A preliminary assessment of the historical, current and future cover of seagrass in the estuary of the Parramatta River

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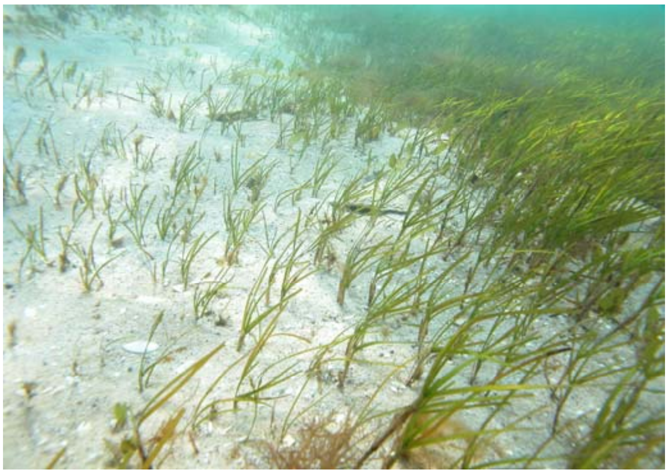

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ACKNOWLEDGEMENTS

This study was initiated by NSW Maritime in conjunction with the Sydney Metro Catchment Management Authority. In its first phase (West *et al*. 2004), an update of the cover of the estuarine macrophytes of the Parramatta River was commissioned by NSW Maritime and financed by the National Heritage Trust Interim Priority Funding. This, the second phase, incorporates data from the first phase, with additional funding from the National Heritage Trust Stage II.

For the first phase, ortho-rectified images of the Parramatta River in 2000 were obtained by the then NSW Fisheries as part of a consortium of state and local government agencies co-ordinated by the then Office of Sydney Harbour Manager. Roger Laird carried out the mapping of seagrass on these images. For the second phase, and subsequent to the incorporation of NSW Fisheries into NSW Department of Primary Industries, Danielle Morrison mapped seagrass on the images derived from aerial photos taken in 1978 and 1986. Ortho-rectified images of the Parramatta River for 2003 were obtained by NSW DPI as part of a consortium with NSW Planning. Isabelle Thiebaud carried out the mapping of seagrass on the latter images.

Andrew Morison and Suzanne Harris of NSW Maritime provided oversight of the project and insight into the management of the foreshore lands of the Parramatta River. James Scandol, Tim Glasby and Bob Creese provided critical comments on the draft manuscript.

NON-TECHNICAL SUMMARY

A preliminary assessment of the historical, current and future cover of seagrass in the estuary of the Parramatta River

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OBJECTIVES:

(a) Conduct PC-based GIS analysis of ortho-rectified aerial photographic images of the Parramatta River taken in 2000 and delimit the boundary of seagrass in the study area.
(b) Conduct field checks to confirm seagrass boundaries.
(c) Create ArcView shape files and associated data tables to indicate the area of cover for seagrass.
(d) Update the data set by including ortho-rectified aerial photographic images of the Parramatta River taken in 2003.
(e) Provide an historical component to the project by analysing aerial photographs from 1978 and 1986.
(f) Provide a predictive model of the distribution of seagrass.
(g) Provide a report to NSW Maritime.

NON TECHNICAL SUMMARY:

The first map of seagrass for the Parramatta River was created from aerial photos taken in the 1970s (West *et al.* 1985). A more recent map, prepared from aerial photos taken in 2000 and processed to create ortho-rectified images, suggested there had been changes in distribution with large losses at some locations and small increases at other locations (West *et al.* 2004). To confirm whether the changes were real or whether they were attributable to differences in the methods employed in the two studies, the 1970s photos were re-analysed in a GIS framework. In addition, ortho-rectified images taken in 2003 were analysed to assist in assessment of short-term change. Photos from 1978 and 1986 were also analysed with GIS facilities as a way by which to extrapolate change over past decades.

Using the software program Desktop GARP, a predictive model of the distribution of seagrass was developed on the basis of the seagrass history and available environmental data. The input variables included depth, substrate type, distance from entrance, and fetch (calculated for the eight principle compass bearings). A random sample of points derived from the seagrass map for 2000 was used to train the model. Output from the model highlights areas within the estuary that are consistently covered with seagrass as well as other areas that might be suitable for colonisation. In theory, considerably more seagrass could grow in the estuary than at present. In future, the model can be refined with additional input data, the most important of which would be water clarity.

