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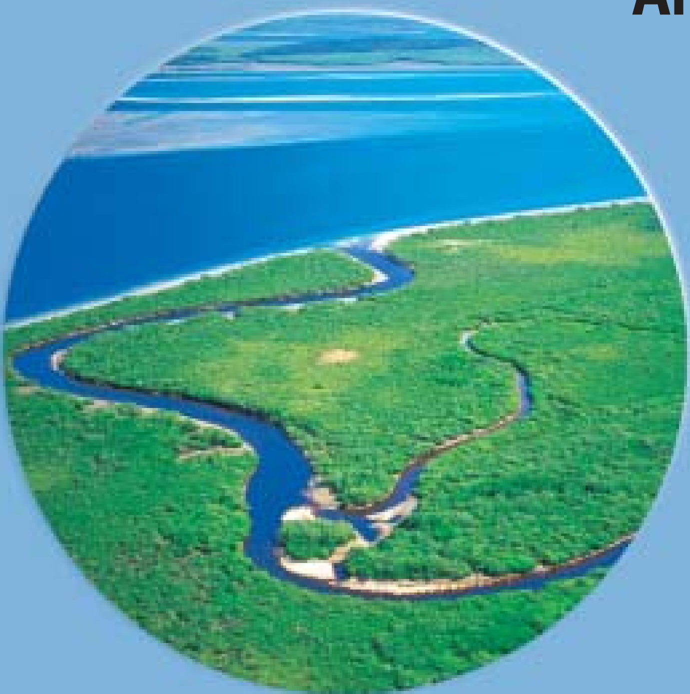

An initial assessment of estuarine geomorphic habitats as indicators of waterway health

Lynda Radke
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Australian Government
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CRC for Coastal Zone
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An initial assessment of estuarine geomorphic habitats as indicators of coastal waterway health – Final report

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June 2006

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Executive summary

The central aim of the Coastal CRC's Comparative Geomorphology of Estuaries Project was to improve understanding of Australia's near-pristine estuaries. The project produced a total of four technical reports. These are:

- A summary report of the project (Radke *et al.* 2006a)
- A literature review of the current knowledge and management of Australia's near-pristine estuaries (Murray *et al.* 2006)
- A report describing the mapping of near-pristine estuaries (Creasey *et al.* 2006)
- A report investigating the potential of the mapped habitat areas as indicators for assessing catchment disturbance (this report: Radke *et al.* 2006b).

An important goal of the Comparative Geomorphology of Estuaries Project of the Coastal CRC was to develop indicators of estuary environmental condition based on geomorphic habitat area information. The habitat areas were derived from the GIS mapping of near-pristine estuaries completed during the life of the project, and a much larger set of similar earlier maps of mainly modified estuaries (NLWRA 2002; Harris *et al.* 2002). It was suggested by the project proponents that the geomorphic areas of near-pristine estuaries would not only provide baseline information on key biophysical attributes of the various types of estuarine systems, they could also be used as benchmarks against which to quantify changes that have occurred in more modified estuaries. An estuarine geomorphic indicator would thus help us understand how catchment modifications such as land clearing have changed the size of habitats in the estuaries and how modifications to the habitats themselves can affect estuary condition.

In this preliminary study, for the various types or classes of Australian estuaries, we compared data for a suite of habitats from estuaries with different levels of modification, based on the NLWRA condition classification. The results were very encouraging. We found systematic changes in geomorphic indicators with diminishing condition status (i.e. from near-pristine, through largely unmodified and modified to severely modified) in the case of most classes of estuary. Estuaries that receive input from the more disturbed catchments had higher levels of maturity, meaning that they contained relatively more sediment. This was evidenced by apparent increases in the areas of tidal sandbanks, intertidal flats and mangroves in tide-dominated systems. For wave-dominated systems, intertidal flats were larger. The wave-dominated class of estuaries also appears to have experienced a reduction in saltmarsh area. Our results suggest that maturity or filling of some Australian estuaries has been accentuated by higher sediment loads that are most likely the result of catchment land clearing. This has produced a change in the distribution and abundance of estuarine depositional environments that can be quantified and may serve as an important type of indicator of environmental condition when compared to the entire dataset. However, we would like to emphasise that a more thorough vetting of the data is needed to confirm these results and this is currently underway at Geoscience Australia.

Introduction

An important aim of the Comparative Geomorphology of Estuaries Project was to increase understanding of the environmental characteristics of near-pristine estuaries and provide a reference dataset for quantifying changes in habitat patterns in modified systems. It was anticipated that this aim would be fulfilled by identifying key geomorphic characteristics of the near-pristine systems that may be used to benchmark the current condition of, and quantify change within, ‘modified’ waterways. Furthermore, the geomorphic habitat area data could be developed as an indicator of the impact on estuaries of changes in catchment land use if significant differences were evident in the areas of habitats in modified estuaries compared to near-pristine estuaries. Here we provide examples of some very promising results obtained from our preliminary analyses of the geomorphic habitat area information contained within the GIS maps available on OzEstuaries (<www. ozestuaries.org>). However, it should be stressed that significantly more work is required to better identify the most reliable habitat-area indicators for the various types of estuaries.

Geomorphic habitats are landforms (‘geo’ = land, ‘morph’ = shape) such as saltmarshes and intertidal flats whose shape and position on the coast are strongly governed by the interaction of physical and biological processes on sediments (Figure 1). They are both distinctive sedimentary environments and habitats for various assemblages of biota. In this project, the relative areas of habitats of both tide- and wave-dominated coastal waterways (Figure 1) were compared on the basis of the condition classifications established during the 2002 NLWRA (Harris *et al.* 2002). We also sought to assess the relative effects of these catchment changes on the various types of coastal waterways, which were classified during the 2002 NLWRA (Harris *et al.* 2002) using the scheme devised by Boyd *et al.* (1992). The distinct types of coastal waterways include tide-dominated estuaries, tide-dominated deltas, tidal creeks, wave-dominated estuaries, wave-dominated deltas, strandplains, coastal creeks and coastal lakes (Heap *et al.* 2001). Each coastal waterway type has a characteristic distribution of habitats. For example, fluvial or bayhead deltas, central basins and barriers are characteristic habitats for wave-dominated estuaries (Figure 1). Conceptual representations of waterway types and their habitats are depicted in Ryan *et al.* (2003) and on the OzEstuaries website (<www.ozestuaries.org>). However, it is important to note that a continuum of coastal waterway physical types (morphotypes) exists between these idealised conceptual end members.

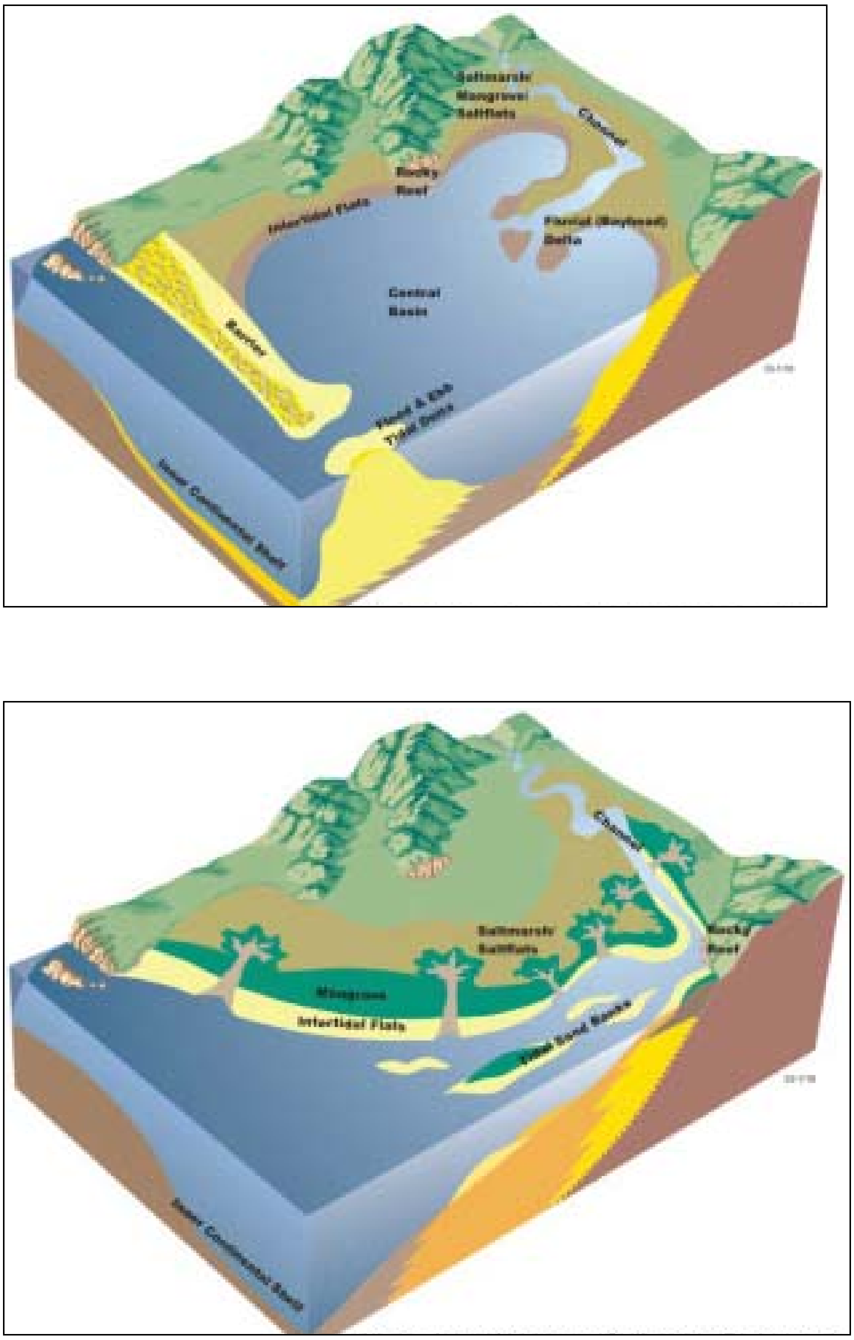

Figure 1. Conceptual models of the arrangement of geomorphic habitats in wave-dominated estuaries (top) and tide-dominated estuaries (bottom); from Ryan *et al*. (2003)

