



Estimation of bedload sedimentation rate in a paleo-drowned river-valley

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Abstract

Extensive, high-resolution seismic data were correlated with borehole, land use, and geological data to calculate the mass of genetically different sediment deposits in the Middle Harbour estuary in Sydney, Australia. Middle Harbour is a drowned-river valley located adjacent to the larger Sydney estuary. The estuary follows a well-defined sedimentation model featuring small fluvial bedload delta deposits in the upper reaches of the embayments, a deep, central extensive mud basin overlying transgressive basal accumulations and a large flood-tide delta at the entrance. Deposits of an estimated 5094 t of bedload, 21,143 t of suspended sediment and 5947 t of transgressive basal material located in the estuary provided average sediment accumulation rates of 0.68 t year⁻¹, 1.29 t year⁻¹, and 2.86 t year⁻¹, respectively. These rates, determined from measured accumulations, were surprisingly low and substantially smaller than modelled rates. However, low sediment accumulation rates for suspended material may be due to fine sediment escaping over the top of the marine tidal delta, which effectively traps all bedload material from exiting the Harbour. Results of this study indicate that Holocene bedload sedimentation in Middle Harbour was slow and regular until a rapid increase after urbanisation commenced in the catchment. Most pre-Holocene material was eroded from Middle Harbour during the Last Glacial period with sediment currently present in the estuary having been deposited since sea-level recovery.

Keywords Holocene · Modelling · Seismic · Stratigraphy · Geological history · Delta

1 Introduction

1.1 Basin erosion and bedload and suspended loads

Fluvial sediments derived from catchments are delivered to a receiving basin by the two processes of bedload and suspended load transport (Einstein, 1950). Suspended material transport takes place within the water column, whereas bedload transport occurs when sediment is transported along the bed of a river or stream during rainfall events, either by rolling, sliding, or saltating. The method of sediment

transport (suspended load, or bedload) is determined largely by particle weight, particle size/shape, and water velocity. Increased urbanisation is directly linked to increases in erosion (Fletcher et al., 2004), resulting in higher rates of runoff and sedimentation in highly urbanised estuaries. Sediment transport plays an important role in determining channel morphology and thus stream water velocity (Houshmand et al., 2014). Accurate fluvial modelling and quantification of sediment transported by runoff are necessary in forming an understanding of sediment accumulation rates in an estuarine system.

1.2 Bedload and suspended load models

Sediment transport in fluvial systems is well-researched with new models released regularly (De Vente et al., 2013), although results of various models are highly variable, particularly in systems where erosion levels are low (Nearing, 2006). However, bedload transport models remain relatively sparse and quantification of bedload materials is often not assessed directly, but rather determined as a percentage of

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the suspended load or taken as a fraction of all sediment greater than a certain size (Rustomji, 2006). This is typically done because measuring bedload is considered difficult, costly, labour intensive, and prone to causing geomorphological damage (Ergenzinger & de Jong, 2003). This knowledge gap results in an incomplete understanding of the overall erosion and sediment accumulation rates and leads to erroneous estimates of delivery to the receiving basin. A better understanding of erosion and sedimentation processes and rates may help explain why some estuaries, such as Sydney estuary, experience low sediment accumulation despite having a relatively large, urbanised catchment with reasonably high rainfall.

In a comparison of erosion and sedimentation models, De Vente et al. (2013) found the most relevant variables in accurately predicting erosion and sedimentation were land use and climate. In an assessment of 32 studies and 14 models, these authors found that all models assumed land cover did not change over time, leading to potential errors in the calculation of sediment yield. Laboratory-tested bedload models have previously been criticised due to tendencies not to account for natural features, such as a diverse range of sediment grain sizes (along with the accompanying variations in shear stress and form resistance), evolving channel morphology and varying spatial and temporal scales (Church & Ferguson, 2015), resulting in a large variation in modelled bedload yield (Bathurst, 2007; Nitsche et al., 2011). As a consequence, the number of field-tested bedload models are vastly outnumbered by laboratory-based evaluations (Recking et al., 2015). When assessed as a fraction of total load, an inverse relationship is found between transport rates of suspended load and bedload, with suspended load typically accounting for a higher portion of sediment load than bedload (Turowski et al., 2010). This dearth of knowledge relating to bedload transport and sediment accumulation rates requires additional information from well-designed field-based studies.

1.3 Objectives

The aim of the present research is to determine bedload masses and sediment accumulation rates in a complex estuarine system by investigating sediment deposits in the upper reaches of eight subcatchments in Middle Harbour, Sydney. Interpretation of sediment accumulation rates involved comparing actual sedimentation with estimated rates based on broad changes in climate and land use since the last sea level rise of ~7400 yBP.

This study is part of a larger investigation of sedimentation within the Sydney estuary. Middle Harbour was selected for the present study as the receiving basin is geographically and hydrologically isolated from the ocean and the main Sydney estuary by a major marine flood-tide delta.

Moreover, the topography, geology, and geomorphology are well known and are typical of other subcatchments on the northern side of Sydney estuary, e.g. Lane Cove, and smaller subestuaries, such as Mosman and Cremorne Bays.

1.4 Study area

The Sydney estuary is a drowned-river valley on the south-east coast of Australia (Fig. 1) and is approximately 30 km long with a catchment of approximately 500 km² (). Tides are semi-diurnal with a mean spring tidal range of 1.2 m (Harris et al., 1991) and salinity ranges from 18 PSU in the upper reaches to about 35 PSU at the harbour mouth (Hatje et al., 2001). Annual precipitation in the Sydney estuary catchment ranges from 800 to 1300 mm (Birch et al., 2010) and the area is highly urbanised (78%) with a population of over 5 million people. The waterway is heavily modified, with approximately 22% of the estuary reclaimed, predominantly upstream of the Sydney Harbour Bridge (Birch et al., 2009).

Sea-levels have been primarily 20–110 m below current levels over the past eustatic cycle (135,000 years) (Ribó et al., 2020), indicating that erosion has been more dominant than deposition within the Sydney estuary over this period (current maximum water depth is 39 m). Following the last glacial maximum approximately 21,500 years ago (Clark et al., 2009), sea level continued to rise until approximately 7400 years ago, when it reached a high stand of +1.5 m relative to present-day levels and the ocean then receded slowly to present-day levels 2000 years ago (Sloss et al., 2007). Aside from formation of flood-tide deltas and transgressive basal sediments, all Holocene sedimentation would need to have occurred after this sea-level recovery.

Unlike many other developed estuaries in Southeast Australia, Sydney estuary does not undergo any regular dredging in the primary navigation channel, with only minor maintenance dredging (McLoughlin, 2000). This apparently low sedimentation rate contrasts with previous studies, which have concluded that large masses of sediment are discharged to Sydney estuary annually (e.g. Liu, 1989; Taylor et al., 2004). This divergence of opinion will be further investigated in the current study which seeks to determine the masses of Holocene bedload sediment present in Middle Harbour and to use these data to model bedload sediment accumulation rates in this estuary.

Middle Harbour is a drowned-river valley connected at its entrance to the larger Sydney estuary, also a drowned-river valley (Roy et al., 2001). Middle Harbour is approximately 10 km in length with a catchment of 75 km², which accounts for approximately 17% of the total Sydney estuary catchment. The area receives an average annual rainfall of 1180 mm (Birch et al., 2010) and is primarily residential (34%) with a population of approximately 200,000 people.