Seagrass locations are shown in a series of example maps derived from the GIS-based analysis. Most patches of seagrass were located in the downstream portions of the estuary. At some sites, cover was highly variable, expanding and contracting around a core bed over time.

1. INTRODUCTION

1.1. Background

The first project to map the distribution of seagrass for the whole of NSW was initiated by the then NSW State Fisheries in the late 1970s. The amalgamation of Fisheries within the Department of Agriculture in 1982 saw continued support for the project and led to the production of an atlas showing the extent of estuarine vegetation for NSW (West *et al.* 1985). The atlas depicted the extent of macrophyte cover for 130 estuaries, with maps of seagrass, mangrove and saltmarsh having been derived from aerial photographs taken in the late 1970s and early 1980s. These maps still have wide use as coastal planning, management and conservation documents. For example, some maps have been and still are being used to identify controls on marina development or locations for channel dredging, while other maps have been used for oil spill planning (e.g., Carter 1994).

In the early 2000s, an interim statement on changes in the cover of seagrass for some NSW estuaries was generated (Table 1, from Williams *et al*. 2003). Of the 22 estuaries for which data were produced, large losses were seen in nine and small losses in six, while large gains and small gains were found in three and three estuaries, respectively. With respect to the Sydney metropolitan region, maps have been produced of the cover and species composition of seagrass in recent years including the Hawkesbury River (West unpublished, Williams and Thiebaud 2007), and the Parramatta River (West *et al*. 2004). The latter study suggested a loss of seagrass of nearly 80 ha, from 126.8 to 51.7 ha, over a 20 year period to 2000.

1.2. Need

Updating maps of estuarine vegetation is necessary for a number of reasons. The first is the rapid increase in population density along the coast of NSW over the past decade and the disturbance this social change may have had on estuarine habitat. As well as the interim trend statement prepared by Williams *et al*. (2003), anecdotal reports have been received of changes in distribution of estuarine macrophytes for a number of sites in a number of estuaries. A large loss apparently occurred in the Parramatta River. Some of the change either recorded or reported might have been caused by natural events such as storms, whereas other losses are almost certainly due to human activity such as dredging and reclamation. The Parramatta River has been subjected to increase in surrounding population density, with one example being the housing expansion around Homebush Bay subsequent to the 2000 Olympic Games.

Table 1. Comparison of historical and recent estimates of area of seagrass for NSW estuaries (based Williams *et al*. 2003). All historical estimates from West *et al*. (1985).

Estuary	**Historical estimates of seagrass area**		**Recent estimates of seagrass area**		**Reference**	**Change**					
	Date of airphoto	**(ha)**	**Date of airphoto**	**(ha)**		**Loss (ha)**	**L>40%**	**L<40%**	**Gain (ha)**	**G>40%**	**G<40%**
Wallis Lake	1981	3078.5	1997	3190.0	G. West, NSW DPI unpublished data				111.5		X
Hunter River	1981	0.0	1994	0.0	Williams *et al*. (1999)	NA			NA		
Lake Macquarie	1981	1339.1	1997	1465.0	G. West, NSW DPI unpublished data				125.9		X
Brisbane Waters	1981	549.0	1997	291.0	G. West, NSW DPI unpublished data	258.0	X				
Hawkesbury River	1977	47.0	1997	32.0	G. West, NSW DPI unpublished data	15.0		X			
Pittwater	1977	193.4	1997	192.0	G. West, NSW DPI unpublished data	1.4		X			
Parramatta River	1978	128.6	2000	51.7	West *et al*. (2004)	76.9	X				
Georges River	1977	26.8	1998	76.4	Pickthall *et al*. (2003)				49.6	X	
Botany Bay	1977	340.3	1995	623.9	Watford & Williams (1998)				283.6	X	
Hacking River	1977	86.9	1999	82.0	Williams & Meehan (2004)	4.9		X			
St. Georges Basin	1979	853.8	1998	299.9	Meehan (2001)	553.9	X				
Lake Conjola	1979	52.7	2001	24.2	G. West, NSW DPI unpublished data	28.5	X				
Burrill Lake	1979	50.8	2002	76.4	G. West, NSW DPI unpublished data				25.6	X	
Tabourie Lake	1975	119.9	1998	21.9	G. West, NSW DPI unpublished data	98.0	X				
Durras Lake	1977	50.9	1998	49.6	G. West, NSW DPI unpublished data	1.3		X			
Lake Brou	1979	7.8	1998	0.0	G. West, NSW DPI unpublished data	7.8	X				
Mummuga Lake	1979	29.4	1998	31.5	G. West, NSW DPI unpublished data				2.1		X
Wagonga Inlet	1979	148.4	1999	75.1	Meehan (2001)	73.3	X				
Corunna Lake	1979	17.9	1998	15.7	G. West, NSW DPI unpublished data	2.2		X			
Wallaga Lake	1979	134.3	1998	108.4	G. West, NSW DPI unpublished data;	25.9		X			
Bermagui River	1979	33.8	1998	28.1	Meehan (2001)	5.7		X			
Merimbula Lake	1977	229.7	1994	163.8	Meehan (1997)	65.9		X			
Pambula Lake	1977	86.8	1994	70.6	Meehan (1997)	16.2		X			
Range	1975 – 1981	0.0 – 3078.5	1994 – 2002	0.0 – 1465.0		1.3 – 553.9			2.1 – 283.6		
No. of estuaries with loss							**7**	**9**			
No. of estuaries with gain										**3**	**3**
Total		**7543.0**		**6999.5**		**1158.0**			**614.5**		

