposit still existed down to 16 m of depth after 17 years. Nevertheless, the total nearshore area between Shoalhaven Heads and Crookhaven Heads showed an accretion of ~1,065,000 m^3 of sediment between 1981 and 2006.

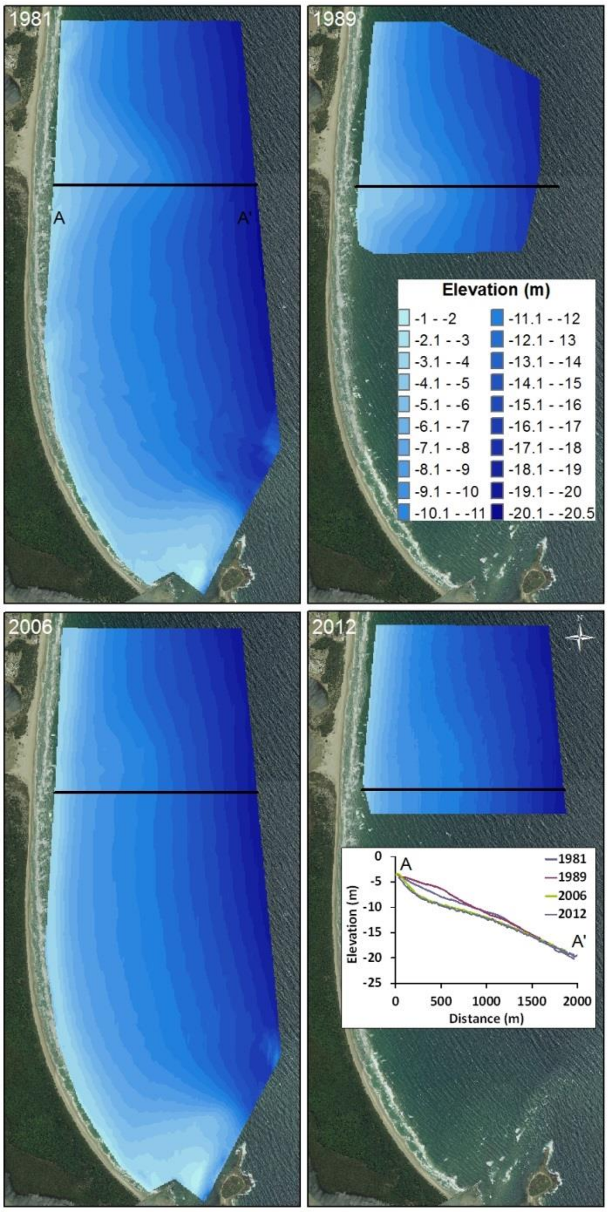

Figure 4 Bathymetric DEMs in 1981, 1989, 2006 and 2012 between Shoalhaven Heads and Crookhaven Heads. Nearshore profile is shown in black line and plotted on the right hand side. Background imagery © NSW Government. Office of Environment and Heritage (OEH) 2014.

The next bathymetric campaign taken in 2012 covered a much more restricted area than the

1981 and 2006 surveys and also did not extend further south as in 1989. However, the 2012 campaign showed that isobaths were much more shore-parallel than in 2006, implying that sand deposited in the nearshore during the flood event was transported and distributed alongshore throughout the embayment and across-shore to the beach. Compared to the same area in 2006, ~400,000 m^3 of sediment was transported from the area by 2012. The graph presented on the right hand side of Figure 4 shows the variation of the nearshore deposit over the years at cross-section A-A'.

The volumetric changes indicate that a considerable amount of fluvial-estuarine sediments were deposited in the nearshore since 1981 and at least 1,065,000 m^3 were discharged by the Shoalhaven River and deposited in the nearshore area between Shoalhaven Heads and Crookhaven Heads, as discerned from the observed accretion that occurred between the 1981 and 2006. These values seem to be in agreement with the average sediment yield of ~528,000 m^3/y for the catchments upstream of Tallowa Dam and the delivery of ~90,000 m^3/y to the estuary in the past 40 years, calculated by Carvalho [3]. Non-parallel depth contour lines deeper than 10 m, in the 2012 bathymetric survey, suggest that remaining sediments from previous breaching events still exist in the Seven Mile Beach-Comerong Island nearshore, and therefore, further beach accretion can be expected once wave-driven transport takes place and sediment is reworked to the beach.

4. Conclusions

This study assesses the volumetric change after the reduction of fluvial input imposed by the construction of Tallowa Dam in 1976, Results showed that the surficial sediments of the Shoalhaven estuary are composed of a complex general pattern involving gradual deposition in the Shoalhaven Heads channel and erosion of Crookhaven channel, with considerable volume changes occurring in estuarine and offshore areas over the years. Modification in the estuary and in the nearshore between 1981 and 2006 seem to be in agreement with the average delivery of ~90,000 m^3/y to the estuary in the past 40 years, calculated by Carvalho [3].

There are constraints on the extent to which a budget of sediments can be effectively created, as there will always exist uncertainties associated with the volumes, processes and exchanges. Nevertheless, this study provides a framework for future research and a basis for management actions, showing a direct application of the concept of conservation of mass to the coastal sediment budget of the Shoalhaven Coast.

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