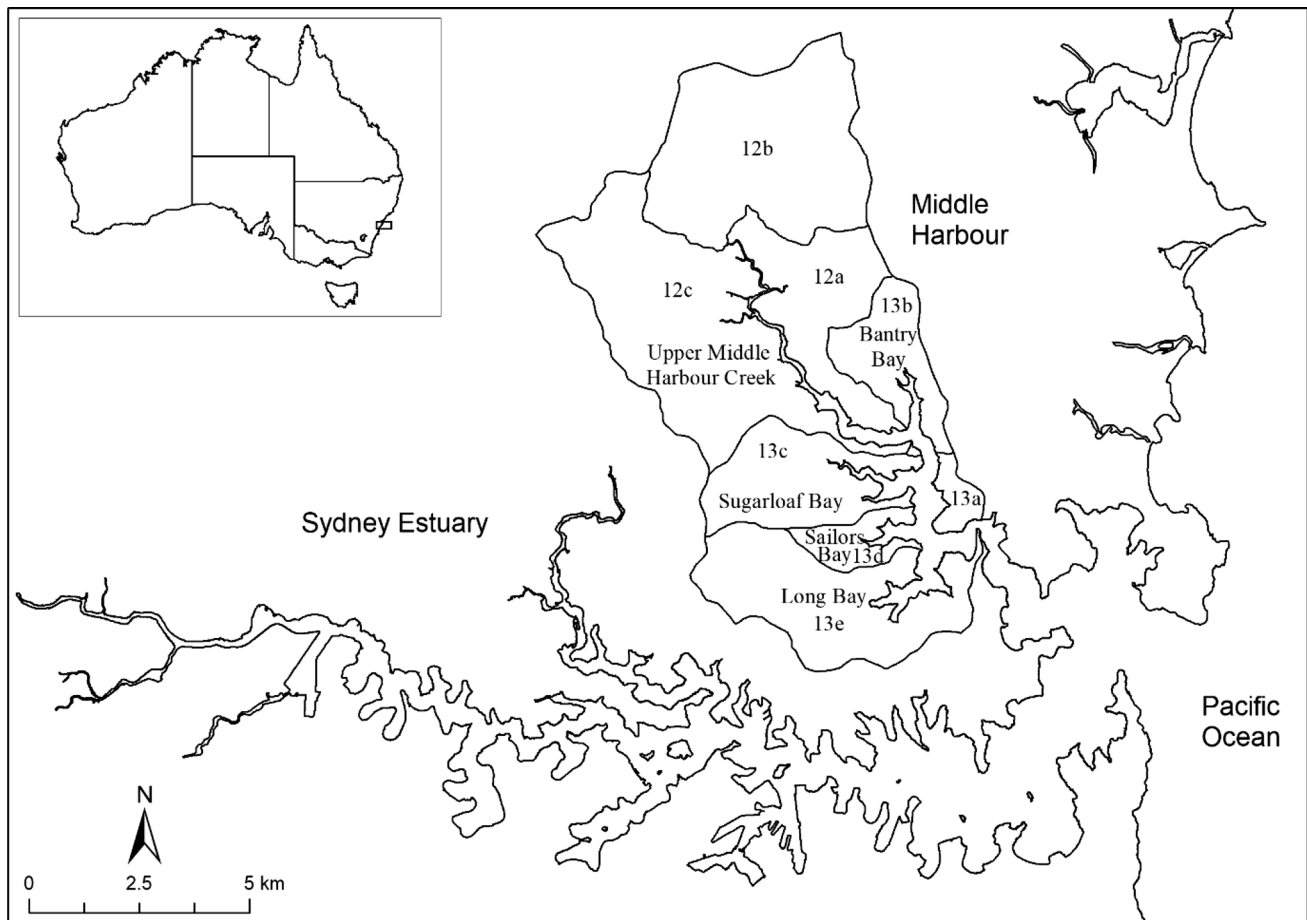


Fig. 1 Sydney estuary and Middle Harbour, including the 8 (coded) Middle Harbour subcatchments

Unlike many of the bays of the Sydney estuary, Middle Harbour has never served as a commercial port, and is instead primarily used for recreation, small commercial interests and by the Royal Australian Navy. Water in the subestuary is up to 20 m deep and the central channel is bounded by relatively steep sides. The Middle Harbour catchment reaches an elevation of almost 200 m and the steep slopes on the edges of the receiving basin are up to 41°. Middle Harbour comprises four major bays: Long Bay, Sailors Bay, Sugarloaf Bay, and Bantry Bay, as well as several other smaller coves. Upper Middle Harbour Creek, which drains water from the Garigal National Park, enters the waterway from the north.

At the mouth of Middle Harbour is a large Holocene flood-tide delta, where sea floor depths change rapidly from approximately 2–5 m before the sea floor drops steeply down into the deep (20 m) central mud basin of the Middle Harbour (Fig. 2). The flood-tide delta completely segregates Middle Harbour from the mouth of the Sydney estuary, effectively confining all bedload transport and preventing any bedload escape to the sea. This physical trapping of bedload makes this subestuary an ideal location to study

bedload sedimentation and transport in a drowned-river valley.

1.5 Subcatchment characteristics

A summary of the characteristics of the 8 subcatchments of Middle Harbour is provided in Table 1.

The Upper Middle Harbour subcatchment (12a, 12b, and 12c—Fig. 1) is by far the largest in Middle Harbour (46.5 km²) and it also features much higher elevations than other subcatchments (maximum of 198 m), as well as being relatively steep (maximum 41°). This subcatchment is the least developed (64%) aside from Bantry Bay (13b) (49%), due to the steep slopes and the presence of Garigal National Park reducing the area of available land for development. Areas of reclamation are located near the Roseville Bridge.

Subcatchment 13a is the most heavily developed of Middle Harbour (97%), though this is almost entirely low-density residential with small areas of commercial use. It is also the smallest subcatchment of Middle Harbour (1.3 km²), being a headland which does not include a substantial river

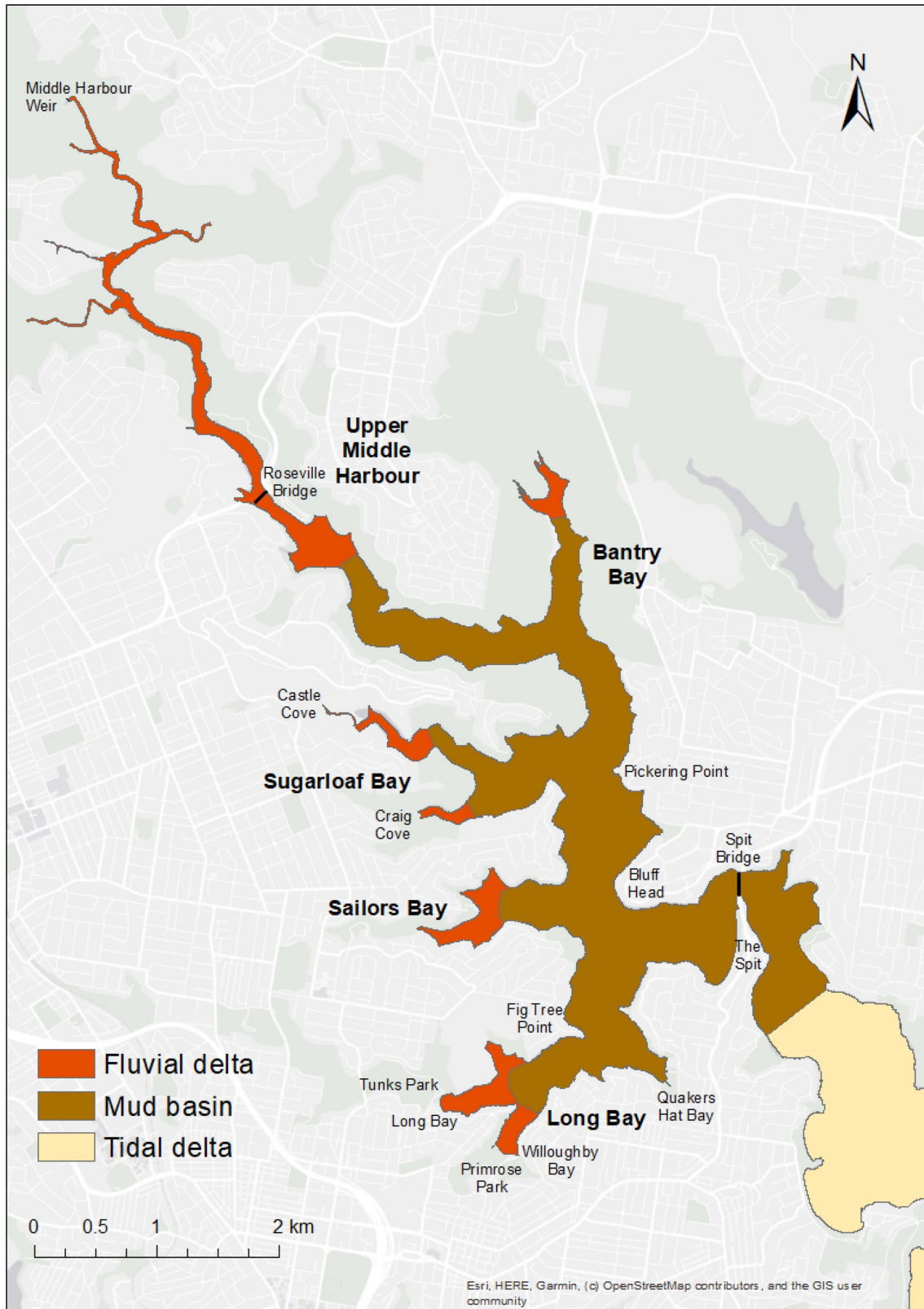


Fig. 2 Middle Harbour sedimentary environments and the relevant locations

Table 1 Characteristics of the eight subcatchments of Middle Harbour

Subcatchment	Subbasin fed	Area (km ²)	Maximum elevation (m)	Percent developed
12a	Upper Middle Harbour Creek	8.58	170	67
12b	Upper Middle Harbour Creek	17.71	198	58
12c	Upper Middle Harbour Creek	20.17	172	70
13a	Middle Harbour central channel	1.28	102	97
13b	Bantry Bay	5.17	154	49
13c	Sugarloaf Bay	8.05	108	84
13d	Sailors Bay	2.32	97	89
13e	Long Bay	12.35	108	88

or bay. It, therefore, does not include a fluvial delta and all sediment is directly deposited into the central channel of the estuary.

The Bantry Bay subcatchment (13b) is the least developed of Middle Harbour (49%), mainly because it largely comprises a national park. It has the highest average slope of all subcatchments (10.8°), as well as a relatively high flush rate of fresh water during rainfall events (Briggs, 2011).

On the western sides of Middle Harbour are Sugarloaf Bay (13c), Sailors Bay (13d), and Long Bay (13e). These subcatchments are all heavily developed (84–89%), predominantly residential, but with some areas of commercial and industrial zoning. Long Bay subcatchment (13e) includes two large parks composed of reclaimed sediment at the heads of each bay (Tunks and Willoughby Parks), largely produced from dredging the adjacent seafloor.

