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Volumetric change in a flood-tide delta: application of the 'Cut and Fill' process flow diagram for decision support in port management at Lakes Entrance, Victoria, Australia.

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KEYWORDS: Ebb-tidal delta, flood-tidal delta, Cut and Fill, time-series, volumetric analysis.

ABSTRACT

Information flow paths in decision support do not always include archival data, especially if it has not been subject to analogue-to-digital conversion. We exemplify the benefit of making such conversion by contrasting the results of 'Cut and Fill' volumetric computations (made possible by the analogue-to-digital conversion of hydrographic charts) with published (non-spatial) accounts of net accretion on the flood-tide delta, directly up-tide of the Entrance Channel, at the artificial entrance to the Gippsland Lakes, Victoria.

A discrepancy of about 20% leaves decision support based on the non-spatial computation relatively unequal to what is required during forthcoming deliberations about planning to mitigate the effects of net accretion on the flood-tide delta, that threatens to make port channels un-navigable.

The greater modelling scope offered by the spatial database developed for this project allows visualisation of the flood-tide delta changes. Application of the visualisations includes stakeholder 'mental map' stabilisation. This will have to be an issue once the explanation for the net accretion of the flood-tide delta is accepted. This explanation refers, again, to the spatial data that would be available in decision support if the spatial data used in this project was incorporated in the decision support system. It is clear that ebb-tidal flows are no longer able to balance the accreting forces of flood-tide flows that bring sands in from Bass Strait. The failure is due to reduced river discharge in the face of entirely documentable falling rainfall trends, inter-regional water transfer, and expanded irrigation in the Gippsland Lakes catchment.

The solution to the channel maintenance problems faced by Gippsland Ports may be in implementation of Integrated Coastal Zone Management (ICZM). In that case, the accompanying Action Plan will probably refer to spatial modelling. Such modelling would support a range of decision support functions, including flood-tide delta volume monitoring, and allocation of rewards for ecological services. Displays for such decision-support data are exemplified from query of the same spatial database as built for the 'Cut and Fill' computations.

BIOGRAPHY OF PRESENTER

Peter Wheeler is a fourth year undergraduate student in the School of Geography and Environmental Science and the Faculty of Education at Monash University, Melbourne, applying GIS technologies to issues related to the geomorphology of coastal systems. His Honours year thesis findings refer partly to work presented in this paper.

INTRODUCTION

The coasts of south-eastern Australia feature many coastal lagoons sheltering behind sandy barriers. The ocean beaches (and fossil beaches under the sand beach-ridges behind them) of such barrier systems are aligned to the refraction pattern of the dominant beach-building swell wave trains (Davies, 1980: 39), and promoted in their evolution by small tidal ranges, abundant sand supply, and very slow, if any, relative sea level change (e.g. see Bird 1967), this latter being a comparatively common environmental attribute since the culmination of the Flandrian Transgression (18000 to 6000 years before present) (e.g. see Bird, 1984: 40-41). One such barrier, separating the extensive coastal lagoon system known as the Gippsland Lakes (Victoria, Australia) (refer Figure 1) from the eastern approaches to Bass Strait, faces the ocean swell wave trains across Ninety Mile Beach.



Figure 1. The outer Holocene sandy barrier system known as the Ninety Mile Beach in the vicinity of the Gippsland Lakes artificial entrance. The township of Lakes Entrance is situated to the right of photograph. Source: Wheeler (2005)

The geomorphological evolution of the Lakes and barrier system has been researched by Bird (1961, 1963, 1965, 1967, 1978) and Thom (1984), and lately outlined with some documentation by Bird (2000: 177). Lagoon

hydrology may be marine if the barrier is permanently open to the sea and the hinterland rivers are of low discharge. However, if barriers are closed to the sea, freshwater ecology will prevail. At the Gippsland Lakes (pre-1889), such was the case, except during periods when floods would cause a narrow break through the outer barrier. At these times, the flood tide could enter the lakes and create what would become an ephemeral entrance, much valued by coastal traders servicing the hinterland area, especially the townships of Sale and Bairnsdale (e.g. see Bird and Lennon, 1989).

