Flood-tidal and fluvial deltas of Tuggerah Lakes, Australia: Human impacts on geomorphology, sedimentology, hydrodynamics and seagrasses

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Flood-tidal and fluvial deltas of Tuggerah Lakes, Australia: Human impacts on geomorphology, sedimentology, hydrodynamics and seagrasses

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Abstract Tuggerah Lakes are a barrier or wave-dominated estuary consisting of three interconnected shallow lagoons impounded by a coastal sand barrier. Sea level rose by about 120 m during the late Pleistocene to about present sea level at about 7900–7700 cal BP. Sea level continued to rise to +1.5 m by 7400 cal BP and persisted until about 2000 cal BP when it regressed to the present level. Throughout most of the early and mid-Holocene, Tuggerah Lakes had two entrances, one in Tuggerah Lake at The Entrance and another in Budgewoi Lake near Budgewoi. Sand completely blocked the entrance near Budgewoi and the remaining channel at The Entrance became ensconced on bedrock. Nevertheless, sandy flood-tidal deltas developed at both entrances, although currently inactive. Where rivers debouche into the lagoons, silt jetties or fluvial deltas have formed. Deep channels have been dredged through river-mouth bars, altering natural sedimentation patterns and the distribution of seagrasses. The geoheritage value of flood-tidal deltas and silt jetties needs to be determined for NSW estuaries so that the most significant can be protected appropriately.

Key words sea level change; entrance atrophy; river-mouth bars; seagrass dynamics; dredging

INTRODUCTION

Tuggerah Lakes consist of three interconnected shallow coastal lagoons (Tuggerah Lake, Budgewoi Lake, Lake Munmorah), which discharge into the ocean at The Entrance on the Central Coast of NSW (Fig. 1). The area surrounding the lakes has been progressively urbanised since the 1950s as part of the Sydney conurbation. The 1400 MW coal-fired Munmorah Power Station has sourced its cooling water from Lake Munmorah and discharged up to 54 m^3/s of heated water into Budgewoi Lake since 1967 (Fig. 1), reversing the natural flow circulation (King & Hodgson, 1995).

Tuggerah Lakes have a dredged permanently open mouth, are a wave dominated estuary at an intermediate evolutionary development stage, drain a catchment area of 670 km^2, have a water surface area of 77 km^2, exhibit no mangroves, 13.4 km^2 of seagrasses, 0.007 km^2 of saltmarsh and yield an average annual commercial wild fish catch of 4227 kg/km^2 $year^{-1}$ (King & Hodgson, 1995; Roberts, 2001; Roy *et al.*, 2001) For a mean annual catchment rainfall of 1200 mm/year, Tuggerah Lakes have over three times greater open water area than the mean for Australian subtropical estuaries and contain more than the average area of seagrass (Bucher & Saenger, 1994). The exceptionally small average tidal range of 0.02–0.03 m (Roberts, 2001) prevents the development of any mangroves in the intertidal zone, a rare occurrence (Bucher & Saenger, 1994).

Estuary management issues of concern to Tuggerah Lakes' stakeholders included, among others:

- Entrance conditions and their impact on tidal exchange and flushing;
- The need for a second entrance;
- Foreshore flooding;
- Sediment deposition at creeks and storm water outlets; and
- Effects of dredging (Roberts, 2001).

The purposes of this paper are to:

- Briefly outline the environmental setting of Tuggerah Lakes;
- Describe the important features of the Tuggerah Lakes estuary;
- Discuss in detail the flood-tidal and fluvial deltas of Tuggerah Lakes; and
- Outline human impacts on the geomorphology, sedimentology, hydrodynamics and seagrasses of the deltas in Tuggerah Lakes.