1.6 Geology

The Sydney estuary is located in the Sydney Basin, which is largely comprised of Ashfield Shale in the southwest of the catchment and Hawkesbury Sandstone in the northeast (Fig. 3). The Sydney Basin began forming during the early Permian, with the majority of sediments within the Sydney estuary catchment formed during the mid-Triassic (Roy, 1983). Due to the geologically stable position of Australia, sediments have undergone little geological change since this time. The geology of this estuary strongly influences sedimentation and drainage processes, as well as shoreline morphology.

The Middle Harbour catchment is primarily composed of Hawkesbury Sandstone (73%) overlain by Ashfield Shale (24%) on the western side of the catchment, with minor additional shale laminites (1%) interbedded within the Hawkesbury Sandstone. The catchment also contains small areas of Quaternary sand (1.5%) and man-made reclamation material (0.5%, Fig. 3). The Hawkesbury Sandstone is primarily quartz (68%), with small amounts of rock fragments (2%), feldspar (1%) and mica (1%). These minerals are held

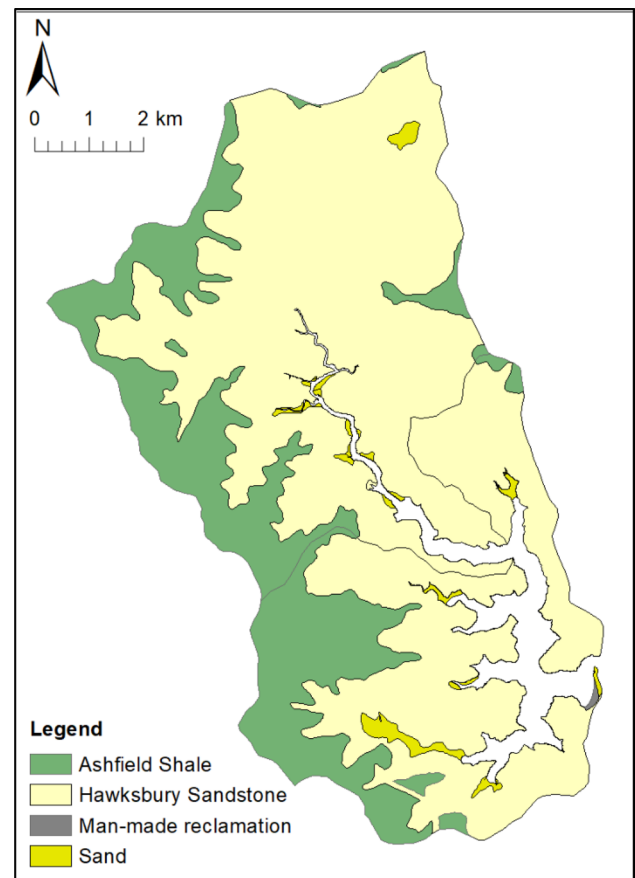


Fig. 3 Geology of the Middle Harbour catchment

in a clay matrix (20%) with a cement composed mainly of secondary quartz (6%) and siderite (2%) (Packham, 1969). The main constituents of Ashfield Shale are clay minerals (45–65%) and quartz (25–55%), with smaller amounts of other minerals (<10%) (Herbert, 1979).

Sandstone, being resistant to erosion, produces small amounts of coarse-grained (bedload) sediment during erosion (Chesnut, 1983). In contrast, the shale-dominated southwestern area of the catchment produces high

levels of mainly fine-textured sediment compared with the sandstone-rich central and eastern catchment of Middle Harbour.

1.7 The ability of Middle Harbour to act as a trap for bedload sediment

The geomorphological structure of Middle Harbour suggests that bedload sediment is unlikely to be able to escape from the estuary. Specifically, the channel narrows from approximately 400–185 m at its mouth near Spit Bridge. Beyond this bridge lies the Holocene flood-tide delta, where seafloor depths shallow from the mud basin at 25 m down to 3 m (Fig. 4), thus preventing bedload material from escaping Middle Harbour. However, it will be demonstrated that bedload sediment is confined to the heads of the bays of Middle Harbour and is unlikely to be transported as far as the flood-tide delta in any event.

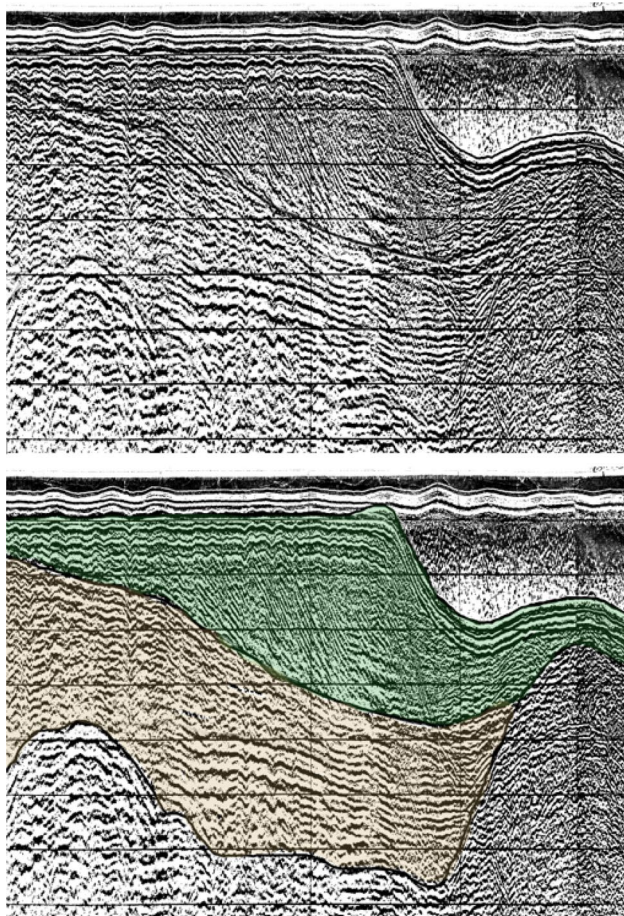


Fig. 4 Seismic scan showing the flood-tide delta at the mouth of Middle Harbour, as well as an interpretation showing the modern (green) and paleo (tan) deltas

2 Methods and materials

2.1 Assessment of fluvial delta sediment volumes

Below sea-level sediment volumes contained in fluvial deltas within embayments of Middle Harbour were well characterised by interpretation of a comprehensive seismic survey comprising 618 transects and 53.6 km of track taken in 1975 (Lean, 1976, Fig. 5). The seismic records are of good quality and were obtained using an electromechanical transducer (boomer) sound source using sound velocities of 1500 m per second in water and 1700 m per second in sediment. These seismic data were used in conjunction with bathymetry maps created in ArcGIS from a 25,546-point dataset obtained from a Sydney Ports Corporation multibeam survey to estimate the extent and thicknesses of mud and sand on the estuary floor of Middle Harbour (Fig. 6). Sand and mud may be readily differentiated on the seismic record through distinctive acoustic signatures (Fig. 7). Sand is represented by multiple, high-contrast reflectors, while mud is displayed by an acoustically transparent layer frequently interrupted