The opening of a permanent engineered entrance to the Gippsland Lakes in 1889 provided a means of year-round navigation between the lakes and Bass Strait, and enabled continued port development nearby at a place that came to be known as Lakes Entrance. Within the Entrance and Reeves Channels (refer Figure 2), the movement of flood and ebb tides distributed and re-distributed sediment. The ebb tide, stronger than the flood tide because of the contribution from the unregulated influent rivers, soon built an ebb-tide delta just offshore in Bass Strait. Kept from dissipating by the ubiquitous swell wave trains, despite the tendency for longshore currents to prevail from time to time, it has constituted a navigation hazard since about 1892. Conversely, any tendency for the flood tide to build a flood-tide delta was long counteracted by the force of the ebb tide, and if that was not enough, it was certain that sooner or later a large catchment flood escaping seaward through the artificial entrance would quickly clear any sand accretion away.

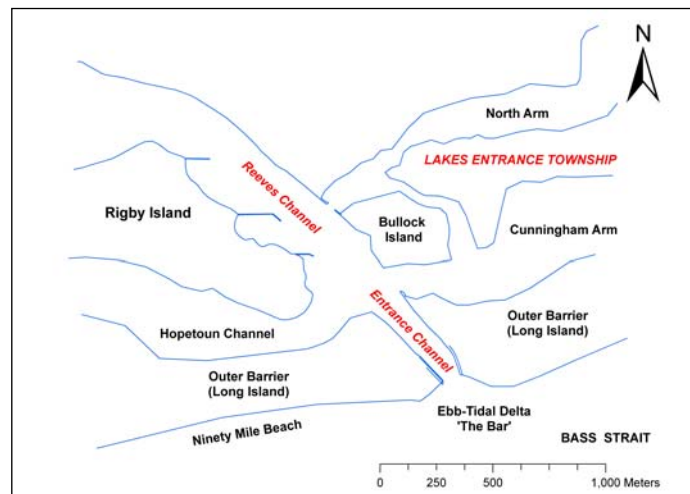


Figure 2. The study area, encompassing the Entrance and Reeves Channels (with 2005 shorelines represented). Since the artificial entrance to Bass Strait was completed in 1889, the formation of extensive flood-tidal deltaic deposits has taken place within the Reeves and Entrance Channels. Source: Wheeler (2005)

Clearly, new trends in sedimentological equilibrium would be expected to emerge with any alteration to the relative significance of ebb and flood tidal flow at the artificial entrance area. The most scope for provoking this lies in catchment management change involving flood control (once a very big issue in Gippsland, see Strom, 1941), and stream regulation, including that required for irrigation scheme expansion (the Macalister Irrigation District) and inter-regional water transfer (via the Thomson Dam) (refer Figure 3). To the extent that these diminish the volume of ebb-tidal flows, flood-tidal delta accretion can be expected along with increases in channel maintenance costs.

Even before such catchment management changes, regular bathymetric survey was called for so that the navigation channels could be well marked. The bathymetric record (1889-2005) offers nineteen channel morphology “snapshots”/charts acceptable for analogue-to-digital conversion as a prelude to time-series spatial modelling.