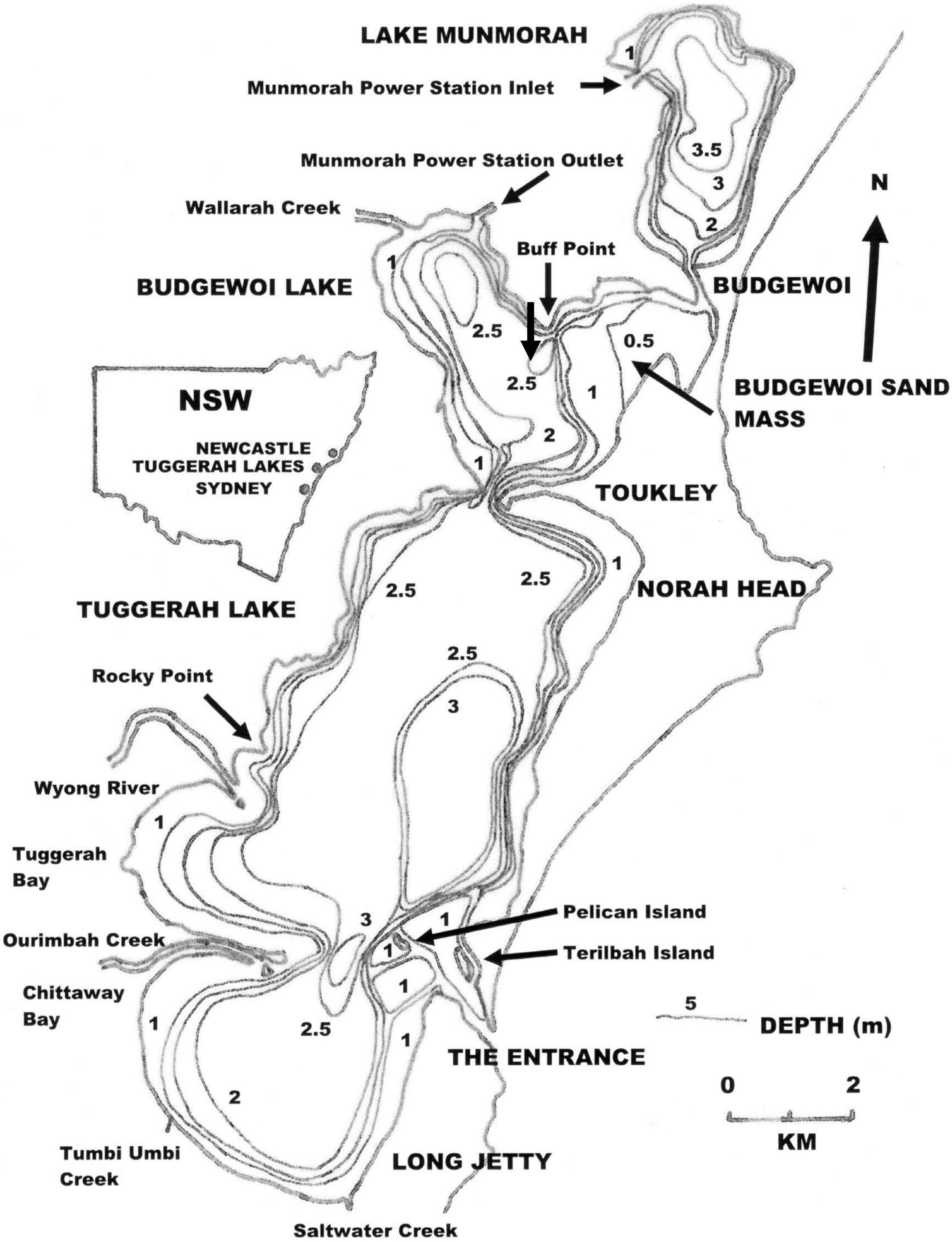

Fig. 1 Bathymetry of the Tuggerah Lakes estuary in eastern Australia.

ENVIRONMENTAL SETTING OF TUGGERAH LAKES

The Tuggerah Lakes drainage basin is largely comprised of Triassic sandstone, shale, claystone and conglomerate of the Hawkesbury Sandstone and Narrabeen Group of Sydney Basin (McNally, 1995). The rocks dip at a low angle to the south. The dominant catchment land uses are national park, state forest, turf farms, grazing, cropping, horse studs and urban areas. Land use is an important determinant of sediment yields for different lithologies in this area (Erskine *et al*., 2002;