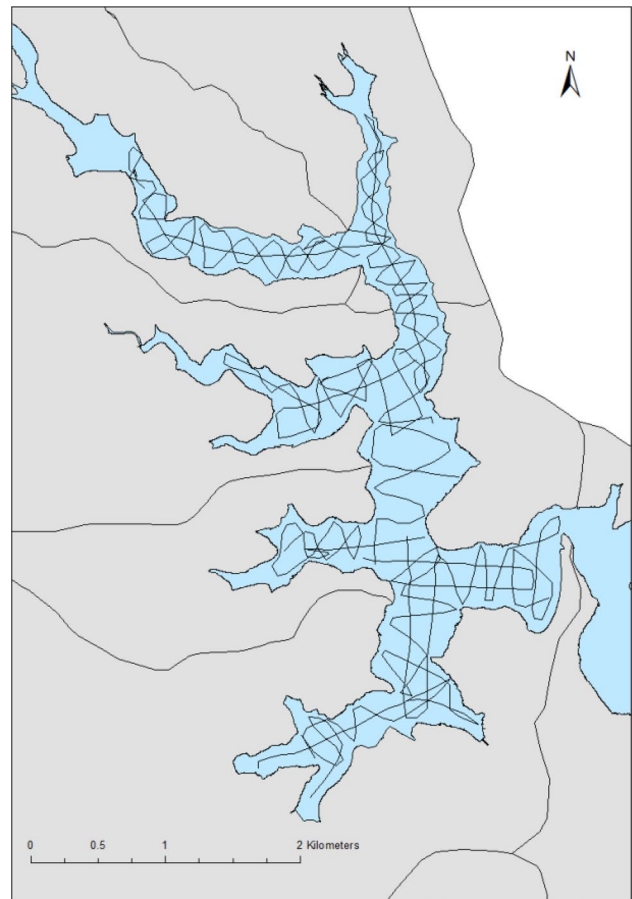


Fig. 5 Seismic tracks in Middle Harbour

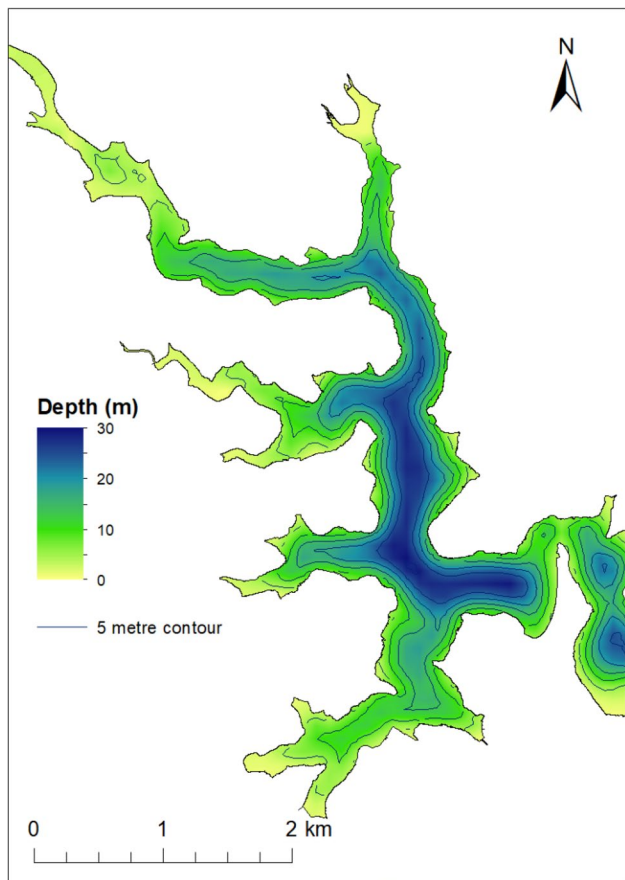


Fig. 6 Bathymetry of Middle Harbour

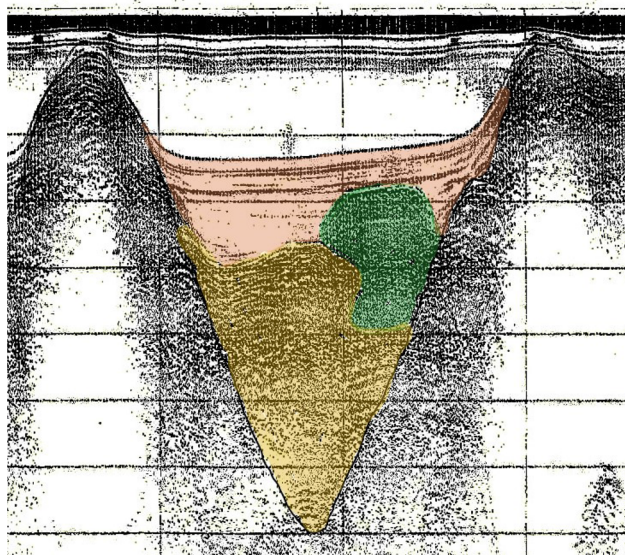


Fig. 7 Seismic interpretation of a cross section of Upper Middle Harbour, showing the deposits of mud (pink), sand (yellow) and gas (green)

by dark bulbous shadows related to the liberation of internal methane gas from decaying organic matter (Fig. 5) (Lean, 1973; Harris et al., 1991). Seismic information was interpreted along with bathymetric data to construct isopach maps of sediment distribution and thicknesses for the fluvial deltas of Long Bay (13c), Sailors Bay (13d), Sugarloaf Bay (13c), Bantry Bay (13b), Upper Middle Harbour, and for the mud basin in central Middle Harbour channel.

2.2 Mass of sediment deposits

The mass of deposited fluvial delta sediment within each subestuary was determined for Long Bay, Sailors Bay, Sugarloaf Bay, Bantry Bay, Upper Middle Harbour Creek, as well as for the central channel of Middle Harbour using the following formula:

$$M = Ar\rho_B C_s [100 - (C_w/100)], \tag{1}$$

where *M* is the total mass of sediment stored in a given area, *A* is the area, *r* is the thickness of sediment in the delta, ρ_B is the bulk wet density, *C_s* is the sand content, and *C_w* is the water content of the sediment. The bulk wet density and water content values were obtained from Taylor (2000). The textural composition of the fluvial deltas was sourced from the proposed Warringah Expressway and from borehole data from the construction of Roseville Bridge in the upper Middle Harbour (Roy, 1983).

Combined total above- and below-sea-level sediment mass for each fluvial delta was normalised to associated subcatchment area and divided by 7400 years to calculate sediment yield. As the seismic data were collected in 1978, yields for each subcatchment were applied for a further 39 years to estimate sediment masses in 2017 in Middle Harbour.

Formula (1) was then applied to calculate the volume of suspended sediment currently deposited in the deep mud basin in Middle Harbour (Figs. 2 and 7). This is necessary to be able to calculate the potential sand-mud ratio of sediment being deposited in Middle Harbour for modelling purposes.

2.3 Holocene precipitation

Information on precipitation during the last 7400 years, i.e. since sea level in the Sydney estuary reached the present-day level (Sloss et al., 2007), is necessary to calculate runoff and sedimentation in each subestuary. However, rainfall is currently unknown over this period in the Sydney area and, therefore, estimates were made for the purpose of sediment modelling.

Holocene annual precipitation during this period was estimated based on the closest quantitative estimate available in the literature, namely a study of Lake George 210 km to

the southwest of Sydney (Coventry, 1976). This study analysed the sediment of dated abandoned beaches in the Lake George catchment and calculated the annual precipitation necessary to maintain lake levels at these elevations. The annual Holocene precipitation in this region ranged from 420 to 770 mm (the present-day annual average precipitation in Lake George is 646 mm). To convert these results to potential annual rainfall in the Middle Harbour catchment, modern annual rainfall records for Sydney and Bungendore (approximately 12 km south of Lake George) between 1890 and 2019 were compared and on average, the annual rainfall in Sydney was found to be 1.98 times greater than that recorded in Lake George in any given year ($p < 0.05$). The Lake George Holocene rainfall was, therefore, adjusted using this value to estimate the annual rainfall in the Middle Harbour region during this period.

2.4 Catchment land use

Land use was considered to be ‘pristine’ to calculate pre-European runoff (from 7400 BP to 1788) in the Middle Harbour catchment, and available historical land use was used for years 1936, 1976, and 2017 to calculate runoff since European settlement (Birch et al., 2015a, 2015b).

2.5 Catchment slopes

A digital elevation model of the Middle Harbour catchment was converted into a slope map (Fig. 8) to calculate the average slope for each subcatchment to assess the effect of slope on sediment accumulation rates.

2.6 Runoff modelling

The following EPA Runoff Model (EPA NSW, 2001) was applied to calculate suspended sediment runoff rates in the Middle Harbour catchment:

$$L = P \times A \times RC \times EMC, \quad (2)$$

where L is the annual loading of total suspended sediment (TSS) in kg year^{-1} , P is the average annual precipitation in mm (as calculated in Sect. 2.3), A is the area of each land use type in km^2 , RC is the runoff coefficient for each land use type, and EMC is the event mean concentration of suspended sediment, which is 35 (Fletcher et al., 2004). The areas of each subcatchment of Middle Harbour (Fig. 1) were obtained from Gunns (2011) (Table 2); the RC and EMC values were from Fletcher et al. (2004). This formula was applied to the Middle Harbour subcatchments for eight time-slices based on changes in precipitation and land use (Table 3).

3 Results

3.1 Main estuary and embayment characteristics

The Middle Harbour embayments (Bantry, Sugarloaf, Sailors and Long Bays) and major tributary (Upper Middle Harbour Creek) (Fig. 1) vary from 2.32 km^2 (Sailors Bay) to 12.35 km^2 (Long Bay) in area and the entire Middle Harbour is 75.69 km^2 .

The Upper Middle Harbour Creek is located between the weir and the distal end of the fluvial delta (5.5 km). Portions of the original fluvial delta have been dredged for reclamation, leaving a pitted/pockmarked bathymetry. Sugarloaf Bay comprises two coves, namely the north arm (Castle Cove) and the south arm (Craig Cove). The Transgressive Basal Sediments (TBS) in this subestuary are confined to the landward side of a rocky sill that extends north–south across the middle of the embayment. In Sailors Bay, two small Holocene fluvial deltas (HFD) (approximately 50 m long) prograde from two minor subestuaries to the north, approximately 75 m long, 50 m wide and 6–18 m thick (Figs. 9 and 10). Long Bay comprises two primary coves, namely Long Bay in the north and Willoughby Bay in the south. The HFDs in Long and Willoughby Bays are modified as these areas have been extensively reclaimed, however, historic maps show the HFD to have extended approximately to the present seawalls (Great Britain Hydrographic Department, 1859). Based on this 1859 bathymetric survey, the Long Bay fluvial delta would have been approximately 800 m long, 150 m wide and up to 10 m thick, and the Willoughby Bay delta would have been approximately 400 m long, 130 m wide and up to 8 m thick.

3.2 Masses of bedload sediments in subestuaries

The masses of below sea-level (BSL) and above sea-level (ASL) bedload sediment deposits stored in each subestuary of Middle Harbour are summarised in Table 4. ‘Slope yield’ was calculated by dividing the mass of each sediment deposit by the average slope of the catchment. The mass of bedload sediment contained in each subestuary varies considerably from 138.2 t of HFD sediment in Sailors Bay to 3511.34 t in the Upper Middle Harbour subestuary, sediment deposited since sea levels reached present-day levels 7400 years ago. Aside from transgressive basal sediments, all sediment in Middle Harbour is known to be of Holocene origin due to the acoustic signature seen in the seismic material (Birch & Lound, 2021) and the fact that bedload deposition could not have occurred until sea-level recovery in the estuary.