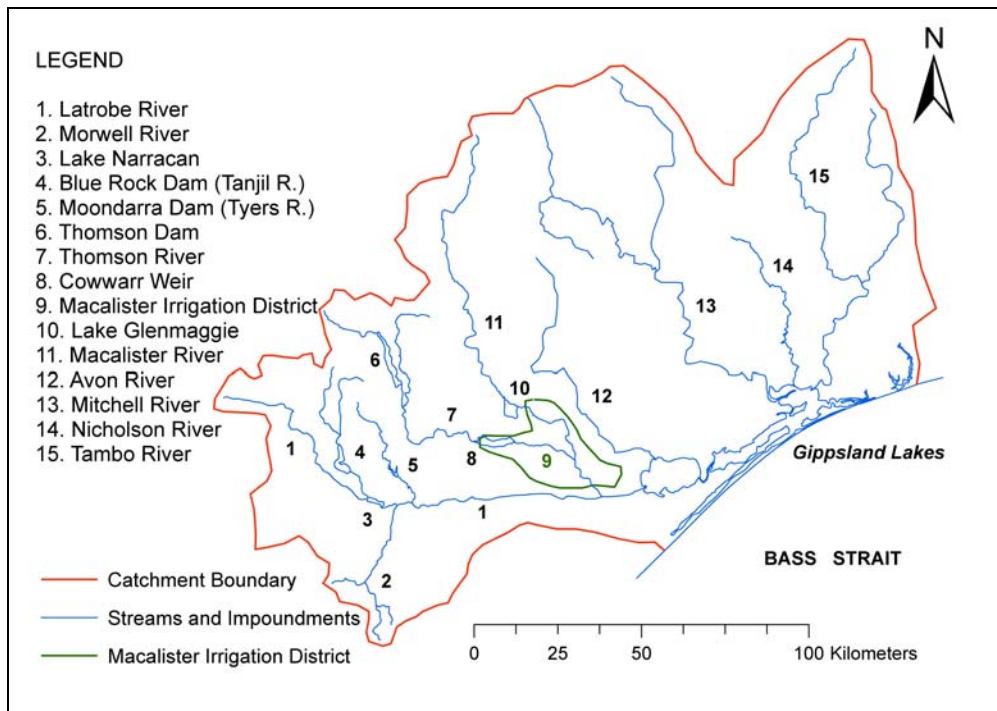


Figure 3. The Gippsland Lakes catchment encompasses over 20000 square kilometres, and is drained by seven major river systems. Major impoundments include the Thomson Dam and Lake Glenmaggie. The Macalister Irrigation District is the largest irrigation scheme in the catchment. Source: Wheeler (2005)

PROJECT SPATIAL DATABASE BUILDING

The scope for analogue-to-digital conversion of time-series port-channel bathymetric data for input to 3D modelling (e.g. using a GIS) has not been taken advantage of by port authorities. The potential benefits of implementing such modelling refer not only to establishing common mental maps among stakeholders, but also to exploiting the support offered by the underlying database for facilitating spatial query, as for instance in monitoring channel morphometry changes. Adoption of the digital spatial data handling involved would be in conformity with State and Commonwealth spatial data policy (VSIS, 2005; SIIAA, 2001).

In this study, we focus on the flood-tidal delta morphometry changes in the Reeves and Entrance Channels with special reference to the former. Bass Strait ebb-tidal delta changes are not well-enough documented for time-series digital spatial modelling of the kind exemplified here to be supported.

From the time-series digital spatial dataset we have derived:

- a) digital elevation models (DEMs) corresponding to each time-series 'snap-shot' so that changes in the nature and distribution/bulk of the flood tide delta could be visualised and also used for;
- b) time-series volumetric quantification of morphometry changes (by use of the 'Cut and Fill' function), and;
- c) time-series mapping of morphological change distribution.

A concise data flow path for this project (refer Figure 4) includes reference to these project outcomes.

Stage 1: Analogue-to-digital conversion

The process of georeferencing all digitised charts to the same horizontal datum (GDA94 MGA Zone 55) entailed the location of common Ground Control Points (GCPs) applying to each chart over the entire time period encompassed in the study. Ideal GCP locations were those whose position had not altered for extended time periods (for example, prominent coastal engineering structures). Upon selection of potential GCP sites, accurate latitude/longitude coordinates were obtained using differential GPS (dGPS) technology. GCPs obtained via dGPS were converted to GDA94 MGA Zone 55 coordinates from World Geodetic System 1984 (WGS84) coordinates in *ArcGIS 9*. Upon

completion of datum transformation of GCP locations, each digitised hydrographic chart image was georeferenced in *ESRI ArcMap*.