2003). Erskine *et al*. (2003) found that measured farm dam sediment yields for shale catchments ranged from 2.5 t/ha·year^{-1} for forest to 2.9 t/ha·year for grazed areas to 6.7 t/ha·year for cropped areas to 6.5 t/ha·year^{-1} for urban areas. For sandstone catchments, Erskine *et al*. (2002) found that measured farm dam sediment yields ranged from 3.1 t/ha·year^{-1} for forest to 3.3 t/ha·year^{-1} for grazed areas to 7.1 t/ha·year^{-1} for cropped areas. Clearly cropping and urbanisation greatly increase sediment yields over those for forest and grazed areas. Historical annual rainfall has alternated from high rainfall (1370 to 1276 mm) between 1863 and 1895, and again between 1949 and 1990, to lower rainfall (1063 to 1072 mm) between 1895 and 1948, and again between 1991 and 2008 at Wyong (Erskine & Townley-Jones, 2009). Both Wyong River and Ourimbah Creek are used as sources for Gosford-Wyong's water supply. Over the last 15 years, an annual average of 10 925 ML have been extracted from Wyong River and 3558 ML have been extracted from Ourimbah Creek (Gosford/Wyong Councils Water Authority, 2007). Clearly less freshwater will be discharged into Tuggerah Lakes in the future, especially as storm water harvesting is also being incorporated into future water supply plans (Gosford/Wyong Councils Water Authority, 2007).

FEATURES OF TUGGERAH LAKES

In southeastern Australia, sea level rose from –120 m at 18 000 cal BP to its present level between 7900 and 7700 cal BP and continued to rise to a maximum of +1.5 m by 7400 cal BP (Sloss *et al*., 2007). This sea level highstand persisted until 2000 cal BP when it relatively slowly regressed to its present level (Baker & Haworth, 1997; Sloss *et al*., 2007). During the Pleistocene, there were many low sea levels when deep bedrock trenches were excavated into bedrock below Tuggerah Lakes. Interestingly, these Pleistocene bedrock trenches are deepest (<–160 m) about 2 km north of The Entrance and are buried by a sequence of fluviatile, estuarine and mixed fluvio-estuarine sedimentary units (Griffin, 1962; Roy & Peat, 1973; Ringis, 1974). Bedrock outcrops at lake level at a number of locations on the western side of Tuggerah Lakes (Griffin, 1964; Roy & Peat, 1973). Sand barriers connect bedrock highs at The Entrance to Norah Head to Wybung Head.

Microtidal barrier estuaries (Roy, 1984) or wave-dominated estuaries (Roy *et al*., 2001) are common on the NSW coast and exhibit mostly open entrances in which tides are attenuated, flood-tide deltas with delta fronts slowly migrating into extensive mud basins, silt jetties or digitate fluvial deltas, mixing by wind shear, temporary stratification in deep water during floods and limited intertidal environments, but extensive areas of seagrasses. Digby *et al*. (1999) proposed a national classification of Australian estuaries, which is simply a listing of their characteristics. According to this scheme Tuggerah Lakes are currently a single constricted mouth, unbranched, bay, with no off-channel embayments. In the early to mid-Holocene when the Budgewoi mouth was open, Tuggerah Lakes were a double, constricted mouth, unbranched, bay with off-channel embayments (Digby *et al*., 1999).

Bathymetry

An echo sounder and leadline were used on a series of transects across each lake to a surface water level datum of 0.2 m Australian Height Datum. Depths were determined to an accuracy of ±0.05 m and a GPS was used to determine the start and end points of each transect to a positional error of ±100 m. The bathymetry is shown in Fig. 1.

The lakes are generally less than 3 m deep, except for Lake Munmorah which exceeds 3.5 m (Fig. 1). Well-developed fluvial deltas are present at the mouths of Wyong River and Ourimbah Creek. Shallow sand banks are present at The Entrance and the Budgewoi Sand Mass. These sand banks are inactive flood-tidal deltas. A relatively deep dredge channel exists on the northern and northwestern margins of the Budgewoi Sand Mass and extends into Lake Munmorah. Significant recent subsidence due to underground coal mining has occurred in northern Lake Munmorah and the northwestern bay of Budgewoi Lake (Roberts, 2001). Measureable recent sedimentation has occurred in Chittaway and Tuggerah bays (Roberts, 2001).

Bottom sediment lithofacies

A total of 210 bulked bottom sediment (top 0.05 m) samples were collected between 2006 and 2010. Samples were oven dried at 105°C. The samples were ground with a mortar and pestle and passed through a 2 mm sieve. All clastic material of >2 mm was examined and the gravel fraction, when present, was further sieved at 1Φ intervals. The fine earth fraction <2 mm was then subjected to grain size analysis by the sieve and hydrometer method (Folk, 1980). All samples were classified into one of Folk's (1980) texture groups. Roy & Peat's (1973) earlier work used their own texture classification scheme that was not based on the Folk (1980) ternary diagram.