The NLWRA (2002) estuary condition classifications were used as an indicator of the degree of estuary modification because they are available for all estuaries in the dataset. The NLWRA (2002) assessments relied heavily on the percentage of natural vegetation cover in the estuary catchment because it is a significant factor governing erosion (hence sediment movement to the coast) in the landscape (Prosser *et al.* 2001). The NLWRA classification comprises four estuary condition classes that correspond to the proportion of catchment natural vegetation cover (Heap *et al.* 2001):

- *Near-pristine:* >90% natural vegetation cover
- *Largely unmodified:* 65–90%
- *Modified:* <65%
- *Severely modified:* <35%.

Methods

Strengths and weaknesses of the dataset

The combined Geoscience Australia/NLWRA/Coastal CRC geomorphic habitat dataset represents Australia's most comprehensive national coverage of estuary biophysical characteristics. The maps comprise industry-standard ARC GIS files consisting of a base map of the estuary boundary, and vector layers showing the extent of sub-aerial, tidal and sub-tidal habitats (geomorphic habitats). They are available for download on the OzEstuaries website (<www.ozestuaries.org>). The dataset contains a significant number of the various estuary types from all the coastal bioregions (IMCRA Technical Group 1998), and from each estuary class established in the NLWRA estuary condition assessment (Heap *et al.* 2001). Although the mapping work was carried out in two phases, the methods and quality control employed were consistent. In the second phase of mapping, the methods employed were refined to improve the efficiency of the mapping process.

There are a few aspects of the geography and geomorphology of estuaries and the mapping procedure that place some limitations on the utility of the geomorphic habitat dataset in terms of assessing the feasibility of geomorphic indicators. The number of geomorphic habitat units that were mapped was restricted by the NLWRA because they wanted relatively simple map products. As a consequence, saltmarshes and salt flats had to be mapped as a single geomorphic unit. This is less than desirable from the perspective of representing habitat diversity, and for obtaining the resolution required for indicator development. This is because salt flats are higher in elevation, tend to occur in arid regions, are mostly unvegetated, and tend to be far more extensive than saltmarshes. Also, salt flats are unlikely to respond to changes in sediment load because of their mostly supra-tidal elevation, whereas densely vegetated saltmarshes are significantly lower in elevation and have been found to be relatively sensitive to increases in sedimentation (Saintilan & Williams 1999).

There may also be limitations regarding the tidal sandbank and flood-ebb delta data, which have arisen due to the difficulty of maintaining consistent interpretation for the many sediment bedforms seen in coastal waterways around Australia. These problems can be rectified in terms of using the habitat areas as an indicator of environmental condition by summing the areas for flood-ebb delta and tidal sandbank areas for each estuary. This combined habitat area can provide an overall measure of the shallow sub-tidal habitat areas in and around the vicinity of the estuary mouth.

Finally, around 50 coastal waterways had geomorphic habitats that overlapped with those of adjacent coastal systems, making it difficult to assess the sizes of these habitats on an individual estuary basis. Some coastal habitats, for example mangroves and intertidal flats (particularly in low-lying, tide dominated areas) are almost continuous along large stretches of coastline, which means that associating maps of these units with discrete coastal waterways is meaningless. The problem is avoided in areas which are divided by significant bedrock structures (e.g. much of wave-dominated NSW). An example from northern Queensland is provided in Figure 2. Geoscience Australia is currently undertaking a more thorough vetting of the NLWRA data to rectify these problems. For each estuary, the vetting process involves examining the ArcGIS shape files of the habitat areas overlain on a Landsat image. Three major criteria are being used to test whether individual estuaries should be included in the reanalysis:

1. Is the estuary already represented in the dataset as part of a larger coastal waterway?
2. Is the estuary located in close proximity to other estuary mouths and can it be clearly separated into its respective geomorphic habitat areas?
3. Are there any underlying problems with the habitat area polygons, especially as related to the boundaries of flood ebb-tide deltas, intertidal flats and fluvial bayhead deltas?

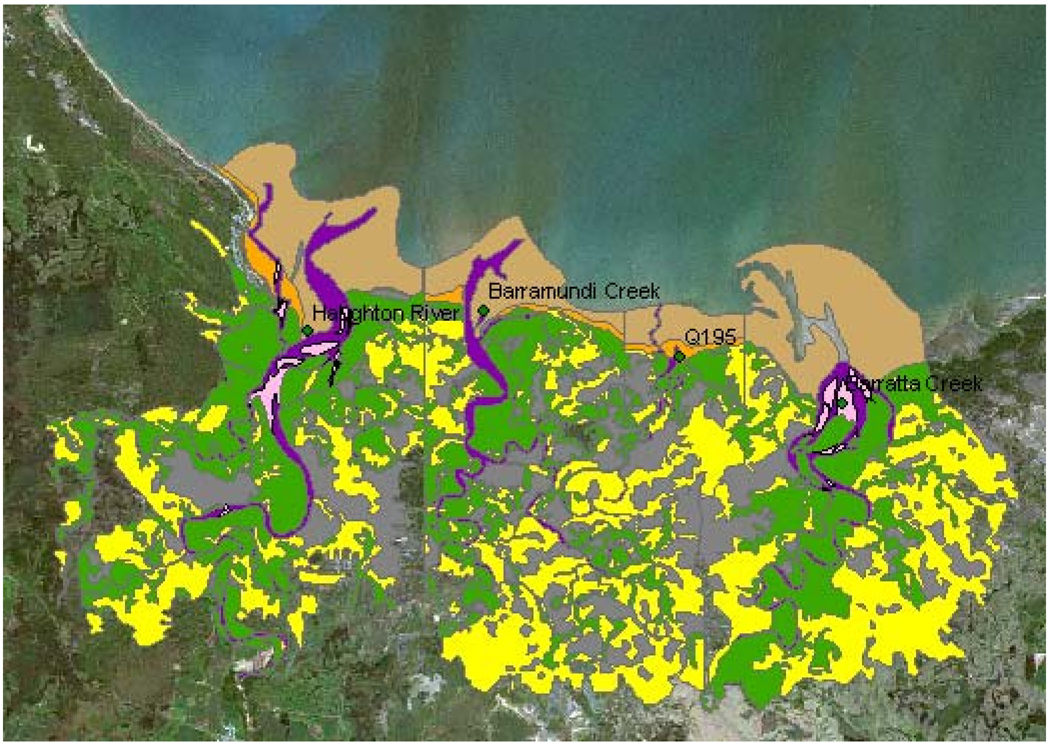

Figure 2. Geomorphic habitat maps of three tide-dominated deltas (Haughton River, Barramundi Creek and Barratta Creek) and a tidal creek (Q195) in Queensland

The close proximity of these coastal waterways makes it difficult to assign geomorphic habitat areas to a given estuary. This is especially apparent in the brown flood ebb-tide delta area.

Data analysis

Notwithstanding the issues discussed above, as an initial exploration of the dataset, all geomorphic habitat areas were included in the statistical analysis. The relative areas of eight different geomorphic habitats were calculated as a percentage of the combined area of the following habitats: intertidal flats, central basins, barrier/back-barriers, fluvial deltas, flood/ebb-tide deltas, mangroves, saltmarshes and tidal sandbanks. Relative areas were used in preference to absolute areas because the overall size of coastal waterways varies greatly across Australia.

For consistency, calculations for the tide-dominated classifications were based on waterways from the tropical and subtropical Northwest and Northeast Coast and Gulf of Carpentaria regions, in the coastal depositional environment framework of Harris *et al.* (2002) and Harris and Heap (2003; Figure 3). Moreover, estuaries from the Kimberley region of northwest WA were not included in these calculations because the size and arrangement of habitats in these estuaries are controlled by bedrock, and are unique in Australia (Table 1). The calculations for wave-dominated estuaries and deltas were based on estuaries located in the temperate southwest and southeast coasts and the Great Australian Bight only (Harris *et al.* 2002; Harris & Heap, 2003; Table 1). Strandplains, coastal lakes and coastal creeks were all grouped together under the collective heading 'strandplains', and the waterways in these classifications from around Australia were used in the calculations in order to increase the dataset to a size suitable for comparative analysis (Table 1). Details of the geomorphic habitat mapping procedures are provided in Heap *et al.* (2001) and Creasey *et al*. (2006).