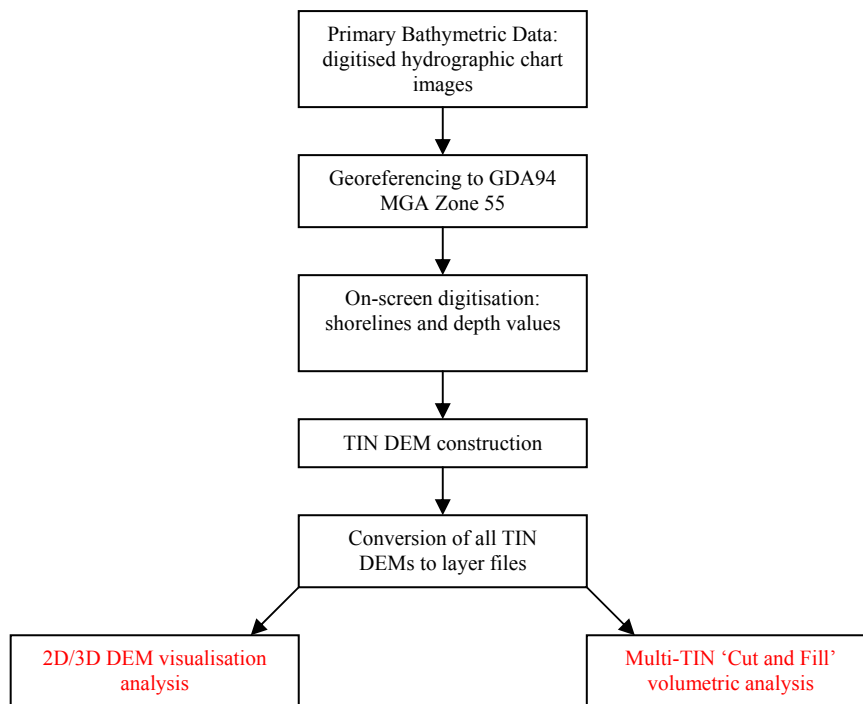


Figure 4. Concise project process flow diagram

Stage 2: DEM Construction

Manually digitised shoreline and depth value data (obtained via on-screen digitising methods) were combined in *ArcGIS 9 3D Analyst* software to facilitate construction of both TIN and Grid DEMs. The accuracy concerns with the use of Grid DEMs referred to by Chang (2004: 147) led us to use only the TIN DEMs throughout the remainder of the project reported here.

Upon completion of initial DEM construction, all models were converted to layer files in *ESRI ArcMap* to reflect the same depth value colour ramp. Thus, all DEMs utilise the same depth legend, allowing all models to be directly comparable over the entire time-series covered by this study.

Stage 3: DEM visualisation

The primary task of bathymetric DEMs is to provide high quality time-series visualisations. DEMs can be displayed in a variety of ways. They can be displayed as two-dimensional images, with colour changes denoting depth differences, and in this way, smaller DEM ‘thumbnail’ images can be displayed besides one another to show the nature of time-series bathymetric evolution within the entire study area (e.g. see Wheeler and Peterson, 2005) (refer Figure 5). However, it is when they are displayed as oblique three-dimensional images that DEMs exhibit their greatest strengths as a visualisation tool. Use of an *ESRI ArcGIS 9* extension called *ArcScene* allows DEMs to be displayed three-dimensionally, and such deployment allows an array of time-series user-defined images to be obtained (refer Figure 6).

Time-series two and three-dimensional DEM visualisations can be queried in different ways to allow a similar ‘mental map’ of bathymetric evolution to be provided for all relevant coastal zone stakeholder groups.

Through these visualisations, the nature of:

- *general study area bathymetric evolution;*
- *the bathymetric evolution at important individual locations;*
- *the influence of physiographic processes on sediment movements;*

- the influence of extreme environmental forcings events on bathymetric evolution;
- the effectiveness of study area coastal engineering structures, and;
- the effectiveness of historical study area dredging regimes

over a long time span within the study area can be comprehended and documented.

Stage 4: ‘Cut and Fill’ volumetric analysis

Quantitative estimation of sediment volumetric change between successive time-series DEM ‘snapshots’ was assembled by application of the ‘Cut and Fill’ function of the *ArcGIS 9* software *ESRI 3D Analyst*. By comparing the bathymetric contours of two separate TIN DEMs using this software, model-dependant area (m^2) and volumetric (m^3) accounts of bathymetric change can be derived. Exemplifying this process, a resultant ‘Cut and Fill’ diagram (from which volumetric change calculations are obtained) is provided at Figure 7. Comparison between all time-series DEMs of similar bathymetric coverage reveals the amount of net sediment gain or loss over user-defined ‘snap-shot’ intervals.