Fig. 8 Slope map of Middle Harbour catchment in degrees

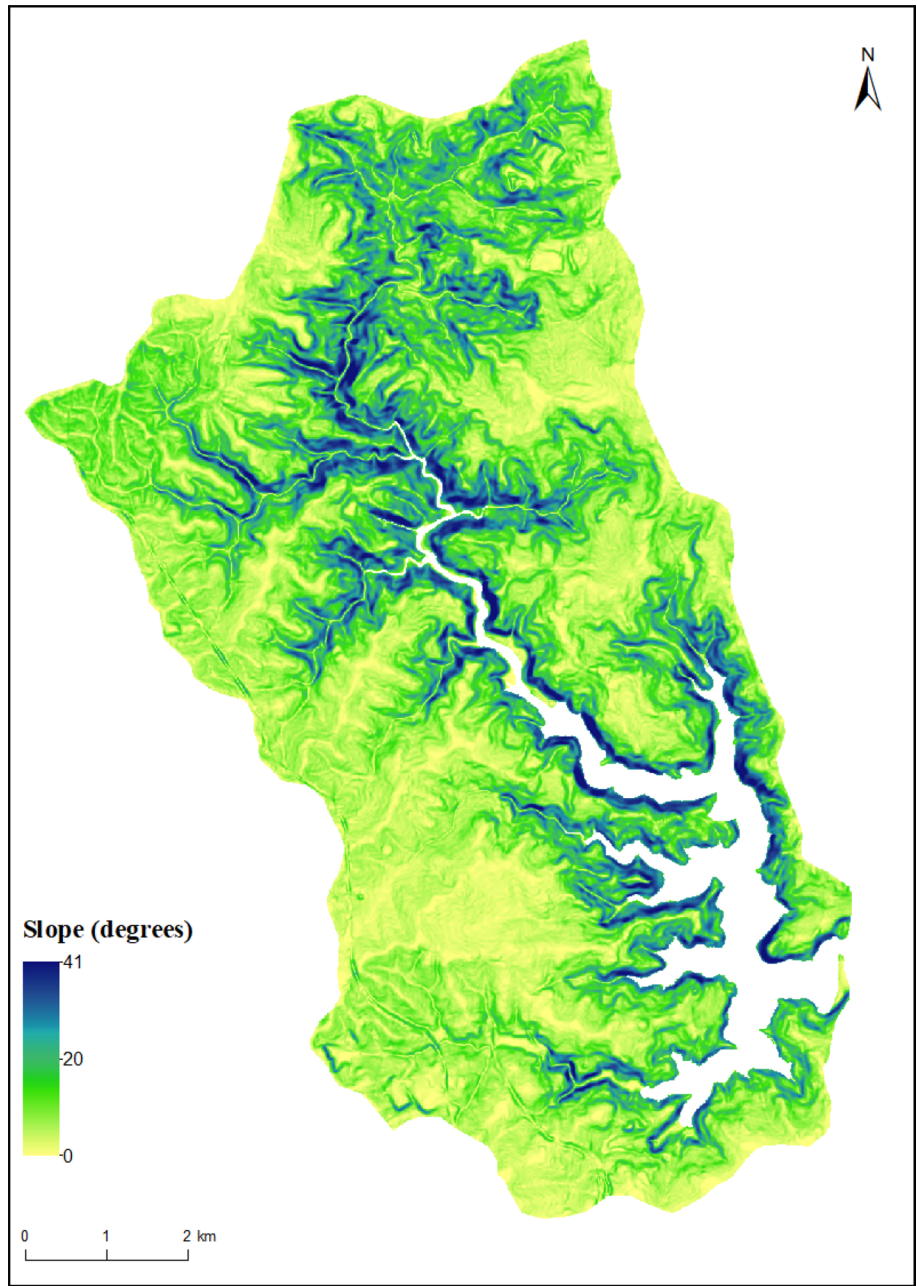


Table 2 Areas of Middle Harbour subcatchments

Subcatchment	Subestuary supplied	Subcatchment area (km ²)	Subestuary area (km ²)
12a	Upper MH Creek	8.58	
12b	Upper MH Creek	17.71	1.41
12c	Upper MH Creek	20.17	
13a	Middle Harbour central channel	1.28	1.77
13b	Bantry Bay	5.17	0.32
13c	Sugarloaf Bay	8.05	0.57
13d	Sailors Bay	2.32	0.35
13e	Long Bay	12.35	1.16

Table 3 Estimated Sydney precipitation, runoff coefficient, and event mean concentration values of suspended sediment (Fletcher et al., 2004)

Time slices	Annual precipitation (mm)	Runoff coefficient
7.4–7 ka	1402	0.36
7–6 ka	1525	0.36
6–4.5 ka	1327	0.29
4.5–1.6 ka	832	0.20
1.6–1788	1055	0.20
1788–1936	1180	0.29
1936–1976	1180	0.29
1976–1999	1180	0.29
1999–2017	1180	0.29

3.3 Suspended sediments

A total of 21,144 t of suspended sediment (mud) was calculated to be present in Middle Harbour. The majority of

this mass (14,427 t) was in the central channel, and of the remaining suspended sediment, 47% (3185 t) was found in Upper Middle Harbour Creek (UMHC), and the remaining 3531 t distributed throughout the bays.

3.4 Transgressive basal sediments

Deposits of transgressive basal sediment (TBS) were located in all bays of Middle Harbour, as well as in the UMHC channel. In total, 5947 t of TBS were calculated, with 59% (3519 t) in UMHC and the rest in the bays. No TBS was found in the central channel of Middle Harbour.

3.5 Holocene precipitation estimates for the Sydney region

Annual precipitation estimates for the Sydney region from 7400 BP to the present day based on rainfall for Lake George for the same period (Coventry, 1976) are given in Table 5 and vary between 832 and 1525 mm. These data were used

