Terara Shoalhaven Sand – Application for Extension of Dredge Area Supplementary Information – Geomorphology

Prepared for:

Terara Shoalhaven Sand

Prepared by:

Fluvial Systems Pty Ltd

PO Box 49, Stockton, NSW Australia, 2295

P: +61 2 4928 4128, F: +61 2 4928 4128; M +61 (0)404 472 114

Email: fluvialsystems@fastmail.net

ABN: 71 085 579 095

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1 Introduction

On 19 April 2022 Shoalhaven City Council provided a request for information (RFI) to Terara Shoalhaven Sand in relation to the Environmental Impact Statement (EIS) for Regional Application - Extension of Dredge Area, to Western End and Northern Side of Pig Island, on the Bed of the Shoalhaven River, Adjacent to Lots 1 and 2 DP 1184790 below MHWM.

Fluvial Systems was commissioned to respond to items in the RFI relevant to geomorphology. The paragraphs of the RFI relevant to this report were:

"15 Amended EIS

An expanded EIS assessment is required to be provided which addresses potential bank and channel instability impacts, including the following:

- *a) A description of the formation of the estuary (geomorphology) at and downstream of the dredging operations, including the formation of Pig Island (e.g. during the Holocene period).*
- *b) Use of historical and other data (such as historical photographs, historical river surveys, and presumably, survey data presumably collected by the dredging operators over time in association with their past EPA licence, academic research papers such as by RC Carvalho of University of Wollongong, for example) to provide an assessment of:*
    - *i. Changes in the location and depth of the channels and banks at and downstream of the dredging operations, from prior to dredging to present day.*
    - *ii. The rate of infilling of deep dredge holes, and infilling of the dredge area more broadly, including recent flood events, over the last 20+ years.*
    - *iii. The impact of deep dredge holes on nearby channels (in terms of channel location and depth).*
    - *iv. An assessment of the sedimentological data (such as the samples collected by the dredging operators in accordance with their EPA licence, and academic research papers as noted above), to clearly describe:*
        - *The volume of sediment removed during dredging (annually)*
        - *For the dredged material, the proportion of sand extracted versus the proportion of material returned to the stock mounds and/or the river, and the grain size(s) of returned material*
- *c) Description of the depth of dredge operations. This information is essential in determining the impact of dredge batters and buffer zones on marine and riparian vegetation.*
- *d) A detailed assessment of the visual impacts of the proposed development, noting that dredging operations are already visible from Nowra Bridge and surrounds.*
- *e) The following further information is required to be provided in relation to the stock mounds on Pig Island:*
    - *i. An assessment of the potential for stockpiled fines being remobilised into the water column by rain / floodwaters, and potential water quality impacts downstream associated with this (including any water quality sampling or modelling).*
    - *ii. An assessment of the past performance of mounds and their likely response during floods, including the likelihood of the mounds being washed away versus the impact to flood levels in the unlikely event that the stock mounds remain stable during a major flood.*
- *f) Given that the sand resource is finite and is being removed permanently from the sediment system, and that past and future approvals are sought for 20 to 50 years or more, assessment of the potential long-term impacts from dredging is sought, including:*
    - *i. Long term impacts to Shoalhaven beaches and beaches further north given that a substantial portion of sand sized material is being removed by dredging rather than being supplied to the coast (noting that the Shoalhaven/Crookhaven River is one of only 2 rivers in NSW that supplies sand sized material to the coast). This assessment needs*

also to consider the combined impact of the dam built upstream in 1976 that will already have contributed to a reduced sand supply to the estuary and coast.

ii. *The long-term changes in the geomorphology of the lower estuary due to the increase in tidal regimes from training of the Shoalhaven River and how this may have interacted or will interact with dredging impacts.*

iii. *Future long-term impacts of sea level rise which is expected to increase the tidal ranges in the estuary and may therefore change the impact of dredging operations on surrounding channels and banks.*"

This report addresses the above items, a), b), e) and f), i.e., excluding items c) and d).

This report is structured as follows: summary of responses to the RFI (note: this summary assumes that the entire report has been read); description of the methodology employed; review of literature and data; results of new analysis and assessment of the potential long-term impacts from dredging; guide to the location of responses to the relevant RFI items within this report; list of references; and appendices.

2 5-page summary response to RFI

a) A description of the formation of the estuary (geomorphology) at and downstream of the dredging operations, including the formation of Pig Island (e.g., during the Holocene period).

During the Pleistocene Epoch (2.59 Ma to 11.5 ka) the sea level fluctuated, and prior to the Holocene interglacial it was up to 125 m below its current level. Stabilisation of the sea level since the beginning of the Holocene (7,900-7,700 yr BP) enabled the Shoalhaven estuary to form. A marine sand barrier formed across the Shoalhaven River entrance and fluvial sediment was trapped landward of this barrier, infilling the Shoalhaven Estuary.

The specific age and formation of Pig Island has not been documented in the literature. It could have formed within the established river channel relatively late in the final phase of estuary infilling, due to an obstruction in the channel accumulating debris and sediment, with the flow of the river bifurcating and expanding around the island as it grew and became stabilised by vegetation. Alternatively, Pig Island could have been carved off a section of established deltaic plain material due to migration and avulsion of the main channel.

b) Use of historical and other data (such as historical photographs, historical river surveys, and presumably, survey data presumably collected by the dredging operators over time in association with their past EPA licence, academic research papers such as by RC Carvalho of University of Wollongong, for example) to provide an assessment of:

   i. Changes in the location and depth of the channels and banks at and downstream of the dredging operations, from prior to dredging to present day.

Parish plans depict Pig Island approximately 1.67 km long and 675 m wide, which is substantially smaller than its current size, measured from a 2021 aerial image, approximately 2.32 km long and 812 m wide. The plans depict the western bank of the Shoalhaven River near Pig Island in a similar position to its current position. However, with the exception of the most recent plan, depict the right bank of the river, for a distance of 1.9 m downstream of Terara, in a more northerly position than its current position. The difference in position is up to 360 m. A 1949 aerial image indicates that the current perimeter of Pig Island and the positions of the left and right banks of Shoalhaven River in the vicinity were achieved 80 years ago.

The earliest recorded flood on the Shoalhaven River was a very large event in February 1860. Ten years later, a large flood occurred in March 1870, followed a month later by the largest flood on record. A correspondent for the Empire newspaper (Empire, 1870) gave an account of flood impacts that included erosion of large areas of river frontage land, exceeding 300 m of bank loss in one location. The article is convincing evidence of large-scale channel change in the Terara area due to the 1870 flood. The accounts of dramatic morphological change associated with the 1860 and 1870 floods possibly explains the differences in the way Pig Island, and the right bank of Shoalhaven River downstream of Terara, are depicted on Parish Plans, compared to aerial imagery since 1949.

Analysis of aerial imagery from 1949, 1970, 1984, 2012 and 2021 undertaken for this report found that there was little change apparent in the shorelines of Pig Island and the Shoalhaven River in the vicinity of Pig Island between 1949 and 2021 (Figure 19), despite this area being recognised as having a bank erosion problem. Carvalho (2018) used visual assessment to map erosion presence and type, armouring presence and type, and presence of erosion of armouring of the Shoalhaven River from Barrington Reach to the river mouth. Bank erosion was common along the shorelines, but Carvalho (2018) did not report whether or not this was an expected phenomenon, considering the land use, riparian cover, and site characteristics, including hydrology and hydraulics. Whilst the analysis of aerial imagery undertaken for this report did not reveal large scale change of bank position in the river reach that included Pig Island, this result is not incompatible with local, perceived problematic, bank erosion, especially close to an urban area where bank erosion is often viewed negatively. To summarise, since 1949 there have been no major changes to bank positions in the Pig Island area despite construction of Tallowa Dam (in 1976), several large floods, and regular sand extraction since the late-1960s or early 1970s. This is in contrast to the apparently high level of geomorphic instability of this reach during the floods of 1860 and 1870.

Carvalho (2018) compared bathymetric surveys undertaken in 1981 and 2006 and found that between these dates, significant fluvial deposition occurred on the bed of the Shoalhaven River upstream of O'Keefes Point. Areas of substantial deposition exceeding than 4 m were located mostly upstream of Nowra, despite Tallowa Dam upstream trapping incoming coarse sediment since 1976. Areas of scour mostly occurred along the estuarine channel, especially on the north of Pig and Numbaa Islands, as well as within some pools upstream from Nowra. Downstream from Numbaa Island, the estuarine thalweg migrated towards the right margin. Approximately 620,000 m^3 of sand was extracted from an area of approximately 200,000 m^2 on southern channel around Pig Island between the two surveys. There are no bathymetric data available prior to the start of sand extraction in the late-1960s or early-1970s, and the literature has not established a link between sand extraction and the historical location and depth of the channels and banks at and downstream of the dredging operations.

Thompson (2012) surveyed the position of Berrys Canal shoreline in the field in 2012 and then compared the results with historical records of bank position mapped by Office of Environment and Heritage (OEH) from aerial photographs dated 1949, 1984, 1993 and 2002. Although not included in the analysis, historical survey data from 1901 (Public Works Department, 1988), provided to Thompson (2012), indicated up to 200 m of shoreline recession on the western shoreline of Comerong Island (left bank of Berrys Canal, in the downstream direction) between 1901 and 1949. Carvahlo and Woodroffe (2013) used LiDAR from 2004 and 2010/2011 to observe that erosion occurred on both banks of the entrance of Berrys Canal, with a prominent loss of land area, especially on the right margin which retreated by more than 10 m. Significant erosion also occurred downstream on the northern end of Apple Orchard Island and along the opposite bank on Comerong Island. Al-Nasrawi et al. (2016) used historical aerial photography and unspecified remotely sensed imagery compiled from years 1949, 1961, 1970, 1981, 1993, 2002 and 2014 to plot the time series of the area of Comerong Island. The plot indicated that from 1949 to 1970 the area increased by 0.22 km^2; from 1981 to 2002 the area declined by 0.22 km^2, and from 2002 to 2014 the area declined a further 0.23 km^2. Over the entire period, the northern part of the island accreted by 0.41 km^2, while the western and southern areas contracted by 0.73 km^2. Analysis of aerial imagery from 1949, 1970, 1984, 2012 and 2021 undertaken for this report found that the historical shoreline positions on the western side of Comerong Island and Nobles/Haven Islands showed a consistent progression of bank recession over time, with substantial and unequivocal recession occurring over most of the length of the measured land. These results, and those of Al-Nasrawi et al. (2016) and Carvahlo and Woodroffe (2013), are consistent with those of Thompson (2012). Thompson (2012) concluded that Berrys Canal has continued a pattern of channel widening and capacity enlargement through time, but at a decreasing rate. The expansion of Berrys Canal reflected adjustment to regular tidal forces, as well as periodic flood flows, some of which result in opening of Shoalhaven Heads. There is no evidence linking bank erosion in this area to reduced sediment supply from the catchment or to sand extraction at Pig Island.

ii. The rate of infilling of deep dredge holes, and infilling of the dredge area more broadly, including recent flood events, over the last 20+ years.

In this report, the benchmark survey data from the Pig Island area was the Sep 2005 to Nov 2006 hydrographic survey of the entire estuary. The first specific survey of the Pig Island sand deposit was undertaken in February 2007, not long after the Sep 2005 to Nov 2006 survey. The next survey was undertaken in December 2018. The surveys undertaken in November 2021 and September 2022 covered relatively small areas that had been dredged.

The 2018 survey was undertaken after 3 years of hydrologically benign conditions following the major flood of August 2015. The survey undertaken in November 2021 was preceded by the major flood of August 2020 followed by two relatively small events in March and May of 2021. The most recent survey undertaken in September 2022 was preceded by a series of relatively small flood events.

The small differences between the DEMs generated from the February 2007 data and the Sep 2005 to Nov 2006 data mostly related to different survey point densities and survey point locations. There were some significant differences between the DEMs generated from the December 2018 data and the Sep 2005 to Nov 2006 data. There was deposition of up to 3 m within the previously extracted area of the southern channel and deepening of up to 6 m in the recently extracted area. A small area where sand had been extracted was surveyed in Nov 2021. Compared to the elevations in Dec 2018, there was up to 3.6 m deposition in the previously extracted areas, and deepening of up to 5 m in the recently extracted area. A small area where sand had been extracted, overlapping part of the 2021 survey area, was surveyed in September 2022. Compared to the elevations in Dec 2018, the majority of the previously extracted area experienced deposition, mostly exceeding 2 m and up to 5.2 m. The bed in this area has not fully recovered to its pre-extraction morphology, but it is within 0.5 – 2.0 m of the 2007 elevations. The bed in the southern channel area appears to have been lowered 5 – 6 m by sand extraction, with the data suggest that about half of this depth has infilled since then.

Overall, the available survey data covering the Pig Island sand deposit suggest that the process of deposition of sand within previously excavated areas does occur. Between Dec 2018 and Sep 2022 rapid infilling of up to 5 m was observed in the recently extracted area. This infilling was likely facilitated by the relatively high frequency of flood events within this period.

iii. The impact of deep dredge holes on nearby channels (in terms of channel location and depth).

There are no data or published research available that would enable an assessment to be made on the impact of deep dredge holes on the location and depth of nearby channels.

iv. An assessment of the sedimentological data (such as the samples collected by the dredging operators in accordance with their EPA licence, and academic research papers as noted above), to clearly describe:
- The volume of sediment removed during dredging (annually)
- For the dredged material, the proportion of sand extracted versus the proportion of material returned to the stock mounds and/or the river, and the grain size(s) of returned material

A volume of 620,000 m^3 of sand aggregate was extracted from the southern channel around Pig Island over the 25-year period (Carvalho, 2018; Carvalho and Woodroffe, 2021) [equivalent to an average annual extraction rate of 24,800 m^3/yr]. Mitchell McCormac (pers. comm., 8 Sep 2022) indicated that over recent years, extraction activities have produced a maximum annual volume of approximately 50,000 tonnes of coarse river sand [equivalent to approximately 32,258 m^3/yr]. RA12/1001 and EPA conditions limit the extraction and production of coarse river sand to a maximum of 100,000 tonnes per year (Panucci and PDC Lawyers & Town Planners, 2021) [equivalent to approximately 64,516 m^3/yr]. These mass to volume conversions were based on a specific gravity of 1.55, as assumed by Carvalho (2018, p. 41). Mitchell McCormac (pers. comm., 8 Sep 2022) indicated that about 4% of the material dredged from the river is fines. The fines are settled in trenches and then transported to nearby properties to be used in building stock mounds. For the proposed extension, the intention is to use the fines to build three new stock mounds on Pig Island.

c) Description of the depth of dredge operations. This information is essential in determining the impact of dredge batters and buffer zones on marine and riparian vegetation.

Not within the scope of this report.

d) A detailed assessment of the visual impacts of the proposed development, noting that dredging operations are already visible from Nowra Bridge and surrounds.

Not within the scope of this report.

e) The following further information is required to be provided in relation to the stock mounds on Pig Island:

i. An assessment of the potential for stockpiled fines being remobilised into the water column by rain / floodwaters, and potential water quality impacts downstream associated with this (including any water quality sampling or modelling).

Risk of erosion of stock mounds was assumed to be negligible for direct rainfall impact and runoff, as it was assumed that this could be controlled by engineering design and maintenance of vegetative cover or temporary protective material with similar erosion resistance properties. On the basis of the results of hydraulic modelling of the proposed stock mounds, which suggested negligible to low risk of fluvial erosion (see following sub-section), the risk of potential water quality impacts downstream associated with erosion of stock mounds was considered negligible. Thus, water quality sampling or modelling was not recommended as a monitoring or mitigation measure. The recommended mitigation measure is to maintain healthy and complete vegetation cover on the sides and top surface of the mounds. When grass cover is being established, or in areas where good grass cover cannot be maintained, alternative erosion control measures should be employed.

ii. An assessment of the past performance of mounds and their likely response during floods, including the likelihood of the mounds being washed away versus the impact to flood levels in the unlikely event that the stock mounds remain stable during a major flood.

The stock mound erosion risk assessed here was fluvial scour by floodwaters. The variable of interest was maximum velocity. The maximum permissible velocity is the greatest velocity that will not cause erosion of a channel body or floodplain surface. In shallow flow situations, as would generally occur on floodplains, it is reasonable to assume from the literature that surfaces covered with sod forming grass would generally tolerate velocities of up to 2 m/s. Hydraulic data modelled using TUFLOW at 50 × 50 m cells, were provided by Martens & Associates Pty Ltd. The variable of interest was maximum velocity for both the existing topography, which includes two small areas of land that can be used as stock mounds, and the developed topography, with three new stock mounds constructed on the island. The modelled floods were 10 yr, 100 yr, 200 yr, 500 yr and PMF (probable maximum flood) events.

The modelled data indicate at least one of the existing mounds maintains some land above flood levels up to the 1 in 500 yr flood event, while at least one of the proposed mounds maintains some land above flood levels up to the 1 in 200 yr flood event. Under the existing and developed scenarios, the two existing mounds are exposed to velocities 3 – 5 m/s for the PMF event, which would likely result in scour of the mounds. However, under these conditions the entire Pig Island would be subject to high risk of major morphological modification. For smaller events, up to the 1 in 500 yr event, the existing mounds would generally not be at risk of scour. This result is consistent with the historical stability of the mounds.

For the central mound under developed topography conditions (i.e., with the 3 proposed mounds developed) for 1 in 10 yr and 1 in 100 yr flood events, the maximum velocity was predicted to be 2.3 m/s and 2.5 m/s respectively. Under this scenario, the velocity around the existing central mound was influenced by its proximity to the proposed central mound. Under the amended positioning of the proposed mounds (not modelled), the existing central mound would not be in close proximity to the new central mound, so exceedance of the 2 m/s threshold would be less likely. Under the developed scenario, the side and top surfaces of the three proposed mounds are exposed to velocities 2.1 – 5.2 m/s for the PMF event, which would likely result in scour of the mounds. However, as for the existing mounds, under these conditions the entire Pig Island would be subject to high risk of major morphological modification. For smaller events, the proposed mounds would not be at risk of scour.

f) Given that the sand resource is finite and is being removed permanently from the sediment system, and that past and future approvals are sought for 20 to 50 years or more, assessment of the potential long-term impacts from dredging is sought, including:

i. Long term impacts to Shoalhaven beaches and beaches further north given that a substantial portion of sand sized material is being removed by dredging rather than being supplied to the coast (noting that the Shoalhaven/Crookhaven River is one of only 2 rivers in NSW that supplies sand sized material to the coast). This assessment needs also to consider the combined impact of the dam built upstream in 1976 that will already have contributed to a reduced sand supply to the estuary and coast.

On the basis of the available data, Carvalho (2018) and Carvalho and Woodroffe (2021), estimated that a total of 1,020,000 m^3 of bed sediment was deposited in the Shoalhaven River estuarine channel between 1981 and 2006, equivalent to an average deposition rate of 40,800 m^3/yr. Carvalho's (2018) sediment budget suggests that approximately 61% of this volume of sand was extracted by the operations at Pig Island. In the hypothetical absence of sand extraction operations, it is likely that a proportion of this sand would have been transported to beaches further north of Crookhaven Heads. It would be speculative to assume that the entire volume of sand would be transported to the beaches, as some or all of that sand might have deposited within the estuarine channel. However, it is reasonable to assume that sand extraction activities likely deny supply of some volume of sediment to beaches. The impact of sand extraction compounds the impact on beach sediment supply of trapping of sediment by Tallowa Dam.

Carvalho (2018, p. 152) noted that long-term shoreface supply of sand to beaches is undetectable on annual and even sub-decadal time scales and is masked by more rapid cyclical changes because the supplied volume is negligible compared to the volume of sand involved in the beach erosion and recovery cycles. Despite these uncertainties, Carvalho (2018, p. 153) suggested that the ongoing supply of sand to the coast by the Shoalhaven River, i.e. despite sand extraction activities since the late-1960s or early 1970s, may be partially responsible for the beach accretion and shoreline progradation observed in the past decades at Seven Mile Beach-Comerong Island. Using data from aerial image analysis, Carvalho (2018, p. 114) reported that, at a cross-section on the southern end of Seven Mile Beach-Comerong Island, in August 1963 the shoreline was located 97 (±14.1) m landwards of its present location. It rapidly accreted approximately 33 m by July 1977. The next aerial photograph taken in January 1982, showed a major retreat of approximately 27 m (related to a major storm in 1978) and it then progressively accreted 91 (±3.6) m to its December 2013 position. Other cross-sections also showed overall accretionary trends. Shoreline accretion was also observed over time at Culburra and Warrain-Currarong beaches, even though these two embayments receive no major fluvial contributions of sand (Carvalho, 2018).

In conclusion, to date, the available literature has not produced data linking historical dredging and sand extraction activities with instability of the beaches to the north of the river mouth.

ii. The long-term changes in the geomorphology of the lower estuary due to the increase in tidal regimes from training of the Shoalhaven River and how this may have interacted or will interact with dredging impacts.

A seawall was constructed on the northern side of Crookhaven Heads between 1902 and 1908. Between 1909 and 1912 this seawall was extended to form the present training wall (Woodroffe et al., 2022). Nichol (1991) noted that engineering works, such as breakwater construction and dredging lead to changes in the tidal regime in estuaries, typically increased tidal range and the strength of tidal currents. This can potentially result in removal of large volumes of tidal delta sands from an estuary.

Given that the training works on the Shoalhaven River have been in place for over a century, their impact on the geomorphology of the estuary would be incorporated in the results of the investigations undertaken to date. It would be very difficult to separate the impact of river training works from other major factors that have influenced geomorphic processes and forms in the estuary, namely, cutting Berrys Canal, hard lining banks, dredging for navigation, flood sequences, construction of Tallowa Dam, and sand extraction at Pig Island. To date, no research has attempted to separate the impact of river training on tidal ranges and consequent impacts on geomorphic process and forms in the estuary, so it would be highly speculative to suggest here what those impacts might have been and how they would interact with the proposed sand extraction.

iii. Future long-term impacts of sea level rise which is expected to increase the tidal ranges in the estuary and may therefore change the impact of dredging operations on surrounding channels and banks.

Using Comerong Island as a case study, Al-Nasrawi et al. (2018) applied future sea-level rise of Intergovernmental Panel on Climate Change (IPCC) hydro-scenarios to assess the impact on the ecological and geomorphic aspects of coastal ecosystems in terms of risk assessment and sustainability. The results suggested that through inundation alone, Comerong Island would lose about 18% of its wetlands and associated habitats by 2050, and approximately 43% of the island would be lost by 2100.

Sea level rise would likely increase the tidal ranges in the estuary and may therefore change the impact of dredging operations on surrounding channels and banks. As noted above, to date, no research has attempted to quantify the impact of river training on tidal ranges and consequent impacts on geomorphic process and forms in the estuary, so it would be highly speculative to suggest here what those impacts might be and how they would interact with the proposed sand extraction.

3 Methodology

3.1 Catchment digital elevation model

The area of the project is covered by Kiama 2011-04-13 2 km x 2 km 1 metre Resolution Digital Elevation Model tiles produced by NSW Spatial Services, Department of Finance, Services and Innovation, available from ELVIS - Elevation and Depth - Foundation Spatial Data, Version 0.1.1.0 (http://elevation.fsdf.org.au/). The coverage of this dataset is over the Kiama region. The area was flown over the period 16/12/2010 to 13/04/2011. Average point density was 1.62 points per square metre. The 1 m Digital Elevation Model (DEM) was produced using the TIN (Triangular Irregular Network) method of averaging ground heights to formulate a regular grid. This data set contains ground surface model in ASCII grid format derived from C3 LiDAR (Light Detection and Ranging) from an ALS50ii (Airborne Laser Scanner). The model is not hydrologically enforced. Standard Airbourne Laser Sensor (ALS) products are processed to ICSM standards level C3. This data has an accuracy of 0.3 m (95% Confidence Interval) vertical and 0.8 m (95% Confidence Interval) horizontal. For the purposes of this study, the LiDAR data was resampled to a 2 m grid resolution.

3.2 Catchment bed material calibre

River Styles is a system for classifying stream geomorphic type based on valley setting, level of floodplain development, bed materials and reach-scale physical features within the stream (Brierley et al., 2011). The potential for physical recovery after disturbance depends on stream geomorphic condition, whereby streams in good condition (undisturbed and close to natural state) are more likely to be resilient and recover faster than those that are already degraded. NSW Department of Planning, Industry and Environment and Macquarie University together developed the River Styles Spatial Layer for New South Wales (NSW Office of Water, 2012). The database provides River Style, fragility, sensitivity to disturbance, condition, rarity and recovery potential for all third and higher order rivers in NSW. The data were derived from a number of sources depending on the Catchment Management Authority area. For the purposes of this study, River Styles data were used to map the Shoalhaven River catchment drainage network, and to describe the bed material calibre of the Shoalhaven River catchment drainage network.

3.3 Catchment sediment load and bed coarse sediment accumulation rates

Over the period 1997-2002, the National Land and Water Resources Audit (NLWRA) coordinated and commissioned a range of assessments that encompassed Australia’s land, water and biodiversity. The audit included the component “Sediment and nutrient supply to river links”, with the processes modelled using SedNet (Sediment River Network Model). Details of SedNet model assumptions, data inputs, algorithms and parameter values can be found in Prosser et al. (2001a).

3.4 Hydrology

Data for selected gauging stations within the Shoalhaven River catchment were downloaded from WaterNSW real time data (https://realtimedata.waternsw.com.au/).

3.5 Parish Plans and Cadastral boundaries

Ten Parish Plans that covered the area of the lower Shoalhaven River were downloaded from NSW Land Registry Services (https://www.nswlrs.com.au/Parish-and-Historical-Maps). These Plans were rectified in GIS using Land Title Lot boundaries from NSW Land Parcel and Property Theme - NSW Cadastre downloaded from NSW Spatial Services (https://data.nsw.gov.au/).

3.6 Aerial imagery

Aerial imagery from 16/01/2021 was obtained from World Imagery; imagery from 5/02/2012 was obtained from NSW Spatial Services, NSW Foundation Spatial Data, Spatial Collaboration Portal (https://portal.spatial.nsw.gov.au/portal/apps/sites/#/home) also known as Six Maps; imagery from 4/04/1949, 7/09/1970, and 29/03/1984 was obtained from Geoscience Australia online Historical Aerial

Photography collection (https://aerialphotography-geoscience-au.hub.arcgis.com/). Additional imagery was obtained for 31/03/2016, 29/05/2019 and 12/03/2020 from World Imagery Wayback (https://livingatlas.arcgis.com/wayback). The imagery from 1949, 1970, 1984, 2016, 2019 and 2020 was rectified in GIS to cadastral boundaries.

3.7 Determination of bank position and rate of change

Bank position was determined for the dates of the aerial imagery by tracing the perceived bank edge in GIS for two areas. One area was on the left (eastern) bank of Berrys Canal along the western shoreline of Comerong Island, and the other area was Pig Island and the left and right banks of Shoalhaven River in the vicinity of Pig Island. This procedure was not without error, as the accuracy of determination of bank edge depends on quality of the imagery, tide or flow height, and extent and type of vegetation present. The accuracy of the manual bank edge delineation procedure was checked for 2012 by comparing it with the results from application of two automatic edge detection algorithms to the 2011 DEM. These algorithms, available in Global Mapper Pro, were first, to find breaklines areas around edges of regions with similar slopes, and second, to find breaklines at any surface break based on edges of curvature. Coverage areas (concave hulls) were created around the breakines found by the second method. The bank edge polygons produced by these two methods had considerable overlap, and identified the area of steep bank face. Bank edges could not be identified using these automated methods where the bank was gently sloping. Almost the entire manually delineated bank edge fell within the bounds of the automatically generated bank edge polygons, which suggested that the manual method was adequate for the purpose.

Change in bank edge position between image dates in metres was determined by converting the bank lines to areas of shoreline using a consistent area template, subtracting the areas, then dividing by the shoreline length. The data were plotted as cumulative change in shoreline position over time.

3.8 Bathymetric survey plans

Bathymetric survey data were obtained in the form of spot elevations. The sources were: 2005-2006 data from Department of Natural Resources Shoalhaven River Hydrographic Survey Sep 2005 – Nov 2006, 2007 data from Allen Price Plan 21519-14, 2018 data from Johnson Procter Plan JP_14152D2014152, 2021 data from Johnson Procter Plan 14152K 21-01-2022, and 2022 data were 23 sounding depths, surveyed from a boat on September 2022, supplied by Mitchell McCormac (on 16 September 2022). The 2022 soundings were converted to elevation in AHD by subtracting measured depths from tide height recorded at Nowra Bridge at the time of each sounding. The point data were converted to DEMs using the TIN (Triangular Irregular Network) method of averaging ground heights to formulate a regular grid. The DEMs were cropped to the spatial extent of the survey data. One of the 2022 soundings was distant from the others and was not used in derivation of the DEM. The bathymetric data from the Shoalhaven River Hydrographic Survey Sep 2005 – Nov 2006 were merged with the Kiama 2011-04-13 resampled DEM to form a seamless 2 m terrain model. Areas of loss or gain in bed elevation between survey dates were derived by subtracting DEM elevations over the relevant areas.

3.9 Flood velocity distributions and risk of erosion of stock mounds

Risk of erosion of stock mounds was assumed to be negligible for direct rainfall impact and runoff, as it was assumed that this could be controlled by engineering design and maintenance of vegetative cover or temporary protective material with similar erosion resistance properties. The risk assessed here was fluvial scour by floodwaters. The variable of interest was maximum velocity. The maximum permissible velocity is the greatest velocity that will not cause erosion of a channel body or floodplain surface. Tables of maximum permissible velocity appear in many channel design, engineering and hydraulics publications (e.g. Chang, 1988). In shallow flow situations, as would generally occur on floodplains, it is reasonable to assume that surfaces covered with sod forming grass would generally tolerate velocities of up to 2 m/s (Chow, 1981; Fischenich, 2001).

Hydraulic data modelled using TUFLOW at 50 × 50 m cells, were provided by Martens & Associates Pty Ltd. The model extent covered the entire estuary, but only the area in the vicinity of Pig Island was of interest to this report. The variable of interest was maximum velocity for both the existing topography, which includes two small areas of land that can be used as stock mounds, and the developed topography, with three new stock mounds constructed on the island. The position and dimensions of the stock mounds were altered after the hydraulic modelling was completed. Whilst the results reported here apply to the stock mounds in their original positions, moving the stock mounds to different locations would not produce materially different results. The modelled floods were 10 yr, 100 yr, 200 yr, 500 yr and PMF (probable maximum flood) events.