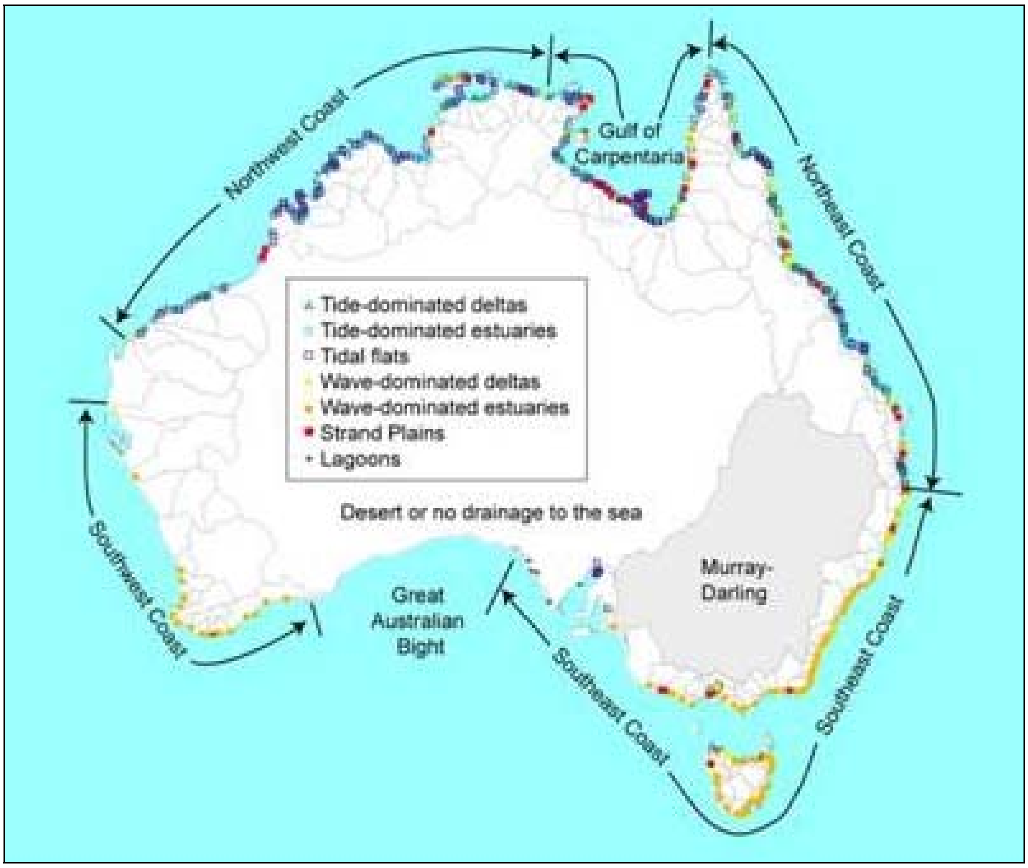

Figure 3. The Australian coastal geomorphic regions of Harris *et al*. (2002)

For the six estuary types (Table 1), the relative geomorphic habitat areas of estuaries in each of the four NLWRA condition classes were compared using box and whisker diagrams made using the STATISTICA 6 statistical analysis software. Principal components analysis was also performed on the datasets using STATISTICA 6, to investigate spatial patterns in, and significant relationships between, the relative habitat area data. Datasets for each of the different estuary types (Table 1) were considered separately.

Principal component analysis (PCA) is an eigenvector analysis of a multi-variate data matrix. It sequentially extracts components that explain diminishing amounts of variance in the data and which are linear combinations of the original variables. The first principle component passes through the direction of greatest spread in the n-dimensional scatter of points (i.e. the habitat area data for a set of one type of estuary). Succeeding axes, each with their own corresponding eigen-values, pass through successive directions of major variation, and are uncorrelated (orthogonal) to all the other axes. Typically, the first few principle components account for most of the variance of a dataset, and effectively summarise the salient features of the data.

Table 1. The various types of coastal waterways included in the analysis and the coastal regions in which they are located (based on Harris *et al.* 2002)

Geomorphic classification	Coastal regions included	Sub-region excluded	Number of estuaries analysed
Tide-dominated estuary	NW and NE Coast, Carpentaria	Kimberley	57
Tide-dominated delta	NW and NE Coast, Carpentaria	Kimberley	64
Tidal creeks	NW and NE Coast, Carpentaria	Kimberley	80
Wave-dominated estuary	SW & SE Coast, Great Australian Bight		141
Wave-dominated delta	SW & SE Coast, Great Australian Bight		93
Strandplains	All Australia		43

Results

Tide-dominated estuaries

Selected results of the PCA for tide-dominated estuaries are shown in Table 2 (factor coordinates of the variables) and Figure 4a (site scores for Axis 2 according to condition classification). The relative areas of intertidal flats, tidal sandbanks, saltmarshes, mangroves and flood/ebb-tide deltas for tide-dominated estuaries are presented in Figure 5a–e. There is a general trend of increasing tidal sandbank areas and decreasing intertidal flat areas as the estuaries become more modified (i.e. from near-pristine down to significantly modified). The near-pristine estuaries are best distinguished in terms of the very small relative areas of tidal sandbanks (Figure 5b). These parameters vary most substantially on Axis 2 of the PCA (Table 2). This gradient explains 18.6% of the variance in the dataset, and varies with condition classification in a general but statistically insignificant way (Figure 4a). Saltmarsh and mangrove areas are strongly correlated to Axis 1 (28.3% of variance) of the PCA and bear no discernible relationship with the condition classification of these tide-dominated estuaries (Figure 5c,d).

Table 2. Factor coordinates of the variables on Axes 1, 2 and 3 of the PCA for tide-dominated estuaries

Tide-dominated estuaries	**Axis 1 (28.3%)**	**Axis 2 (18.6%)**	**Axis 3 (16.3%)**
Total facies area	-0.56	0.22	0.01
% barrier/back-barrier	0.22	0.00	0.67
% flood/ebb-tide delta	0.32	-0.52	0.59
% intertidal flats	0.47	-0.56	-0.40
% mangrove	0.62	0.35	-0.33
% saltmarsh	-0.93	-0.23	-0.01
% tidal sandbanks	0.16	0.71	0.27

Tide-dominated deltas

The results of the PCA are shown in Table 3 (factor coordinates of the variables) and Figure 4b (site scores according to condition classification).The relative areas of intertidal flats, tidal sandbanks, saltmarshes, mangroves and flood/ebb-tide deltas for tide-dominated deltas are presented in Figure 6a–f. Axis 1 of the PCA explains 29.1% of the variance in the dataset.

The site scores for this axis correlate with NLWRA condition classification (Figure 4b), with statistically significant differences evident between the near-pristine estuaries and the modified and severely modified estuaries. Figure 6c,d confirms that these differences are mainly caused by the larger relative areas of saltmarshes and smaller relative areas of mangroves in the near-pristine systems. The relative areas of intertidal flats, flood/ebb delta and tidal sandbank areas also tend to increase with increasing modification and thus figure prominently on Axis 1 (Table 3). As in the case of tide-dominated estuaries, tidal sandbank areas tend to be considerably smaller in near-pristine estuaries than in modified and severely modified estuaries (Figure 6b).

Table 3. Factor coordinates of the variables on Axes 1, 2 and 3 of the PCA for tide-dominated deltas

Tide-dominated deltas	Axis 1 (29.1%)	Axis 2 (14.8%)	Axis 3 (13.7%)
Total facies area	0.33	-0.26	0.50
% barrier/back-barrier	-0.17	0.59	-0.06
% fluvial delta	-0.04	-0.26	-0.80
% flood/ebb-tide delta	-0.45	0.64	0.16
% intertidal flats	-0.32	-0.23	0.10
% mangrove	**-0.78**	-0.20	-0.17
% saltmarsh	**0.98**	-0.01	-0.03
% tidal sandbanks	**-0.56**	-0.44	0.36

Tidal creeks

The results of the PCA are shown in Table 4 (factor coordinates of the variables) and Figure 4c (site scores according to condition classification). The relative areas of barrier/back-barriers, central basins, flood/ebb-tide deltas, intertidal flats, mangroves, saltmarshes and tidal sandbanks for creeks are presented in Figure 7a–f. Axis 1 of the PCA explains 29% of the variance in the total dataset (Table 4). The site scores for this axis correlate with NLWRA condition classification (Figure 4c), with statistically significant differences between the near-pristine estuaries and the modified and severely modified estuaries.

As with the tide-dominated deltas, these differences are mainly caused by smaller relative areas of mangroves and larger relative saltmarsh areas in the near-pristine systems (Figure 7c,d). The relative areas of intertidal flats and flood/ebb deltas also generally increase with the extent of modification and thus figure prominently on Axis 1 (Figure 7a,e; Table 4). Interestingly, tidal sandbank areas are larger in the pristine estuaries in the case of tidal creeks (Figure 7b).