Figure 2 shows the bottom sediment lithofacies of Tuggerah Lakes. The use of Folk's (1980) texture groups generalises lithofacies distribution and some of the detail shown by Roy & Peat (1973) is lost. Most of the bottom of the lakes is composed of very fine to fine sandy silt, sandy mud and sandy clay. The two flood-tidal deltas are composed largely of quartzose (<5% rock fragments with rounded to sub-rounded quartz grains) medium and fine sand, granular fine and

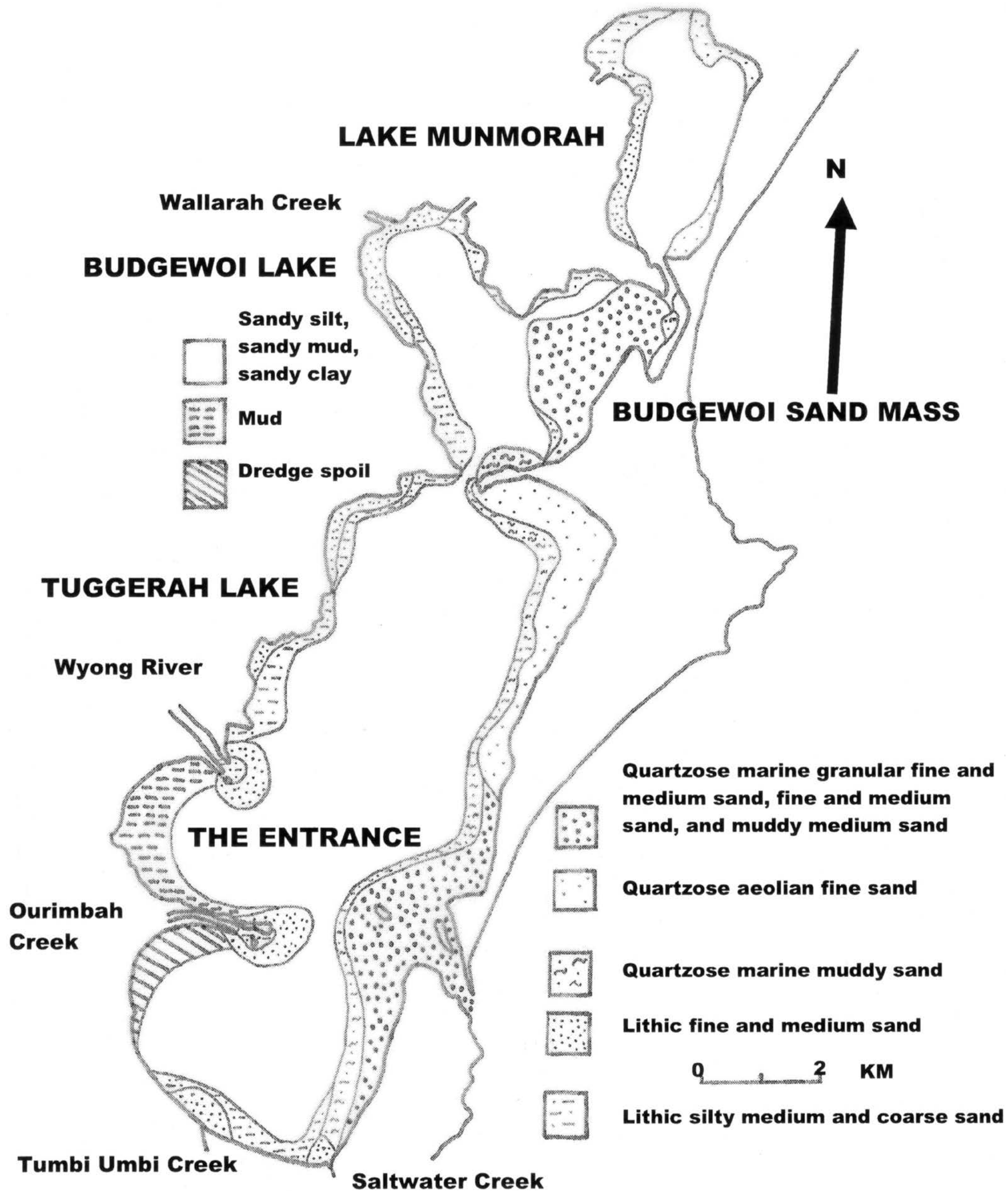

Fig. 2 Bottom sediment lithofacies of the Tuggerah Lakes estuary in eastern Australia.