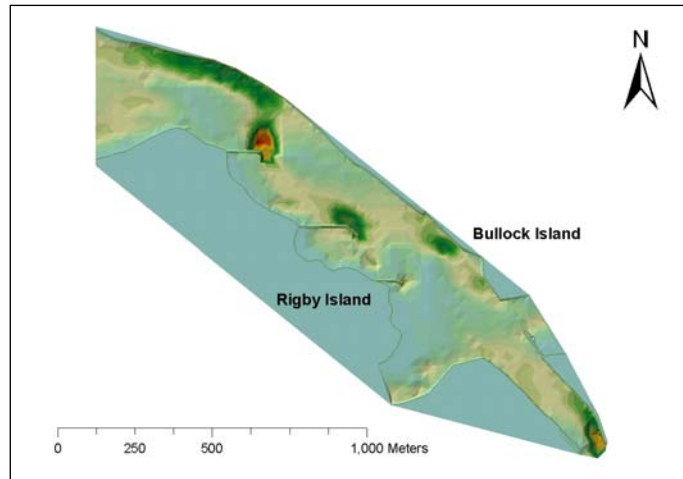


Figure 5. 2D TIN DEM image of Entrance and Reeves Channels (1993 thumbnail image shown). Source: Wheeler (2005)

As all DEMs developed for this research study

exhibited differing study area bathymetric coverage,

Cut and Fill ‘Analysis Masks’ (consisting of a polygon shapefile constructed in *ESRI ArcCatalog* and *ArcMap*) were built. This allowed only certain uniform sections of the study area to undergo Cut and Fill comparative analysis. Thus, whilst an indication of overall flood-tidal accretion can be obtained by viewing net volumetric change figures, only figures referring to particular analysis masks can be directly compared in time series.

It should be noted that all area and volumetric figures derived from Cut and Fill analysis of study area DEMs are model dependent. Inherent and introduced data errors may well have affected the accuracy of the input data (DEM). The proximity of hydrographic data survey timings to dredging operation timings can never be quantified, and this is a variable factor that should be considered when assembling data on net volumetric change. The seasonal timings of hydrographic surveys must also be considered, because the operation of dynamic environmental forcings/regimes (and their effects upon channel bathymetry and sediment volumes) will differ between surveys. Thus, a linear volumetric gain/loss trend between DEM ‘snap-shots’ should not be assumed.

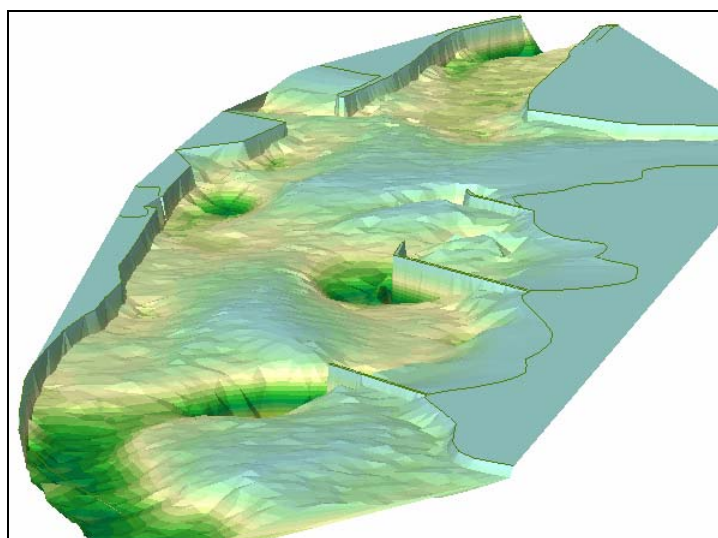


Figure 6. Oblique TIN DEM visualisation (1994 model shown) of the Reeves (foreground) and Entrance (background) Channels. Use of such models allows 3D visualisation of flood/ebb channels and sediment accretionary areas. Source: Wheeler (2005)