Table 4. Factor coordinates of the variables on Axes 1, 2 and 3 of the PCA for tidal creeks

Tidal creeks	Axis 1 (29%)	Axis 2 (17.5%)	Axis 3 (15.8%)
Total facies area	0.49	-0.30	0.03
% barrier/back-barrier	-0.14	0.83	0.22
% central basin	-0.24	0.63	-0.42
% flood/ebb-tide delta	-0.54	-0.02	-0.54
% intertidal flats	-0.46	-0.42	-0.26
% mangrove	**-0.71**	-0.10	0.35
% saltmarsh	**0.97**	0.15	-0.09
% tidal sandbanks	-0.21	0.03	0.74

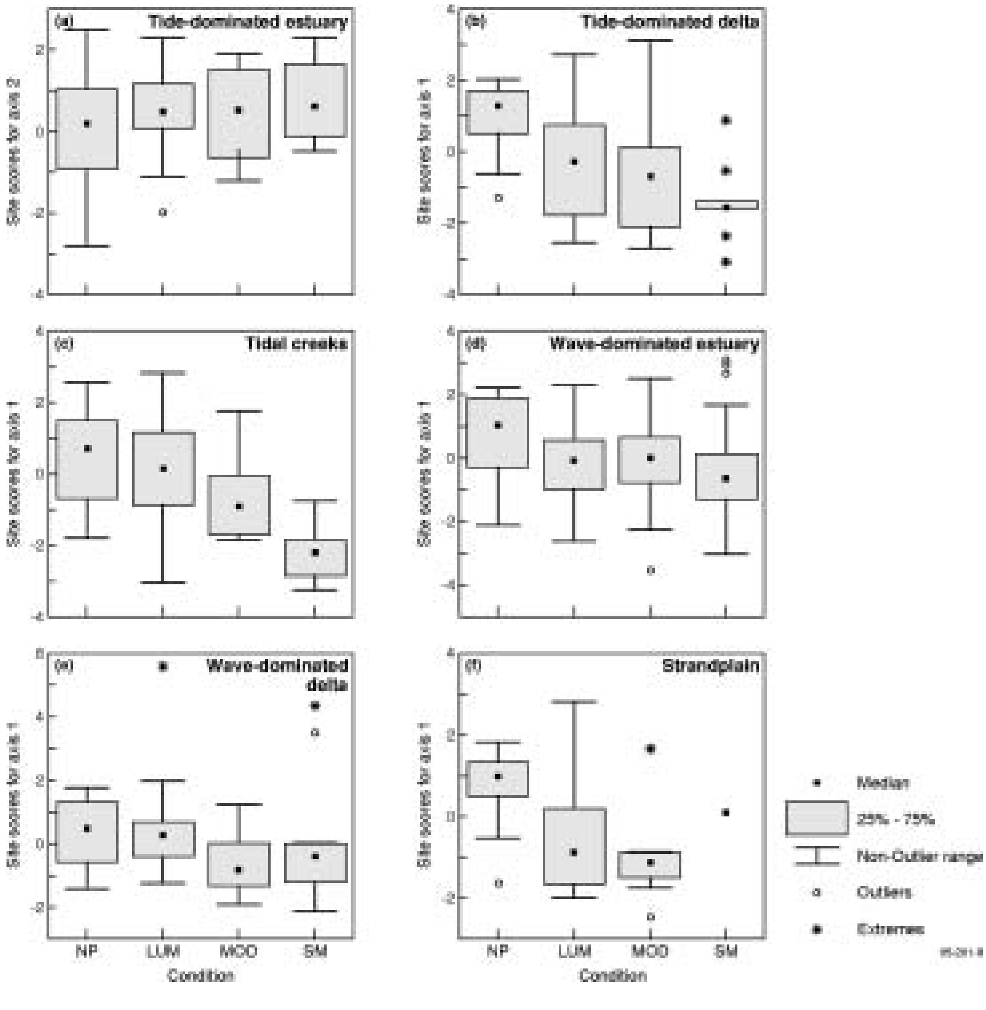

Figure 4. Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges of sites scores for the different NLWRA condition criteria (X axis) arranged according to the different waterway geomorphic classifications

In most cases catchment condition (i.e. NLWRA status) was a driver of change on Axis 1 but it occurred on Axis 2 in the case of tide-dominated estuaries (a). NLWRA condition classifications are: near-pristine (NP); largely unmodified (LM); modified (MOD); and severely modified (SM).

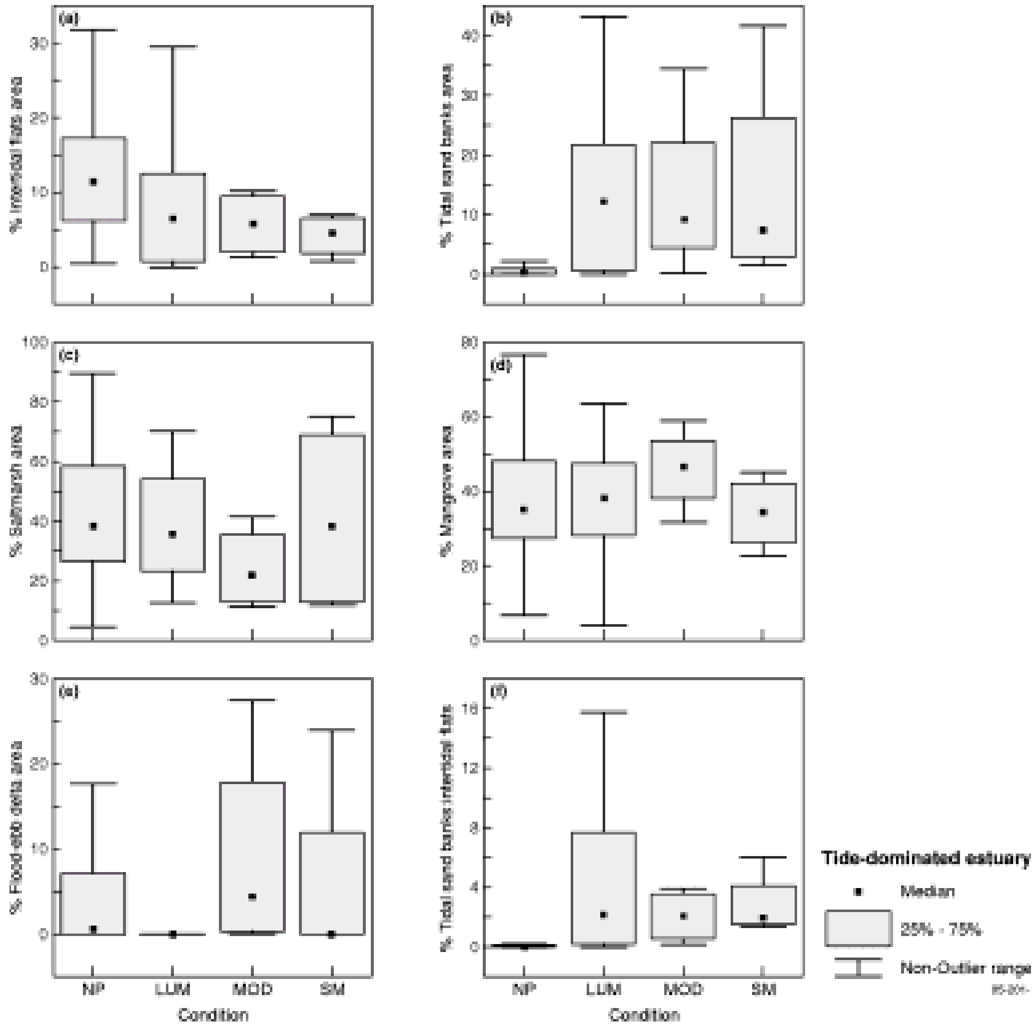

Figure 5. Tide-dominated estuaries

Box and whisker diagrams show medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) mangroves; (e) flood/ebb-tide deltas; and the ratio tidal sandbanks:intertidal flats (f). Condition classifications are: near-pristine (NP; n = 25); largely unmodified (LM; n = 24); modified (MOD; n = 4); and severely modified (SM; n = 4).