medium sand and muddy medium sand. A delta front of quartzose muddy sand usually occurs on the landward side of the flood-tidal deltas. Banks of aeolian quartzose fine sand are present on the lake-side of the sand barriers in Tuggerah Lake and Lake Munmorah. Lithic sediments (>5% rock fragments and <95% angular to sub-angular quartz) dominate on the catchment side of the Tuggerah Lakes. The fluvial deltas of Wyong River and Ourimbah, Wallarah, Tumbi Umbi and Saltwater creeks all have arcuate fine and medium sand bodies where the channels debouche into the lakes. Fine and medium sands also occur along the western edge of the lakes near bedrock outcrops. Inside the river channels, the sediments are silty medium and coarse sand. Silty fine and medium sand often occurs on the lakeward side of the lithic sands. Dredge spoil has been sidecast into Chittaway Bay and contains laterite and basalt pebbles, as well as lead fishing sinkers.

DELTAS OF TUGGERAH LAKES

Flood-tidal deltas

Budgewoi Sand Mass This delta atrophied during the late Holocene, probably due to a 1.5 m sea level fall after 2000 cal BP. The sand barrier width here is the narrowest (Fig. 3(a)), except for the current mouth. Quartzose sand from the delta was transported into the southern end of Lake Munmorah when this mouth was open (Peat, 1973). The sand mass consists of a shallow flat-topped sand body with a delta front into Budgewoi Lake and mud deposits near the sand barrier (Roy, 1971). A dredged channel around the northern edge maintains circulation into Lake Munmorah for the power station.

The entrance flood-tidal delta This well-developed delta is ensconced on bedrock at its mouth and, except for dredging, is largely inactive between floods (Fig. 3(b)–(d)). The restricted mouth reduces tidal exchange and flushing as well as fish biodiversity. Although Tuggerah Lakes are oligomesotrophic, based on water column nutrients (King & Hodgson, 1995), eutrophic conditions were thought to have existed during the 1980s and 1990s (Roberts, 2001). Sediment attached nutrients and their release are now significant issues because Council has greatly reduced current nutrient inflows (Roberts, 2001).

Fluvial deltas

The fluvial deltas are essentially digitate deltas or silt jetties (Bird, 1962) although there is a very small island, most likely produced by dredging, at the mouth of both Wyong River and Ourimbah Creek (Fig. 1). All fluvial deltas correspond to the stable channel-mouth bar delta of Smith (1991) or Postma's (1990) mouth bar type delta. However, all deltas have a single channel draining a delta plain (no distributaries) and would have had an arcuate river-mouth bar similar to that described by Flack & Erskine (1996) for Middle Creek in Narrabeen Lagoon, NSW. However, for navigation and ease of access, the river-mouth bars on Wyong River and Ourimbah, Wallarah, Tumbi Umbi and Saltwater creeks have had relatively deep channels dredged through them (Fig. 4).

Wyong River Delta Interestingly, NSW Fisheries annual reports from the late 1880s mention shoaling at the mouth of Wyong River before urbanisation but after first settlement. This is expected for this type of delta because of sand deposition and bar formation as flow leaves the confines of the delta channel and enters Tuggerah Lake (Flack & Erskine, 1996). A well-defined delta front and prodelta develop on the lake side of the river-mouth bar (Flack & Erskine, 1996).

This process occurs irrespective of whether sediment supply is increased by clearing, construction and/or other types of human disturbance.

Ourimbah Creek Delta NSW Fisheries annual reports for the 1880s also refer to shoaling at the mouth of Ourimbah Creek and the above comments also apply. Before dredging, this was one of the best examples of a silt jetty, along with Dora Creek in Lake Macquarie, in NSW (Fig. 4).

Wallarah Creek Delta This delta does not extend very far into Budgewoi Lake (Fig. 4) because Wallarah Creek currently has a largely undeveloped, small, lowland catchment. Urbanisation is restricted to near the mouth but further development will occur in the future.