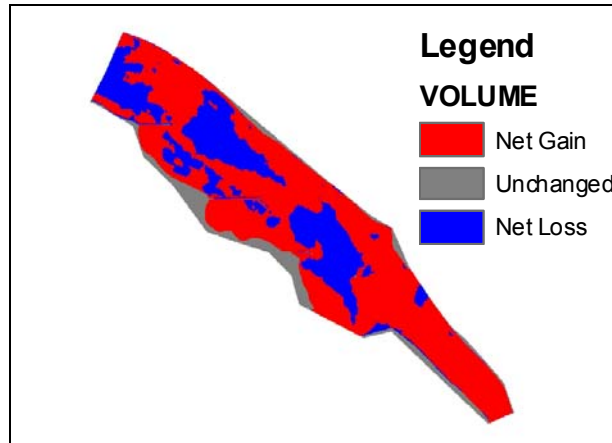


Figure 7. Resultant 'Cut and Fill' diagram produced after combination of TIN DEMs in *ESRI 3D Analyst*. This diagram of sediment net loss/gain in the Entrance and Reeves Channels relates to the period June 1994 - January 1998, when volumetric analysis shows there was a resultant sediment gain of some 189,876.7 m³. Source: Wheeler (2005)

RESULTS

Continual ports authority channel dredging maintains Entrance Channel navigation by removing flood tide delta sands. However the growth of the delta has gradually imposed greater demands on the dredging programme. Most of the flood-tide delta accretion is in the Reeves Channel, and the rate and pattern of its growth (undredged except for its proximal periphery) is documentable from the bathymetric record.

Results derived from 'Cut and Fill' analysis of generated DEMs is provided at Table 1. An inexorable growth in the flood-tide delta is apparent: slow during the period 1889-1975 (in the 'snap-shot' interval that encompasses the Macalister Irrigation District development and expansions between 1924-1959 (SRW, 2005)), and faster since the Thomson Dam commissioning and commencement of large-scale inter-regional water transfers after 1983 (Melbourne Water, 2004). Sediment management regimes also were altered in 1977 with the permanent introduction to Lakes Entrance of the side-cast dredger *April Hamer* (refer Figure 8), whose dredging methods across the ebb-tidal delta are considered by Bird (2000, 238) to enhance flood-tidal delta nourishment. Despite the *April Hamer* shifting an estimated 255,000 to 355,000 m³ of sand per year at various locations within the ebb and flood-tidal delta areas (DNRE 1998), and the introduction by Gippsland Ports in January 1999 of a sediment transfer system, (which has either bypassed or removed nearly 1,000,000 m³ of sediment from the Entrance and Reeves Channels to January 2005) (SSPL, 2005), both DEM visualisations and volumetric analysis (refer Table 1) indicates that large-scale flood-tide delta sediment accretion has been continuous.



Figure 8. The *April Hamer* dredging at the offshore ebb-tidal delta during the ebb-tide. Source: Wheeler (2005)

The information assembled in Table 1 would be extremely useful in formulating dredging strategies such as would lie behind the present programme for navigation channel maintenance at Lakes Entrance. According to Port Authority estimates, the Reeves Channel between August 1975 and January 2005 saw approximately 522000 m³ of sediment accumulation (Gippsland Ports, 2005). This figure is less (by 186,612 m³) than the sediment accumulation figure derived from 'Cut and Fill' modelling (Table 2). It can be argued that at present, the flood-tide delta is so big as to place hitherto uncalled for demands upon the current dredging programme, and the estimations should be replaced by spatially quantitative modelling.

Analysis Mask/Year	Volumetric Gain (m ³)	Volumetric Loss (m ³)	Net Vol Gain/Loss (m ³)
A: 1889-1892	35517.9	360972	-325454.1
A: 1892-1914	209754.07	135267.72	74486.35
B: 1926-1941	424586.06	135425.88	289160.18
C: 1941-1964	360442.91	214192.44	146250.47
D: 1964-1975	106467.61	358722.39	-252254.78
D: 1975-1985	403946.45	93031.89	310914.56
D: 1985-1987	127096.94	89075.51	38021.43
E: 1987-1989	221690	70354.4	151335.6
E: 1989-1991	118137.91	202423.14	-84258.23
E: 1991-1992	71879.75	160594.28	-88714.53
E: 1992-1993	197422	86801.3	110620.7
E: 1993-1994	144594	71286.4	73307.6
E: 1994-Jan 1998	290792.6	100915.9	189876.7
E: Jan 1998-Jul 1998	62271.4	232043.6	-169772.2
E: Jul 1998-1999	255797.21	67126.9	188670.31
E: 1999-2000	118273.5	132952.9	-14679.4
E: 2000-2005	181615.76	89326.62	92289.14