The existing stock mounds were irregular-shaped, so their perimeters were defined by the 5 m contour. A 20 mere buffer was formed around the perimeter of each mound; mean and peak velocity were measured within these areas, for both existing and developed scenarios. For the rectangular-shaped new mounds, a 20 m buffer was formed around the perimeter of each mound to create edge areas. Mean and peak velocity were measured within the edge areas, and also within the top surface area, for the developed scenario.

4 Review of literature and data

4.1 Formation of Shoalhaven estuary

Davies (1974) proposed a four-stage model of estuary infilling applicable to NSW from the most recent glacial to interglacial transition, summarised by Kidd (1978) and Nichol (1991):

- Phase I: deposition of fluvial sediment on the continental shelf during the glacial low sea-level period.
- Phase II: early period of the high-stand (7000 – 4000 yr BP) during which onshore movement of reworked sediments was relatively rapid and continuous, whereas delivery from rivers was low due to the elevation of river base levels associated with the Postglacial Marine Transgression.
- Phase III (c. 4000 yr BP), the shelf had attained equilibrium with the new sea level and the offshore supply of sediment became virtually depleted. Also, estuaries had achieved partial infilling by this time.
- Phase IV: characterised by complete estuary infilling, allowing sediment to be delivered to the coastal compartment store.

During the Pleistocene Epoch (2.59 Ma to 11.5 ka) the sea level fluctuated and prior to the Holocene interglacial it was up to 125 m below its current level. Stabilisation of the sea level since the beginning of the Holocene (7,900-7,700 yr BP) enabled the Shoalhaven estuary to form. A marine sand barrier formed across the Shoalhaven River entrance and fluvial sediment was trapped landward of this barrier, infilling the Shoalhaven Estuary (Roy, 1984; Woodroffe et al., 2022) (Figure 1).

Davies (1974) noted that few NSW rivers currently supply significant volumes of sediment to the coast, largely attributed to the effective sediment trapping ability of estuaries. The Shoalhaven River and Narrawallee Creek were the two exceptions that had entered Phase IV, characterised by channels traversing the prior basin surface. Nichol (1991) suggested that these systems were in an early stage of Phase IV, but Woodroffe et al. (2022) concluded that the estuary was mostly infilled 3,000 years ago. Hails (1967, 1969) and Bird (1967) found evidence at Twofold Bay that Towamba River was supplying sand to the coast at the present time. Observing similar degrees of infilling in the Shoalhaven, Moruya and Bega estuaries, Bird (1967) suggested that these rivers were possibly also delivering sand to the coast. Wright (1967, 1970) observed that longshore trends of mean grainsize and sorting along Seven Mile Beach in Shoalhaven Bight could be explained by contemporary additions of fluvial sand to this beach after floods. Reffell (1980) noted that Wright’s (1967) hypothesis was uncertain, and Nichol (1991) was also not convinced that the Shoalhaven River was delivering sand to the coast. However, more recently, Carvalho et al. (2019) found evidence that that fluvially-derived sand is intermittently delivered to the shoreface at Shoalhaven Heads during floods, contributing to Seven Mile Beach to the north.

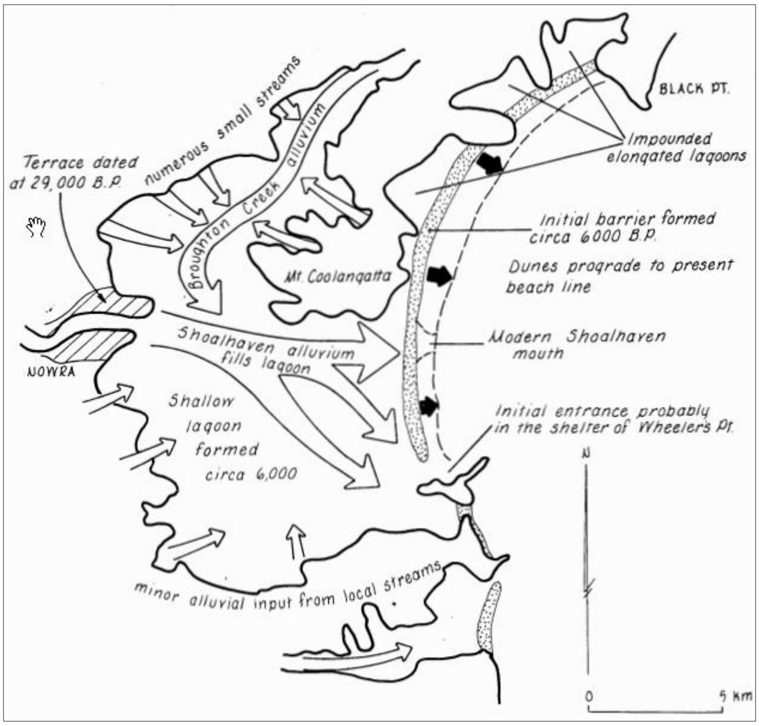


Figure 1. Schematic evolution of the lower Shoalhaven valley during Holocene times. Source: Reffell (1980) based on work from Walker (1962) and Wright (1967).

The review of literature by Kidd (1978) found general agreement that in most NSW estuaries, river sands and gravels terminate as small deltaic deposits on the landward margin of the basins, and only part of the suspended load escapes to the sea during floods. For much of its course, the Shoalhaven River flows through narrow valleys and gorges, with coarse sediment deposition limited to inset benches. As the river reaches the coastal plain, it loses its capacity to transport coarse sediment, forming a deltaic plain. Most of the deltaic plain is composed of fine-grained material, with sandy bed material confined to the river channel.

4.2 Formation of Pig Island

The specific age and formation of Pig Island has not been documented in the literature. It could have formed within the established river channel relatively late in the final phase of estuary infilling, due to an obstruction in the channel accumulating debris and sediment, with the flow of the river bifurcating and expanding around the island as it grew and became stabilised by vegetation. Alternatively, Pig Island could have been carved off a section of established deltaic plain material due to migration and avulsion of the main channel. Whatever its mode of formation, the island has created hydraulic conditions conducive to formation and maintenance of a sand deposit on the upstream half of the island (Reffell, 1980). It is possible that the sand deposit accumulated gradually over time and then stabilised. It is also possible that the sand deposit is mobilised by very high bed shear stresses during flood events exceeding a certain magnitude, and reforms on the recession limb.

The sand deposit is a prominent feature and can be identified on historical aerial images since 1949 (Figure 2). The effects of expanding sand extraction operations within the southern channel are apparent on the imagery from the 1984 image onwards. Visual inspection of the imagery suggests that, over the period 1984 to 2021, the excavated areas have not refilled with sand back to the original levels. This suggests that if the sand deposit mobilises and reforms during large flood events, then this process could be limited to extreme events, such as the 1860 and 1870 floods.

Figure 2. Selection of aerial imagery through time depicting the sand deposit upstream of Pig Island. From 1984 image onwards the sand deposit shows evidence of extraction from the southern channel.

4.3 Estuary sediment budget

The transport of sediment to the Shoalhaven estuary is interrupted by Tallowa Dam, located at the junction of the Shoalhaven and Kangaroo rivers, and completed in 1976. The impounded waters above the dam are known as Lake Yarrunga, which has a capacity of 85,500 ML. The reservoir is a key part of the Shoalhaven Scheme, used to supply local communities and supplement other Sydney storages when dam levels drop to 75 percent (WaterNSW, 2015). The catchment areas upstream and downstream of the dam indicate that 78% of the total area drains to Tallowa Dam (Table 1 and Figure 3). The measured areas were similar to the values that have been variously reported in the literature.

Table 1. Shoalhaven River catchment area, measured from DEM using GIS.

Catchment	Area (km^2)	Percent of total
Upstream of Tallowa Dam	5,633.8	78%
Downstream of Tallowa Dam to Pig Island	1,153.0	16%
Downstream of Pig Island to the Sea	353.9	5%
Areas draining directly to the coast	74.9	1%
Total	7,215.6	

The Shoalhaven River catchment contains extensive surface exposures of silicious rock, which, on weathering, yields quartz fragments (Reffell, 1980). The sources of sand and gravel are distributed throughout the catchment, with little sand derived from the northern Kangaroo River catchment and the estuarine deltaic plain catchment downstream of Pig Island (Figure 4). Under the assumption that nearly all sand that enters Tallowa Dam is trapped in the reservoir, most of the sand currently delivered to the estuarine reaches of the Shoalhaven River is sourced from the river channel downstream of the dam, including inset benches, and a few small tributaries downstream of the dam.

Walsh et al. (2014) sampled bed material composition at 12 sites within the Shoalhaven River catchment, 5 of which were upstream of Lake Yarrunga, 4 of which were within Lake Yarrunga at depths of 3 – 5 m within arms of watercourses draining to the reservoir, and 3 of which were on the Shoalhaven River downstream of Tallowa Dam. Sand was present at all sites, although it was not dominant. At the four sites sampled within the Yarrunga Reservoir, the bed material was mud and silt, as well as boulders and bedrock. Al-Nasrawi et al. (2016) sampled reservoir bed material at six sites on the Kangaroo River arm of Lake Yarrunga, close to the dam wall. The bed material average size distribution was 58.5% silt and clay, and 41.5% sand, sampled at an average depth of 1.3 m.

Kermode et al. (2015) examined inset depositional benches within a 25 km long confined gravel-bed section of the Shoalhaven River downstream of Tallowa Dam and upstream of the tidal limit in order to examine the formative and destructive processes of these landforms. Tallowa Dam has a sediment trapping efficiency estimated at 88%. This sediment trapping has led to maximum thalweg incision of up to 3 m close to Tallowa Dam and a coarsening of bed sediments to Yalwal Creek junction. Yalwal Creek is a major source of sand and gravel to the Shoalhaven River, such that downstream of Yalwal Creek junction there was little evidence of bed coarsening or channel incision caused by bedload sediment trapping by Tallowa Dam (Kermode et al., 2015). Kermode et al. (2015) found that floods of all sizes appear to be significant contributors to bench formation and destruction. The work of Brierly et al. (1999) and Brooks and Brierley (1997) would suggest that sediment liberated by clearing and land use changes, as well as mining upstream in the Shoalhaven and Mongarlowe goldfields since 1851 (McGowan, 1996; NSW DPI, 2007), could have provided a source for the recent alluvium deposited in high level benches. Whilst dating revealed that sediment in the benches has been reworked within the period of European settlement, Kermode et al. (2015) noted that this did not prove that the benches were specifically associated with sediment liberated by human settlement.

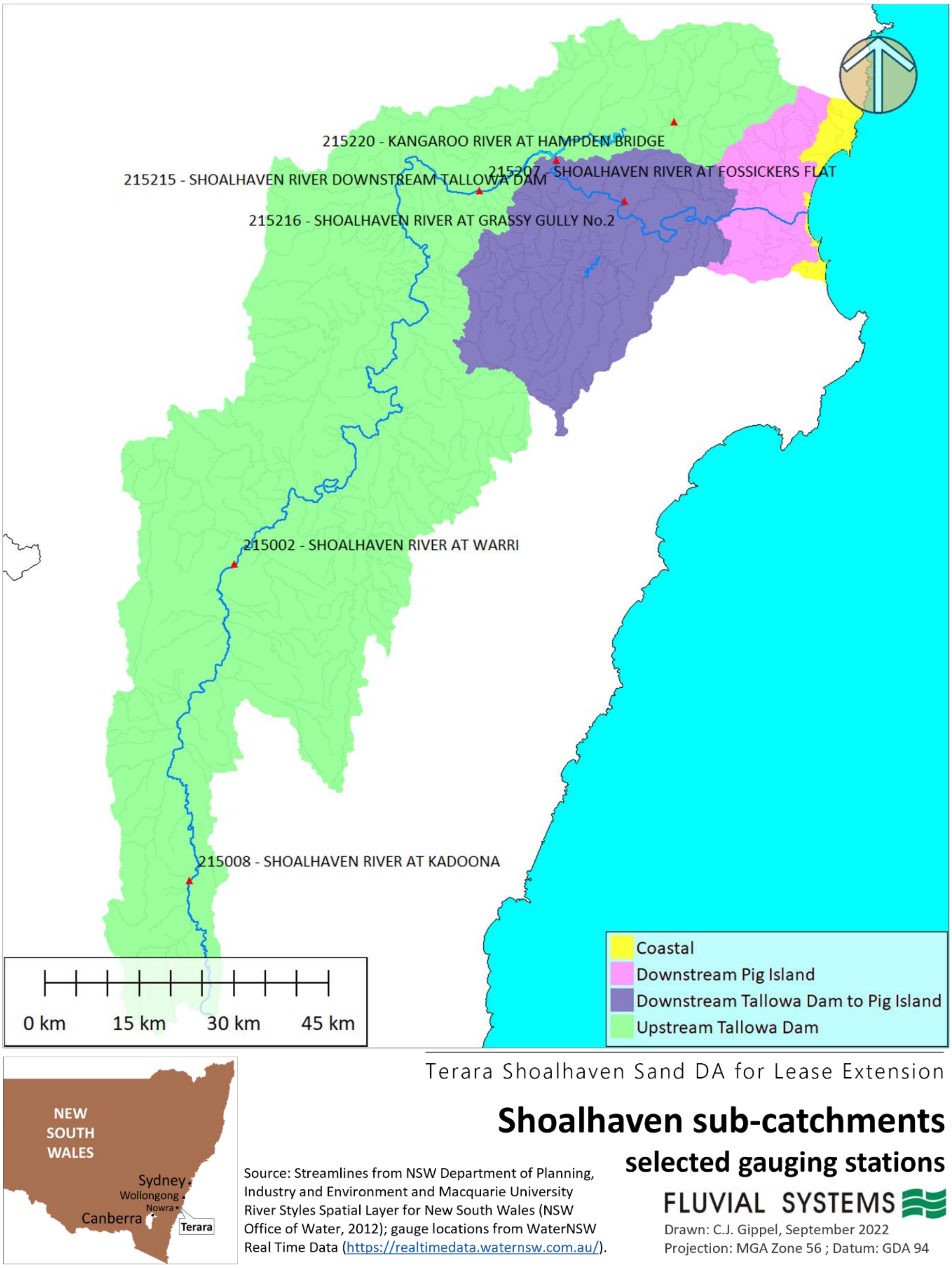


Figure 3. Shoalhaven River catchment and major sub-catchments. Locations of key gauging stations are also indicated.

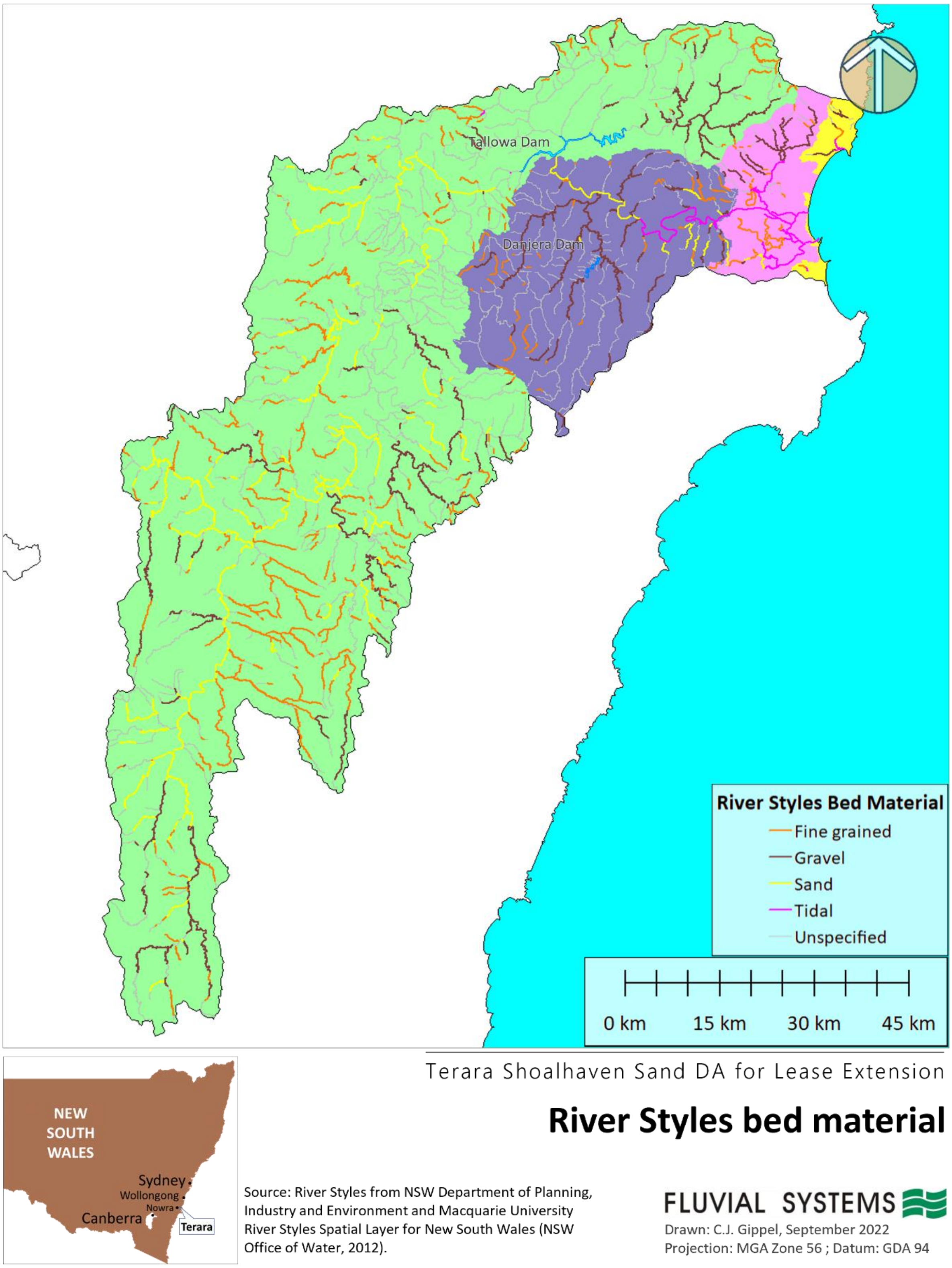


Figure 4. Bed material of the Shoalhaven River catchment River Styles.

The NLWRA SedNet model estimated pre-European suspended sediment delivery rates to Lake Yarrunga reach of the Shoalhaven River of 9,000 t/yr, and current rates of 137,200 t/yr (Prosser et al. 2001; Figure 5 and Figure 6). This appears to be an underestimate, based on the Carvalho's (2018) comparison of bathymetric surveys of Lake Yarunga 11 years apart, which suggested that an average of 720,750 t/yr of sediment was deposited in the lake. Assuming a trapping efficiency of 88%, and accounting for the additional supply of sediment from an unmodified creek downstream of the dam, Carvalho (2018) calculated that the Shoalhaven River delivers 86,000 m^3/yr [equivalent to 133,300 t/yr] on average to the estuary.

The NLWRA SedNet model estimated that most streams within the Shoalhaven River would not accumulate deposits of coarse bed material over the long-term (Figure 7). The tidal reach of the river was an exception, with the modelled deposition rate from Long Reach to Broughton Creek (Numbaa Island) being 0.7 m/100 years, and from Broughton Creek to Crookhaven Heads the modelled deposition rate was 0.6 m/100 years.

Carvalho's (2018) comparison of Shoalhaven River bathymetric surveys taken in 1981 and 2006 indicated that approximately 400,000 m^3 of sediment was deposited throughout most of the estuary channel (from Long Reach to both Shoalhaven Heads and Crookhaven Heads entrances - the area covered in the 1981 survey) over the 25-year period, but there were areas of aggradation and areas of scour. The river bed from Long Reach to upstream of O'Keefes Point aggraded approximately 2,000,000 m^3, while downstream of O'Keefs Point the river bed scoured approximately 1,600,000 m^3. Upstream of O'Keefes Point, areas of bed scour occurred on the north of Pig and Numbaa Islands, as well as at some pools upstream of Nowra.

A volume of 620,000 m^3 of sand aggregate was extracted from the southern channel around Pig Island over the 25-year period (Carvalho, 2018; Carvalho and Woodroffe, 2021) [equivalent to an average annual extraction rate of 24,800 m^3/yr]. Mitchell McCormac (pers. comm., 8 Sep 2022) indicated that over recent years, extraction activities have produced a maximum annual volume of approximately 50,000 tonnes of coarse river sand [equivalent to approximately 32,258 m^3/yr]. RA12/1001 and EPA conditions limit the extraction and production of coarse river sand to a maximum of 100,000 tonnes per year (Panucci and PDC Lawyers & Town Planners, 2021) [equivalent to approximately 64,516 m^3/yr]. These mass to volume conversions were based on a specific gravity of 1.55, as assumed by Carvalho (2018, p. 41). Mitchell McCormac (pers. comm., 8 Sep 2022) indicated that about 4% of the material dredged from the river is fines. The fines are settled in trenches and then transported to nearby properties to be used in building stock mounds. For the proposed extension, the intention is to use the fines to build three new stock mounds on Pig Island.

On the basis of the available data, Carvalho (2018) and Carvalho and Woodroffe (2021), estimated that a total of 1,020,000 m^3 of bed sediment was deposited in the Shoalhaven River estuarine channel between 1981 and 2006, equivalent to an average deposition rate of 40,800 m^3/yr. Carvalho's (2018) sediment budget suggests that approximately 61% of this volume of sand was extracted by the operations at Pig Island.

The methodology of Carvalho (2018) assumes that the processes of bed aggradation upstream of O'Keefes Point and scour downstream of O'Keefes Point were continuous over the period 1981 to 2006, but the result actually measures net aggradation and net scour. In other words, the processes of aggradation and scour could have alternated through the 25-year period, with the total sediment deposited upstream of O'Keefes Point being significantly greater than the measured net deposition of 1,020,000 m^3.

Carvalho (2018) provided a reasonable estimate of mean net sediment deposition rate applicable to the measured period 1981 to 2006. This period included moderately large flood events in 1988 and 1990, and smaller events in 1991, 1998 and 1999, but the rest of the period was relatively hydrologically benign (see later in this report). Sequences of very large floods like those that occurred in 1860s, 1870s, 1950s and the 1970s could result in much greater rates of aggradation and scour than those observed between 1981 and 2006. Hean and Nanson (1987) modelled bedload yield of the Shoalhaven River over two hydrologically contrasting periods. The period 1924 – 1944 was within a Drought Dominated Regime (DDR) period, while the following period 1945 – 1976 was within a Flood Dominated Regime (FDR) period. The latter period (1945-1976) had a 60 to 100 percent higher modelled bedload yield than the former (Hean and Nanson, 1987), which highlights the high temporal variability of coarse sediment delivery to the estuary.

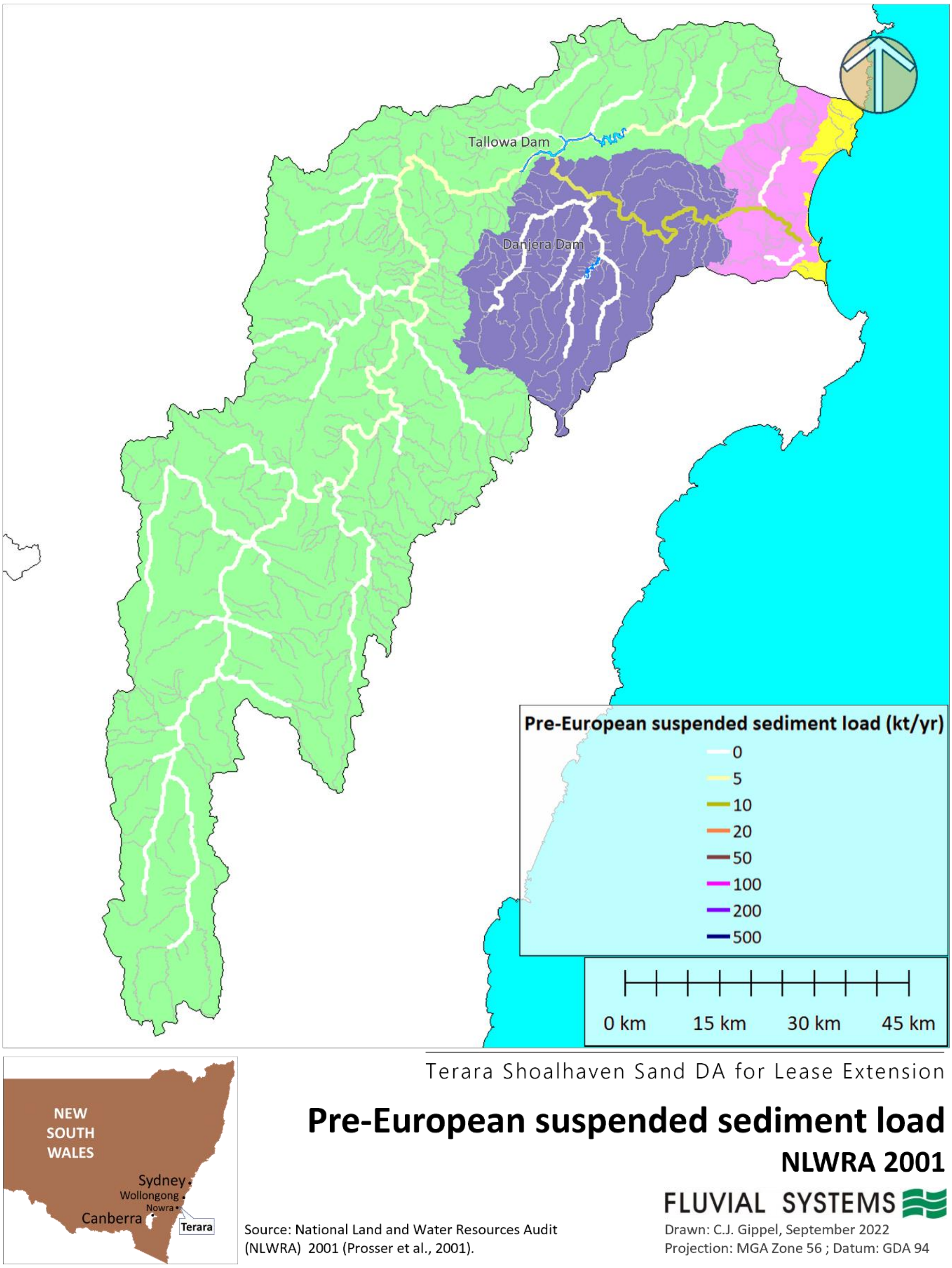


Figure 5. Modelled Pre-European suspended sediment load of streams within the Shoalhaven River catchment.

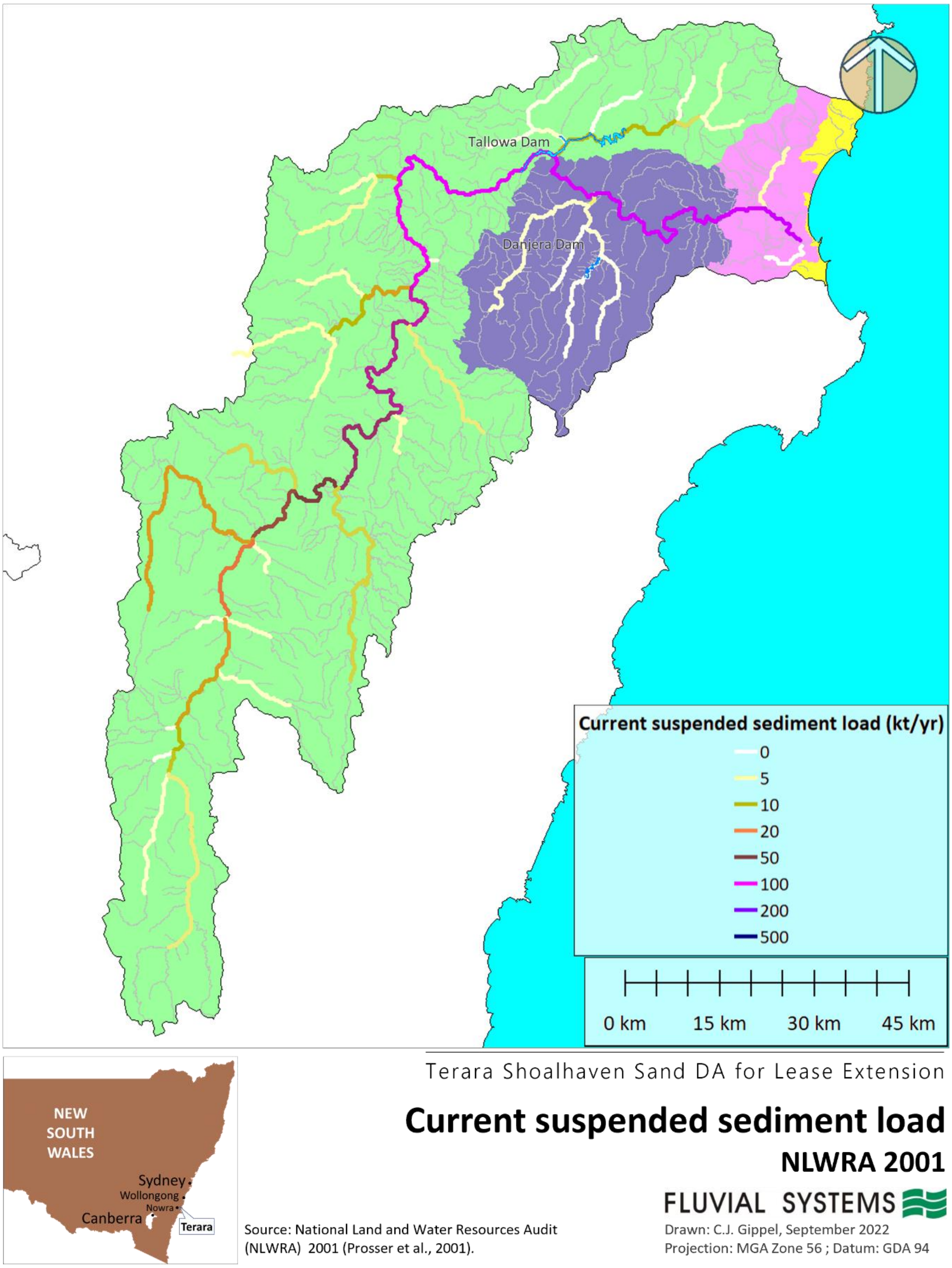


Figure 6. Modelled current suspended sediment load of streams within the Shoalhaven River catchment.