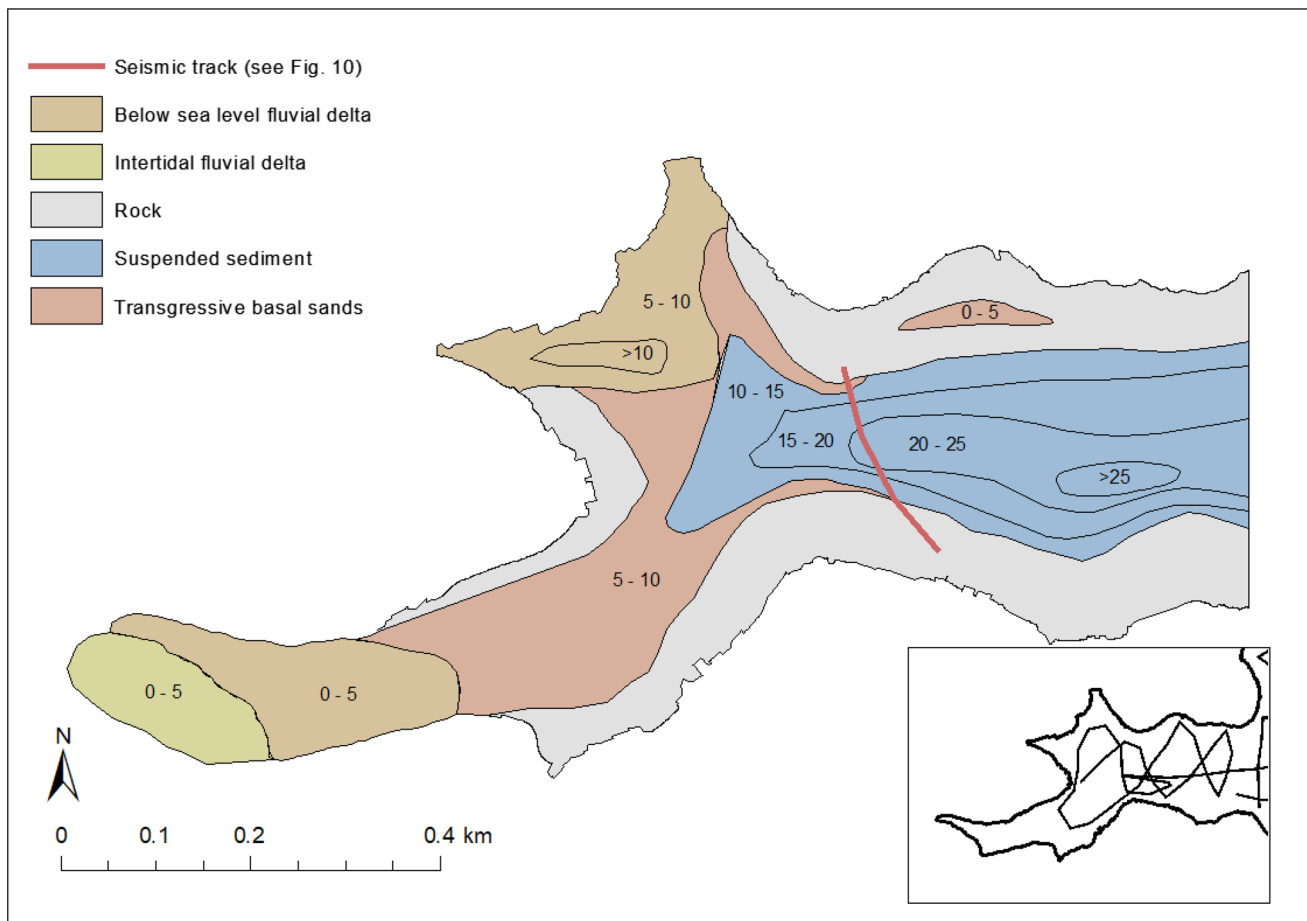


Fig. 9 Sediment deposits in Sailors Bay including thickness in metres

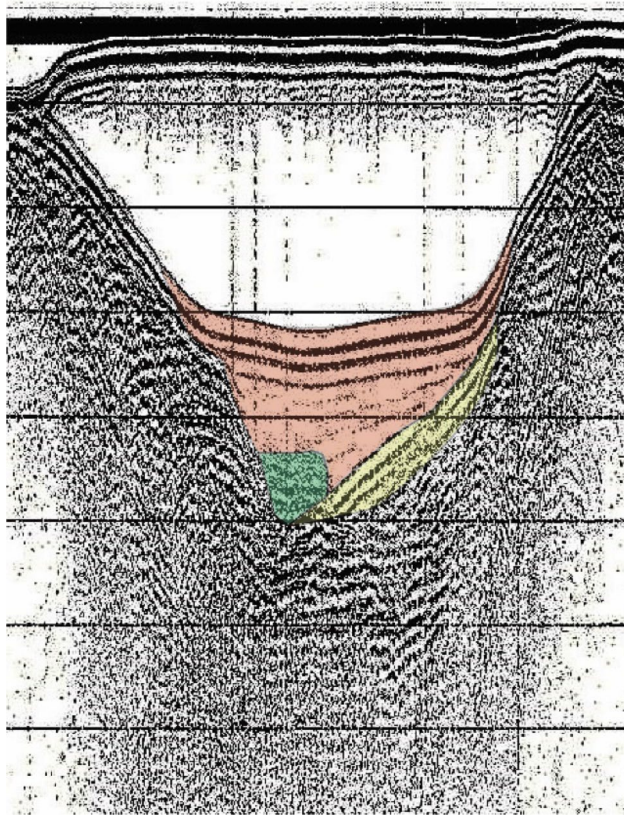


Fig. 10 Seismic interpretation of a cross section of Sailors Bay, showing the deposits of mud (pink), sand (yellow) and gas (green)

in modelling potential sediment deposition rates in Middle Harbour for the time slices outlined in Sect. 2.3.

3.6 Historical land use changes in Middle Harbour

Land use change in Middle Harbour follows a trend of increasing urban development from 1892 to 1999. Until 1945, development was primarily focused on the lower Middle Harbour catchment, but after this time development expanded rapidly into upper Middle Harbour. By 1999 only 28% of the Middle Harbour catchment remained undeveloped, predominantly due to the protection afforded by Lane Cove National Park. From 1999 to 2017, the percentage of developed land remained largely unchanged. A summary of land use changes in Middle Harbour is listed in Table 6.

3.7 Supply of suspended load to Middle Harbour

Sedimentation modelling from formula (2) estimated that 5.3×10^6 t of suspended sediment was produced by subcatchments of Middle Harbour since Holocene sea level recovery (7400 BP) (Table 7). Modelling suggested the sedimentation rate increased substantially following European settlement (Fig. 11), due to increasing urbanisation and vegetation removal, which is consistent with other research (e.g. McLoughlin, 2000; Birch et al., 2015b).

Table 4 Above sea level (ASL) and below sea level (BSL) bedload deposits in each subestuary of Middle Harbour and sediment yield from each subcatchment

Bay/Channel	Catchment area (km ²)	Average Slope (°)	Sediment deposit	Sediment mass (t)	Sediment yield (t km ⁻²)	Slope yield (t degree ⁻¹)
Long Bay (13e)	12.35	6.9	BSL	11.55	0.94	0.14
			ASL	605.12	49	7.1
			Total	616.67	49.93	7.24
Sailors Bay (13d)	2.32	9.9	BSL	138.21	59.57	6.02
			ASL	0	0	0
			Total	138.21	59.57	6.02
Sugarloaf Bay (13c)	8.05	7.34	BSL	173.08	21.50	2.93
			ASL	346.84	43.09	5.87
			Total	519.93	64.59	8.8
Bantry Bay (13b)	5.17	10.77	BSL	159.7	30.89	2.87
			ASL	148.42	28.71	2.67
			Total	308.12	76.87	7.14
Upper Middle Harbour Creek (12a, b, c) (combined)	46.46	10.77	BSL	159.70	30.89	2.87
			ASL	148.42	28.71	2.67
			Total	308.12	76.87	7.14

Table 5 Annual precipitation estimates (in mm) from 7.4 BP to present (in mm) for Lake George (Coventry, 1976) and Sydney

Years before present (ka)	Lake George	Sydney
0	646	1180
0–1.6	533	1055
1.6–4	420	832
4.5–5.5	670	1327
6–6.5	770	1525
7–7.4	708	1402

4 Discussion

4.1 Mass of bedload sediment in Middle Harbour

Interpretation of seismic records indicate that Holocene sediment in Middle Harbour is present as bedload in fluvial deltas and as thick mud deposits in the central basin with only small deposits of Pleistocene sediment remaining as erosional lag in the Upper Middle Harbour Creek and as restricted deposits on the margins of the main channel. This interpretation is supported by borehole data from the proposed Warringah Expressway Bridge and Roseville Bridge (Roy, 1983) (Fig. 12), which shows a thin (<5 m) veneer of relict Pleistocene clay and sandy clay mantling the western flank of Middle Harbour at the Expressway and a shallow (<10 m) deposit of basal clean to slightly muddy Late Pleistocene sand at the western side of the cross section.

This evidence suggests that the sediment which accumulated in Middle Harbour during the pre-Holocene was largely eroded during the most recent glacial period and removed to the adjacent continental shelf. The extent of sediment accumulation in Middle Harbour during high stands of the Late Pleistocene period is not known, however, bedload sediment accumulation rates determined in the current study would suggest only a moderate supply during this period. The minor amount of sediment deposited in Middle Harbour during this period would have been remobilised and transported out of the estuary by fluvial processes during the long periods of low stand. The thin

deposit of Pleistocene sediment high on the side of Middle Harbour detected by boreholes associated with the survey of Warringah Expressway (Fig. 12) is likely to be a relict delta and not an indication of Pleistocene sediment depth. Middle Harbour shows a similar sedimentological structure to Port Hacking, a drowned-river valley 30 km south of Sydney, comprising a large flood-tide delta, a deep central mud basin devoid of bedload sediment and small fluvial deltas occupying embayments (Birch et al., 2020; Roy et al., 2001).

4.2 Sediment mass in deltas

The total bedload sediment mass calculated for each sub-estuary delta ranges from the largest delta mass in UMHC (3511 t), followed by Long Bay (617 t), Sugarloaf Bay (520 t), Bantry Bay (308 t), and Sailors Bay (138 t). The large range in mass between deltas is expected as the bedload mass is proportional to catchment size, which varies between 46.46 km² for the UMHC to 2.32 km² in Sailors Bay. Delta mass, expressed on a catchment-area normalised basis, varies from 49.9 to 75.6 t km⁻² for Long Bay and UMHC, respectively, and on an annual supply basis yield ranges from 0.006 to 0.01 t km⁻² year⁻¹, respectively.

Table 7 Modelled sediment deposited into Middle Harbour

Time period	Annual precipitation (mm)	Annual loading (t)	Total loading (t) ^a
7–7.4 ka	1402	1342	536,924
7–6 ka	1525	1460	1,460,073
6–4.5 ka	1327	1025	1,537,797
4.5–1.5 ka	832	445	444,962
1.5 ka–1788	1055	564	239,043
1788–1936	1180	912	386,227
1936–1976	1180	4728	189,135
1976–1999	1180	9098	373,032
1999–2017	1180	8597	154,740
		Total	5,321,932

^aTotal loading = annual loading × number of years

Table 6 Historical land use areas (in km²) in the Middle Harbour catchment (Birch et al., 2015b)

Year	Parkland	Residential	Commercial	Industrial	Education/ Medical	Road
1892	61.68	5.40	0	0	0	2.06
1936	56.13	19.50	0	0	0	7.42
1945	51.13	22.97	0.31	0.89	0.34	8.74
1976	52.65	32.74	0.09	0.51	0.44	12.46
1999	26.04	44.77	1.76	1.30	1.76	17.04
2017	20.67	34.25	1.35	0.96	1.36	12.22

Fig. 11 Annual loading of suspended sediment into Middle Harbour (note change of scale on x-axis after 500 BP)