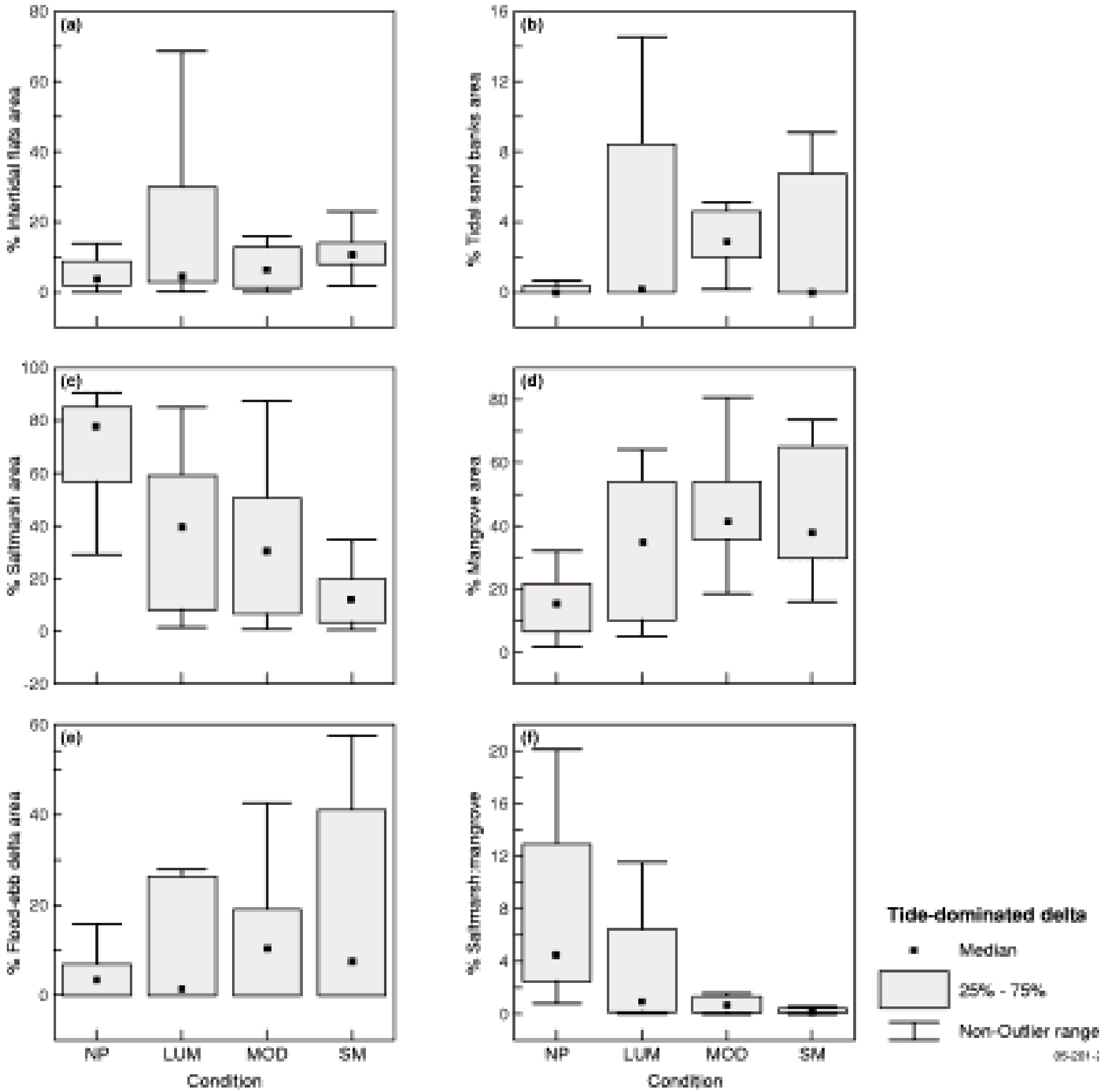

Figure 6. Tide-dominated deltas

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) mangroves; (e) flood/ebb-tide deltas; and the ratio saltmarsh:mangroves (f). Condition classifications are: near-pristine (NP; n = 28); largely unmodified (LM; n = 15); modified (MOD; n = 12); and severely modified (SM; n = 9).

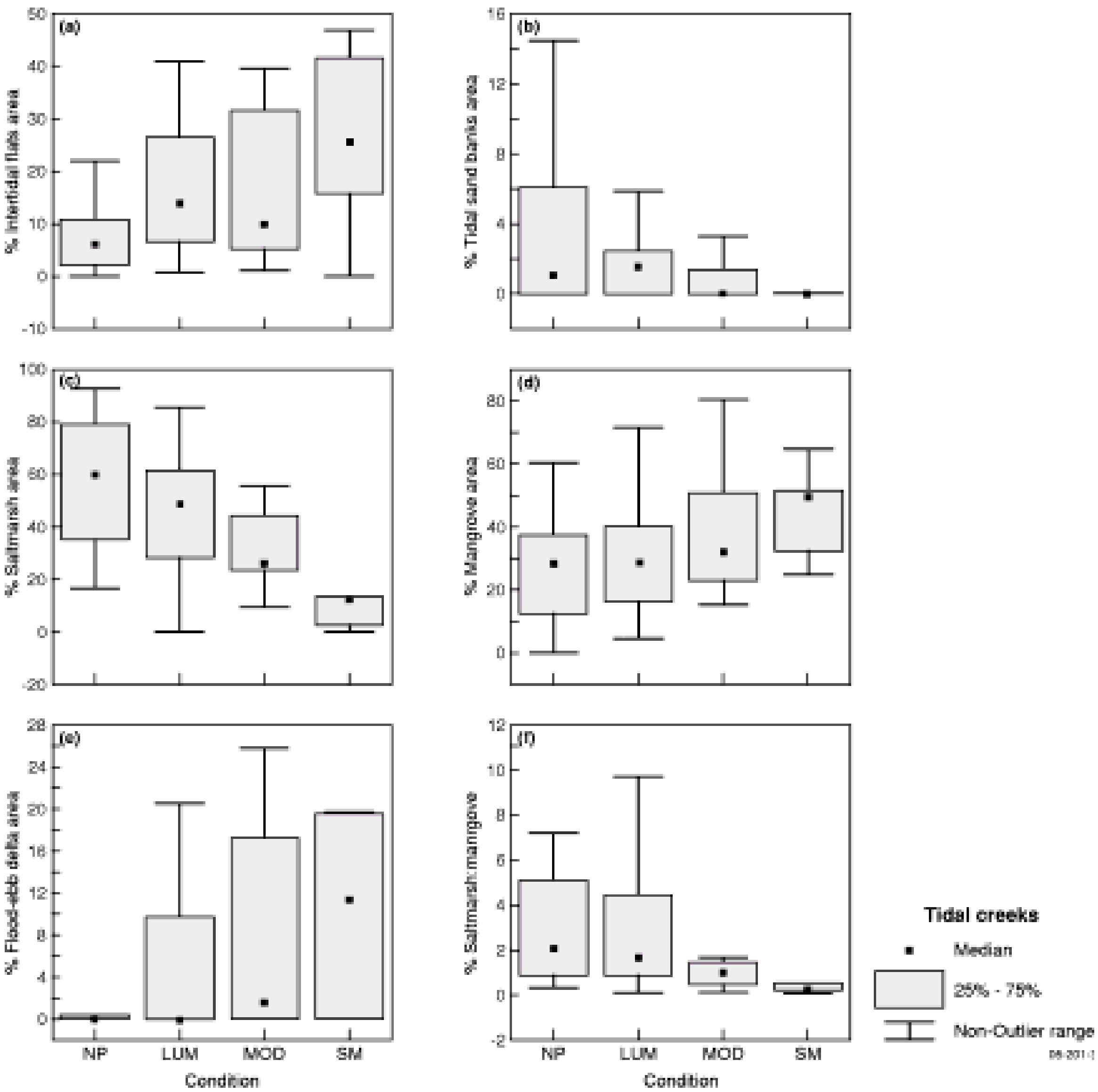

Figure 7. Tidal creeks

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) mangroves; (e) flood/ebb-tide deltas; and the ratio saltmarsh:mangroves (f). Condition classifications are: near-pristine (NP; n= 25); largely unmodified (LM; n = 41); modified (MOD; n = 8); and severely modified (SM; n = 6).

Wave-dominated estuaries

The results of the PCA are shown in Table 5 (factor coordinates of the variables) and Figure 4d (site scores according to condition classification). The total area of the estuaries, and the relative area of the diagnostic geomorphic habitats (central basins, fluvial deltas and barrier/back barriers) are shown with respect to condition classification in Figure 8a–d. The relative areas of saltmarsh, mangroves, intertidal flats, flood/ebb-tide deltas and tidal sandbanks are shown in Figure 9a–f. There is a weak correlation between the site scores on Axis 1 of the PCA and condition classifications of the estuaries (Figure 4d). The near-pristine estuaries tend to have smaller (but not statistically significant) areas of central basins, fluvial deltas and barrier/back barriers (Figure 8b,c,d). The near-pristine estuaries also have slightly (but not statistically) larger areas of saltmarsh, intertidal flats and flood/ebb-tide deltas (Figure 9a,c,e). The near-pristine wave-dominated estuaries are considerably smaller overall than the modified estuaries (Figure 8a), and had a higher ratio of intertidal flats plus saltmarsh: fluvial deltas (Figure 9f).

Table 5. Factor coordinates of the variables on Axes 1, 2 and 3 of the PCA for wave-dominated estuaries

Wave-dominated estuaries	Axis 1 (19.7%)	Axis 2 (15.1%)	Axis 3 (14%)
Total facies area	-0.49	0.03	-0.39
% barrier/back-barrier	0.23	-0.71	-0.28
% central basin	**-0.90**	0.24	0.02
% fluvial delta	-0.04	-0.33	0.35
% flood/ebb-tide delta	0.30	0.01	0.68
% intertidal flats	**0.58**	0.43	0.01
% mangrove	0.20	0.09	-0.43
% saltmarsh	**0.41**	0.50	-0.41
% tidal sandbanks	0.19	-0.50	-0.30

Wave-dominated deltas

The results of the PCA are shown in Table 6 (factor coordinates of the variables) and Figure 4e (site scores according to condition classification). The relative areas of intertidal flats, saltmarshes, mangroves, tidal sandbanks and barrier/back barriers are shown in Figure 10a–f. Axis 1 of the PCA explains 19.4% of the variance in the total dataset (Table 6). The site scores for the near-pristine and largely unmodified deltas are moderately, but not statistically, higher than the site scores for the modified and severely modified deltas on this axis (Figure 4e). Likewise, there are differences between the near-pristine and modified deltas and the relatively more modified deltas in terms of intertidal flat, saltmarsh and barrier/back barrier relative areas (Figure 10a,c,e). The near-pristine systems are especially distinguished in terms of the generally higher ratio of saltmarsh to intertidal flat areas in these systems (Figure 10f).