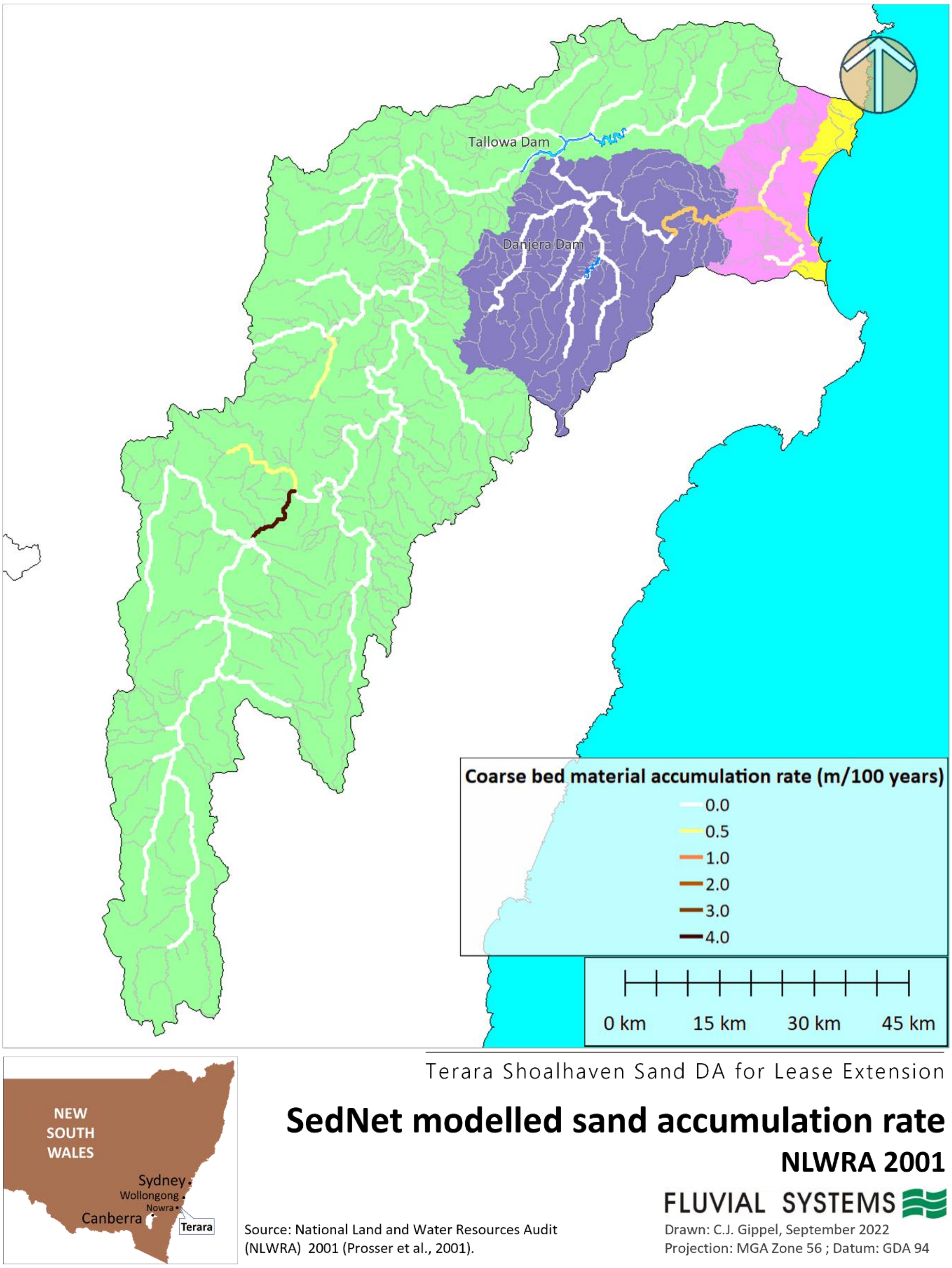


Figure 7. Modelled long-term coarse bed material accumulation rate for streams within the Shoalhaven River catchment.

4.4 History of dredging and sand extraction

The Shoalhaven River has been dredged to facilitate navigation since the 1860s. The history of this dredging was reviewed by RPS Group (2019). The dredge Pluto operated on the Shoalhaven River from 1863 to 1898 to deepen the Crookhaven and Shoalhaven River entrances and channels. In 1867 Pluto operated for 255 days and removed 61,371 cubic yards of sand [equivalent to around 90,000 tonnes or 47,000 m^3] (South Coast Register, 2014). As early as 1863 calls were made to dredge the Shoalhaven River up to Nowra, but navigation remained limited until 1903, at which point the Government, with the Illawarra Steam Navigation Company, removed an outcrop which blocked the river at Bomaderry Creek (RPS Group, 2019). This provided access for ocean-going steamers as far upstream as Nowra. Improved road transport contributed to the decline of river transport. By 1920, dredging on the Shoalhaven River had declined, with a dredge sent from Sydney only in circumstances of consistent shoaling (RPS Group, 2019). Department of Lands Parish Map Parish of Numbaa, Land District of Nowra, Shoalhaven City, dated 27 November 1957, is annotated with arrows pointing from Pig Island to Shoalhaven Heads and the note "*Tenders may be called to remove sand & gravel from whole of Shoalhaven River, see LB68/1025*". The potential long-term impact of dredging for navigation on geomorphic processes has not been assessed in the literature.

Active mining for coarse river sand within the Shoalhaven River in the vicinity of Terara and Pig Island has been ongoing since the late-1960s or early-1970s. The first Permissive Occupancy (PO) issued by the Lands Department, Nowra Office, in this general location was 65/53, granted in 1965 to George Schadel (Panucci and PDC Lawyers & Town Planners, 2021). The second PO 1968/29 was issued to Schadel's Concrete Products Pty Limited on the 1 October 1968. Approvals to allow the sand mining operation covered by PO 1968/29 have been issued by Shoalhaven City Council over time, with RA12/1001, presented to the Regional Planning Panel in June 2013 and granted Consent on the 28th August 2014, being the last and current approval (Panucci and PDC Lawyers & Town Planners, 2021). RA12/1001 and EPA conditions limit the extraction and production of coarse river sand to a maximum of 100,000 tonnes per year (Panucci and PDC Lawyers & Town Planners, 2021), although the annual volume extracted has been half that or less (Mitchell McCormac, pers. comm., 8 Sep 2022).

4.5 Shoalhaven River hydrology

Erskine and Bell (1982), Erskine and Warner (1988) and Warner (1994a, 1994b, 1994c) reported that river systems in southeastern Australia alternated between a flood dominated regime (FDR) and a drought dominated regime (DDR). FDRs are characterised by episodic catastrophic floods and persistent flood activity, with a periods of large floods separated by shorter periods of smaller floods. DDRs consist of relatively long periods of low flood activity with periods of floods separated by longer periods of little flood activity (Erskine and Warner, 1998). Evidence suggests that channels responded to the alternating flood regimes by bank erosion, channel widening and floodplain chute cutting during FDRs; and by deposition, channel contraction and chute infilling during DDRs (Warner, 1997; Erskine and Warner, 1998). Bank erosion is an active sediment source during FDRs, but the landforms being eroded are often ephemeral, and were usually constructed during the preceding DDR (Erskine and Warner, 1998). In southeastern Australia, FDRs occurred from 1799 to 1820, 1857 to 1900 and 1949 to at least 1983 (the extent of the data initially used). In a later article, Warner (2014) established the end of the FDR at 1990. Despite an attempt by Kirkup et al. (1998) to discredit the existence and importance of the FDR/DDR theory, which was challenged by Erskine and Warner (1998), statistically significant evidence for the FDR/DDR phenomenon has been found in inland and coastal rivers of NSW, although the effect is not as strong in the south of the State (Erskine and Warner, 1998).

The flood history for the Shoalhaven River from 1860 to 1988 was collated by Public Works Department (1988) using stage elevation at Nowra Bridge (Figure 8). The flood sequences from 1860 to 1988 (Figure 8) roughly accord with the FDR/DDR sequence identified by Erskine and Warner (1998). Historical annual flood data from gauging stations within the Shoalhaven catchment suggests that flood activity has been frequent since the 1990s, but the events were not exceptionally large (Figure 9).

Owing to its small operational capacity relative to mean and median annual inflows (3.3 and 5.5%, respectively), Tallowa Dam frequently overtops, creating unmanaged spills of water to the river downstream

(Kermode et al., 2015). Peak flow rates for events equal to and greater than the 90% annual exceedance probability (AEP) flood, equivalent to 0.43 year ARI (average recurrence interval) and instantaneous maximum flow approximately 10,000 ML/d, are largely unaffected, but their receding hydrograph limbs are typically truncated (Kermode et al., 2015).

In terms of both mean annual flow and maximum annual flood flows, hydrological data at gauge 215216 Shoalhaven River at Grassy Gully No. 2 (the most downstream gauge) were highly correlated with data from stations upstream, including those upstream of Tallowa Dam (Figure 10). Also, in terms of these flow indicators, despite the existence of Tallowa Dam, discharge increased in downstream order. This confirms the small influence that Tallowa Dam exerts on moderate and major floods, as described by Kermode et al. (2015). The claims of Al-Nasrawi et al. (2016) that "*The dam has blocked most of the water…"* and caused a *"new water level within the Shoalhaven River that dropped below the dam (for 58.8 km until it reached Comerong Island)"* do not apply to mean flows, or flood flows that transport the majority of the sediment and are responsible for shaping the channel.

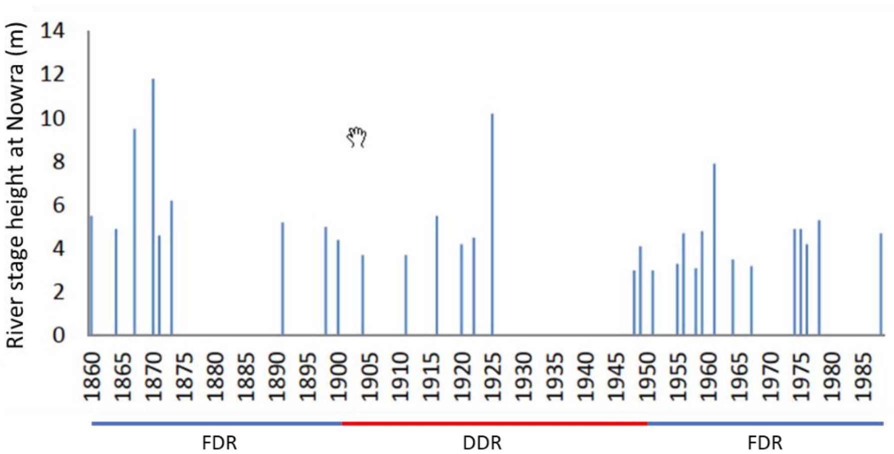


Figure 8. Flood data between 1860 and 1988 at Nowra Bridge. Source: Modified from Figure 8 in Thompson (2012, p. 22).

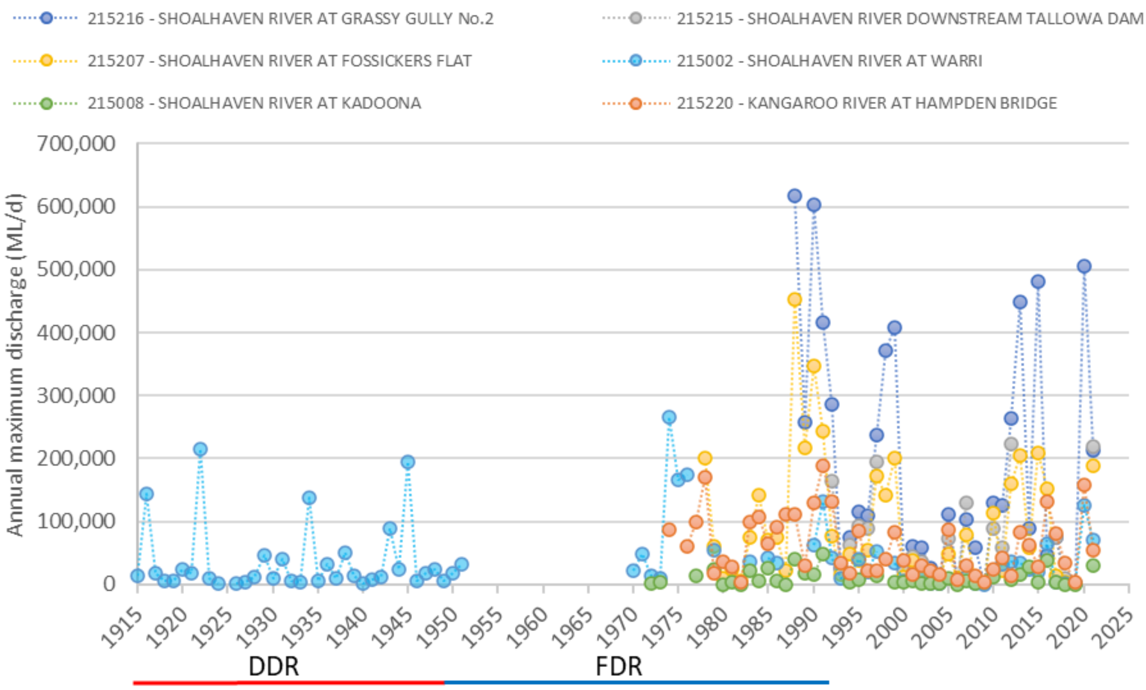
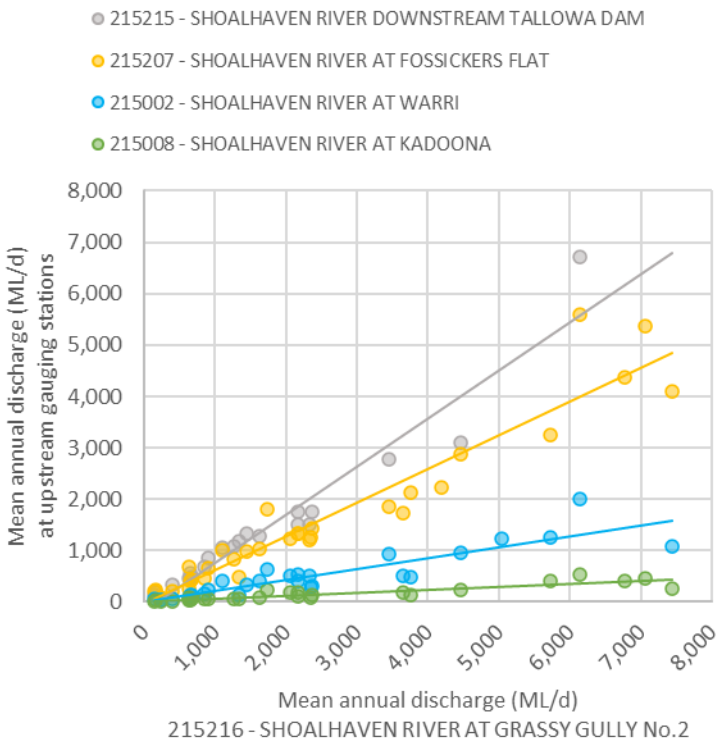


Figure 9. Annual maximum flood data between 1915 and 2021 at selected gauging stations within the Shoalhaven River catchment Source: WaterNSW real time data (https://realtimedata.waternsw.com.au/). Note: Plotted data represent available records; data gaps exist.



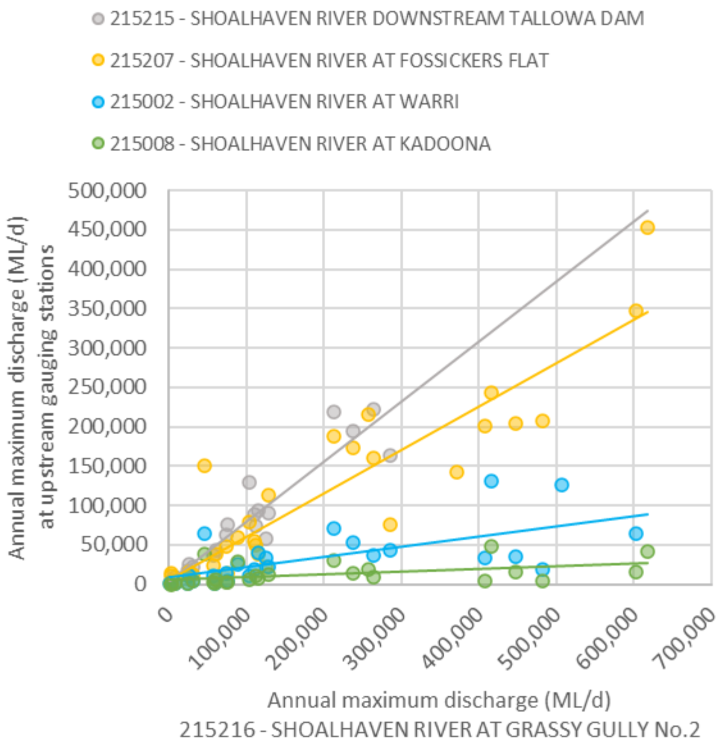


Figure 10. Mean annual discharge (top) and annual maximum flood (bottom) data Grassy Gully No. 2 gauge relative to data from selected upstream gauging stations within the Shoalhaven River catchment Source: WaterNSW real time data (https://realtimedata.waternsw.com.au/). Note: Plotted data represent available records; data gaps exist.

4.6 Channel morphological changes

4.6.1 Vicinity of Pig Island

Martens & Associates (2019), referring to the Lower Shoalhaven River: Floodplain Risk Management Study (Webb, McKeown and Associates 2008), reported that the Island has been actively accreting since European settlement, increasing in width (650 m to 850 m approximately) and in length (1,680 m to 2,400 m approximately). The source of this information is likely a comparison of current aerial imagery with Parish Plans. Ten Parish Plans that covered the area of the lower Shoalhaven River were downloaded from NSW Land Registry Services (https://www.nswlrs.com.au/Parish-and-Historical-Maps):

- Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, June 1894 3rd Ed
- Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, Dec 1918
- Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, Oct 1935
- Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, Nov 1957
- Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, July 1903
- Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, February 1904
- Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, Aug 1916
- Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, Sep 1938
- Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, May 1961
- Parish of Bunberra County of Camden, Land District of Nowra, Dept Lands Sydney, 7 April 1976

All of the above plans (see a selection of plans at Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15) depict Pig Island approximately 1.67 km long and 675 m wide, which is substantially smaller than its current size, measured from a 2021 aerial image, approximately 2.32 km long and 812 m wide. These dimensions are similar to those reported by Martens & Associates (2019). The plans depict the western bank of the Shoalhaven River near Pig Island in a similar position to its current position. However, the plans, with the exception of the 1976 Bunberra Plan, depict the right bank of the river, for a distance of 1.9 m downstream of Terara, in a more northerly position than its current position. The difference in position is up to 360 m. The right bank was redrawn on the 1976 Bunberra Plan to a position similar to its current position, but Pig Island perimeter was not redrawn. The problem with these plans is that a 1949 aerial image indicates that the current perimeter of Pig Island and the positions of the left and right banks of Shoalhaven River in the vicinity were achieved 80 years ago. It seems unlikely that the river banks were re-surveyed for the production of each plan, rather, these boundaries were likely copied from previous plans. Thus, the positions of the river banks illustrated on each plan are not necessarily a true reflection of the position of the banks on the date of plan publication. There is no reason to doubt that the original survey faithfully represented the river bank line positions at the time of the survey. The date of the original river survey is unknown, but it was possibly undertaken prior to two very large floods that occurred in 1860 and 1870, which were reported to have changed the morphology of the river channel in the vicinity of Pig Island.

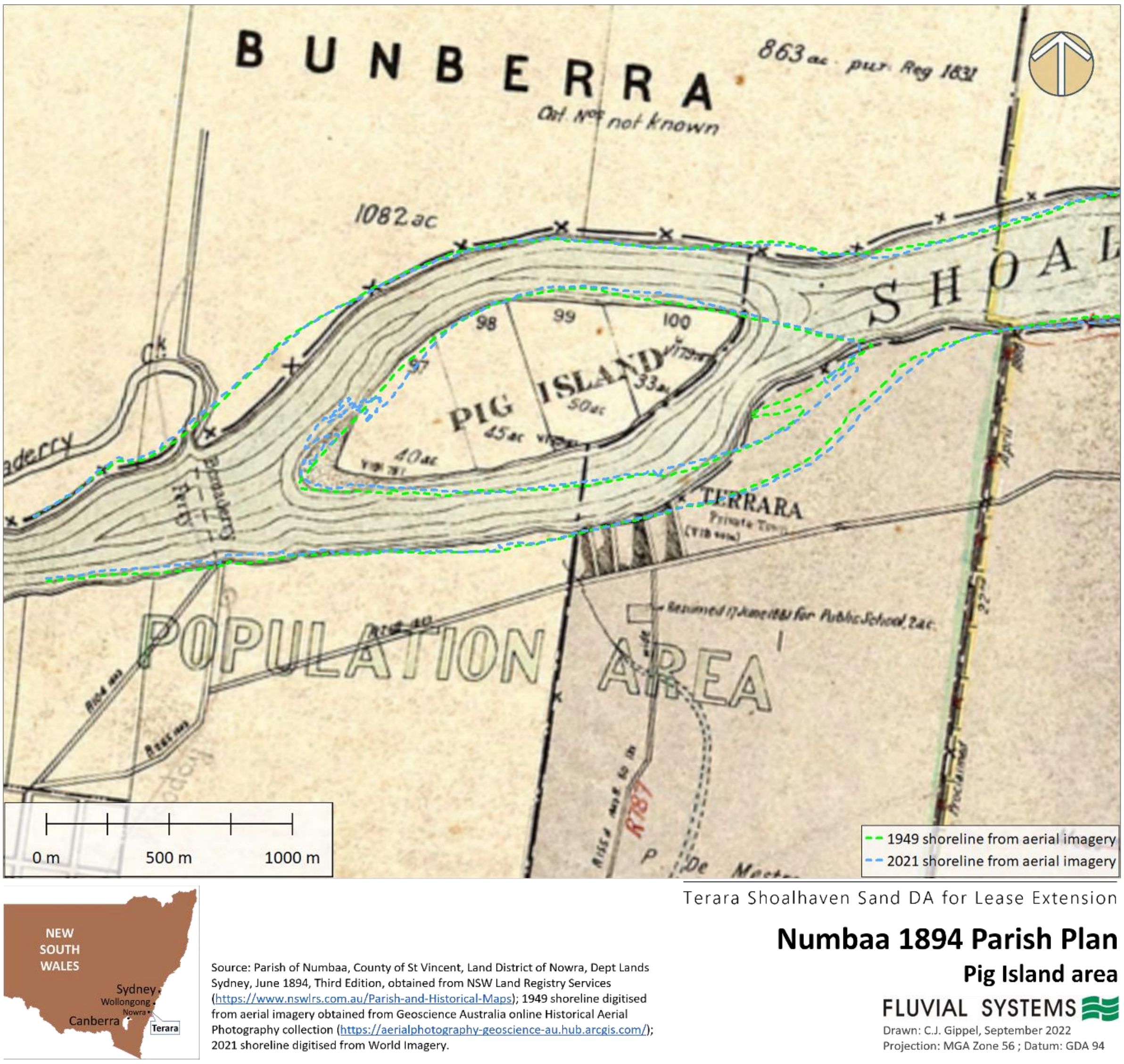


Figure 11. Section of Parish Plan Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, June 1894 3rd Ed.

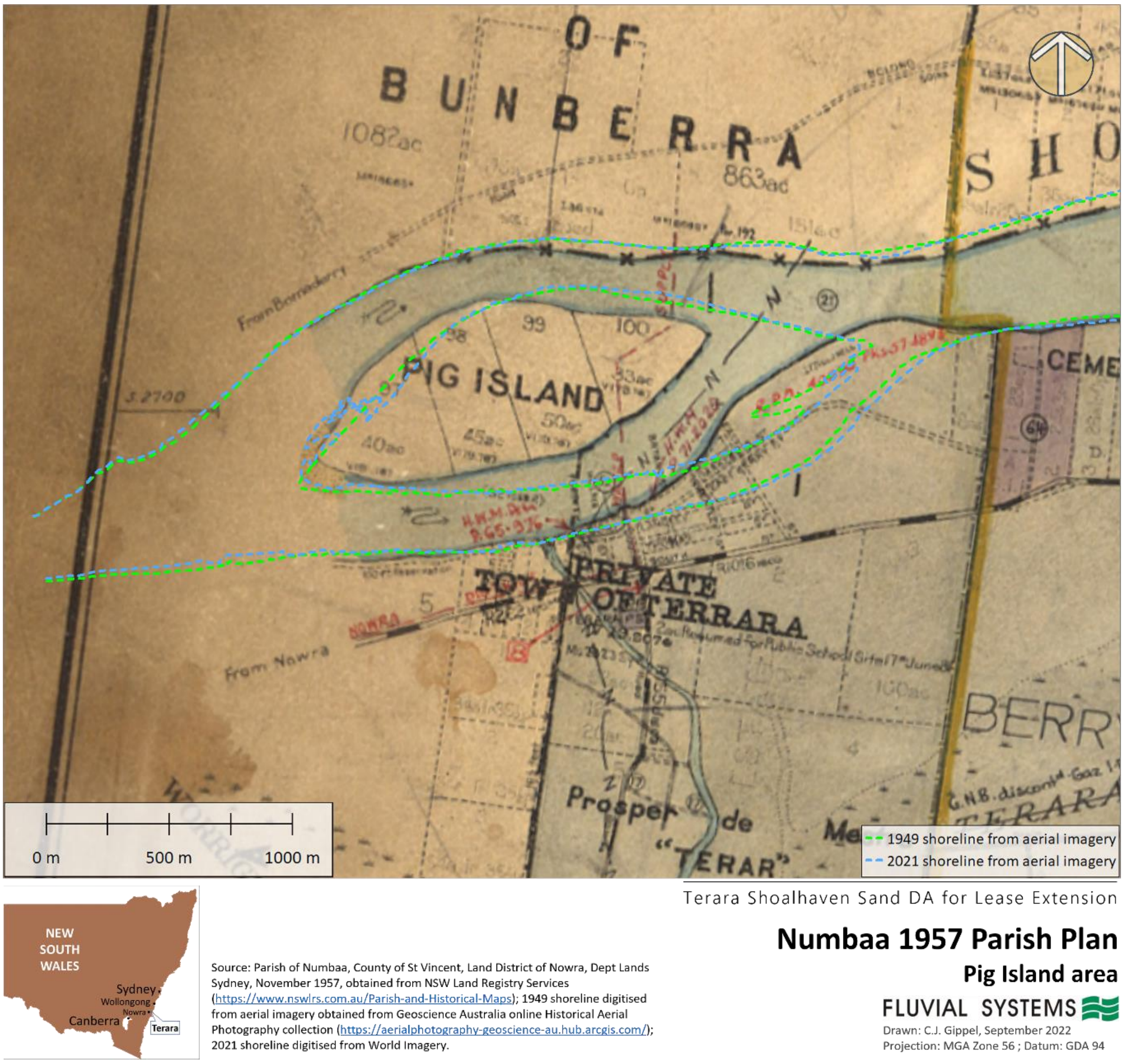


Figure 12. Section of Parish Plan Parish of Numbaa, County of St Vincent, Land District of Nowra, Dept Lands Sydney, Nov 1957.

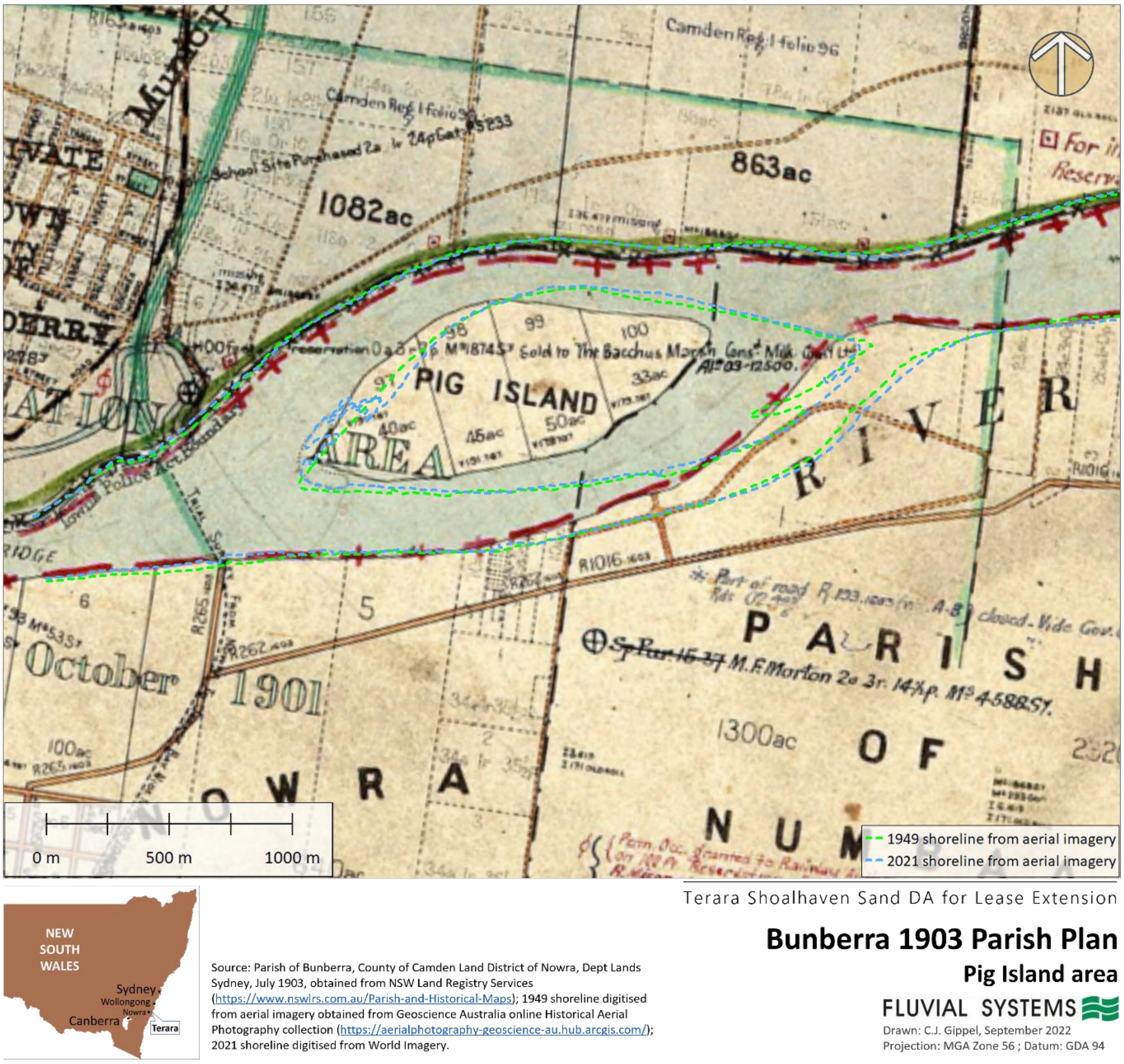


Figure 13. Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, July 1903.