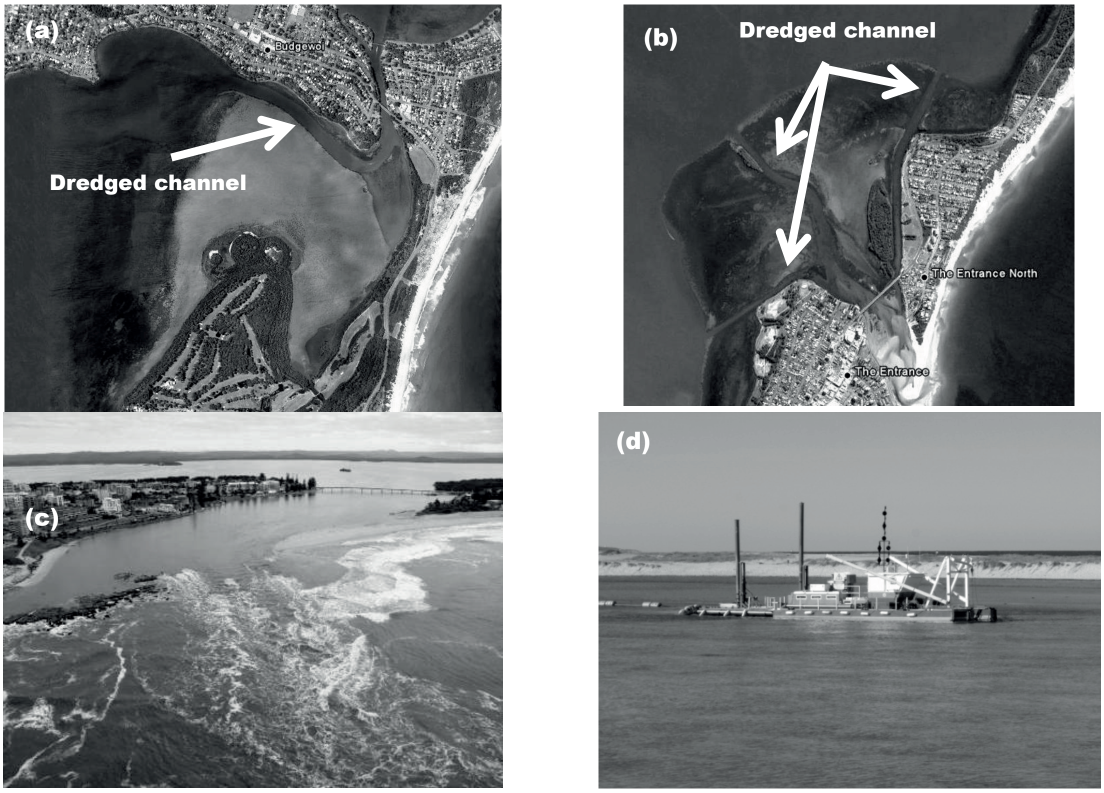

Fig. 3 (a) Budgewoi Sand Mass at atrophied flood-tidal delta, December 2009. (b) The Entrance flood-tidal delta, June 2005. (c) June 2007 flood discharging through The Entrance. Note the bedrock outcrop in the middle left of photo. (d) Dredge working at The Entrance, 23 April 2006.