Table 6. Factor coordinates of the variables on Axes 1, 2 & 3 of the PCA for wave-dominated deltas

Wave-dominated deltas	Axis 1 (19.4%)	Axis 2 (17.9%)	Axis 3 (15.0%)
Total facies area	0.71	0.29	-0.42
%barrier/back-barrier	-0.27	0.23	0.20
%central basin	-0.06	0.27	0.16
%fluvial delta	0.41	0.62	-0.45
%flood/ebb-tide delta	-0.34	-0.20	-0.10
%intertidal flats	-0.58	0.51	0.01
%mangrove	0.09	-0.74	-0.50
%saltmarsh	0.65	-0.13	0.69
%tidal sandbanks	-0.28	-0.03	-0.43

Strandplains

The results of the PCA are shown in Table 7 (factor coordinates of the variables) and Figure 4f (site scores according to condition classification). The relative areas of saltmarshes, intertidal flats, flood/ebb-tide deltas, barrier/back barriers and tidal sandbanks are shown in Figure 11a–f. Axis 1 of the PCA explains 24.2% of the variance in the total dataset (Table 7). The site scores for the near-pristine systems are statistically higher than those for the largely unmodified, modified and severely modified estuaries on this axis (Figure 4f). Likewise the relative areas of saltmarshes in the near pristine systems are considerably larger than those that are modified (Figure 11c). The intertidal flat areas also tend to be much smaller (Figure 11a). The relative areas of flood/ebb-tide deltas and barrier/back-barriers are generally smaller in the near-pristine estuaries, but these differences are not statistically significant (Figure 11d,e). The near-pristine strandplains have a generally higher ratio of saltmarsh to intertidal flat areas (Figure 11f).

Table 7. Factor coordinates of the variables on Axes 1, 2 and 3 of the PCA for strandplains and coastal lakes and creeks

Strandplains/coastal lagoons/coastal creeks	Axis 1 (24.2%)	Axis 2 (20.7%)	Axis 3 (15.9%)
Total facies area	0.52	-0.42	-0.48
% barrier/back-barrier	**-0.62**	0.24	-0.33
% central basin	-0.04	0.31	-0.29
% flood/ebb-tide delta	-0.35	0.26	-0.61
% intertidal flats	**-0.53**	-0.45	0.49
% mangrove	0.28	-0.80	-0.31
% saltmarsh	**0.78**	0.54	0.25
% tidal sandbanks	-0.20	-0.18	0.17

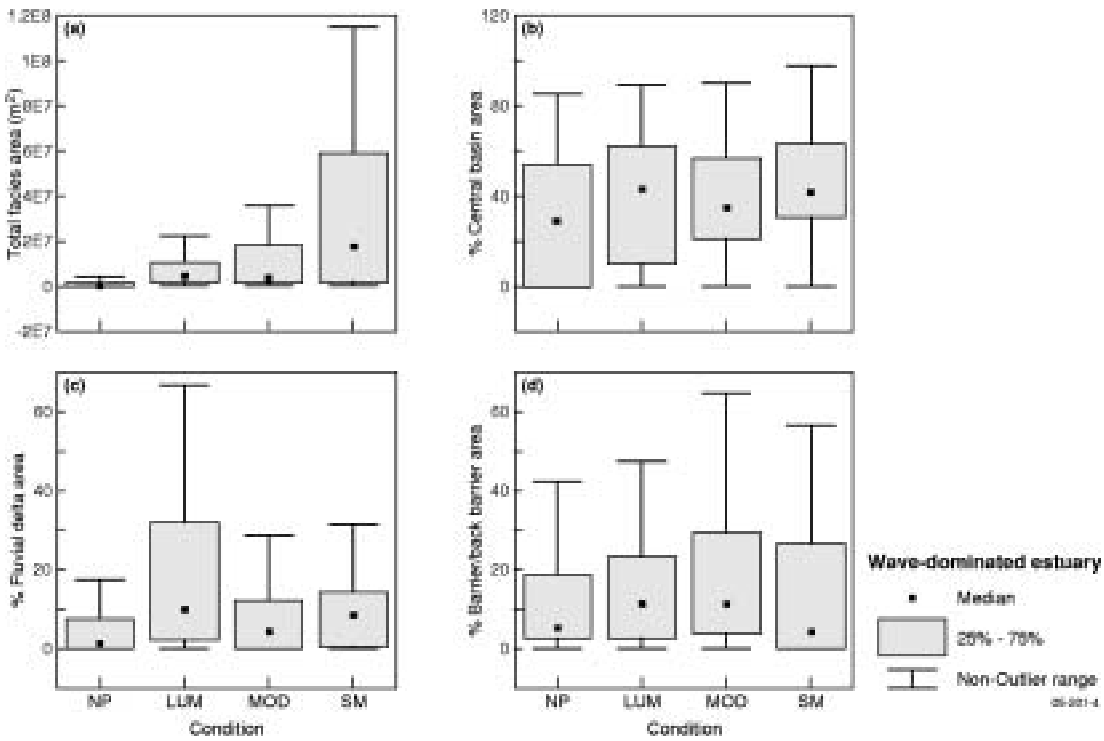

Figure 8. Wave-dominated estuaries I

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in (a) the total areas of these estuaries and the following geomorphic habitats: (b) central basins; (c) fluvial deltas; and (d) barrier/back barriers. Condition classifications are: near-pristine (NP; n = 23); largely unmodified (LM; n = 38); modified (MOD; n = 52) and severely modified (SM; n = 26).

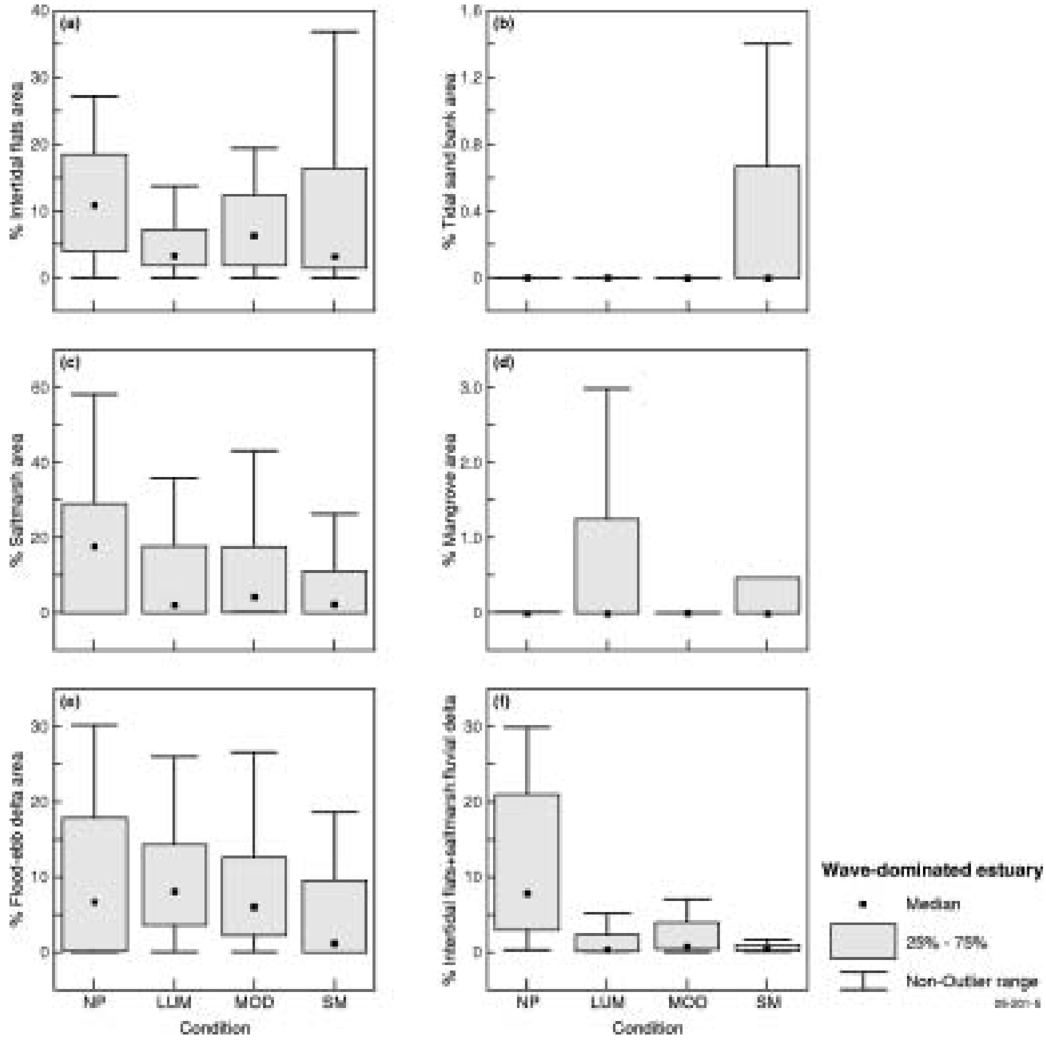

Figure 9. Wave-dominated estuaries II

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) mangroves; (e) flood/ebb-tide deltas; and the ratio of intertidal flats+saltmarsh: fluvial delta (f). Condition classifications are: near-pristine (NP; n = 23); largely unmodified (LM; n = 38); modified (MOD; n = 52) and severely modified (SM; n = 26).