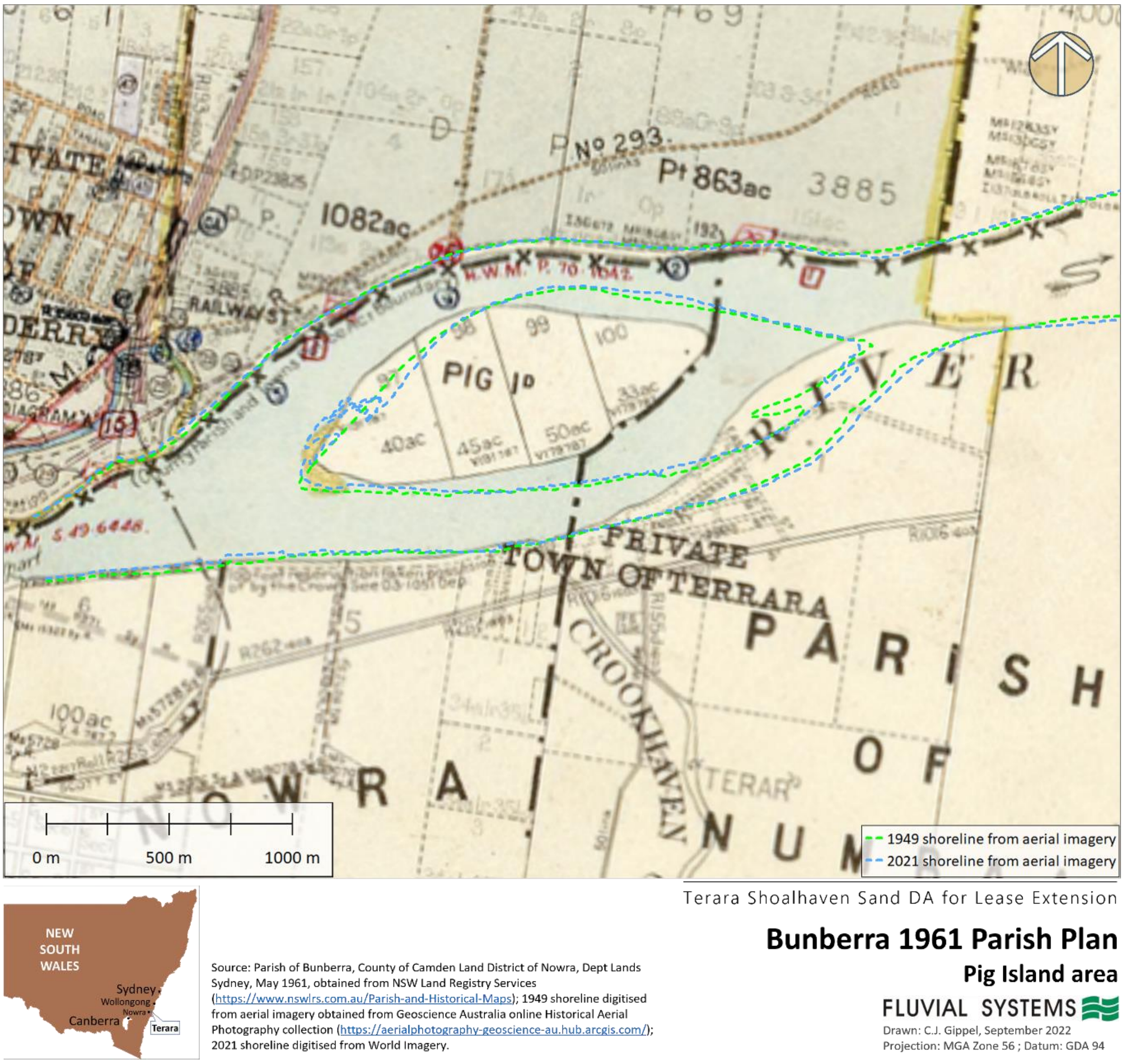


Figure 14. Parish of Bunberra, County of Camden, Land District of Nowra, Dept Lands Sydney, May 1961.

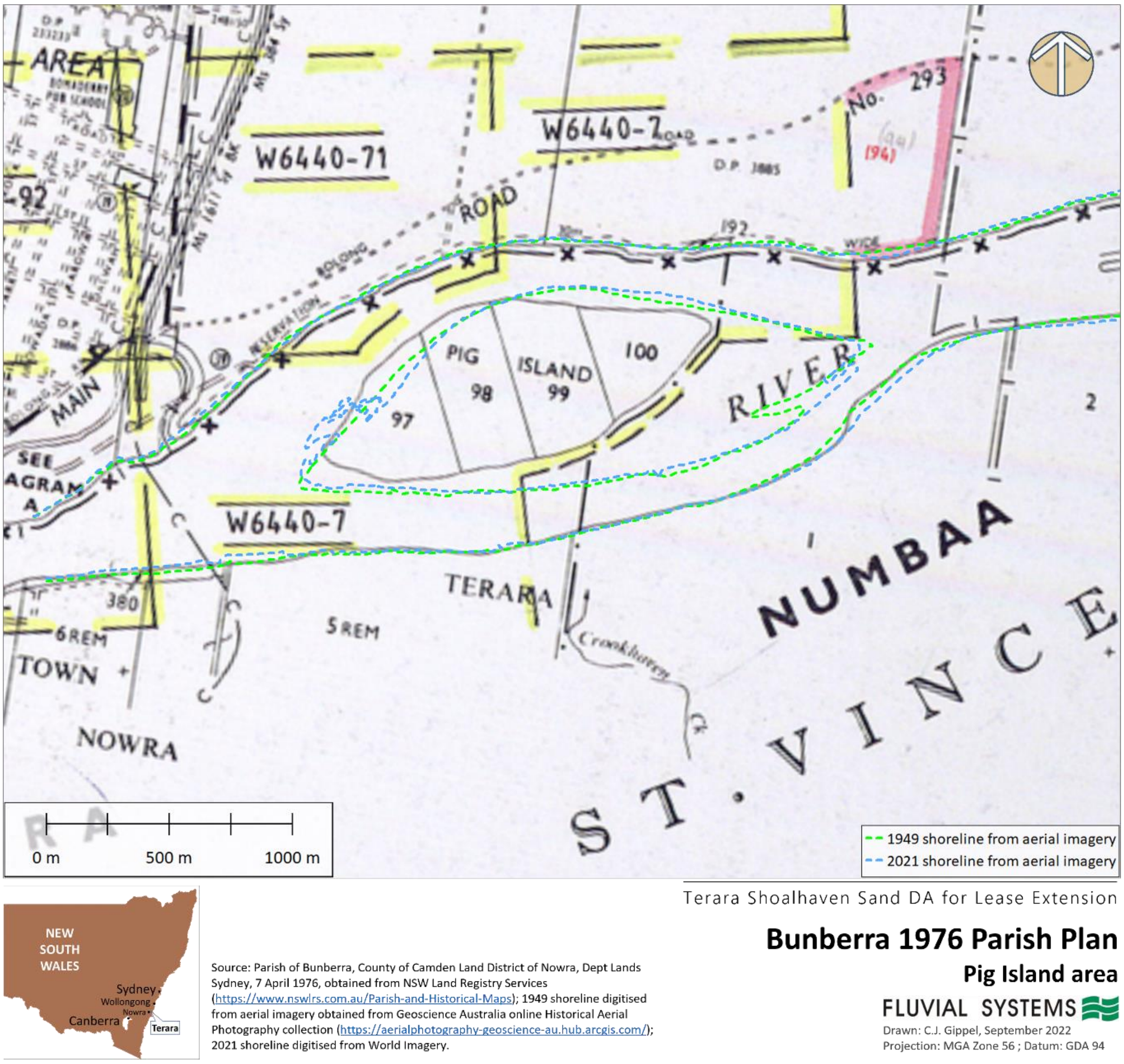


Figure 15. Parish of Bunberra County of Camden, Land District of Nowra, Dept Lands Sydney, 7 April 1976.

The earliest recorded flood on the Shoalhaven River was a very large event in February 1860. The Sydney Morning Herald (1860) reported that: "*The Mackenzies, a numerous, well-to do, and happy family of farmers, residing on the same estate, have lost house, barn, other out-buildings, and all they contained, also money ; indeed, they had barely time to save their lives; the headland, called 'Mackenzie's Point', jutting out some distance into the stream, has wholly disappeared, and better judges than I am say that from twenty to thirty acres, including portions of several Terara town allotments have been engulphed* [sic] *in the swollen river*". Ten years later, a large flood occurred in March 1870, followed a month later by the largest flood on record. Wardin (2017) quoted from Shoalhaven News reports at the time that the 1870 flood washed away the township of Terara, after which the town was abandoned by residents who moved to higher ground at Nowra. Further reports of the 1870 flood were provided by Thomson (2020), who described loss of life and property, including "*Dead horses, drawing room tables, posts and rails, couches, pigs, calves, buggies turned over, and sanded-up roofs of houses, galvanized iron, brass and iron bedsteads, and debris of every description half-buried in sand*." A correspondent for the Empire newspaper (Empire, 1870) gave an account of flood impacts that included erosion of large areas of river frontage land: "*At Terara the bank has been crumbling away for years, and the flood swept it away in acres. On reference to the plan of the Terra township, prepared by H. Morton, Esq, in 1860, where the chainage of all the lots is given from the river bank, I find the distance from Jones's store to the river three chains five links* [61.4 m]*; it is now very little over a chain* [20.1 m]*. From Isaacs's*

Hotel to the river, 307 links [61.7 m]*; it is now about thirty feet* [9.1 m]*. From the Junction of East-and Langley streets to the river fifteen chains fifty-eight links* [313.4 m]*, it is now about four chains* [80.5 m]*. As far as East-street about from sixteen to eighteen acres* [6.5 – 7.3 ha] *of the township must have been swept away*". This account suggests bank recession of up to 230 m. Note that East and Langley streets do not appear on current maps of Terara. Read in its entirety, the article published in the Empire, provided here in the Appendix (Section 8.1), is convincing evidence of large-scale channel change in the Terara area due to the 1870 flood.

The accounts of dramatic morphological change associated with the 1860 and 1870 floods possibly explains the differences in the way Pig Island, and the right bank of Shoalhaven River downstream of Terara, are depicted on Parish Plans, compared to aerial imagery since 1949. This explanation requires that the survey used to depict the river on the Parish Plans was undertaken prior to the 1860 and 1870 floods, and was not updated on later plans. This is a reasonable assumption.

Carvalho (2018, pp. 58-60) compared bathymetric surveys undertaken in 1981 and 2006 and found that between these dates, significant fluvial deposition occurred on the bed of the Shoalhaven River upstream of O'Keefes Point. Areas of substantial deposition exceeding 4 m were located mostly upstream of Nowra, despite Tallowa Dam upstream trapping incoming coarse sediment since 1976. Areas of scour mostly occurred along the estuarine channel, especially on the north of Pig and Numbaa Islands, as well as within some pools upstream from Nowra. Downstream from Numbaa Island, the estuarine thalweg migrated towards the right margin. Approximately 620,000 m^3 of sand was extracted from an area of approximately 200,000 m^2 on southern channel around Pig Island between the two surveys. There are no bathymetric data available prior to the start of sand extraction in the late-1960s or early-1970s, and the literature has not established a link between sand extraction and the historical location and depth of the channels and banks at and downstream of the dredging operations.

Carvalho (2018, pp. 68-75) used visual assessment to map erosion presence and type, armouring presence and type, and presence of erosion of armouring of the Shoalhaven River from Barrington Reach to the river mouth. Bank erosion was common along the shorelines, but Carvalho (2018) did not report whether or not this was an expected phenomenon, considering the land use, riparian cover, and site characteristics, including hydrology and hydraulics.

4.6.2 Vicinity of Berrys Canal and river mouth

Berrys Canal was cut in June 1822 to provide an alternative entry point to the Shoalhaven estuary through Crookhaven heads, avoiding the dangerous Shoalhaven heads. The original channel was only 191 m long and 5.5 m wide. Berrys Canal was dredged in the late 1900s to allow steam ships to travel upstream to Nowra Wharf. The canal is now the main pathway for both river and tidal flows for the Shoalhaven River. Thompson (2012) surveyed the position of Berrys Canal shoreline in the field in 2012 and then compared the results with historical records of bank position mapped by Office of Environment and Heritage (OEH) from aerial photographs dated 1949, 1984, 1993 and 2002. Although not included in the analysis, historical survey data from 1901 (Public Works Department, 1988), provided to Thompson (2012), indicated up to 200 m of shoreline recession on the western shoreline of Comerong Island (left bank of Berrys Canal, in the downstream direction) between 1901 and 1949. Carvahlo and Woodroffe (2013) used LiDAR from 2004 and 2010/2011 to observe that erosion occurred on both banks of the entrance of Berrys Canal, with a prominent loss of land area, especially on the right margin which retreated by more than 10 m. Significant erosion also occurred downstream on the northern end of Apple Orchard Island and along the opposite bank on Comerong Island. These results are consistent with those of Thompson (2012). Thompson (2012) concluded that Berrys Canal has continued a pattern of channel widening and capacity enlargement through time, but at a decreasing rate. The expansion of Berrys Canal reflected adjustment to regular tidal forces, as well as periodic flood flows, some of which result in opening of Shoalhaven Heads. Analysis of aerial photographs and Landsat imagery by Carvalho and Woodroffe (2017) revealed that the river mouth at Shoalhaven Heads was open in 1961, 1974-1980, 1988-1994, 1998-1999, 2013-2014 and 2015-2016.

Al-Nasrawi et al. (2016) used historical aerial photography and unspecified remotely sensed imagery compiled from years 1949, 1961, 1970, 1981, 1993, 2002 and 2014 to plot the time series of the area of Comerong

Island. The plot indicated that from 1949 to 1970 the area increased by 0.22 km^2; from 1981 to 2002 the area declined by 0.22 km^2, and from 2002 to 2014 the area declined a further 0.23 km^2. Over the entire period, the northern part of the island accreted by 0.41 km^2, while the western and southern areas contracted by 0.73 km^2. Al-Nasrawi et al. (2016) did not describe or map the boundaries of these two partitions of the island.

Thompson (2012, Fig 13, p. 33) included a map of the extensive bank protection works that have been constructed on the banks of Berrys Canal, mostly during the 1960s and 1970s. This is evidence of a perceived erosion problem on Berrys Canal at that time.

Carvalho (2018, pp. 58-60) compared bathymetric surveys undertaken downstream of O'Keefes Point in 1981, 1989, 2006 and 2015. The comparison revealed that scour dominated most of the Crookhaven channel over the past 34 years, and deposition dominated along the Shoalhaven channel including Shoalhaven Heads, despite the gross losses that might occur during breaching events. The observed trend of erosion and deposition was explained by the diversion of the river flow via Berrys Canal, and the continuing adjustment of the Canal morphology to fluvial and tidal scouring since 1822, and the benign hydrodynamic conditions experienced at Shoalhaven channel when Shoalhaven Heads is closed.

4.7 Causes of observed river and beach erosion/accretion

The area covered by RA12/1001 and the area covered by the current application are almost identical. The 2012 application extraction area was previously investigated in accordance with the then Director General's Requirements in 2011. Panucci and PDC Lawyers & Town Planners (2021) stated that the various reports prepared to accompany the EIS in 2012 concluded that the proposal would not result in environmental or ecological harm to the river and environs.

Carvalho (2018, pp. 68 - 75) and Carvalho and Woodroffe (2021) found that erosion was common on the banks of the estuarine reach of the Shoalhaven River but did not associate the erosion with sand extraction activities.

Al-Nasrawi et al. (2016) attributed erosion of western and southern areas of Comerong Island to trapping of fluvial sediment and altered river hydrology by Tallowa Dam. Al-Nasrawi et al. (2016) claimed that "*The dam has blocked most of the water and its sediment derived from the upper catchment making it effectively inactive*". They attributed accretion of the northern area of Comerong Island to barrier deposition by natural tidal processes that have affected the northern area during periods when the river mouth was open. Al-Nasrawi et al. (2016) concluded:

> "*The aerial photographs and RS data (1949, 1961, 1973 and 1982) show that the island has grown constantly. After 1982, however, the island has eroded and its size has declined as shown in the aerial photographs and RS data (1993, 2002 and 2014). The reason behind this change was the building of Tallowa Dam, which blocked most of the sediments collected from the catchment. Thus 80.1% of the catchment (5,750 km^2 of 7177.5 km^2) was converted to inactive catchment geomorphologically. That caused serious sediment transport and availability problems, which changed the positive sedimentation rates to negative values, and favored erosion."*

Inconveniently for this theory, the data indicated that Comerong Island expanded after Tallowa Dam became operational in 1976, at least until 1982. To explain this apparent inconsistency, Al-Nasrawi et al. (2016) conjectured:

> *Initially after Tallowa Dam was constructed in 1976, the sediment rates remained high and the island continued to grow. This was due to the new water level within the Shoalhaven River that dropped below the dam (for 58.8 km until it reached Comerong Island) which caused erosion of the river bed and edges providing sediment to the Comerong Island area. This occurred for a few years only, after which the natural processes failed to erode additional sediment resulting in less sediment availability and deposition in the lower reaches. This is reflected in higher erosion rates that now control the site. This study has shown that the shoreline eroded by 0.73 km^2 since 1982 (0.02 km^2 annually). Meanwhile, the northern part of the island has grown significantly (about 20% between 1949 and 2014). This can be related to barrier deposition by natural tidal processes that have affected northern area during periods when the river mouth was open*."

Al-Nasrawi et al. (2016) provided no evidence of suddenly lowered river levels downstream of Tallowa Dam, they did not explain how supposedly lower flow levels increased bed scour and bank erosion, when the opposite would be expected, and they failed to provide evidence of bed scour or bank erosion on the Shoalhaven River downstream of Tallowa Dam from 1976 to 1982.

Carvalho (2018, p. 152) noted that long-term shoreface supply of sand to beaches is undetectable on annual and even sub-decadal time scales and is masked by more rapid cyclical changes because the supplied volume is negligible compared to the volume of sand involved in the beach erosion and recovery cycles. Despite these uncertainties, Carvalho (2018, p. 153) suggested that the ongoing supply of sand to the coast by the Shoalhaven River, i.e. despite sand extraction activities since the late-1960s or early 1970s, may be partially responsible for the beach accretion and shoreline progradation observed in the past decades at Seven Mile Beach-Comerong Island. Using data from aerial image analysis, Carvalho (2018, p. 114) reported that, at a cross-section on the southern end of Seven Mile Beach-Comerong Island, in August 1963 the shoreline was located 97 (±14.1) m landwards of its present location. It rapidly accreted approximately 33 m by July 1977. The next aerial photograph taken in January 1982, showed a major retreat of approximately 27 m (related to a major storm in 1978) and it then progressively accreted 91 (±3.6) m to its December 2013 position. Other cross-sections also showed overall accretionary trends. Shoreline accretion was also observed over time at Culburra and Warrain-Currarong beaches, even though these two embayments receive no major fluvial contributions of sand (Carvalho, 2018).

In conclusion, to date, the available literature has not produced data linking historical dredging and sand extraction activities with erosion of the Shoalhaven River, or instability of the beaches to the north of the river mouth.

4.8 Particle size distribution of estuarine channel and deltaic plain deposits

Al-Nasrawi et al. (2016) measured the clay, silt and sand content of 113 sediment samples taken over Comerong Island. Sand dominated the eastern marine side of the island (up to 99.5% sand), while clay/silt (up to 51.3% clay and up to 28.2% silt) dominated the western riverine side of the island. Sand was present on the western side of the island in proportions as low as 28.3%. Sampling by Thompson (2012) found that the southwestern bank of Comerong Island area was mainly composed of fine sand underlain by a layer of sandy silt, underlain by medium and fine sand.

Carvalho (2018) collected and sized 209 samples of sediment from estuarine, beach and offshore surficial sediments of Shoalhaven River estuary area. A number of these samples were located on or near the Pig Island sand deposit. Carvalho's (2018) results for the estuarine channel samples are reproduced here (Figure 16). Carvalho (2018) reported that grain size ranged from very coarse sand to medium silt, with a general pattern characterised 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 was found in shallow areas, whereas medium to very fine sand was found in the pools. From Pig Island to 10 km upstream of Nowra Bridge the river bank was composed of medium sand intercalated with finer sediments down to medium silt. Samples with gravel content above 2% occurred mostly upstream from Pig Island and in the Crookhaven entrance. Mud was found in all but 18 samples and these were mostly located in the lower estuary towards Crookhaven channel.

The data of Carvalho (2018) indicated that the Pig Island sand deposit comprised moderately sorted sand, but the extraction area on the southern channel comprised medium silt (Figure 16). Data from an earlier sampling of bed material from the Pig Island area by Boyd et al. (1977) was presented by Carvalho (2018). Carvalho's (2018) mapping of the data of Boyd et al. (1977) is reproduced here (Figure 17). In contrast to the results of Carvalho (2018), Boyd et al. (1977) found the Pig Island sand deposit comprised generally coarser sand, and sand extended upstream along the area of the southern channel, where sand would later be extracted, and also upstream along the northern channel. Carvalho (2018) had difficulty explaining these differences, but suggested possible reasons that included: different sampling methodologies; modifications in the hydraulic regimes; channel erosion in the last 40 years; and, in the sand extraction area on the southern channel, the current finer sediments could represent residual material left after extraction of the coarser material.

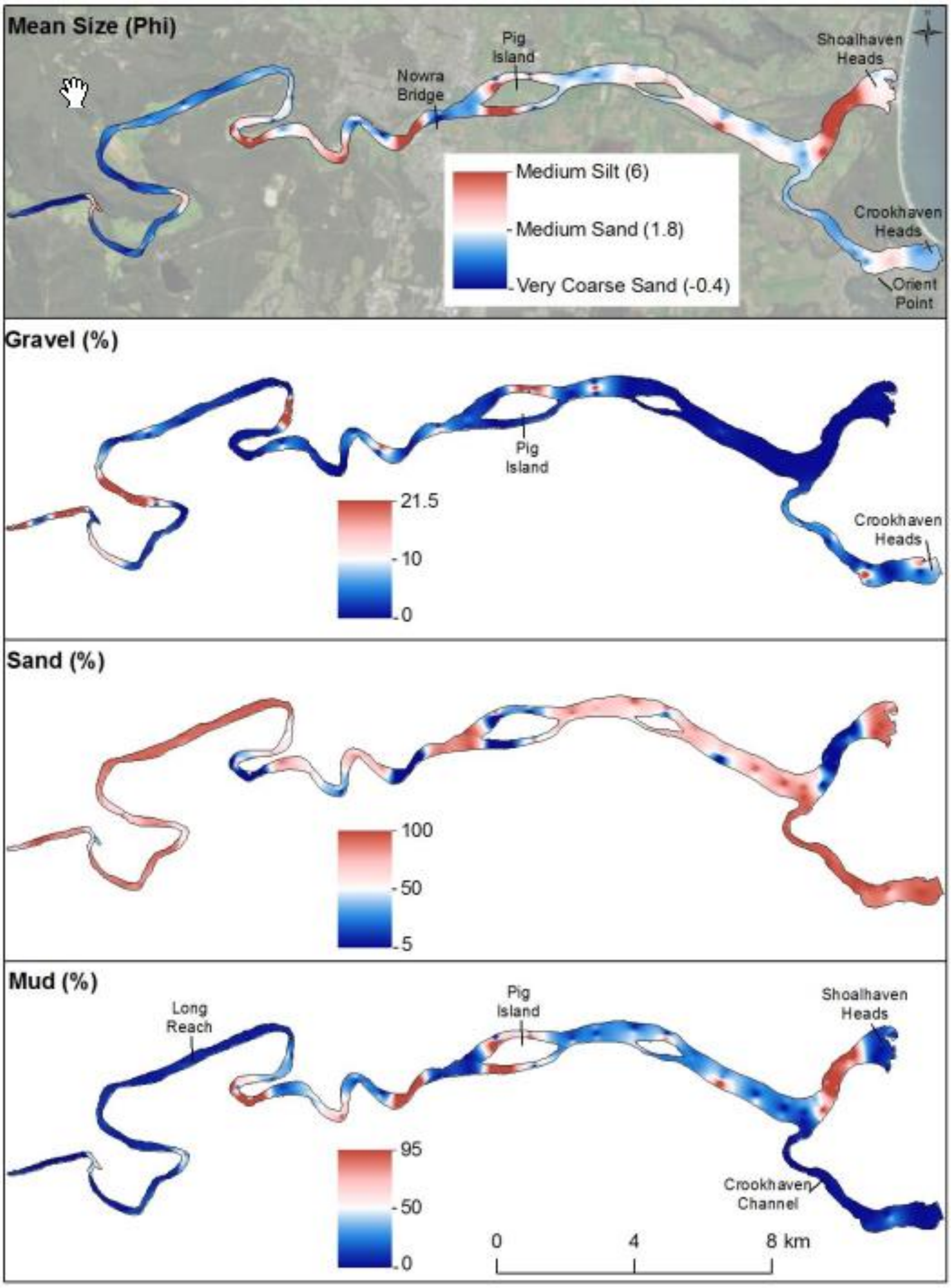


Figure 16. Mean grain size and percentage of gravel, sand and mud content in estuarine samples. Source: Carvalho (2018, Figure 4.13, p. 76).

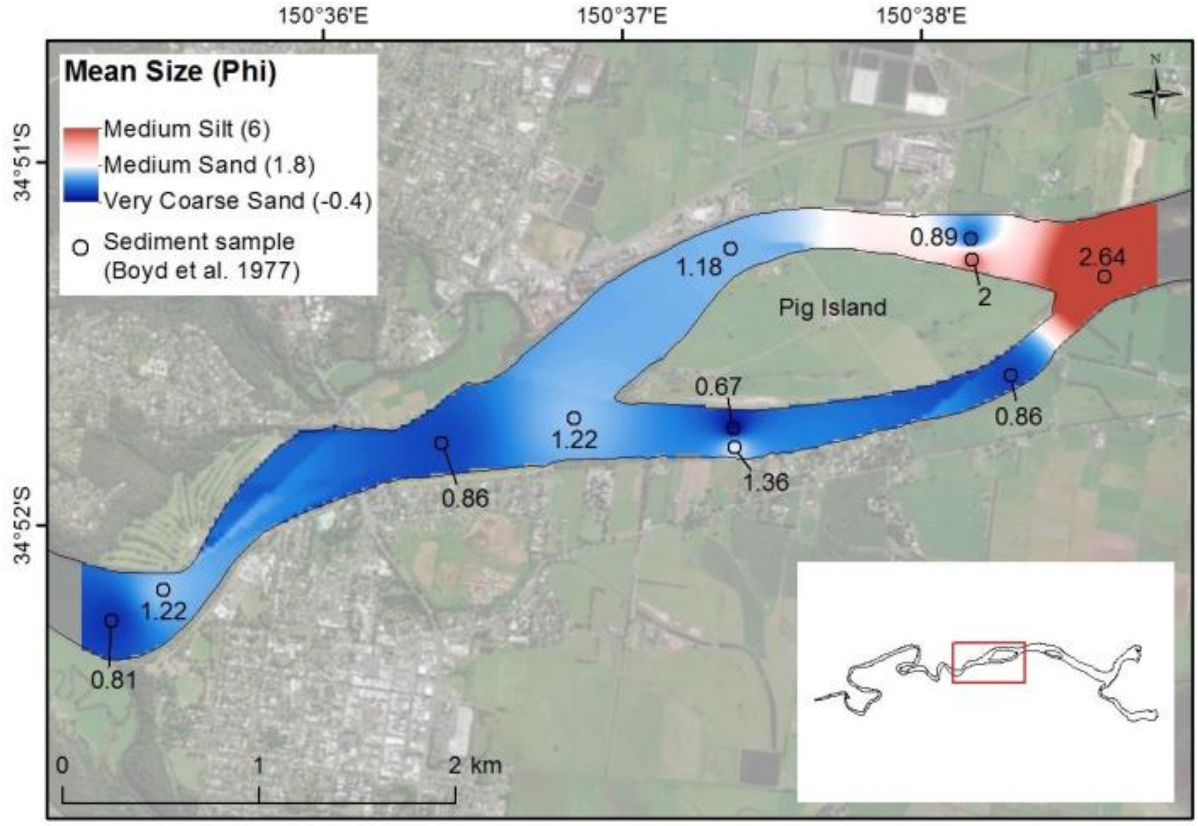


Figure 17. Mean grain size distribution after Boyd et al. (1977). Sample values converted from mm to phi scale and labelled in the map. Phi values were interpolated at 25 m pixels. Source: Carvalho (2018, Figure 4.15, p. 80).

5 Results

5.1 Measurement of channel position through time

The aerial images referred to in this report were all flown at times of relatively low river flow (Figure 18), so while variable river flow rate did not impact the interpretation of bank lines, variable tide levels could have introduced error. There was little change apparent in the shorelines of Pig Island and the Shoalhaven River in the vicinity of Pig Island between 1949 and 2021 (Figure 19), despite this area being recognised as having a bank erosion problem. Carvalho (2018) and Carvalho and Woodroffe (2021) found that erosion was common on the banks of the estuarine reach of the Shoalhaven River, mostly in the form of shallow or planar mechanism, with extensive rotation failure happening in some banks and considerable volumes of material being eroded on both sides of the estuary. Less than 20% of the analysed reaches had parts of the bank naturally armoured with bedrock, whereas 25% had revetment present. Whilst the aerial imagery did not reveal large scale change of bank position in this reach, this result is not incompatible with local, perceived problematic, bank erosion, especially close to an urban area where bank erosion is often viewed negatively. This reach of the river can be considered relatively geomorphologically stable over the period 1946 to 2021 when compared to its apparent high level of geomorphic instability during the floods of 1860 and 1870.

The historical shoreline positions on the western side of Comerong Island and Nobles/Haven Islands showed a consistent progression of bank recession over time, with substantial and unequivocal recession occurring over most of the length of the measured land (Figure 20).