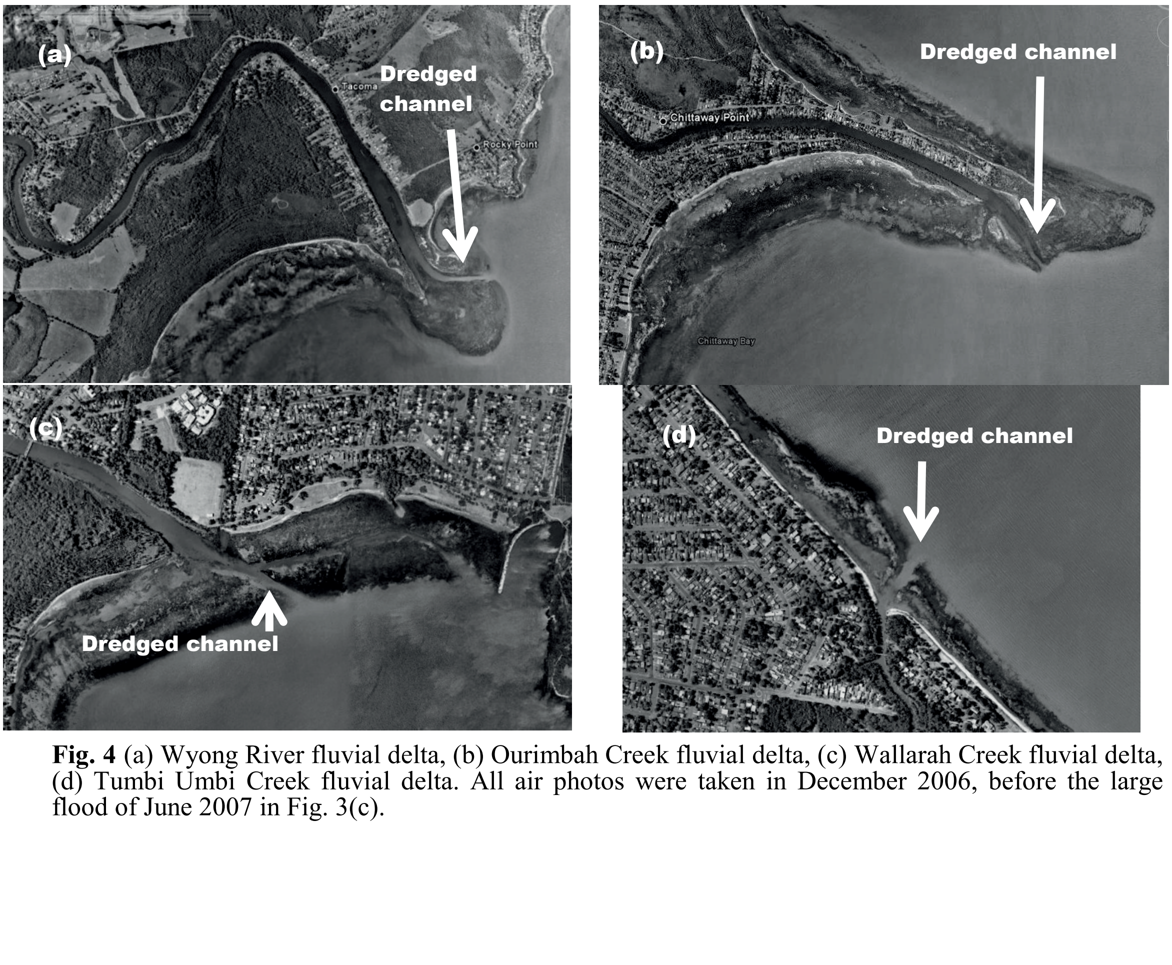

Fig. 4 (a) Wyong River fluvial delta, (b) Ourimbah Creek fluvial delta, (c) Wallarah Creek fluvial delta, (d) Tumbi Umbi Creek fluvial delta. All air photos were taken in December 2006, before the large flood of June 2007 in Fig. 3(c).

Small fluvial deltas Catchment urbanisation since the 1950s and channel disturbance accelerated delta sedimentation on Tumbi Umbi and Saltwater creeks. River-mouth bars prevented boat access to Tuggerah Lake and led to extensive dredging (Fig. 4). Funding for dredging the mouth of Tumbi Umbi Creek was an issue for the 2009 Commonwealth Government elections because the incumbent government approved expenditure for dredging without a proposal.

HUMAN IMPACTS ON THE DELTAS OF TUGGERAH LAKES

Geomorphology

The flood-tidal deltas are currently inactive, except for modification by wind-induced currents and floods. While they provide important shallow water habitats, the Budgewoi atrophied entrance is not ensconced on bedrock (Roy, 1971; Peat, 1973) and may offer the potential for greater tidal exchange through a rock-trained artificial entrance. Such an action may cause the final atrophy of the mouth at The Entrance.

The dredged channels through the river-mouth bars of Wyong River and Ourimbah Creek have changed the orientation of the channel and hence the locus of deposition. The geomorphological significance of digitate deltas in NSW has never been assessed before large scale human-induced changes have been undertaken. The new orientation of the channel is likely to change the locus of deposition, transforming a digitate delta to a bird's foot delta. The essential difference between these types of deltas is that bird's foot deltas evolve by repeated avulsion, changing the locus of deposition and leading to large scale changes in the location of the delta channels. Digitate deltas, on the other hand, continue to build long linear silt jetties, like fishing rods, into the receiving lake (see Bird, 1962; Bird & Rosengren, 1971). The geoheritage value of silt jetties in NSW is likely to be significant internationally and greater protection needs to be afforded such landforms from short sighted and poorly justified modifications.

Sedimentology

The age of the Budgewoi Sand Mass and the barrier separating it from the ocean are currently unknown. A program of dating by single grain optically stimulated luminescence should be carried out before the barrier and sand mass are further altered in any way. If the Budgewoi mouth was abandoned by a 1.5 m lowering of sea level during the late Holocene, as postulated, then historical sea level rise due to a CO_2-warmed Earth may maintain a new artificial entrance, particularly as rates of rise increase in the near future.