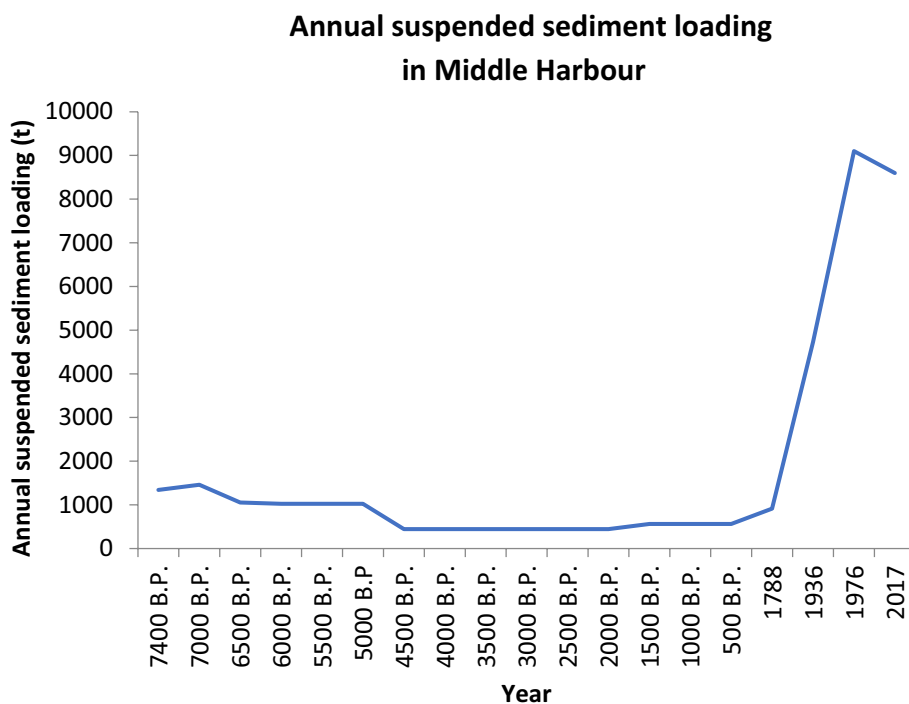
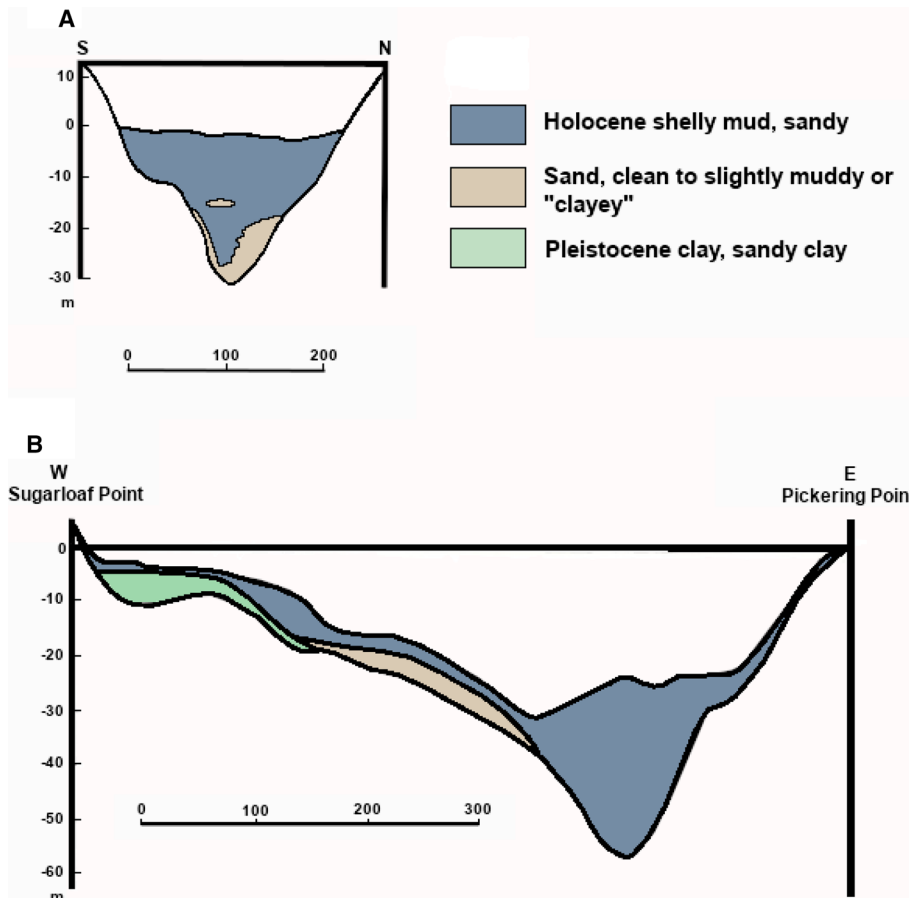


Fig. 12 Sediment cross sections of **a** the Roseville Bridge and **b** the proposed Warringah Expressway Bridge in Middle Harbour (Roy, 1983)



4.3 Factors potentially influencing the sedimentation rate

Factors possibly influencing bedload sediment rates in the subcatchments are explored further.

Geology As the Middle Harbour catchment surface is comprised mostly of Hawkesbury Sandstone (73%), a potential to produce a greater proportion of bedload material might be expected to be deposited in the subestuary. However, the resistance of this rock type to weathering (Chesnut, 1983) and its location mainly on the lower slopes may reduce erosion and help explain the low sediment accumulation rates for bedload material in Middle Harbour. The remaining surface rocks of Middle Harbour catchment (24%) comprise Ashfield Shale, which is more susceptible to weathering and erosion (Chesnut, 1983). These deposits are located on the steeper, outer margins of the catchment (Fig. 3) and are more easily eroded, but these sediments are likely to supply suspended sediment to Middle Harbour and not contribute significantly to fluvial deltas at the head of the subestuaries. However, an examination of subcatchments with predominantly Hawkesbury Sandstone (i.e. Sailors Bay, Bantry Bay, UMHC) and mostly Ashfield Shale surface rocks (Long Bay, Sugarloaf Bay) does not explain the different mass of deltas occupying adjacent subestuaries.

Slope Increased catchment slope would suggest enhanced erosion and greater sediment supply to the adjacent receiving basin. Maximum slope of the Middle Harbour catchment is 41° in the UMHC catchment, with average subcatchment slopes ranging from 6.9° to 10.8° for Long Bay and Bantry Bay subcatchments, respectively. Though previous research found little correlation between catchment slope and sediment yield (Kinsey-Henderson et al., 2005), the current data suggest that when slope is accounted for in yields, the variance in bedload sediment accumulation rates decrease and range from 6 to $8.8 \text{ t km}^{-2} \text{ deg}^{-1}$. Normalising bedload sediment accumulation rates for slope considerably reduced the variance between bedload sediment accumulation rates between subcatchments with the catchments with the higher yields (Sugarloaf Bay and Upper Middle Harbour Creek) having yields reduced from 64.6 and 75.6 t km^{-2} to 8.8 and $7.3 \text{ t km}^{-2} \text{ deg}^{-1}$, respectively (Table 7).

Vegetation It is well known that a high vegetation cover reduces surface erosion (e.g. Kittredge, 1948; Osterkamp et al., 2012), however, little is known regarding the pre-European vegetation cover in the vicinity of Middle Harbour. An examination of areas of the catchment that have not been greatly disturbed suggests that the vegetation cover is largely unchanged since sea-level has recovered until Western colonisation in the area. It has been assumed in the modelling undertaken in the current work that vegetation type in the Middle Harbour catchment was consistent throughout the

Holocene and that the area of vegetation cover has reduced greatly during the period of urbanisation.

Following European settlement in Sydney in 1788, sediment accumulation rates increased rapidly due to extensive deforestation (McLoughlin, 2000). Land clearing and urbanisation produced an increase in the impervious fraction of the subcatchment surface and increased runoff (Taylor et al., 2004), as is evident from sediment modelling in the current study (Fig. 11). Recent mapping of the growth of the fluvial delta in Scotts Creek and Sugarloaf Bay in the years 1978, 1985, and 2003 by the local Council (Willoughby City Council, 2003) provided an opportunity to verify runoff modelling being used in the present investigation (Fig. 13). Analysis of this recent sediment deposit indicates a mass of 6.70 t has accumulated from 1978 to 2003, or an average yield of 1.51 t km^{-2} or $0.6 \text{ t km}^{-2} \text{ year}^{-1}$. The magnitude of this increase equates to a 60–85 times increase from the overall bedload sedimentation rate of $0.007\text{--}0.01 \text{ t km}^{-2} \text{ year}^{-1}$, which is consistent with the increase in the modelled suspended sediment yield (Fig. 11).

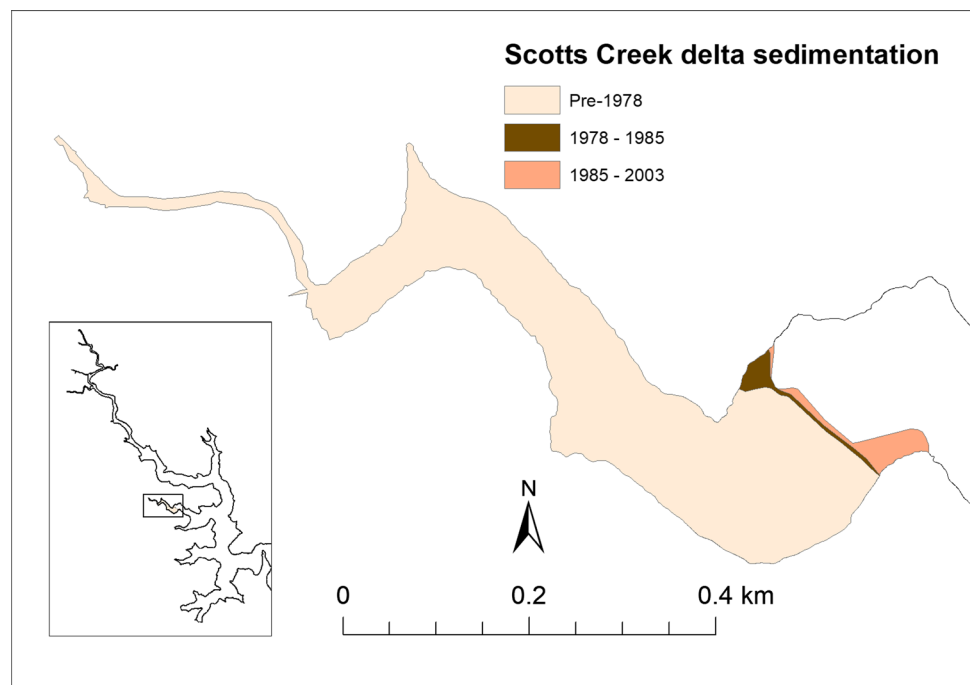
Based on this examination of the data, it appears that the main factors influencing sediment accumulation rates in Middle Harbour are urbanisation and to a lesser degree, the slope of the catchment. Surprisingly, evidence that surface geology affects the nature or mass of sediment being delivered to Middle Harbour is lacking while the influence of reduced vegetation cover cannot be assessed directly due to a lack of data.