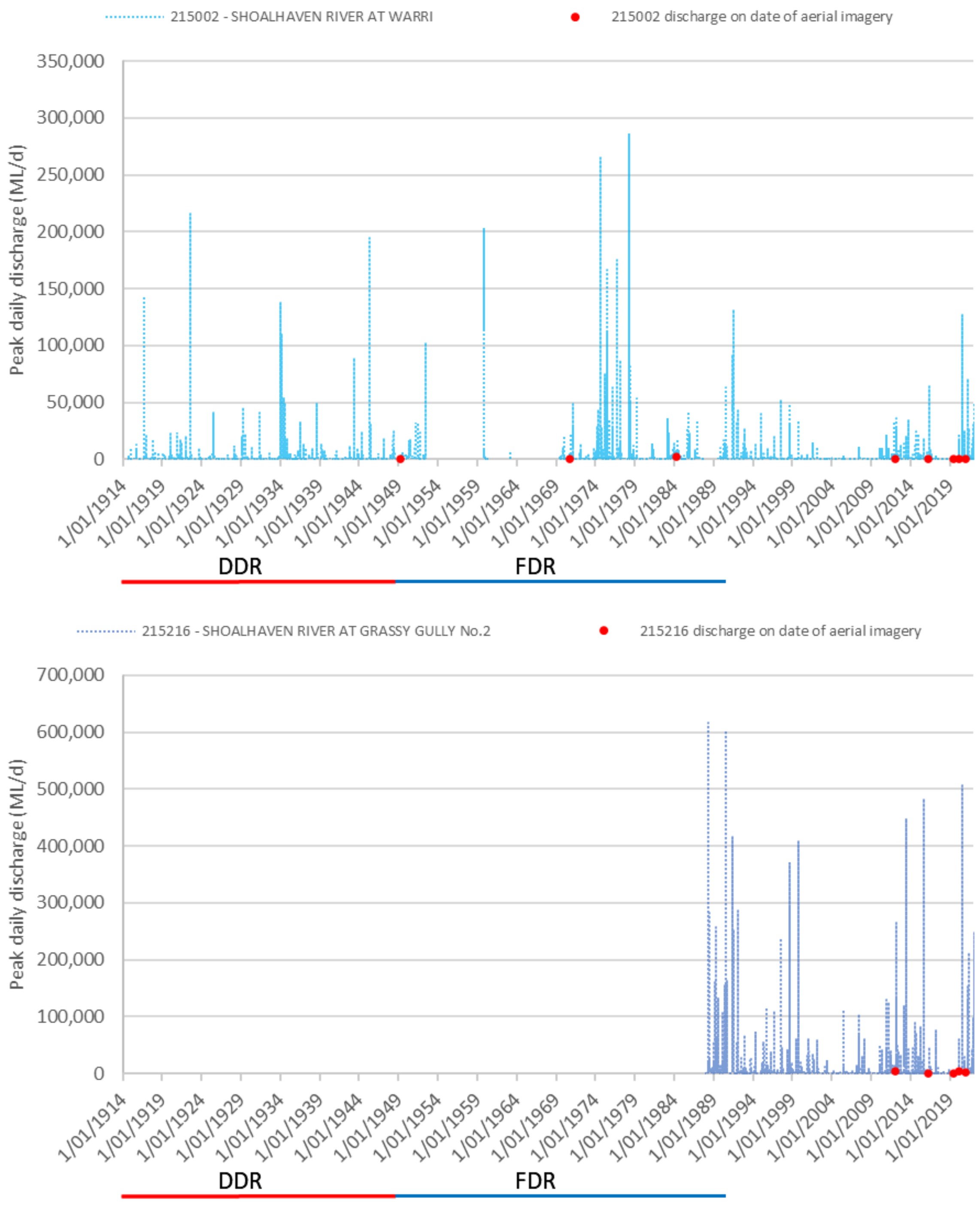


Figure 18. Flow at two Shoalhaven River gauges on days when aerial imagery used in this report was flown. Recognised DDR (drought dominated regime) and FDR (flood dominated regime) periods are indicated for reference. Note: Plotted data represent available records; data gaps exist.

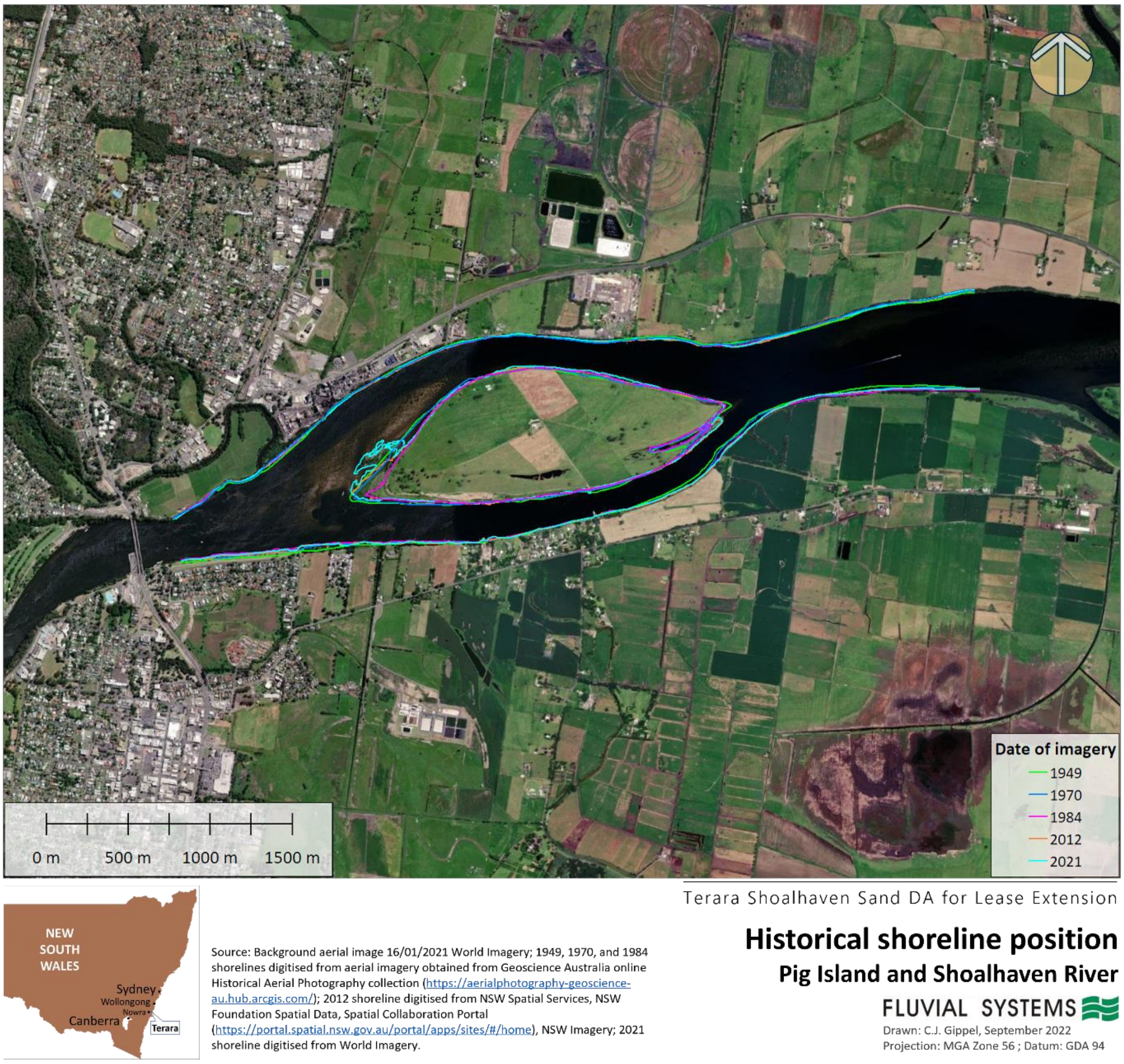


Figure 19. Historical shoreline positions on Pig Island and Shoalhaven River in the vicinity of Pig Island, measured from aerial imagery at 5 dates.

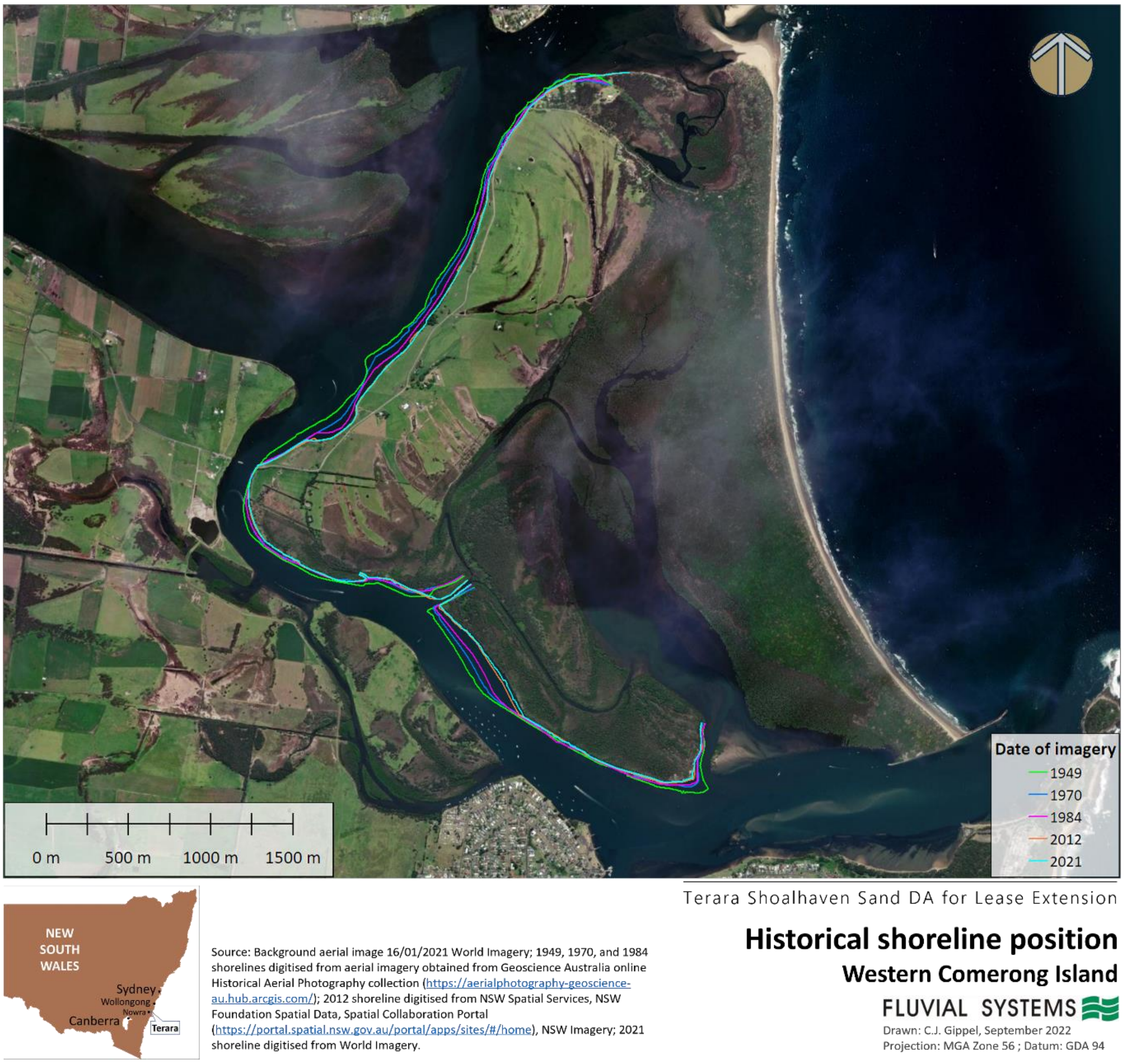


Figure 20. Historical shoreline positions on the western side of Comerong Island and Nobles/Haven Islands, measured from aerial imagery at 5 dates.

The cumulative change in bank position measured in the Comerong Island and Nobles/Haven Islands area (Figure 21) was consistent with similar measurements made by others and reported in the literature (reviewed previously in this report). As concluded by Thompson (2012), bank erosion in this area can be largely explained as an ongoing adjustment of Berrys Canal to the diversion of estuary flows to Crookhaven Heads. There is no evidence linking erosion in this area to reduced sediment supply from the catchment, as suggested by Al-Nasrawi et al. (2016).

The cumulative change in bank position in the Pig Island area was small (Figure 21), and possibly within measurement error. Since 1949 there have been no major changes to bank positions in this area despite construction of Tallowa Dam (in 1976), several large floods, and decades of sand extraction.

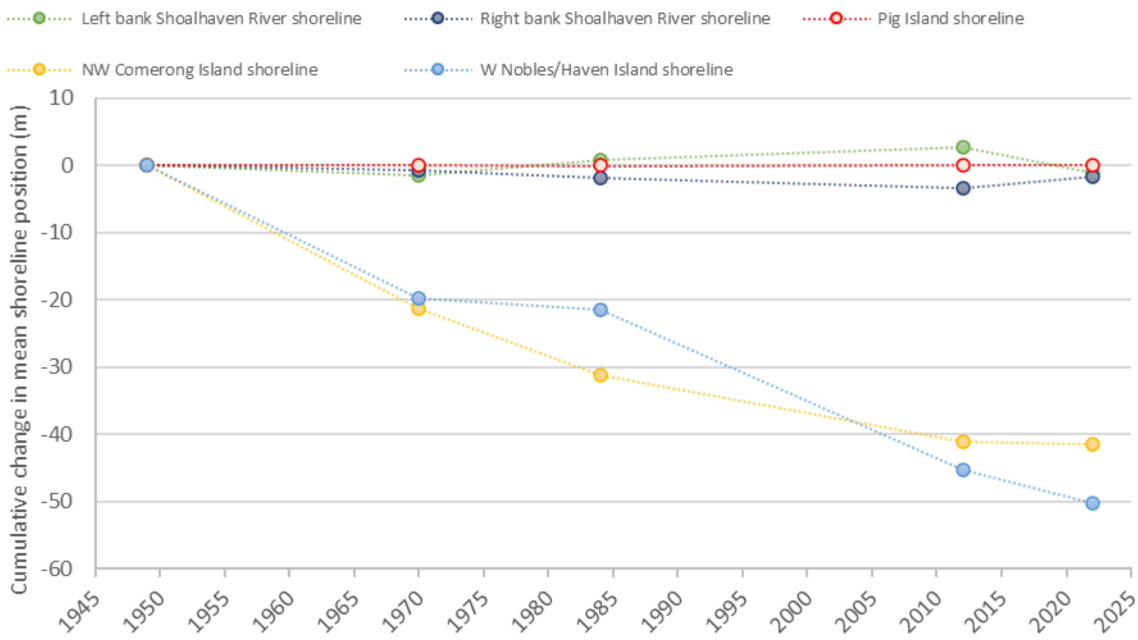


Figure 21. Cumulative change in shoreline positions on the western side of Comerong Island and Nobles/Haven Islands, Pig Island, and left and right banks of the Shoalhaven River in the vicinity of Pig Island, measured from aerial imagery between 1949 and 2021.

5.2 Bathymetric changes in Pig Island sand deposit over time

A number of sand extraction area boundaries have been mapped at Pig Island (Figure 22). Historically, most of the sand has been extracted from the southern channel, while the currently proposed extension area would extend into the northern channel. Data from five bathymetric surveys were used to investigate changes in bed elevations in relation to sand extraction operations (Figure 23).

The benchmark survey data from the Pig Island area was the Sep 2005 to Nov 2006 hydrographic survey of the entire estuary (Figure 24). The first specific survey of the Pig Island sand deposit was undertaken in February 2007 (Figure 25), not long after the Sep 2005 to Nov 2006 survey. The next survey was undertaken in December 2018 (Figure 26). The surveys undertaken in November 2021 (Figure 27) and September 2022 (Figure 28) covered relatively small areas that had been dredged.

The 2018 survey was undertaken after 3 years of hydrologically benign conditions following the major flood of August 2015 (Figure 29). The survey undertaken in November 2021 was preceded by the major flood of August 2020 followed by two relatively small events in March and May of 2021 (Figure 29). The most recent survey undertaken in September 2022 was preceded by a series of relatively small flood events (Figure 29).

As expected, there were only small differences between the DEMs generated from the February 2007 data and the Sep 2005 to Nov 2006 data (Figure 30). The differences mostly related to different point densities and point locations. There were some significant differences between the DEMs generated from the December 2018 data and the Sep 2005 to Nov 2006 data (Figure 31). There was deposition of up to 3 m within the previously extracted area of the southern channel and deepening of up to 6 m in the recently extracted area (Figure 31). A small area where sand had been extracted was surveyed in Nov 2021. Compared to the elevations in Dec 2018, there was up to 3.6 m deposition in the previously extracted areas, and deepening of up to 5 m in the recently extracted area (Figure 32). A small area where sand had been extracted, overlapping part of the 2021 survey area, was surveyed in September 2022. Compared to the elevations in Dec 2018, the majority of the previously extracted area experienced deposition, mostly exceeding 2 m and up to 5.2 m (Figure 32). The bed in this area has not fully recovered to its pre-extraction morphology, but it is within 0.5 –

2.0 m of the 2007 elevations. An isolated point sounded in Sep 2022 was located within the previously extracted area of the southern channel. This point had a bed elevation of -3.1 m AHD. The closest point from the Sep 2005 to Nov 2006 hydrographic survey, 4.8 m distance away, had a bed elevation of -6.32 m AHD, suggesting 3.2 m deposition over 17 years at this location. The bed in this southern channel area appears to have been lowered 5 – 6 m by sand extraction, with the data suggesting that about half of this depth has infilled since then.

Overall, the available survey data covering the Pig Island sand deposit suggest that the process of deposition of sand within previously excavated areas does occur. Between Dec 2018 and Sep 2022 rapid infilling of up to 5 m was observed in the recently extracted area. This infilling was likely facilitated by the relatively high frequency of flood events within this period.

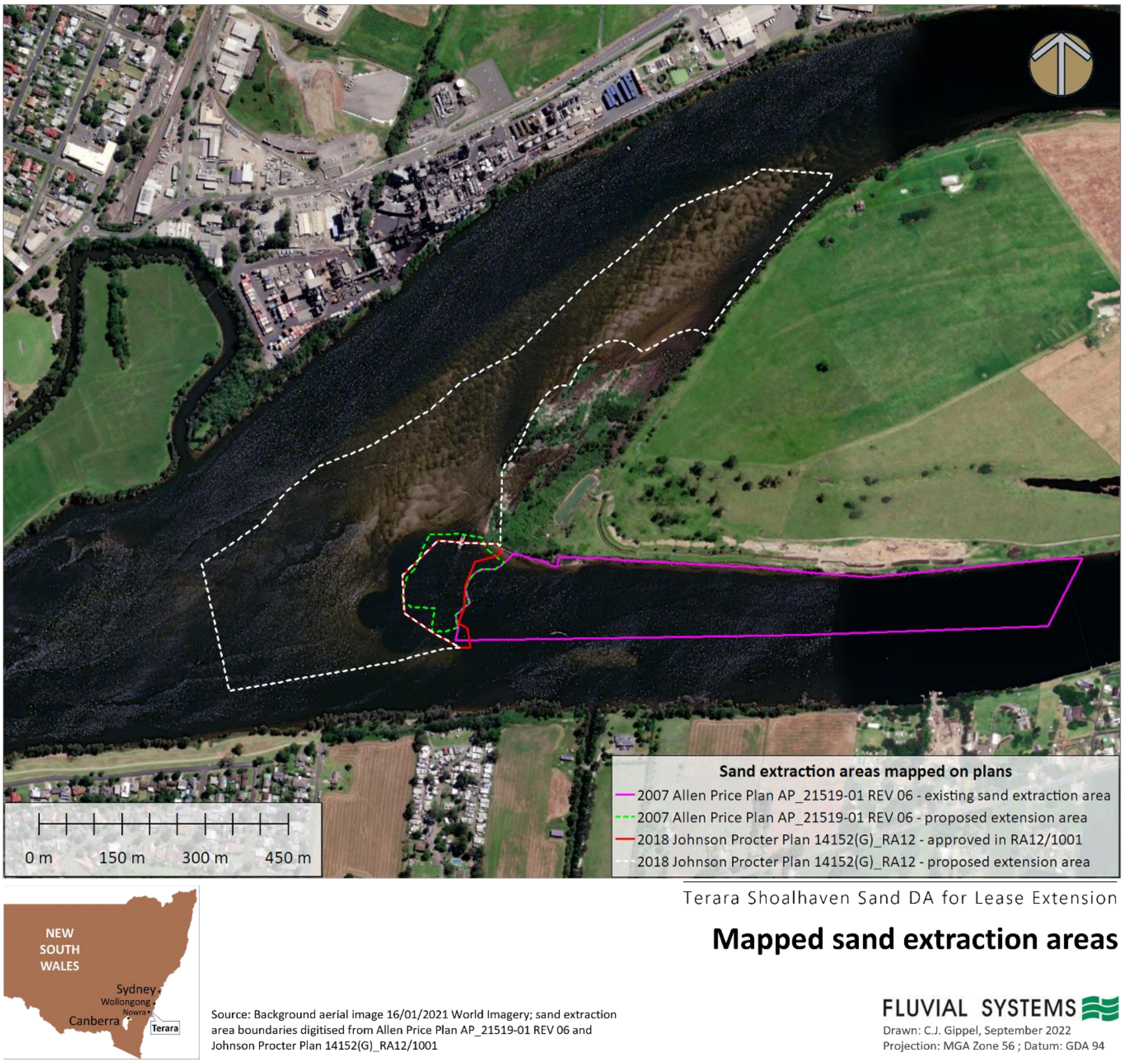


Figure 22. Mapped sand extraction areas at Pig Island.

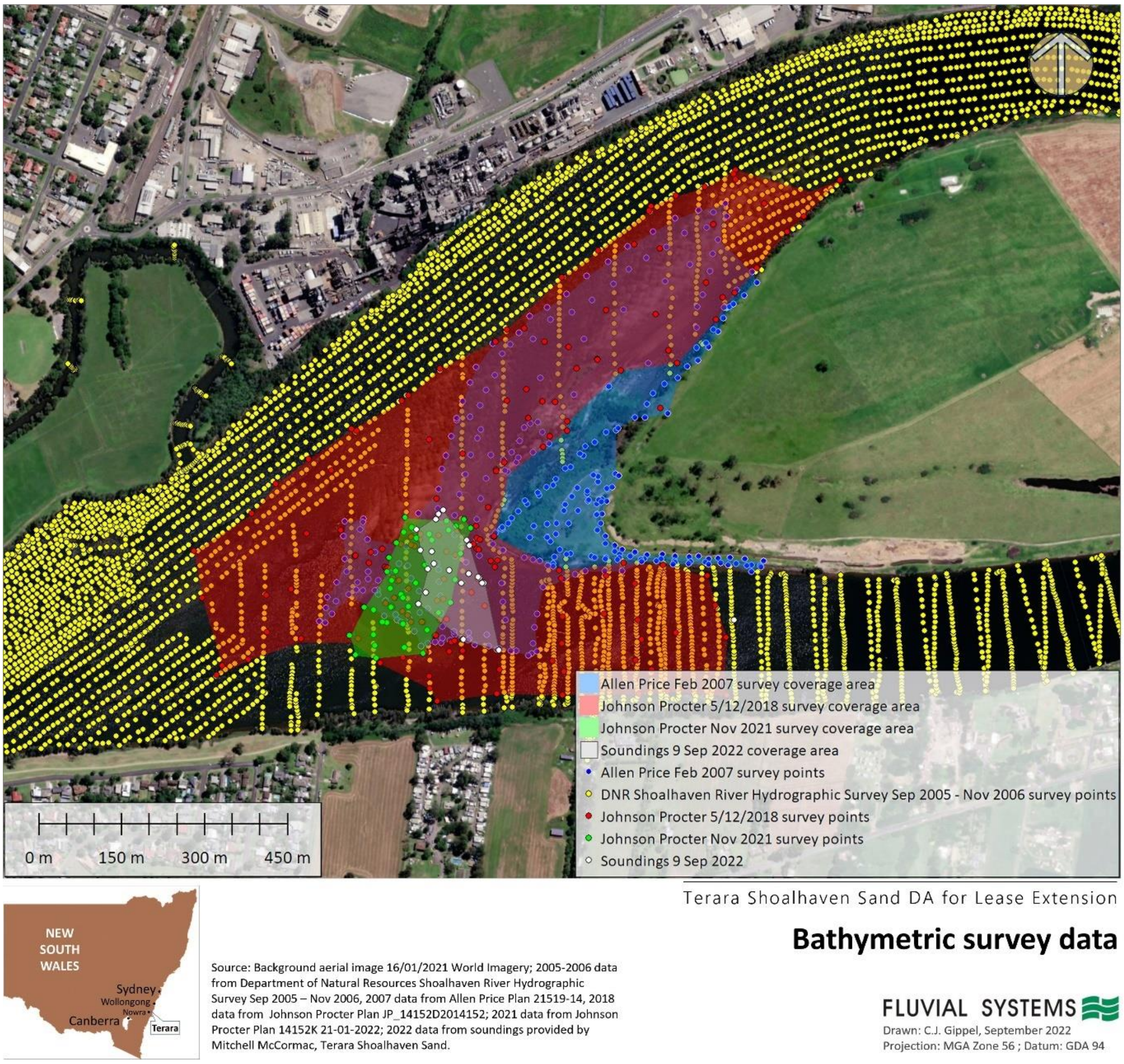


Figure 23. Bathymetric survey data used to create DEMs of the topography of the bed of the river. Each DEM was cropped to the extent of the survey data.

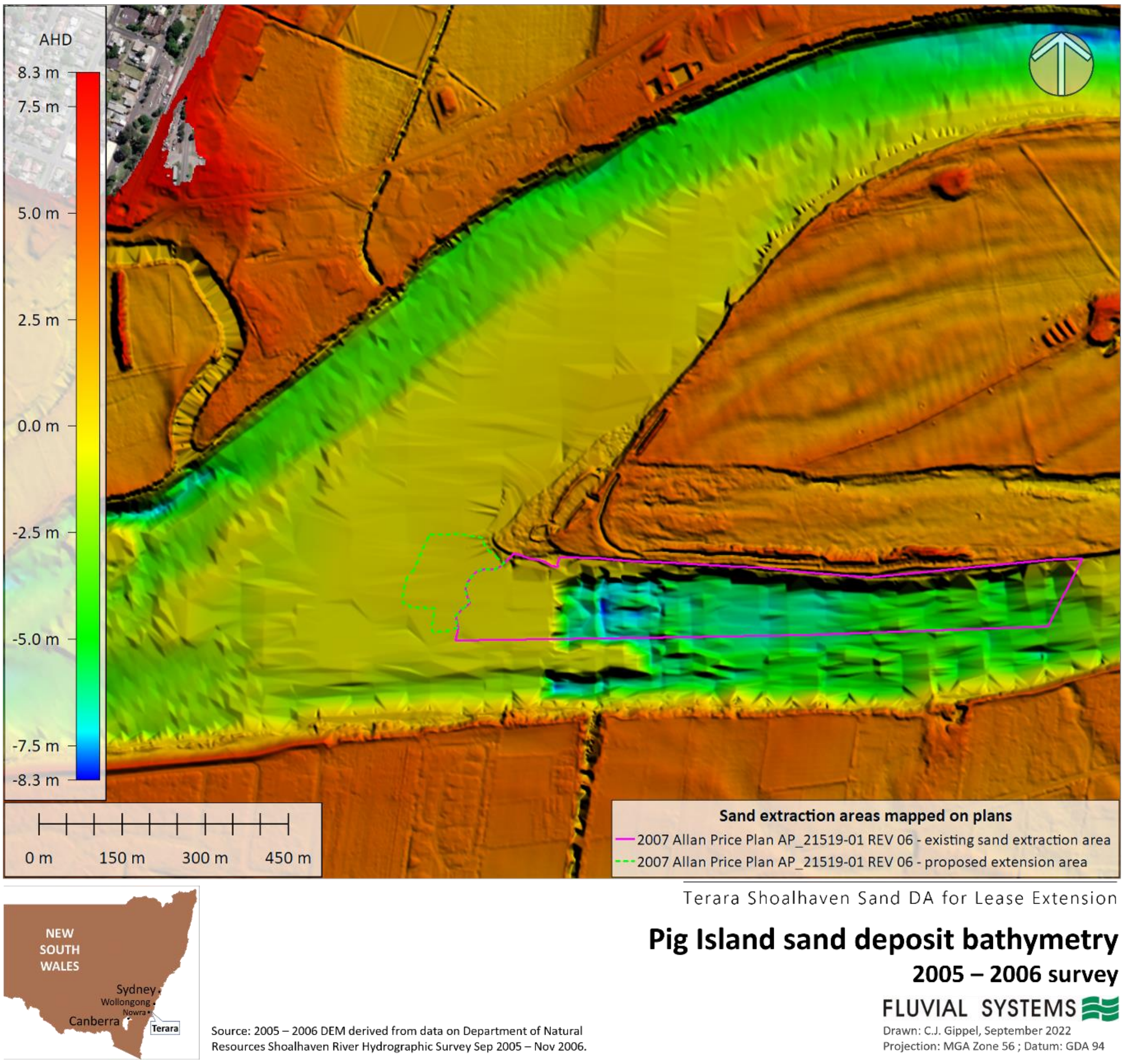


Figure 24. Bathymetry of Pig Island sand deposit derived from hydrographic survey conducted over the period Sep 2005 to Nov 2006.