Little is currently known of river-mouth sedimentation in Tuggerah Lakes despite the whole-sale modification by dredging. Such work should be conducted before any more dredging is completed to determine whether the results of Flack & Erskine (1996) are relevant here.

Hydrodynamics

Given the low tidal range in the estuary (0.02–0.03 m), wind stress by moderate to strong winds is the most important mixing process in the absence of floods (King & Hodgson, 1995; Roberts, 2001). The lagoons have a large surface area and are shallow, resulting in well mixed conditions (King & Hodgson, 1995; Roberts, 2001). However, all fluvial deltas are lined by tall pure stands of *Casuarina glauca* Sieber ex Spreng, which protect the delta channels and reduce the effect of wind shear. As a result, during low spring and summer streamflows, stratification often develops where there are deeper pools (Erskine *et al.*, 1999; Turner & Erskine, 2005). Where dredging locally deepens the channel in the fluvial delta to exceed a threshold depth, stratification also develops, causing hypolimnetic anoxia and benthic fish kills (Erskine *et al.*, 1999; Turner & Erskine, 2005). It is a common local misconception by delta residents that dredging is the solution to increased fish production in the delta channels because they cannot "see" stratification, unless iron oxidation occurs across the oxycline, as documented in the Snowy River in the autumn of 1998 (Erskine *et al.*, 1999; Turner & Erskine, 2005). Furthermore, during the annual autumn cooling when there are also low streamflows, salt stratification persists because the density change induced by declining water temperatures is more than compensated for by the high salinity below the halocline. Indeed, the clear salt water below the halocline can be many degrees warmer than the surface water, producing reverse thermal stratification (Erskine *et al*., 1999; Turner & Erskine, 2005). Provided hypolimnetic anoxia does not occur, "warm" fish are often caught from deep pools during autumn.

Fluvial shear by small summer floods on the pycnocline occasionally cause mixing of deep pools in the upper estuarine channels of Wyong River and Ourimbah Creek. The mixing of deep hypolimnetic anoxic water with well oxygenated shallow epilimnetc water has produced occasional small scale fish kills. Harvesting of these small summer floods for Gosford-Wyong's water supply should be adopted to reduce the magnitude and frequency of such fish kills.

Seagrasses

Extensive seagrass loss with little recovery has occurred in recent years throughout the world because of many interacting factors usually involving reduced light penetration (e.g. Walker & McComb, 1992). Three aquatic angiosperms occur in Tuggerah Lakes: *Zostera capricorni* Ascherson, *Halophila ovalis* (R. Brown) Hooker f. and *Ruppia megacarpa* Mason (Higginson, 1965; King & Holland, 1986; King & Barclay, 1986; King & Hodgson, 1986, 1995; Underwood *et al*., 2003). While the quality of seagrass mapping in Tuggerah Lakes is variable, King & Holland (1986) showed that all three species of seagrasses were present on both flood-tidal and fluvial deltas in the summer of 1985. Seagrasses were also present on other landforms but the deltas were the preferred habitats. King & Hodgson (1986) documented changes in seagrass spatial distribution between 1980 and 1985 in Tuggerah Lakes and demonstrated that there are marked natural fluctuations that do not appear to follow any regular or predictable pattern. They quite rightly concluded that any change in seagrass distribution must be greater than natural variability assessed for control areas to be a "real" change. While such control areas may be difficult to determine, there is little evidence that the seagrasses on the deltas of Tuggerah Lakes have declined. Furthermore, Higginson's (1965) conclusion that *Zostera* tends to favour sandy sediments, *Ruppia* clayey sediments and a mixed community on intermediate sediments is not supported by comparison of King & Holland's (1986) maps with Fig. 2.

CONCLUSIONS

The geoheritage value of flood-tidal and fluvial deltas in NSW needs to be assessed because dredging is modifying the formative processes and changing the evolutionary pathway. Geoheritage also needs to include depositional landforms, as well as traditional subjects such as type sections, fossils and karst. The flood-tidal deltas of Tuggerah Lakes have either atrophied or become inactive, greatly reducing tidal exchange and flushing. The reactivation of the Budgewoi mouth should be considered given that it is not hung up on bedrock, sea level is currently rising and rock training walls could protect the mouth from sedimentation. The rationale for dredging the river-mouth bars of the silt jetties needs detailed scrutiny to determine whether the detriments exceed the benefits, both of which are currently undocumented. Seagrass dynamics are so variable that it is difficult to unambiguously determine whether human impacts have caused a recent decline.

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