Table 1. Flood-tidal delta (Entrance and Reeves Channels) sediment volumetric change figures: 1889-2005 (Source: Wheeler, 2005)

Analysis Mask/Year	Volumetric Gain (m ³)	Volumetric Loss (m ³)	Net Vol/Loss Gain (m ³)
D: 1975-2005	770386	61774	708612

Table 2. Flood-tidal delta (Reeves Channel only) sediment volumetric change figures: 1975-2005 (Source: Wheeler, 2005)

DISCUSSION

Reduction in the power of ebb flows during the last three decades is related to catchment development issues, such as increased irrigation demands, water appropriation from the catchment via impoundments such as the Thompson Dam, and flood control. However, the falling catchment water yield refers also to falling rainfall trends (Wheeler, 2005) and de-watering of aquifers (on-shore and off-shore, see Lawrence, 1992; DSE, 2005), and to long-term land-use management and practice changes. It is interesting to note that Rosenfeld (2000) has published research results suggesting that the falling rainfall trend may be due to aerosol cloud pollution from up-wind urban and industrial sources (e.g. from Melbourne and Adelaide) which can alter rain-producing processes. Falling rainfall trends have been noted in such situations in other parts of the world (e.g. see Givati and Rosenfeld, 2004).

Whilst deliberate release of water from the controlled western catchments (Latrobe and Thomson Rivers) at times of flooding in the largely unregulated eastern catchments (Avon, Mitchell, Tambo and Nicholson Rivers) may encourage greater ebb-tidal scouring at the artificial entrance by simulating natural flow regimes, the flood tide delta is now so large (refer Figure 9) that any increased flow may be diverted into the North Arm to flood the Lakes Entrance township as occurred in June 1998 (e.g. see McMaster, 1998; Tan *et al.*, 2002; Wheeler, 2005).

Clearly, to continue the current dredging strategies into the future (as proposed by Gippsland Ports (2005) in their recently released Draft Long-Term Management Plan for Dredging) will not significantly reduce the flood-tidal delta volume. One strategy planned is to continue the use of the *April Hamer*. However, whilst the use of this vessel has been important for maintaining navigability across the ebb-tidal delta since 1977, it is clear that its dredging operations during flood-tide may have contributed heavily to flood-tidal delta nourishment. In sediment transport terms, the side-cast dredging operation promotes continued suspension of sediment throughout the water column, which simulates high wave energy conditions at the ebb-tidal delta (even in calm sea conditions) during dredging operations. Thus, the scope for flood tide entrainment to augment the volume of the flood-tidal delta is enhanced.

The application of volumetric results reported here is relevant for future Gippsland Lakes catchment Integrated Coastal Zone Management (ICZM). Integration is clearly called for, and is long overdue in this instance, because the flood-tide delta changes refer to matters falling within the jurisdiction of all the managers represented in the Gippsland Lakes catchment (refer Figure 10). Whilst port maintenance problems must be dealt with by Gippsland Ports (the authority charged with maintaining navigation at the Gippsland Lakes artificial entrance area), they have been created partly by other catchment authorities (including: Melbourne Water, Southern Rural Water, East Gippsland and West Gippsland Catchment Management Authorities, and the Gippsland Coastal Board).