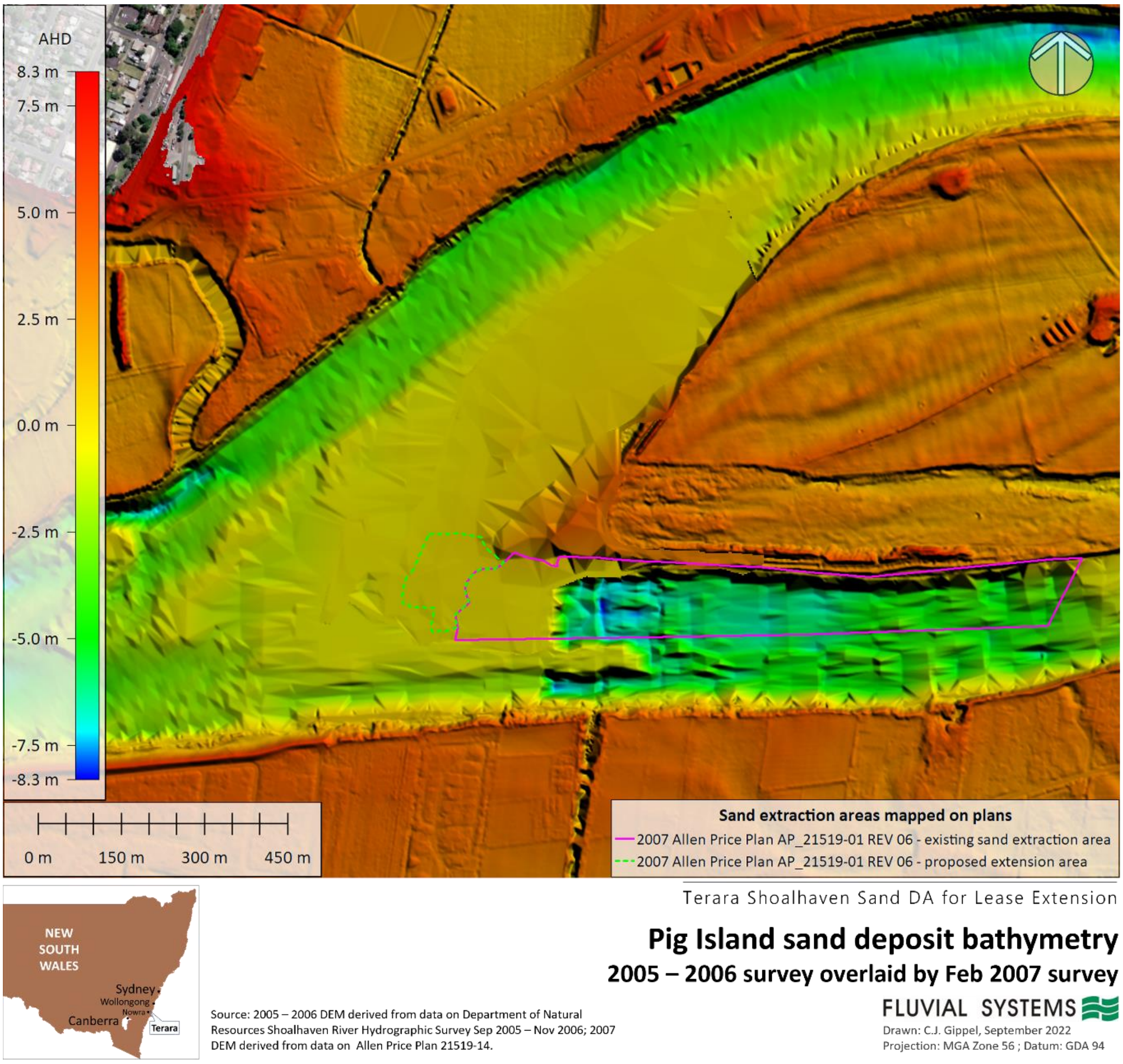


Figure 25. Bathymetry of Pig Island sand deposit derived from hydrographic survey conducted over the period Sep 2005 to Nov 2006 overlaid with data from the Feb 2007 survey.

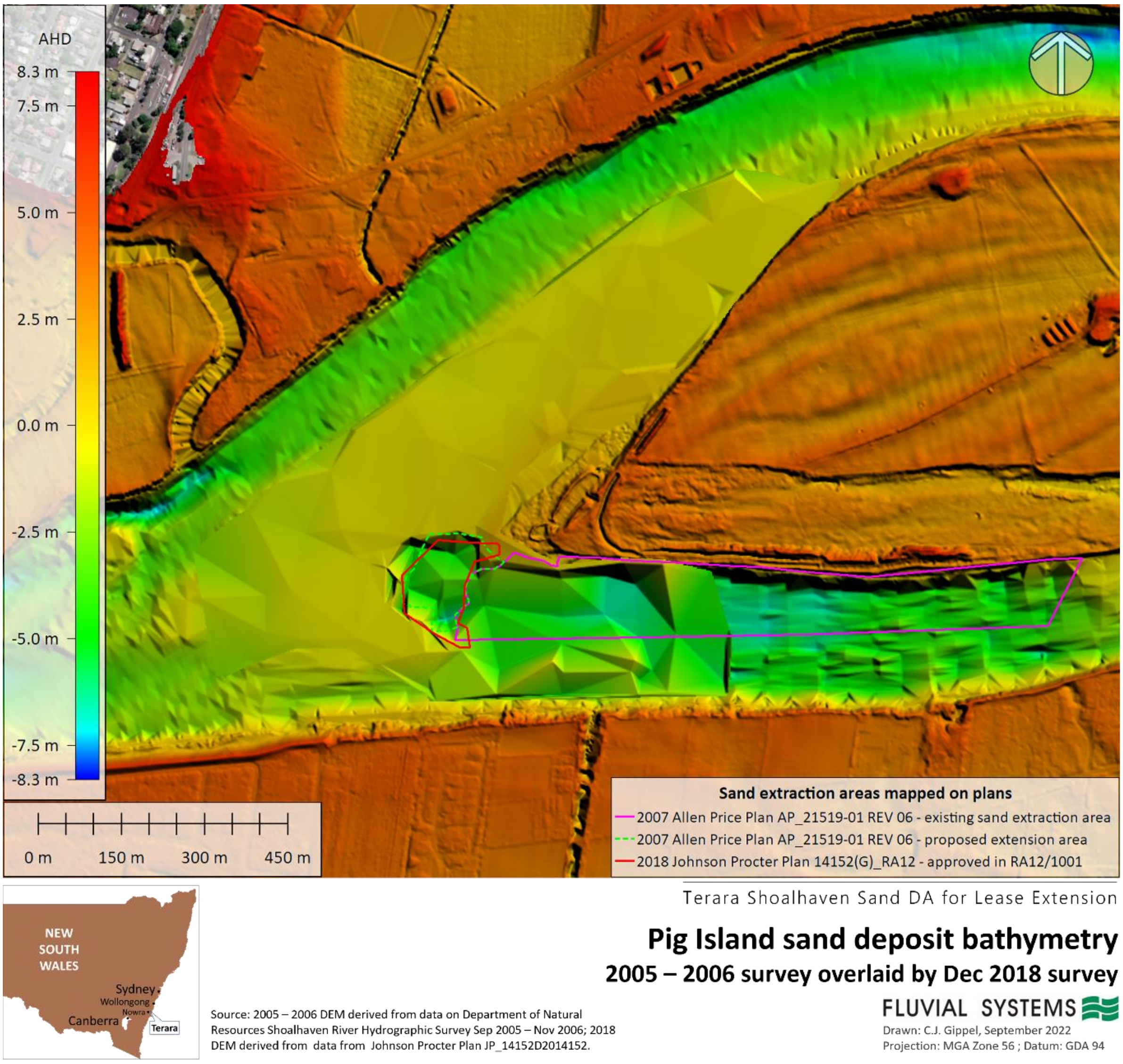


Figure 26. Bathymetry of Pig Island sand deposit derived from hydrographic survey conducted over the period Sep 2005 to Nov 2006 overlaid with data from the Dec 2018 survey.

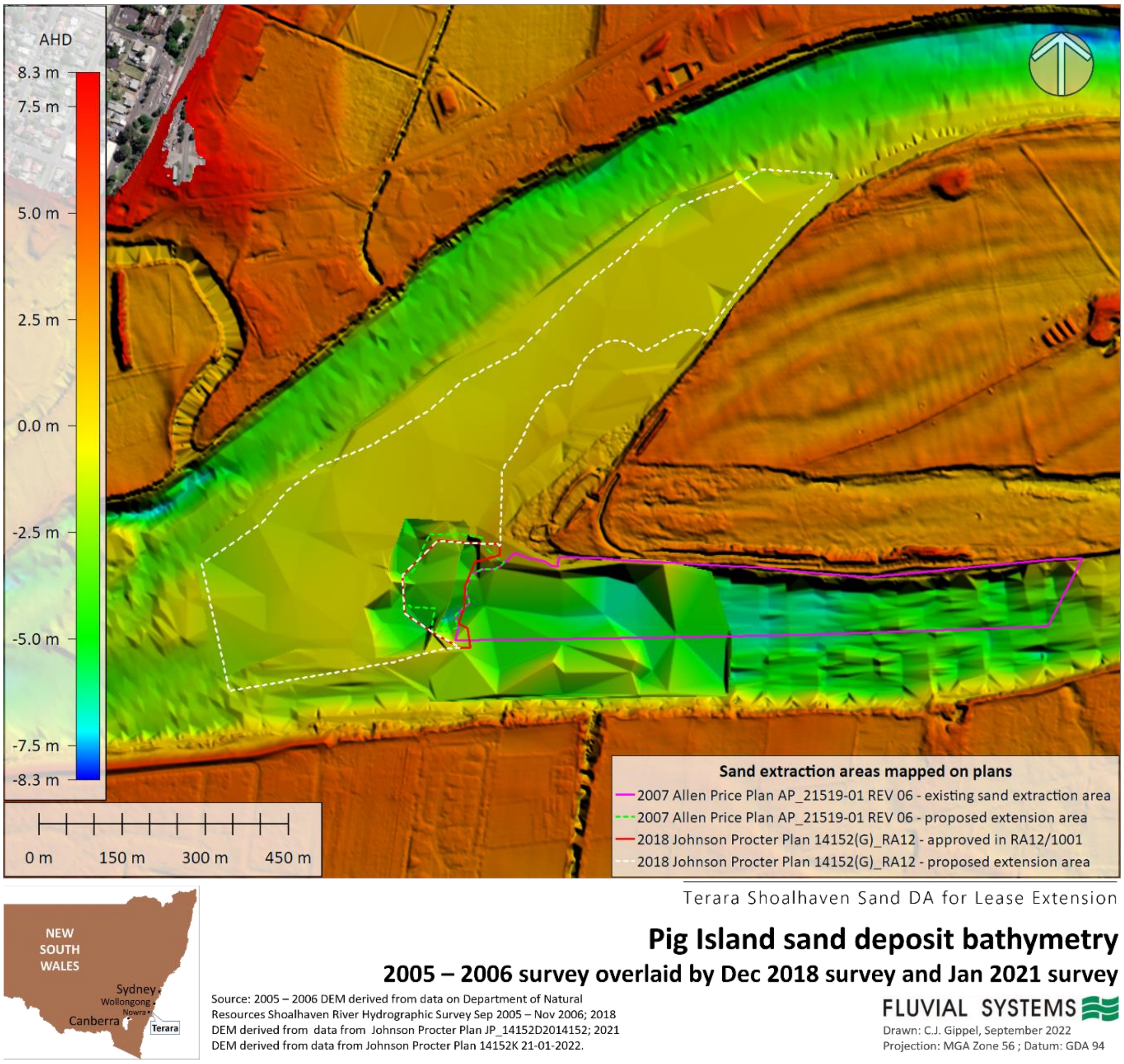


Figure 27. Bathymetry of Pig Island sand deposit derived from hydrographic survey conducted over the period Sep 2005 to Nov 2006 overlaid with data from the Dec 2018 survey and the Jan 2021 survey.

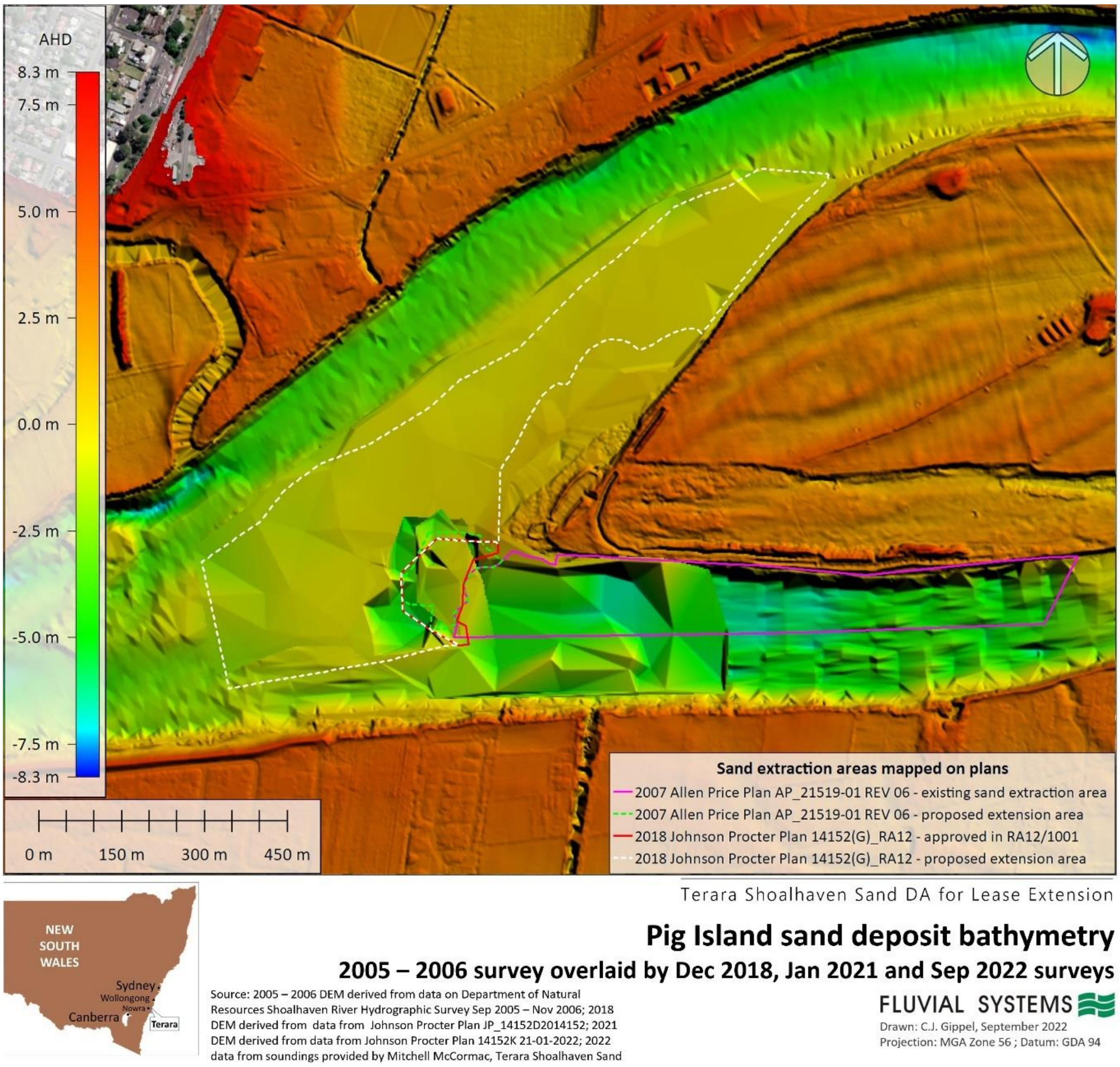


Figure 28. Bathymetry of Pig Island sand deposit derived from hydrographic survey conducted over the period Sep 2005 to Nov 2006 overlaid with data from the Dec 2018, Jan 2021 and Sep 2022 surveys.

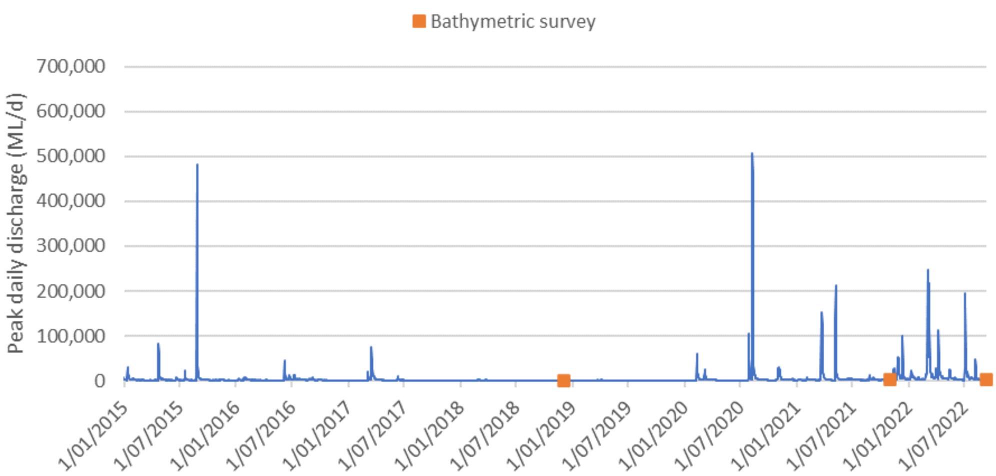


Figure 29. Peak daily discharge at 215216 – Shoalhaven River at Grassy Gully No. 2, 1 Jan 2015 to 16 Sep 2022.

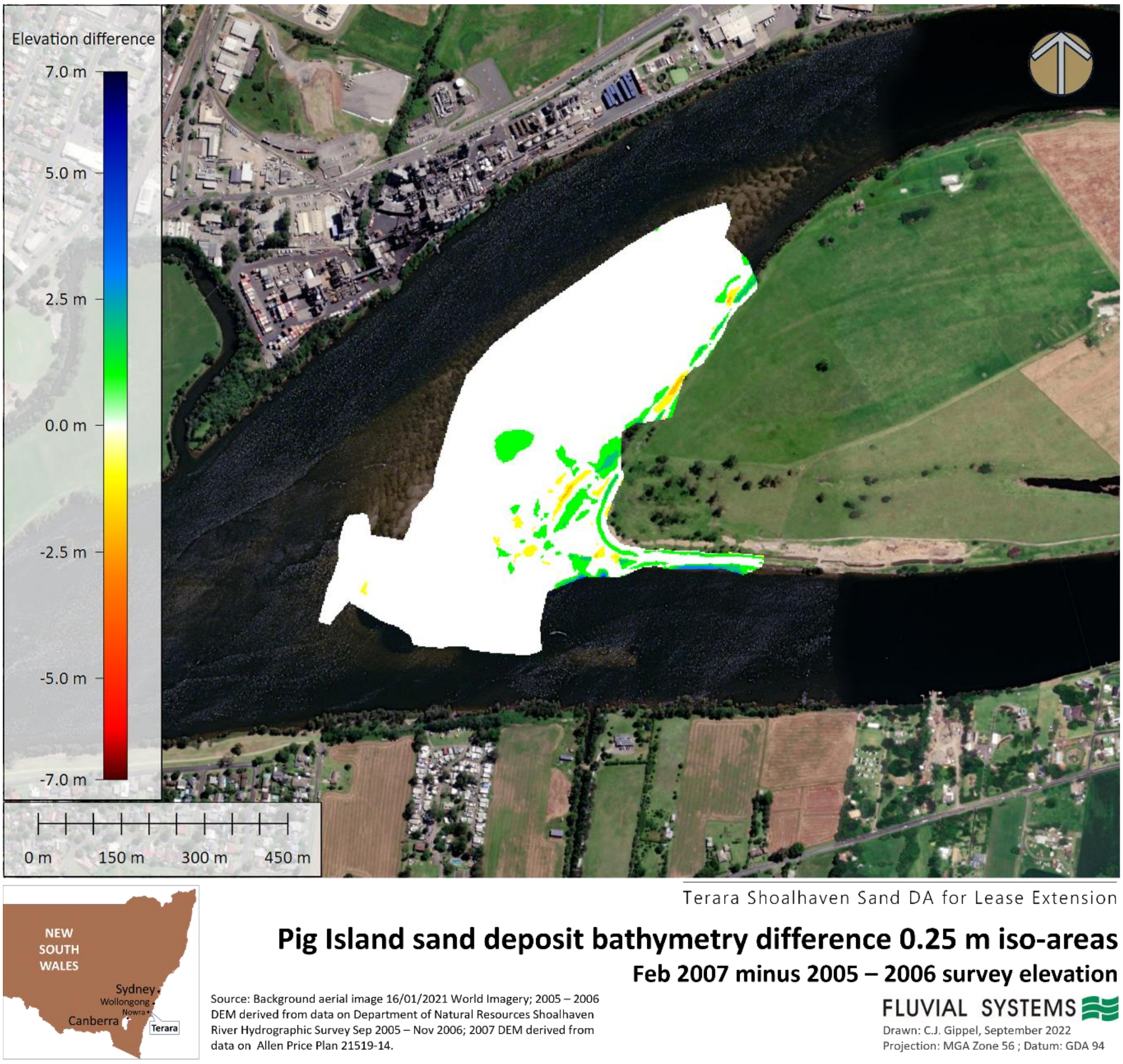


Figure 30. Difference in bed elevations surveyed in Feb 2007 and 2005 – 2006.

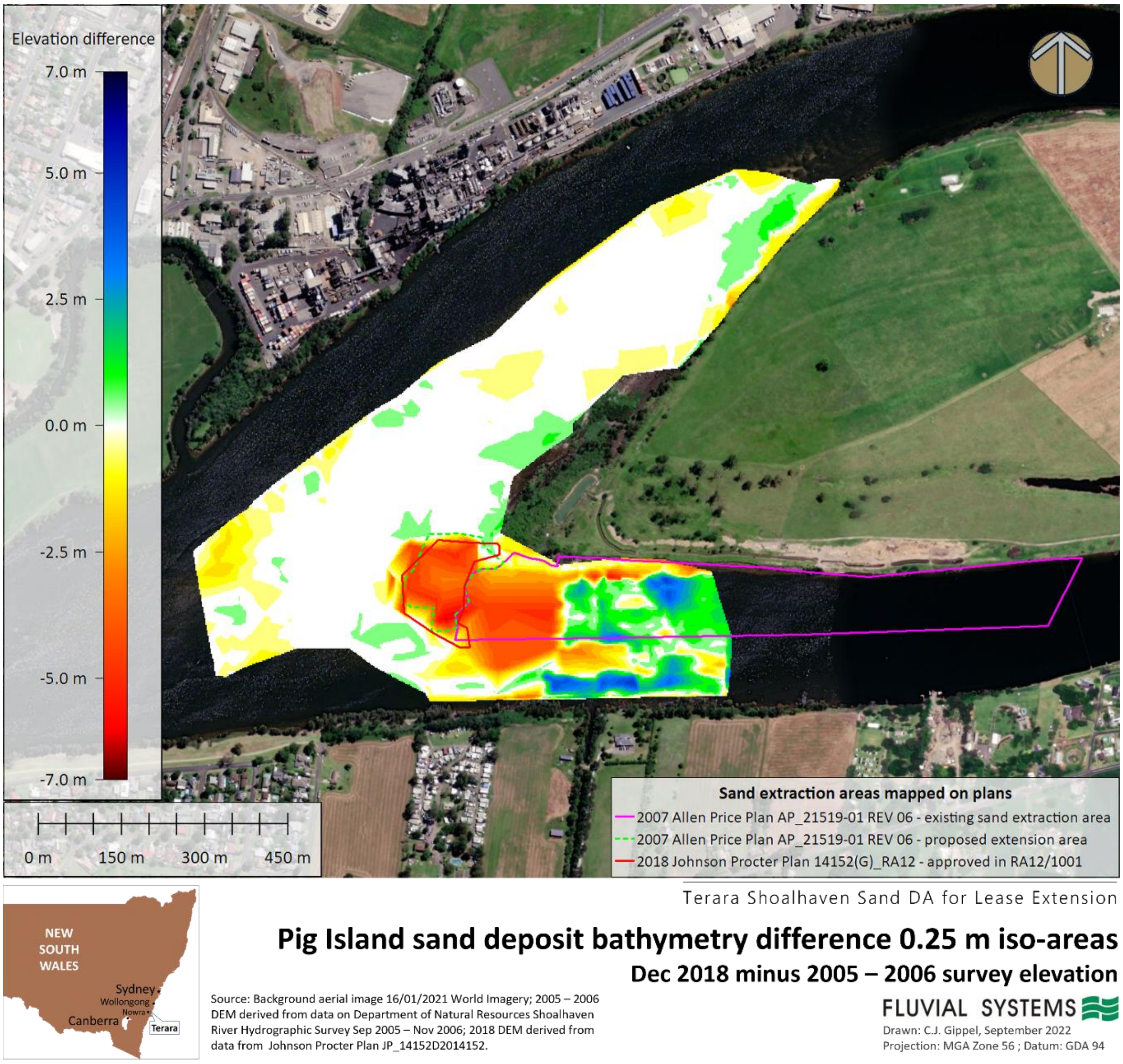


Figure 31. Difference in bed elevations surveyed in Dec 2018 and 2005 – 2006.

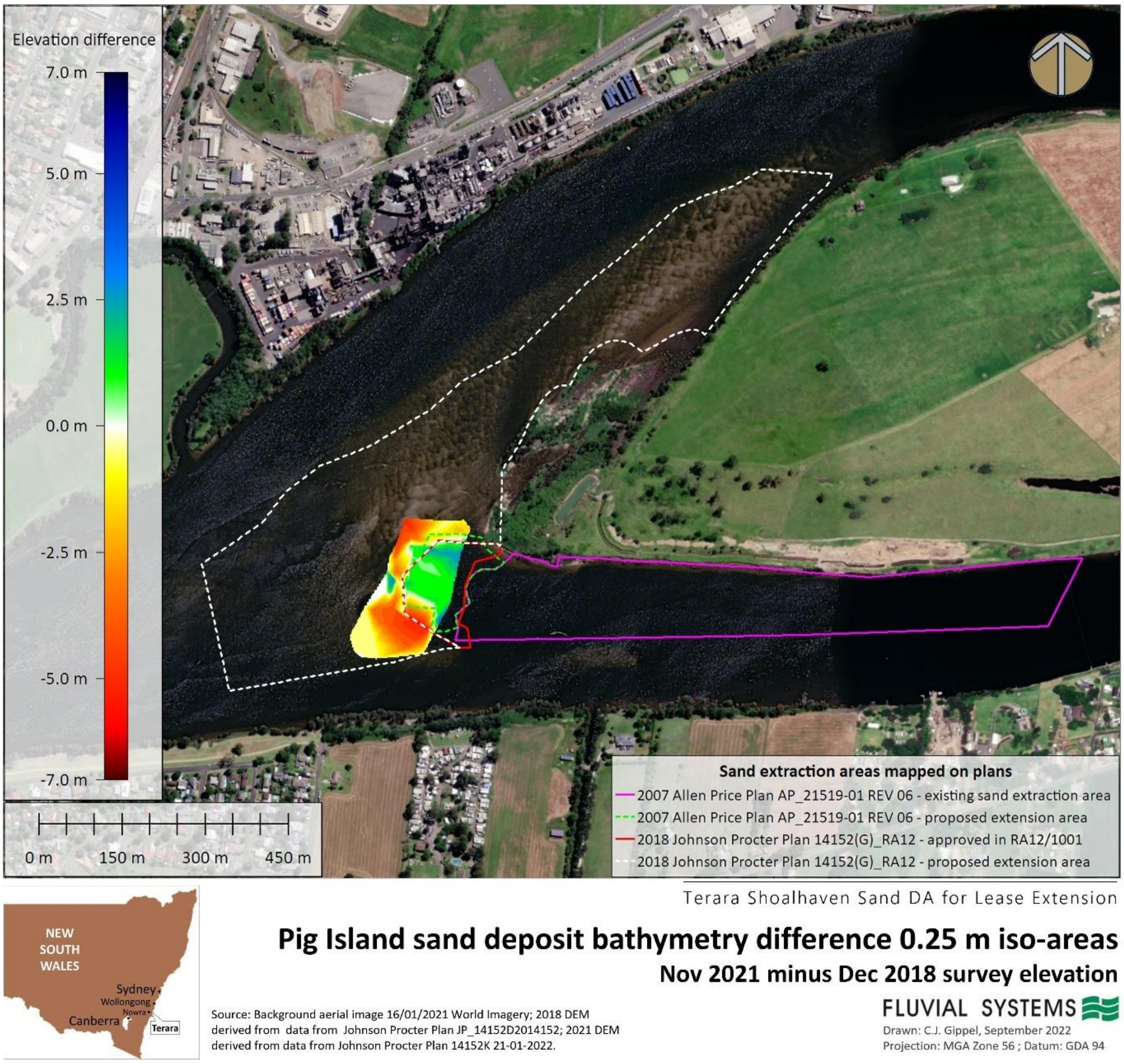


Figure 32. Difference in bed elevations surveyed in Nov 2021 and Dec 2018.

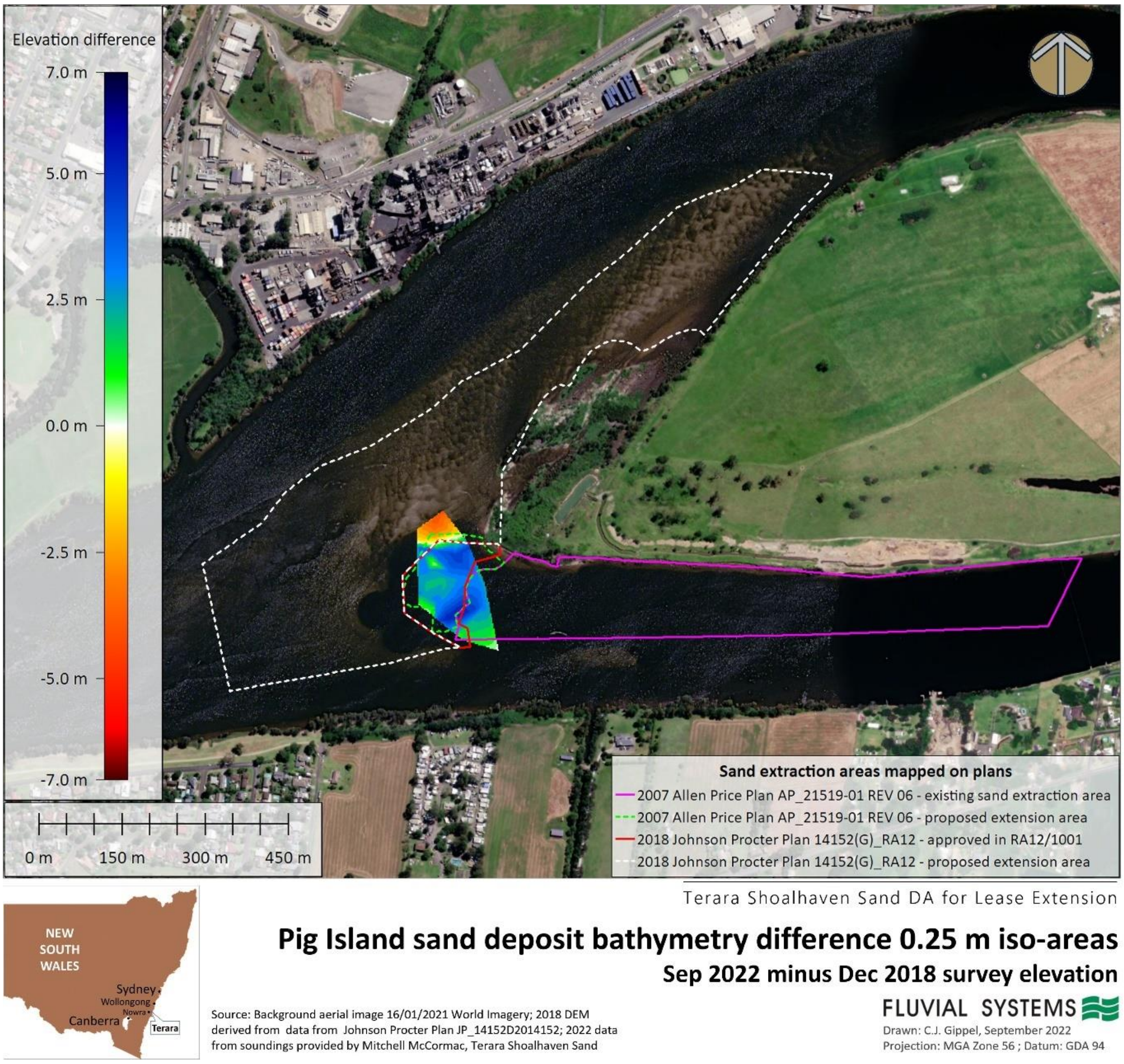


Figure 33. Difference in bed elevations surveyed in Sep 2022 and Dec 2018.