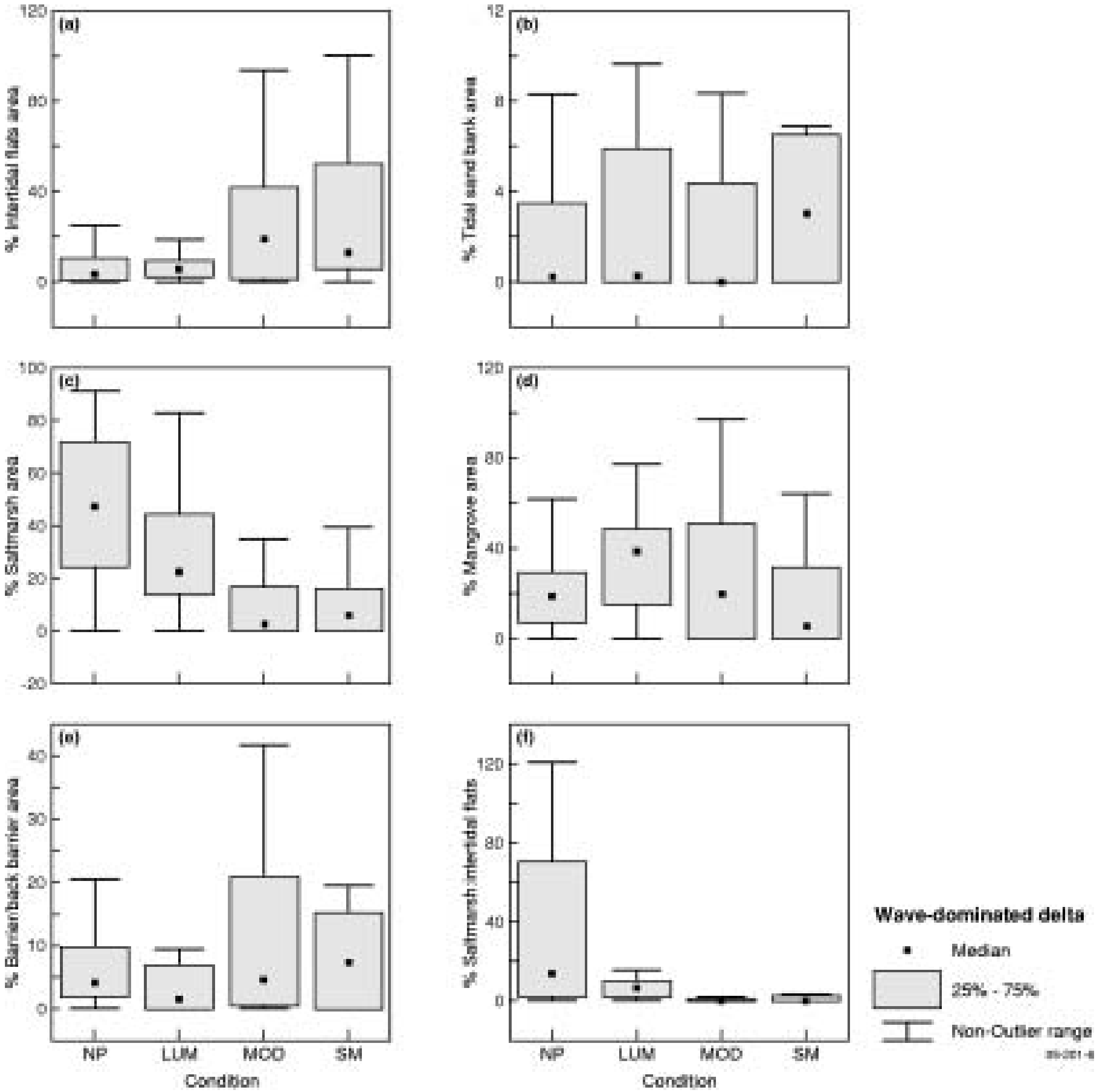

Figure 10. Wave-dominated deltas

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) mangroves; (e) barrier/back barrier area; and the ratio saltmarsh:intertidal flats (f). Condition classifications are: near-pristine (NP; n = 28); largely unmodified (LM; n = 24); modified (MOD; n = 26) and severely modified (SM; n = 12).

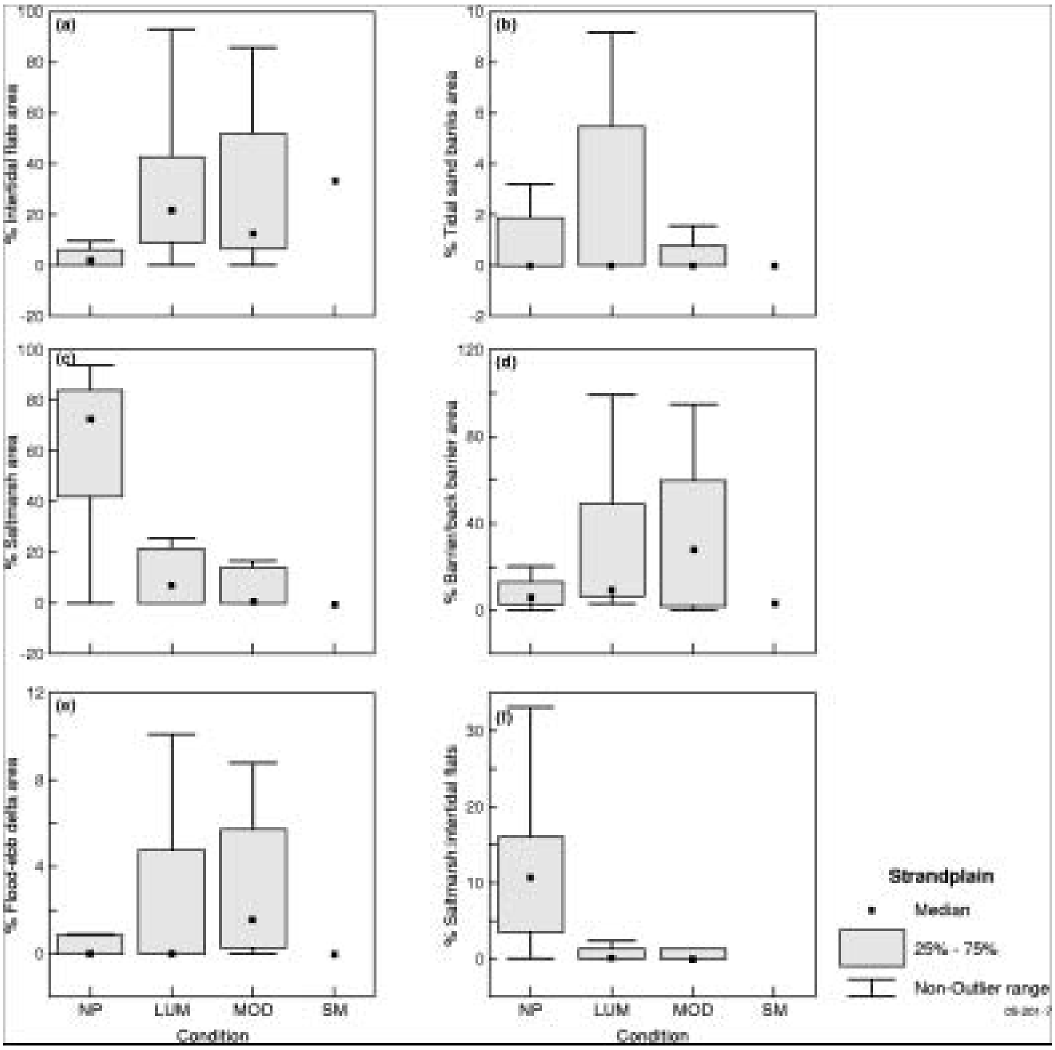

Figure 11. Strandplains

Box and whisker diagrams showing medians, 25th and 75th percentiles and ranges in the relative area data of the following geomorphic habitats in strandplains: (a) intertidal flats; (b) tidal sandbanks; (c) saltmarshes; (d) barrier/back barriers; (e) flood/ebb-tide deltas; and the ratio saltmarsh:intertidal flats (f). Condition classifications are: near-pristine (NP; n = 20); largely unmodified (LM; n = 14) and modified (MOD; n = 7).

Discussion

Habitat changes and their causes

Tide-dominated waterways

The extent to which coastal waterways have filled with sediment is indicative of different degrees of geological maturity, which gives rise to different configurations of habitats. Geological maturity (or stage of sediment filling) can be an important factor governing aspects of habitat distributions and the ecological function of estuaries (Roy *et al.* 2001). In the relatively modified estuaries, more of the accommodation space for sediment has been filled, which was evidenced by an increase in the relative areas of inter- and near-tidal habitats (mangroves and intertidal flats). This infill gives rise to a concomitant proportional decrease in saltmarsh/salt flat areas (i.e. but not necessarily a change in actual habitat area). The fact that in most cases these 'maturity' changes coincide with diminishing NLWRA condition status (Figure 6c and 7c) suggests that some estuaries are experiencing more rapid infilling as a result of enhanced sediment loads from catchments that have lost a significant proportion of their native vegetation.