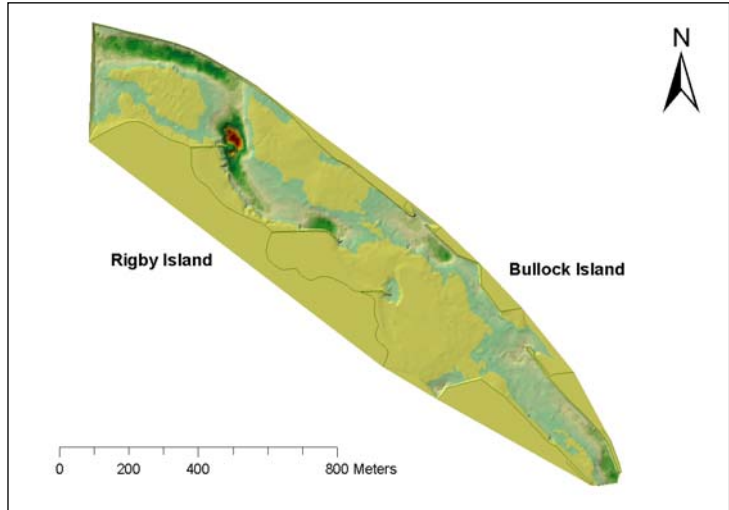


Figure 9. Flood-tidal delta shoaling areas can be viewed by shading all DEM depths under 1.5 m the colour yellow. Thus, the extent of shallow flood-tidal delta zones can be compared in time-series (2005 2D DEM image shown). Source: Wheeler (2005)

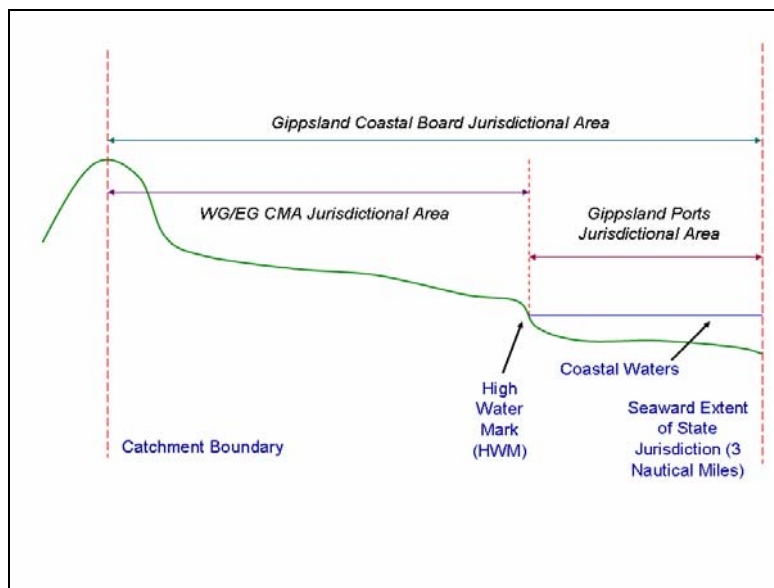


Figure 10. Gippsland Lakes catchment management agency zones of jurisdiction. Gippsland Ports must obtain a permit for dredging from DSE, who manage the sea-floor from the high water mark to 3 nautical miles offshore (seaward extent of state jurisdiction). Source: Derived from reference to Wescott (1998) and DSE (2004)

Implementation of ICZM within the Gippsland Lakes catchment would require *all* catchment stakeholders to cooperate while planning for the allocation of access to natural resources. More formally, Gippsland Ports could be granted the equivalent of land-use planning Referral Authority status (e.g. see Eccles and Bryant, 1999, 22-23), so that each catchment planning decision that threatens to reduce streamflow inputs to the Gippsland Lakes (which would impact upon sediment management operations at the artificial entrance) is subject to Gippsland Ports approval.

As it may indeed prove impossible for Gippsland Lakes catchment authorities to reinstate natural streamflow regimes in the future (so as to enhance ebb-tidal sediment scouring), it seems that deliberations over any future sediment management scenarios for the artificial entrance area will most likely centre upon the use of coastal engineering options. We suggest that any such mitigation strategy must be planned to utilise and harness existing natural processes in order to create a sustainably engineered sediment management regime.

CONCLUSIONS

'Cut and Fill' volumetric modelling has clearly shown that flood tide delta accretion in the Entrance and Reeves Channel has been inexorable since the mid-1970s; evidently, the most significant modification to sediment transport and depositional processes occurred over the relatively short time period between 1975 and 1985. The continuation of this net sediment accretionary trend in the channels to January 2005 indicates that only restoration of the ebb-flow dominance (e.g. by restoring the streamflow input to the lakes from the catchment) and/or significant engineering input is likely to reverse this accretionary trend.

Any options for adoption of engineering solutions should all be tested via three-dimensional hydrodynamic modelling. Adoption of a three-dimensional modelling approach has been shown here to 1) yield the more defensible monitoring, and 2) create potential for a greater stakeholder understanding of coastal issues. Digital spatial data handling and spatial analysis in future decision support is clearly called for.

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