5.3 Risk of erosion of stock mounds

The modelled velocity distributions are provided in the Appendix (Section 8.2) for the existing topography scenario (Figure 36, Figure 37, Figure 38, Figure 39 and Figure 40), and for the developed topography scenario (Figure 41, Figure 42, Figure 43, Figure 44 and Figure 45).

The modelled data indicate at least one of the existing mounds maintains some land above flood levels up to the 1 in 500 yr flood event, while at least one of the proposed mounds maintains some land above flood levels up to the 1 in 200 yr flood event.

The threshold for erosion risk of the mounds is 2 m/s, assuming the mounds have a complete coverage of grass or other soil-binding vegetation.

Under the existing and developed scenarios, the two existing mounds are exposed to velocities 3 – 5 m/s for the PMF event (Figure 34), which would likely result in scour of the mounds. However, under these conditions the entire Pig Island would be subject to high risk of major morphological modification. For smaller events, up to the 1 in 500 yr event, the existing mounds would generally not be at risk of scour (Figure 34). This result is consistent with the historical stability of the mounds. The exception was the central mound under developed topography conditions (i.e., with the 3 proposed mounds developed) for 1 in 10 yr and 1 in 100 yr flood events, where the maximum velocity was predicted to be 2.3 m/s and 2.5 m/s respectively (Figure 34). Under this scenario, the velocity around the existing central mound was influenced by its proximity to the proposed central mound. Under the amended positioning of the proposed mounds, the existing central mound would not be in close proximity to the new central mound, so exceedance of the 2 m/s threshold would be less likely.

Under the developed scenario, the side and top surfaces of the three proposed mounds are exposed to velocities 2.1 – 5.2 m/s for the PMF event (Figure 35), which would likely result in scour of the mounds. However, as for the existing mounds, under these conditions the entire Pig Island would be subject to high risk of major morphological modification. For smaller events, the proposed mounds would not be at risk of scour (Figure 35).

On the basis of the results of hydraulic modelling of the proposed stock mounds, which suggested negligible to low risk of fluvial erosion, the risk of potential water quality impacts downstream associated with erosion of stock mounds was considered negligible. The risk of erosion of the stock mounds due to local rainfall impact was considered negligible under conditions of full grass cover. Thus, water quality sampling or modelling was not recommended as a monitoring or mitigation measure. The recommended mitigation measure is to maintain healthy and complete vegetation cover on the sides and top surface of the mounds. In areas where good grass cover cannot be maintained, alternative erosion control measures should be employed.

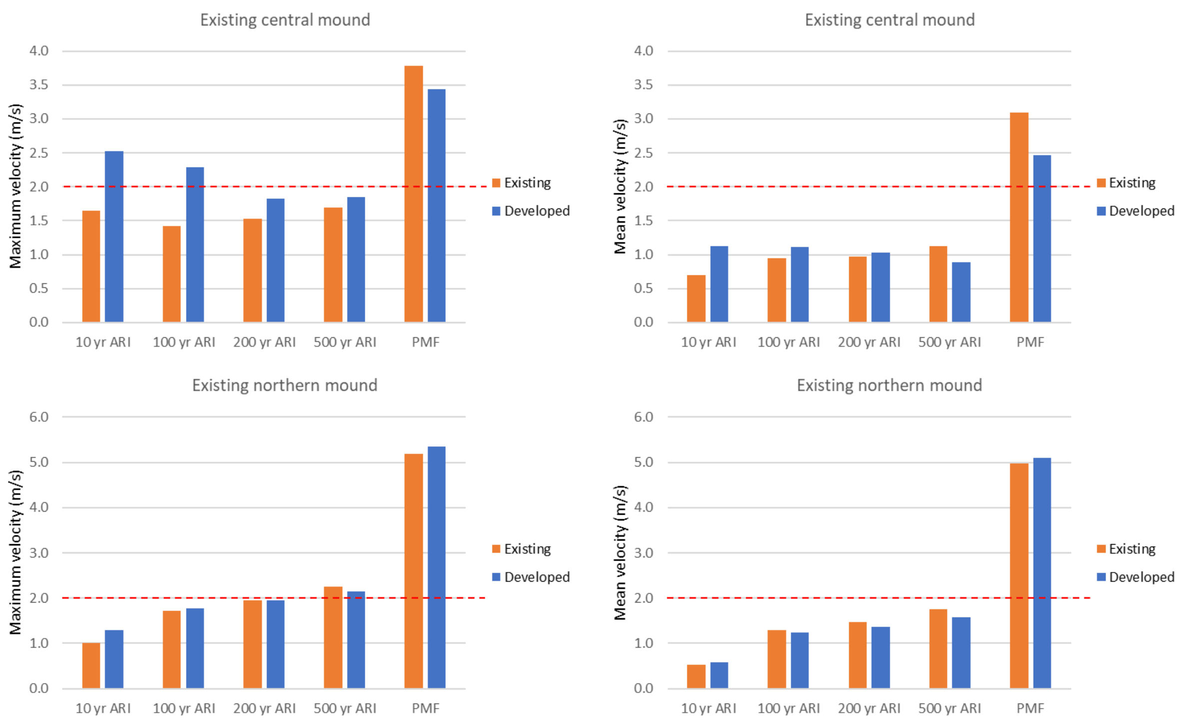


Figure 34. Comparison of modelled maximum and mean velocity around the vicinity of the existing stock mounds on Pig Island for the existing mound topography and developed proposed mound topography scenarios. The threshold for risk of fluvial scour of the mounds is 2 m/s.

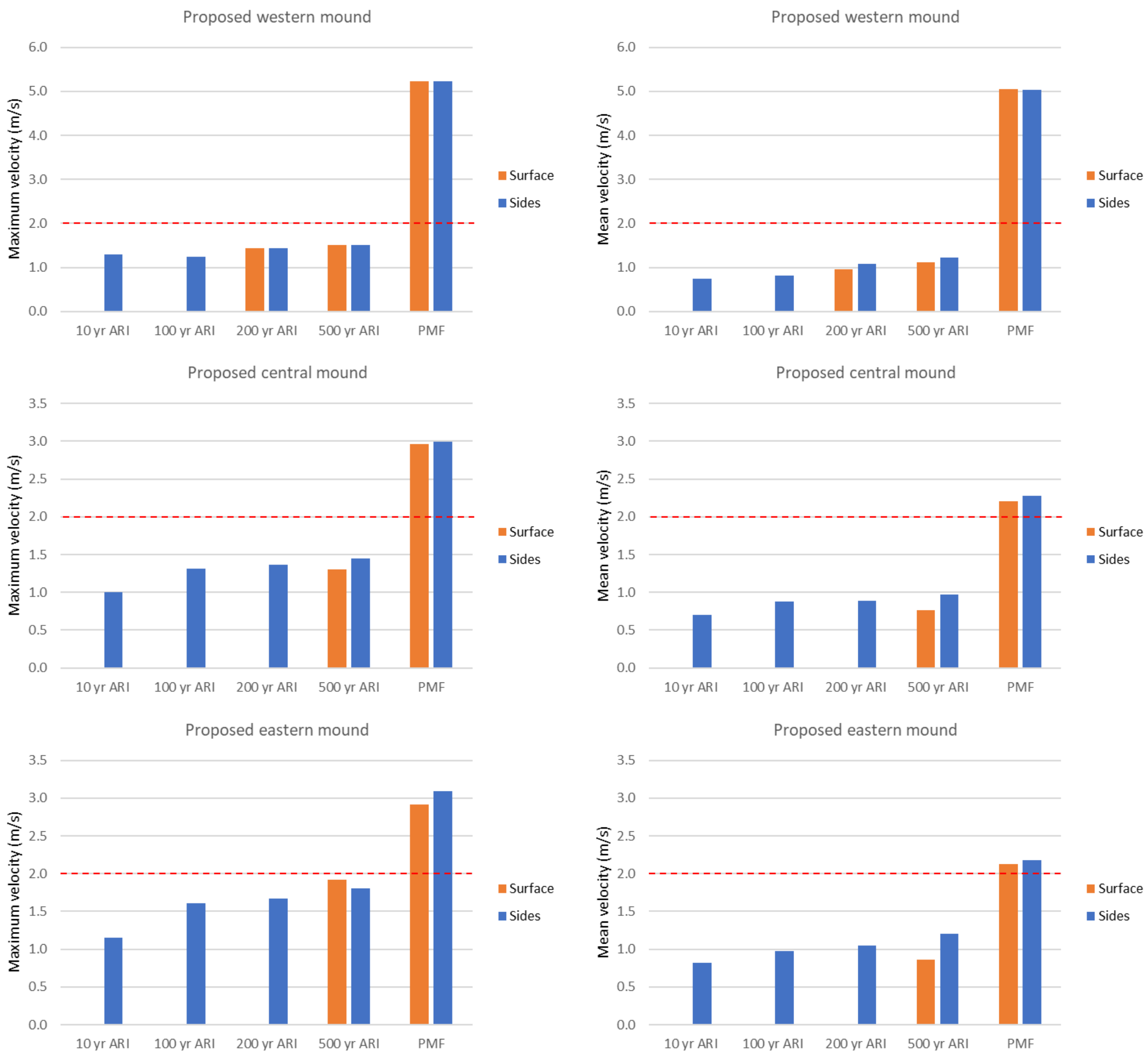


Figure 35. Comparison of modelled maximum and mean velocity at the sides and top surface of the proposed stock mounds on Pig Island for the developed proposed mound topography scenarios. The threshold for risk of fluvial scour of the mounds is 2 m/s.

5.4 Assessment of the potential long-term impacts from dredging

5.4.1 Long term impacts to Shoalhaven beaches and beaches further north

On the basis of the available data, Carvalho (2018) and Carvalho and Woodroffe (2021), estimated that a total of 1,020,000 m^3 of bed sediment was deposited in the Shoalhaven River estuarine channel between 1981 and 2006, equivalent to an average deposition rate of 40,800 m^3/yr. Carvalho's (2018) sediment budget suggests that approximately 61% of this volume of sand was extracted by the operations at Pig Island. In the hypothetical absence of sand extraction operations, it is likely that a proportion of this sand would have been transported to beaches further north of Crookhaven Heads. It would be speculative to assume that the entire volume of sand would be transported to the beaches, as some or all of that sand might have deposited within the estuarine channel. However, it is reasonable to assume that sand extraction activities likely deny supply of some volume of sediment to beaches. The impact of sand extraction compounds the impact on beach sediment supply of trapping of sediment by Tallowa Dam.

At the present time it appears that sand supplied from the reduced catchment area downstream of the dam, and from within the river channel itself, has been sufficient to maintain supply of a quantity of sand to the beaches. It cannot be assumed that this is sustainable in the long-term, as the current transport of sand to the estuary could be depleting stored sand within the catchment and channel. These comments are with respect to average hydrologic conditions. In the event of a very large flood, a pulse of sand could be delivered to the beaches over a short time period.

5.4.2 Long-term impacts of training of the Shoalhaven River on tidal regimes

A seawall was constructed on the northern side of Crookhaven Heads between 1902 and 1908. Between 1909 and 1912 this seawall was extended to form the present training wall (Woodroffe et al., 2022). Nichol (1991) noted that engineering works, such as breakwater construction and dredging lead to changes in the tidal regime in estuaries, typically increased tidal range and the strength of tidal currents. This can potentially result in removal of large volumes of tidal delta sands from an estuary.

Given that the training works on the Shoalhaven River have been in place for over a century, their impact on the geomorphology of the estuary would be incorporated in the results of the investigations undertaken to date. It would be very difficult to separate the impact of river training works from other major factors that have influenced geomorphic processes and forms in the estuary, namely, cutting Berrys Canal, hard lining banks, dredging for navigation, flood sequences, construction of Tallowa Dam, and sand extraction at Pig Island. To date, no research has attempted to separate the impact of river training on tidal ranges and consequent impacts on geomorphic process and forms in the estuary, so it would be highly speculative to suggest here what those impacts might be and how they would interact with the proposed sand extraction.

5.4.3 Long-term impacts of sea level rise

Using Comerong Island as a case study, Al-Nasrawi et al. (2018) applied future sea-level rise of Intergovernmental Panel on Climate Change (IPCC) hydro-scenarios to assess the impact on the ecological and geomorphic aspects of coastal ecosystems in terms of risk assessment and sustainability. The results suggested that through inundation alone, Comerong Island would lose about 18% of its wetlands and associated habitats by 2050, and approximately 43% of the island would be lost by 2100.

Sea level rise would likely increase the tidal ranges in the estuary and may therefore change the impact of dredging operations on surrounding channels and banks. As noted above, to date, no research has attempted to quantify the impact of river training on tidal ranges and consequent impacts on geomorphic process and forms in the estuary, so it would be highly speculative to suggest here what those impacts might be and how they would interact with the proposed sand extraction.

6 Guide to information supplied in this report

Table 2 provides a guide to the location of the requested information supplied in this report.

Table 2. Guide to location of the requested information supplied in this report

No.	Description of information required	Location/ comment
a)	A description of the formation of the estuary (geomorphology) at and downstream of the dredging operations, including the formation of Pig Island (e.g., during the Holocene period).	3.1, 3.2
b)	Use of historical and other data (such as historical photographs, historical river surveys, and presumably, survey data presumably collected by the dredging operators over time in association with their past EPA licence, academic research papers such as by RC Carvalho of University of Wollongong, for example) to provide an assessment of:	See 3 and 4, and 2 for method
b)i	Changes in the location and depth of the channels and banks at and downstream of the dredging operations, from prior to dredging to present day.	3.6, 3.7, 4.1
b)ii	The rate of infilling of deep dredge holes, and infilling of the dredge area more broadly, including recent flood events, over the last 20+ years.	4.2
b)iii	The impact of deep dredge holes on nearby channels (in terms of channel location and depth).	No specific data available
b)iv	An assessment of the sedimentological data (such as the samples collected by the dredging operators in accordance with their EPA licence, and academic research papers as noted above), to clearly describe:	3.8
b)iv●	The volume of sediment removed during dredging (annually).	3.3
b)iv●	For the dredged material, the proportion of sand extracted versus the proportion of material returned to the stock mounds and/or the river, and the grain size(s) of returned material.	3.3
c)	Description of the depth of dredge operations. This information is essential in determining the impact of dredge batters and buffer zones on marine and riparian vegetation.	Not within scope
d)	A detailed assessment of the visual impacts of the proposed development, noting that dredging operations are already visible from Nowra Bridge and surrounds.	Not within scope
e)	The following further information is required to be provided in relation to the stock mounds on Pig Island:	See 4.3
e)i	An assessment of the potential for stockpiled fines being remobilised into the water column by rain / floodwaters, and potential water quality impacts downstream associated with this (including any water quality sampling or modelling).	4.3
e)ii	An assessment of the past performance of mounds and their likely response during floods, including the likelihood of the mounds being washed away versus the impact to flood levels in the unlikely event that the stock mounds remain stable during a major flood.	4.3
f)	Given that the sand resource is finite and is being removed permanently from the sediment system, and that past and future approvals are sought for 20 to 50 years or more, assessment of the potential long-term impacts from dredging is sought, including:	See 4.4
f)i	Long term impacts to Shoalhaven beaches and beaches further north given that a substantial portion of sand sized material is being removed by dredging rather than being supplied to the coast (noting that the Shoalhaven/Crookhaven River is one of only 2 rivers in NSW that supplies sand sized material to the coast). This assessment needs also to consider the combined impact of the dam built upstream in 1976 that will already have contributed to a reduced sand supply to the estuary and coast.	3.7, 4.4.1
f)ii	The long-term changes in the geomorphology of the lower estuary due to the increase in tidal regimes from training of the Shoalhaven River and how this may have interacted or will interact with dredging impacts.	4.4.2
f)iii	Future long-term impacts of sea level rise which is expected to increase the tidal ranges in the estuary and may therefore change the impact of dredging operations on surrounding channels and banks.	4.4.3

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8 Appendices

8.1 Account of 1870 flood in Empire 1870

The following is a transcript of the article published in Empire (1870), written by the correspondent on 6 May 1870, describing impact of the 1870 flood on the Terara area.

FLOODS DEVASTATIONS AT SHOALHAVEN.

[FROM OUR CORRESPONDENT.]

May 6

Accounts from all parts of the district respecting the flood confirms the opinion that it is the highest ever known within the memory of the oldest resident. At Burria, Mr. Thompson's house is hanging over the bank; his smithy was swept away. The Burria estate has suffered greatly: so has Erle, the property of Mr. Biddulph; also Mr. Mackenzie's land at Bundanon. The land has been swept away by acres, wholesale in many parts. Along the Greenhill's estate, below Bomaderry Ferry, the bank has been cut away in places, and filled up in others. The river came in at the Bomaderry Ferry wharf, owing to the trustees cutting away the high bank according to a specification of the Government, and placing loose rabble stone against the cutting, which lasted a very short time. The roadway to the ferry ought to have been paved with stone, and the high bank not meddled with. I hope the Government will grant a sum to fill up the holes, and protect this part from the river, as it was an absurd thing to cut down the high bank.

At Terara the bank has been crumbling away for years, and the flood swept it away in acres. On reference to the plan of the Terra township, prepared by H. Morton, Esq, in 1860 where the chainage of all the lots is given from the river bank, I find the distance from Jones's store to the river three chains five links; it is now very little over a chain. From Isaacs's Hotel to the river, 307 links; it is now about thirty feet. From the Junction of East- and Langley streets to the river fifteen chains fifty-eight links, it is now about four chains. As far as East-street about from sixteen to eighteen acres of the township must have been swept away. The floods of 1860 swept away over twenty buildings from this part of the town of Terara with the loss of life. I ask is it just or humane on the part of the Government to erect any public building in places of this kind, so as to encourage a population to be drowned like dogs? It is time the Government showed an example of only patronizing with their public buildings sites above the reach of floods. If this is done much misery will be prevented as it is well known that business people will follow public buildings, and many have sacrificed their lives in consequence. What a mercy that no person was in the post or telegraph office when it was hurled to destruction. Where Goulding's house and barn stood about thirty acres of land have been swept away. In the flood of 1860 over thirty acres must have been sweat away likewise, together with Mr. McKenzie's house and barn. The depth of water was over 4 feet in Isaac's Hotel and further up the street at Kemp's new stone building, opposite the Commercial Bank, the height of the water could not have been less than 8 feet in the roadway. There is a canal left between Hyams' hotel and Jones' store. According to appearance, the next flood must cut in between Hyams' hotel and the Commercial Bank-time will tell. Holmes's house is still hanging over the bank; it has been cleared of its contents, as also Mrs. Isaacs' hotel. The house adjoining Holmes is being taken down, and conveyed to Nowra by the owner. Other parties in Terara and Numbaa have made arrangements to remove into Nowra.

Mr. O'Connor, the constable has shifted to Greenhills. The back and end of his Terara his house is washed away, and all his furniture swept by the current, except, I believe, a bedstead and a few other things. This will be a great loss to him.

Pollick will be a great loser, Mr. McGarvy, and most of the people in this locality. Such a very high flood was not expected. When the people left their houses for the two storied buildings they left hurriedly, and only prepared for the small floods which we have been subjected to since 1860.

Had there been no high buildings in Terara what would have been the consequences. Many must have been drowned. As it is, all the largo buildings, such as Kemp's brick building and the Temperance hotel, were over two foot deep in water. Terara is so liable to floods, and such a violent current, that a person only risks his life to reside there. But I trust now the residents will open their eyes, and be duped no longer by these interested knaves who would sacrifice life after life to make the Terara township the centra of the district.

Immediately after the flood. Mr. Moss, at his own expense, sent a telegram to Kiama, addressed to the Colonial Secretary for relief for the washed away sufferers by the flood. Mr. Moss took the same steps after the flood of 1860, when the present gentleman was at the hood of the Government. At that time a large supply was sent to the district on the faith of Mr. Moss's letter. At the present time Mr. Moss was the only person here to take prompt stops to communicate with the Government for supplies. He oven sent a messenger to Mossvale, in fear the Kiama telegraph was interrupted. The supplies were sent to Greenwell Point. Mr. Moss managed to get them up by the Pearl, steamer, below Terara, where the Pearl grounded. He then sent boats to convey the provisions to Nowra Wharf, as It would have been unfair to land them at Terara. Ho got volunteer drays to shift the goods to the Court-house, and then he asked the band of magistrates and clergymen of the district to co-operate with him in distributing the provisions. On Tuesday last James Aldcorn, Esq., J.P., Michael Hyam, Esq., J.P., John Monaghan, Esq., J.P., Donald McLean. Esq., with the Rev. Mr. Davis, the Rev. Mr. Hough, the Rev. Father Cunningham, and Mr. Moss entertained and relieved about sixty applicants. The applications were not so numerous as was expected. A great number will require clothing, some completely swept away with large families. Mr. Moss stated that he would report progress to the Colonial Secretary, and ask for a further sum for clothing. This ls very necessary and ought to be allowed.

The people, greatly Interested In Terara, fearful of the Terara residents removing to Nowra, have, or Intend to open a township on the high land at Boston at the back of Terara, about a mile. This is too far from the river. Nowra Is on the river, and all the principal roads pass through it; besides, it is connected with the north side of the river, where there is a great population. Boston is away from all the main roads and river traffic, and will not take.

The Coolangatta steamer Is still high and dry, alongside the building in course of erection for the School of Arts. It is the duty of the Government I think, to stop further progress with this work. Those Interested in Terara will never do so, until all the town is washed away, and everyone is drowned, they are so infatuated with the rising prospects of the future capital of Shoalhaven. God help them. They have many lives to answer for through inducing poor people to settle here. The Bomaderry punt Is high and dry, and the Pearl, steamer, likewise. This is a sad state of things.

8.2 Flood maps of Pig Island

The following are flood maps produced from hydraulic data modelled using TUFLOW at 50 × 50 m cells, provided by Martens & Associates Pty Ltd.

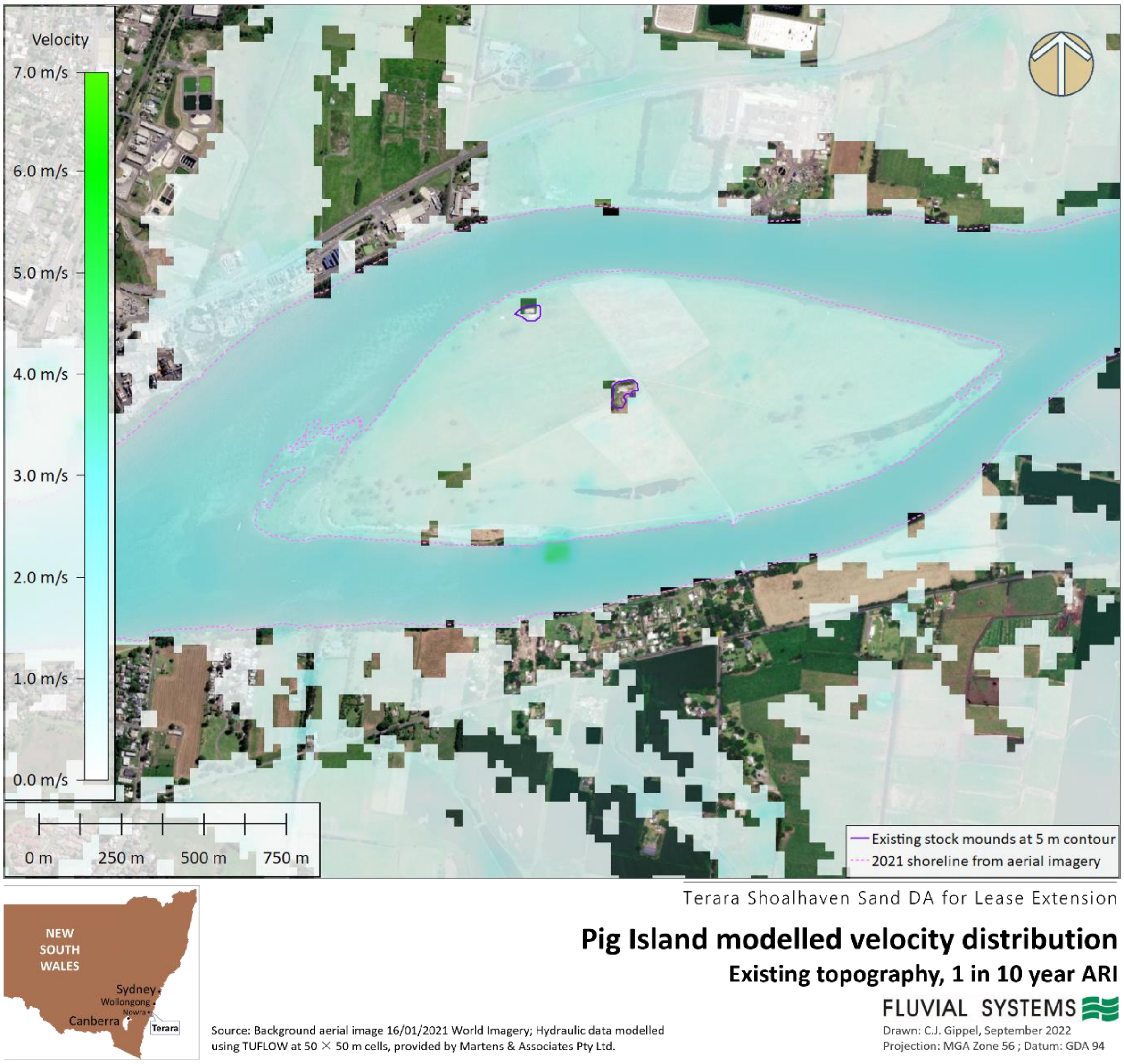

Figure 36. Modelled velocity Pig Island area for existing topography, 1 in 10 year ARI.

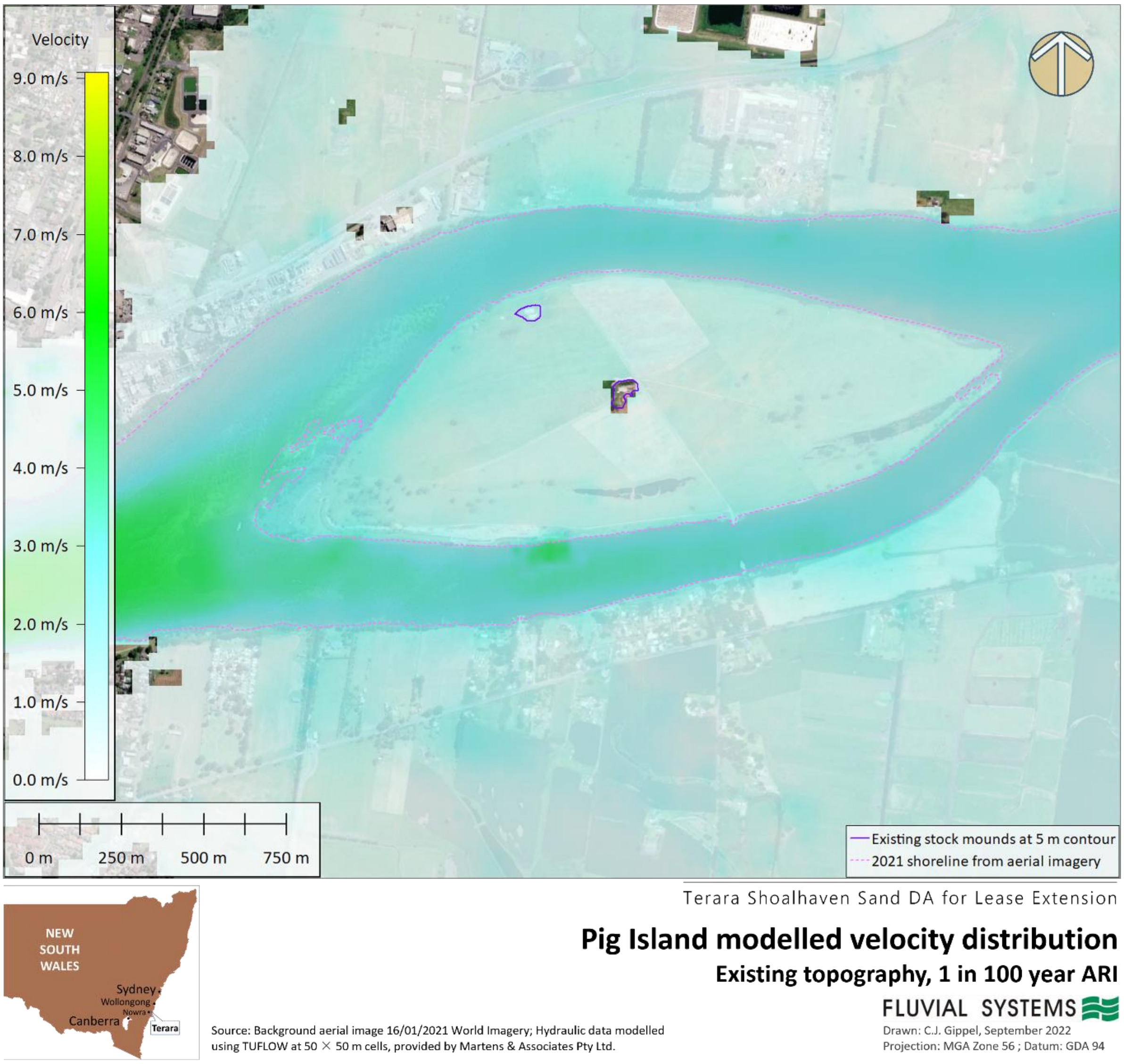

Figure 37. Modelled velocity Pig Island area for existing topography, 1 in 100 year ARI.