An increase in the relative areas of tidal sandbanks with increasing modification was observed in tide-dominated estuaries and tide-dominated deltas (Figures 5b and 6b), and the opposite trend was observed in tidal creeks (Figure 7b). The most likely explanation for the increase in the relative areas of tidal sandbanks in the waterways with more disturbed catchments is a larger coarse sediment load component in the source rivers caused by hydrological changes and erosion in the catchment, as previously suggested by Heap *et al.* (2004). As an example, images (an historical map and two air photos) of the mouth of the Fitzroy River estuary clearly demonstrate the augmentation of tidal sandbanks areas in a time series inclusive of 1895, 1941 and 1999 (Duke *et al.* 2003). The Fitzroy River estuary is a tide-dominated estuary with 80% catchment clearance, and the major phase of land clearing coincided with the Brigalow clearing scheme between 1960 and 1980 (Furnas, 2003).

In contrast, the decrease in the relative area of tidal sandbanks in tidal creeks may be related to changes in the nearshore sediment budget due to factors such as sediment bypassing the creek entrance, a reduction in the supply of sediment alongshore, and dredging and/or sand extraction within the creeks, because these systems are characterised by very low (or negligible) fluvial input (Ryan *et al.* 2003). However, tide-dominated (particularly macrotidal) systems are characterised by the landward transport of marine-derived sediments (Ryan *et al.* 2003).

In future studies, the relative contribution of marine- and catchment-derived sediment would have to be quantified to more accurately assess the impacts of catchment changes on tide-dominated systems.

Wave-dominated waterways

A decrease in the relative areas of saltmarshes with increasing catchment modification was clearly evident in the data for wave-dominated deltas and strandplains (Figure 10c and 11c). Likewise, the relative intertidal flat and flood/ebb-delta areas were found to increase (Figure 10a and 11a,e). Although clear-cut trends with respect to NLWRA (2002) condition criteria are not evident in the current dataset for wave-dominated estuaries, the median percent saltmarsh area for the near-pristine estuaries was still higher than the 75th percentiles of all the other modified estuaries (Figure 9c). In the case of the wave-dominated systems, the apparent reduction in saltmarsh areas may be due to actual habitat loss (e.g. land reclamation for development), as opposed to it being an artefact of the analysis methods (as described above for the tide-dominated classifications).

Saltmarsh is a vulnerable habitat and fisheries resource on the temperate east coast of Australia. Many estuaries have lost more than 25% (and as much as 80%) of their saltmarsh in the last 50 years (Saintilan & Williams, 1999; see also Harty, 2002). A trend of mangrove transgression into saltmarsh areas has also been identified for reasons that are believed to include: reclamation for agriculture, increased sedimentation (and nutrients), altered tidal regimes, sea level rise and increased rainfall (Saintilan & Williams, 1999). Although reciprocal relationships between the relative areas of saltmarsh and mangroves are not evident in the data, mangroves were only observed in modified systems in the case of wave-dominated estuaries.

Overall, interpretation of the data for wave-dominated estuaries is less straightforward than that of the tide-dominated systems. This is probably due to the fact that near-pristine estuaries are underrepresented, and only the smallest examples of these systems remain in near-pristine condition (Figure 8a). It is worth noting that the catchments of the larger wave-dominated estuaries (which provide better ports and more reliable freshwater supplies) were preferred areas for European settlement in southern Australia.

Suggested indicators

Tide-dominated classifications

The results for these systems are summarised in Table 8. Changes in the areas of tidal sandbanks stand out as a good geomorphic indicator of changes in land use in the catchments of tide-dominated estuaries, where an increase in tidal sandbank area matches an increase in catchment disturbance. Whether or not increases in the areas of tidal sandbanks alone impacts upon estuary health is not yet known. This indicator can be monitored relatively simply and inexpensively using aerial photos and remote sensing technologies. However, high turbidity may severely limit water penetration and limit their application in subtidal environments. As tidal height can influence the supra-tidal areas of tidal sandbanks, images used in the time series should be carefully selected to achieve approximately the same tidal height (e.g. low tide). Changes in the tidal sandbank:intertidal flat ratio (%) is also a very good indicator (Figure 5f), but is more time-consuming to measure. However, as noted earlier, there is some inconsistency in the mapping of these geomorphic habitats and the potential of this creating an artefact in the dataset needs to be further investigated, possibly by combining tidal sandbank and flood-ebb delta habitat areas.

The results of this study also suggest that intertidal flats, mangrove and probably saltmarsh (as opposed to salt flat) areas are sensitive to changes in the quantity of sediment delivered to tide-dominated coastal waterways, as suggested by Ward *et al.* (1998) in the context of State of Environment reporting. These areas are also the most accessible and suitable areas for urban and agricultural development. However, it has yet to be confirmed whether saltmarsh/saltflat areas are actually diminishing in the more modified estuaries, or if the observed trends are artefacts of the percentage data caused by the expansion of other intertidal/near-tidal facies (i.e. mangroves, intertidal flats etc.) into the available accommodation space. Historical data, such as time-series aerial photographs and survey documents, may help identify the drivers of this change. Notwithstanding these issues in the interpretation of results, clear trends are evident—the ratio of mangrove to saltmarsh/saltflat areas appears to be a good indicator of catchment modification in tide-dominated deltas (Figure 6f) and a fairly reliable indicator in tidal creeks (Figure 7f). The ratio of saltmarsh/salt flat to mangrove plus intertidal flats could also be used.

Table 8: Summary of findings for tide-dominated estuaries and suggested indicators

Geomorphic classification	%bbb	%cb	%fbd	%fed	%if	%man	%sm	%tsb	Ratio
Tide-dominated estuary									TSB:IF
Tide-dominated delta									SM:MAN or SM:MAN+IF
Tidal creek									SM:MAN or SM:MAN+IF

Grey shading denotes that weak trends are evident in the data; while black fill denotes that strong trends are present (i.e. no overlap between the 25th and 75th percentiles of near-pristine estuaries and modified estuaries and severely modified estuaries). The habitats include: barrier/back-barrier (%bbb), central basin (%cb), fluvial bay-head delta (%fbd), intertidal flats (%if), mangrove (%man), saltmarsh (%sm) and tidal sandbanks (%tsb).

Wave-dominated classifications

The results of this study for wave-dominated systems are summarised in Table 9. Saltmarsh stands out as the habitat most sensitive to catchment condition across the different geomorphic types, thus substantiating work by Saintilan and Williams (1999). Saltmarsh areas, as an indicator, could be monitored on their own, or in a ratio with intertidal flats (i.e. area of saltmarsh to intertidal flats) in the case of wave-dominated deltas and strandplains (Figures 10f and 11f). Based on the results of this study, there are no unambiguous geomorphic indicators in the wave-dominated estuaries. Although the saltmarsh plus intertidal flats:fluvial delta ratio provides a reasonable separation of the data (Figure 9f), the delineation of the fluvial delta areas needs to be checked and the environmental basis of the ratio would have to be established before it could be used effectively as an indicator.

Table 9. Summary of findings for wave-dominated estuaries and suggested indicators

Geomorphic classification	%bbb	%cb	%fbd	%fed	%if	%man	%sm	%tsb	Ratio
Wave-dominated estuary									sm+if:fbd
Wave-dominated delta									sm:if
Strandplain									sm:if

Grey shading denotes that a trend is present between the habitat areas and NLWRA condition criteria; and black shade denotes habitats in which there is no overlap between the 25th and 75th percentiles of near-pristine estuaries and modified estuaries and severely modified estuaries. The habitats include: barrier/back-barrier (%bbb), central basin (%cb), fluvial bay-head delta (%fbd), intertidal flats (%if), mangrove (%man), saltmarsh (%sm) and tidal sandbanks (%tsb).

Conclusions

Systematic changes in some geomorphic habitat areas (and area ratios) were shown to coincide with diminishing condition status in the NLWRA framework (i.e. from near-pristine, through largely unmodified and modified, to severely modified). The changes include larger tidal sandbank areas and increases in the proportional areas of intertidal flats and mangroves in tide-dominated classifications, and a reduction in saltmarsh areas and higher percentages of intertidal flat areas in wave-dominated classifications (estuaries excluded).

These results suggest that the maturity of many Australian estuaries has recently increased due to changes in catchment land use and the associated enhanced sediment loads. Also interesting was the fact that only very small wave-dominated estuaries remain in near-pristine condition. The results show the potential of geomorphic habitat areas as an indicator of broadscale biophysical change in estuaries and could be especially useful for identifying estuaries that warrant further investigation. It needs to be noted, however, that we have identified some of the limitations of the NLWRA mapping methods and potential artefacts generated in the dataset. Further vetting of the dataset is being undertaken at Geoscience Australia to improve the robustness of the results.

The results of this study highlight the potential of the new near-pristine estuary geomorphic habitat dataset, in combination with the NLWRA data, for providing the baseline for a national assessment of the impact on estuarine habitats of vegetation clearance and development in catchments and the coastal zone. The strong trends in the geomorphic data analysis with respect to the estuary condition criteria also show that the NLWRA has provided a valuable national-scale estuarine dataset.

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