4.4 Other sediment deposits in Middle Harbour

Suspended sediment Of the 21,144 t of suspended sediment present in Middle Harbour, 59% is located in the central Middle Harbour channel with all subcatchments contributing to this deposition. It is not known how much of the suspended sediment has been transported beyond Middle Harbour, although a study on re-suspension in the Sydney estuary (Lee, 2013) found only 7% of suspended sediment was transported beyond the estuary, which may suggest that only a minor amount of suspended sediment has escaped Middle Harbour.

Transgressive basal sediment A total of 5947 t of TBS was deposited in Middle Harbour, the majority (59%) of which accumulated in the UMHC, with minor material in the bays. These materials would have been deposited as sea level recovered and inundated the paleo-valley, although some may be relict stream overbank and channel accumulations. The period between the ocean entering Middle Harbour at approximately 13,000 BP and reaching its maximum height at 7400 BP was approximately 5600 years, which translates to a sedimentation rate of 1.06 t year^{-1} , a rate of approximately 1.5 times the calculated sedimentation rate for the modern bedload sediments. This suggests the possibility

Fig. 13 Progression of the Scotts Creek fluvial delta



that a portion of the sediment classified as TBS in Middle Harbour is stream overbank sediment deposited during sea-level low stand.

4.5 Modelling sediment accumulation rates

Suspended sediment The modelled suspended sediment load to Middle Harbour was 5.3 MT over the period of 7400 years since sea-level reached its present position, including 562,167 t since urbanisation. In contrast, suspended sediments measured in Middle Harbour were 21,144 t, or 0.4% of the modelled sediment volume. Therefore, either 99.6% of suspended sediment is escaping the estuary, or sediment accumulation rates are lower than modelled.

Bedload modelling The calculated bedload sedimentation rate for the Middle Harbour catchments varied from 49.93 to 75.57 t km⁻² for the Long Bay and UMHC sub-catchments, respectively. A direct, field measurement of bedload is difficult (Ergenzinger & De Jong, 2003; Turowski et al., 2010; Ziegler et al., 2014) and sediment accumulation rates determined from dam sites in the Sydney region combine suspended and bedload materials (Erskine et al., 2002, 2003), however, bedload sediment accumulation rates have been estimated as a proportion of suspended rates (Brocard & Van der Beek, 2006; Hindall, 1976; Maddock & Borland, 1950; Ziegler et al., 2014). A literature review by Turowski et al. (2010) estimated a bedload fraction of 30–50% for sand-bed rivers. Applying a 30% and 50% of the total load to modelled data would suggest a bedload mass of 2–3.4 Mt for Middle Harbour, which is 364–607% of that calculated from

field measurements. For modelled sedimentation to be correct, the proportion of 5517 t of bedload would need to be 0.001% of total sediment, indicating that either published bedload sediment accumulation rates are excessive, or that modelling of suspended load is over-estimated, or that the assumed bedload/suspended load ratio is incorrect.

Based on the results summarised in Table 7, a total of 5094 t of bedload material and 21,144 t of suspended sediment were measured in Middle Harbour. This equates to a ratio of 79% suspended sediments and 21% bedload material. Applying this bedload fraction to modelled data would imply that from 5.3 Mt of suspended sediment modelled to be deposited in Middle Harbour in the 7400-year time frame, 1.4 Mt of bedload material would also be deposited, or 6.7 Mt of total sediment. As an unknown mass of suspended sediment has exited Middle Harbour, the 21% proportion of bedload is a maximum and the actual proportion of bedload may be significantly lower. A total of 5517 t of bedload sediment was measured in Middle Harbour, compared with 1.4 Mt modelled. This indicates that actual sediment rates are vastly lower than the model prediction, i.e. at least 0.4%. This may reflect a lower than expected sediment supply of Hawkesbury Sandstone due to a slow weathering rate (Chesnut, 1983). The suspended sediment model may also have over-estimated sediment accumulation rates as it is better suited to short-term urban stormwater runoff, rather than long-term sedimentation in a catchment that was pristine for the majority of the modelled time. If 5094 t of bedload sediment was divided into time slices according to the estimated precipitation changes in Sect. 3.3, it would suggest a total annual bedload material loading ranging from 0.4 t year⁻¹

during low precipitation years (i.e. 4.5–2000 ka) to 8.2 t y^{-1} in high rainfall (e.g. 1976).

4.6 Holocene evolution model

Based on the seafloor depth of Middle Harbour, flooding would have occurred in this estuary at about 9000 years BP (Sloss et al., 2007). As flooding took place in Middle Harbour, sediments would have been deposited in transgressive, backstepping fluvial deltas, whereby coarse material was deposited on the floor of the previously exposed creek bed. As flooding advanced, these sediments would have been deposited backwards up the exposed valley floor. The thickness and distribution of these TBS would be determined by the speed of flooding advancement and the configuration of the valley. Seismic data indicate that the TBS are thin towards the south end of Middle Harbour and increase in thickness landward of Pickering Point where the paleo-valley narrows and becomes sinusoidal, with a maximum thickness of 25 m being attained in the upper Middle Harbour area.

After full sea-level recovery at 7400 years BP (Sloss et al., 2007), fluvial deltas began to form at the headwaters of Upper Middle Harbour Creek and in the other four subestuaries. During this period, material being discharged from creeks and entering Middle Harbour would have fractionated into bedload and suspended load, and been deposited close to the river mouths and transported into deeper water, respectively. The bedload component produced prograding strata of coarse material fining towards the distal parts of the delta, while the fine fraction was transported further seawards in the water column, settling in various parts of Middle Harbour depending on hydrodynamic conditions (Fig. 2).

The geological cross section derived from 12 deep boreholes drilled during the construction of the Roseville Bridge (Fig. 12) has allowed the construction of a detailed sedimentation history of the fluvial delta of Upper Middle Harbour Creek (Fig. 5). This section shows Hawkesbury sandstone bedrock overlain by Pleistocene gravels and sands, followed by Holocene muds with sands at the surface. The TBS were laid down with sea-level advance followed by prograding packages of fluvial sediment advancing over the basal deposits into the estuary.

5 Conclusions

The masses of bedload sediment, suspended sediment, and transgressive basal material present in Middle Harbour have been estimated using an extensive coverage of seismic data. Holocene bedload sediment has been prevented from escaping Middle Harbour by the geomorphological structure of the estuary and by a flood-tide delta blocking the exit to the

ocean. This unusual configuration has allowed the bedload sedimentation rate for the post-recovery period to be calculated for the fluvial deltas occupying the five subestuaries of Middle Harbour. An unknown mass of suspended sediment has escaped Middle Harbour over the top of the tidal delta and the estimated sedimentation rate is the minimum, nevertheless evidence from the adjacent Sydney estuary suggests this mass to be relatively minor. Transgressive basal sediment deposited during sea-level recovery was present in all of the bays of Middle Harbour. The mass of suspended load has been modelled and the mass of bedload was estimated as a proportion of suspended material. The key finding of the present study is that bedload sediment accumulation rates in Middle Harbour are exceptionally low at $0.007\text{--}0.01 \text{ t km}^{-2} \text{ year}^{-1}$ and that modelled suspended load is probably excessive ($9.5 \text{ t km}^{-2} \text{ year}^{-1}$) considering the measured mass (5,300,000 t). Based on the variances in sediment masses between the subestuaries, it can be concluded that the primary catchment influences on bedload sedimentation are the level of urbanisation and to a lesser degree the catchment slope. A reconstruction of the recent geological history of the estuary indicates that little pre-Holocene sediment remains in Middle Harbour and that with the low sediment accumulation rates estimated in the current work, only a small proportion of the estuary would have been occupied by sediment deposited during the long period of low stand.

Author contributions SL: writing, resources, visualization, data curation, editing. GB: conceptualisation, methodology, resources, editing, data curation. DD: resources, editing.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The findings of this paper are appropriate for the 'Journal of Sedimentary Environments'. The paper is an original work that has not been published previously and is not currently being considered for publication elsewhere. The work is not funded and the authors have no conflicting interests.

Human and animal rights This article does not contain any studies with human participants, or animals by any of the authors.

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