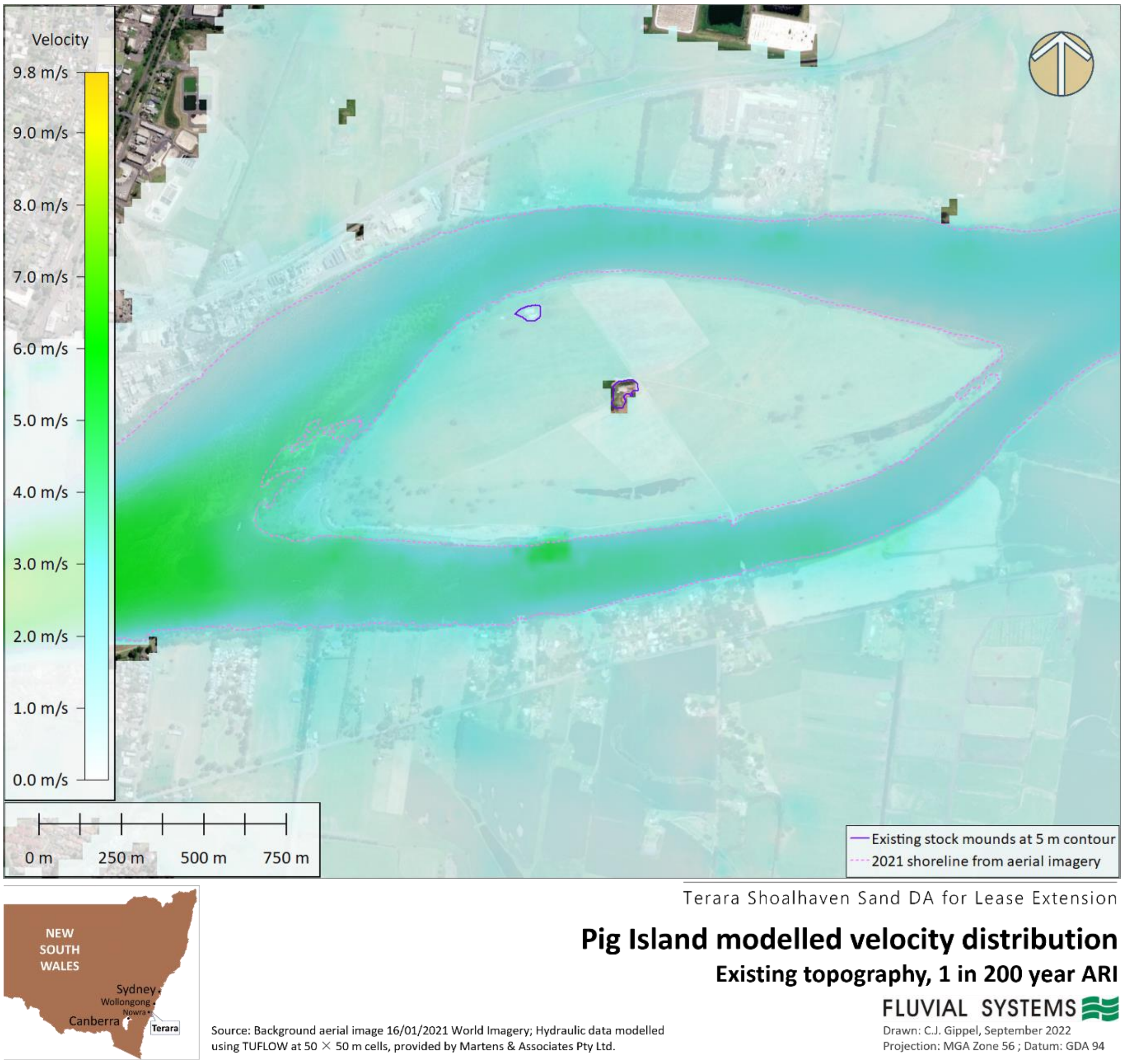

Figure 38. Modelled velocity Pig Island area for existing topography, 1 in 200 year ARI.

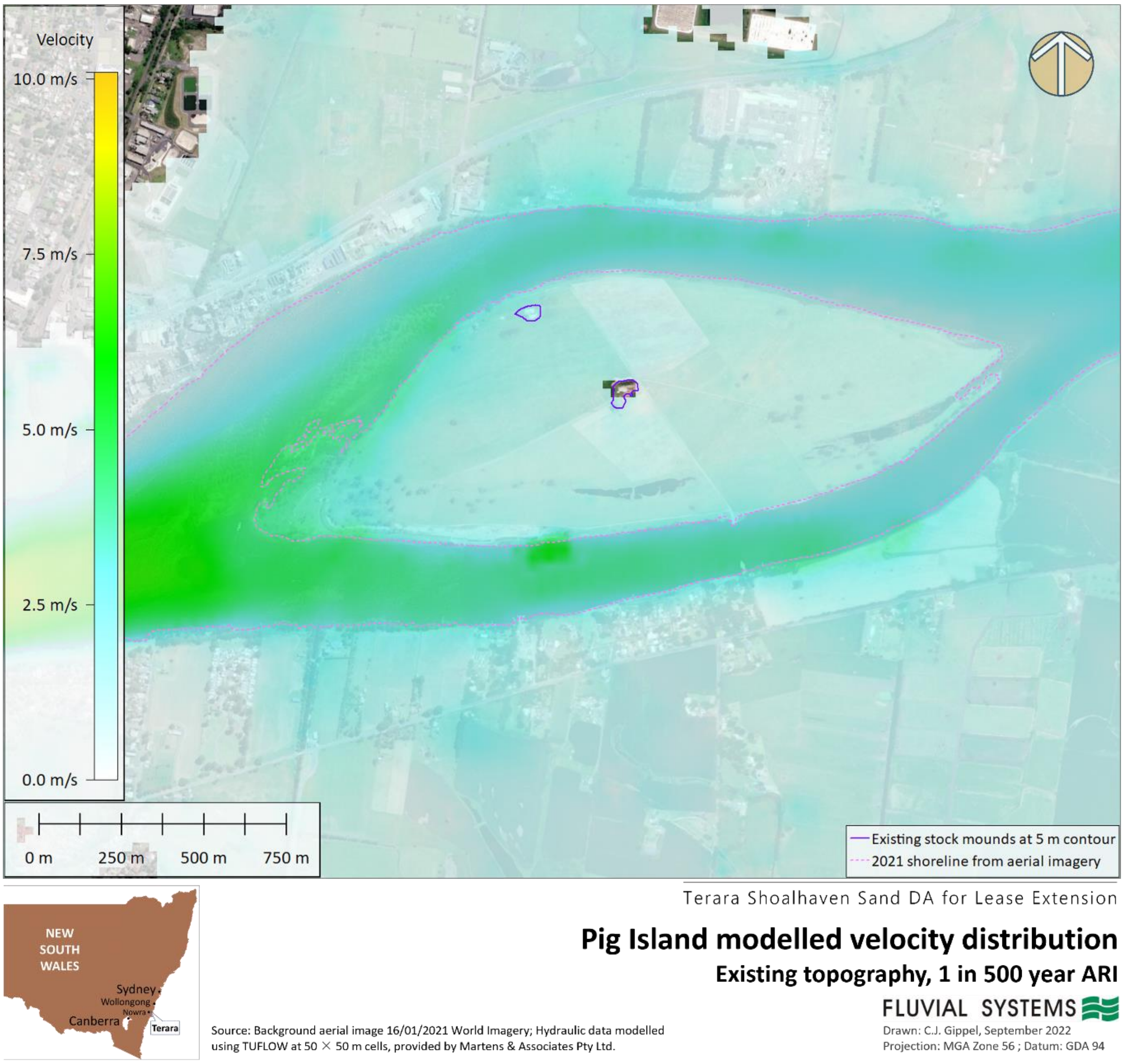

Figure 39. Modelled velocity Pig Island area for existing topography, 1 in 500 year ARI.

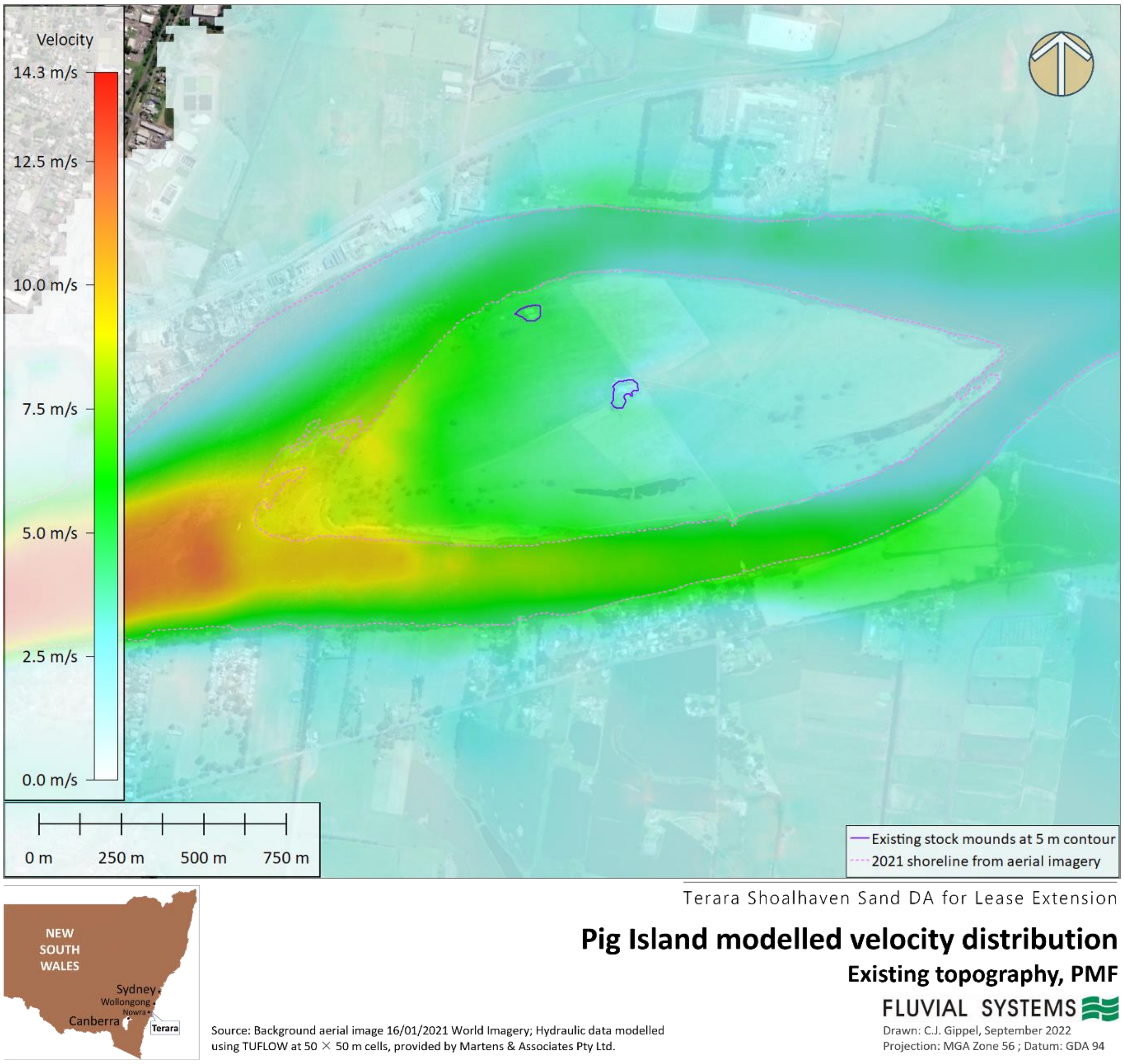

Figure 40. Modelled velocity Pig Island area for existing topography, PMF.

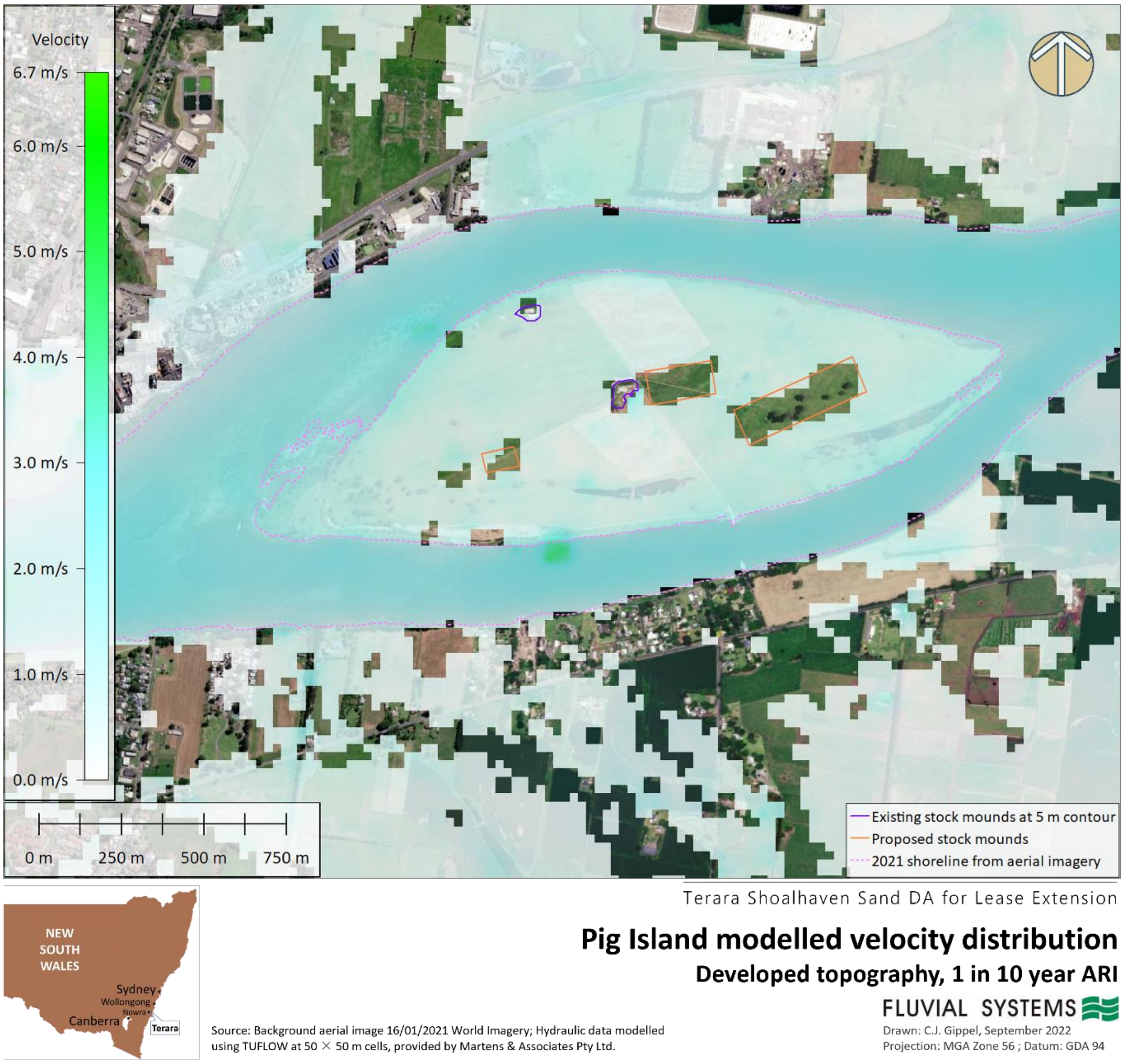

Figure 41. Modelled velocity Pig Island area for developed topography with proposed stock mounds, 1 in 10 year ARI.

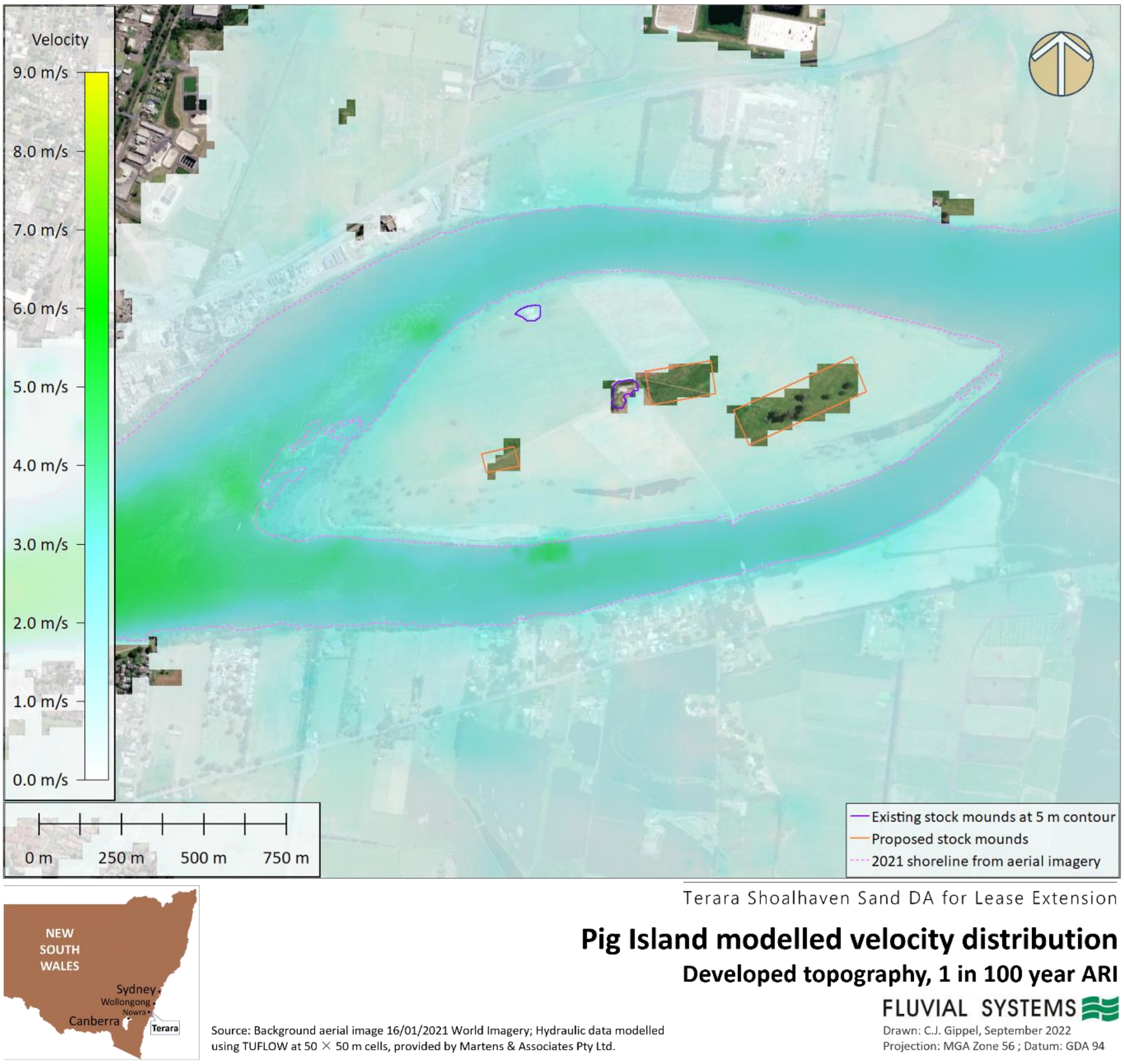

Figure 42. Modelled velocity Pig Island area for developed topography with proposed stock mounds, 1 in 100 year ARI.

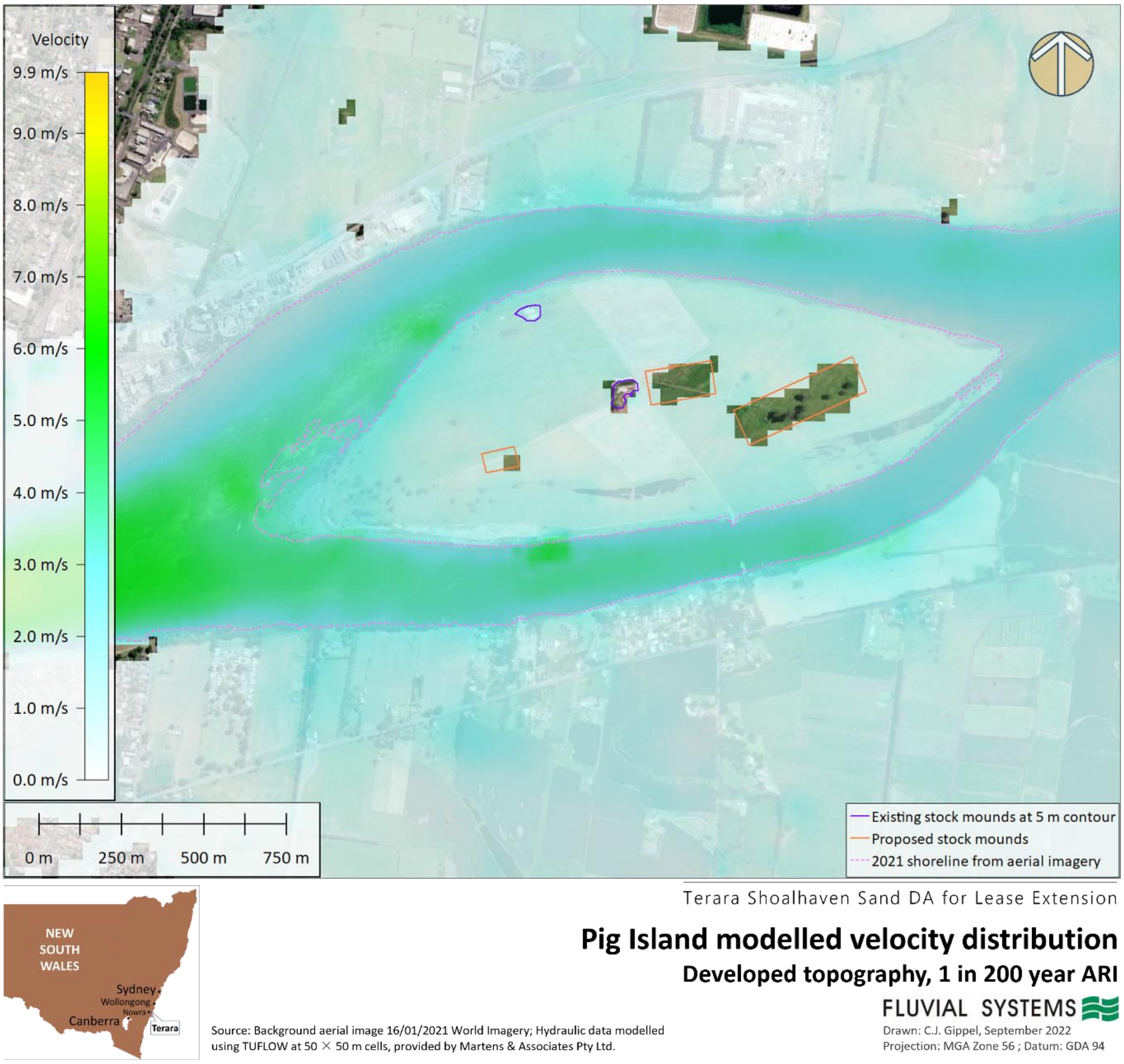

Figure 43. Modelled velocity Pig Island area for developed topography with proposed stock mounds, 1 in 200 year ARI.

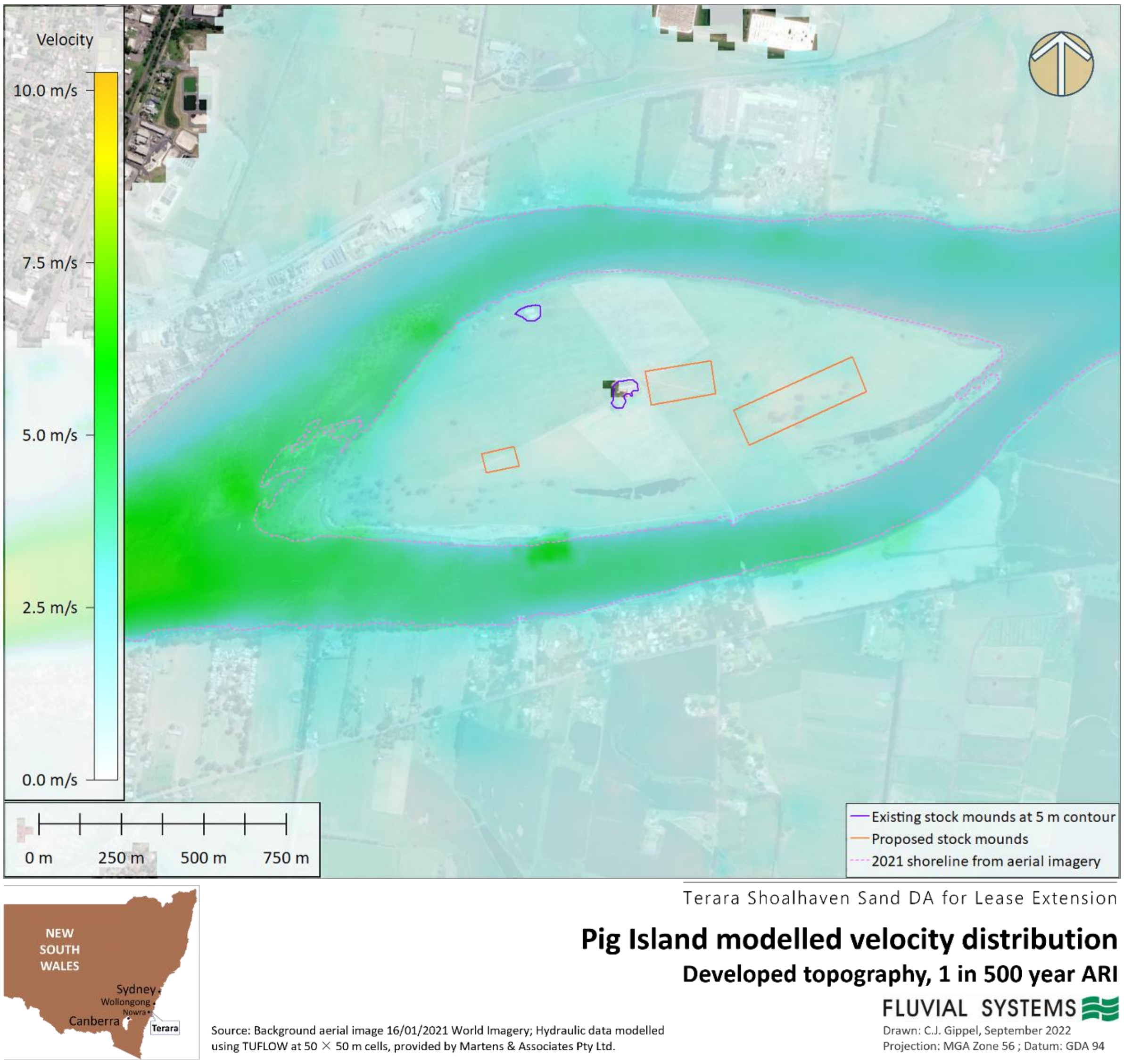

Figure 44. Modelled velocity Pig Island area for developed topography with proposed stock mounds, 1 in 500 year ARI.

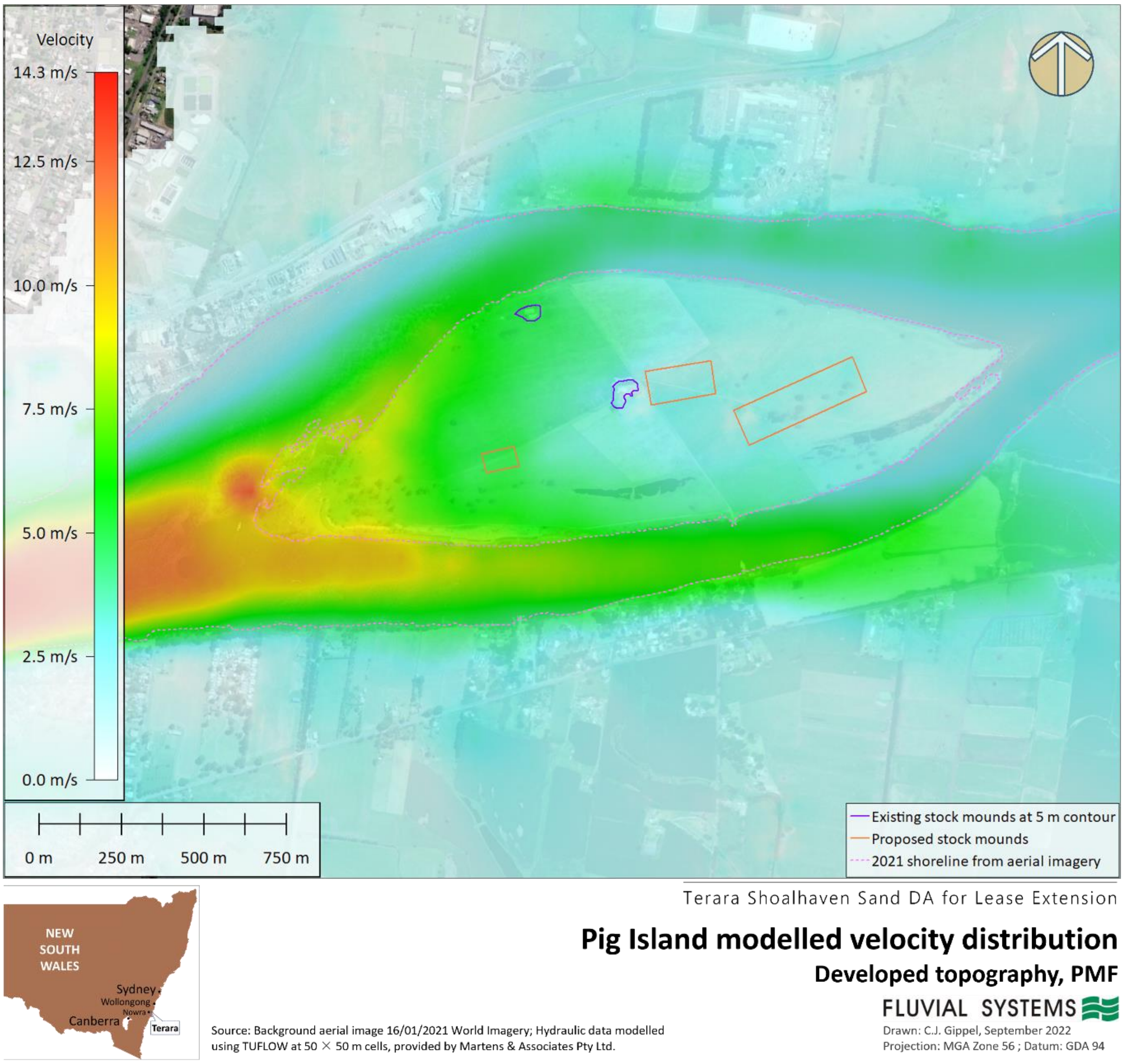

Figure 45. Modelled velocity Pig Island area for developed topography with proposed stock mounds, PMF.