A second reason to remap the distribution of seagrass in the Parramatta River relates to spill of oil and other toxic substances. There is a large traffic of commercial, military, and recreational vessels on the river, which, coupled with the vehicular traffic on roads adjacent to the water, and the existence of a refinery and other industrial operations, enhances the potential for spills. Prior recognition of resources of ecological and social value is one key to rapid response. In Carter's (1994) categorisation of ecological attributes for the Parramatta River, he identified seagrass as a resource of extreme sensitivity. As seagrass contributes to estuarine productivity, and as natural and human factors can influence the location and extent of these communities, its distribution needs to be regularly assessed in order to assure an appropriate response to the spill of oil and other materials.

A third reason for which remapping is necessary is that mapping methodology has evolved over the past 20 years. Previously, estuarine vegetation maps were produced from aerial photographs but with simplistic methods of interpretation. For example, West *et al*. (1985) used the *camera lucida* technique in which an optical image projected onto a scaled map was traced and then evaluated for accuracy in the field. In recent times the falling cost of computer-based hardware and software, coupled with the ease of use of the software, has meant that it is now possible to produce much more accurate maps than was possible previously. These new facilities are collectively known as geographic information systems (GIS). The advent of GIS implies that any attempt to create a trend analysis of cover of estuarine macrophytes by comparing maps produced by various methods may give misleading indications (Meehan *et al*. 2005).

Table **2** sets out a comparison of technical details between the investigations of West *et al.* (1985) and West *et al.* (2004). Both were exercises in aerial photographic interpretation (API), but the earlier study used the *camera lucida* technique while the latter engaged GIS. Both exercises implemented ground checks of cover to confirm what had been discovered in the aerial photos. The comparison suggests a major loss of seagrass occurred over 20 years in the Parramatta River.

The extent of this loss, if it was not an artefact of the difference in methods, needed to be investigated. Further, as DPI's seagrass management policy is predicated on the no net loss principle, by monitoring locations at which change has occurred, it may be possible to manage any losses.

Table 2. Comparison of area of seagrass between West *et al*. (1985) and West *et al*. (2004).

	Parramatta River		
	West *et al.* 1985 (ha)	**West *et al.* 2004 (ha)**	**% change**
Photo date and scale	1978 – 1:16 000	2001 – 1:16 000	
Method	API by *camera lucida*	API by GIS	
Field inspection	Jan. 1981	May 2002 & March – June 2003	
Seagrass (ha)	128.6	51.7	-59.8%

One aspect of change in cover of seagrass is its maximum upstream extent. On the Georges River the most upstream occurrence is at Williams Creek (Voyager Point) (Pickthall *et al*. 2004), a distance of about 15 km from the entrance to the estuary. In the Parramatta River, West *et al*.

(1985) identified the most upstream of the patches of seagrass on the north side of the Parramatta River at Henly, about 17 km from the heads, and on the south side at Elizabeth Bay, about 7 km from the heads (Table 3). West *et al*. (2004) found seagrass further upstream, at Morrisons Bay on the north side, 19 km from the entrance, and on the south side at Hen and Chicken Bay, 18 km from the entrance. In Middle Harbour, West *et al*. (2004) confirmed the presence of seagrass at Bantry Bay on the east side 10 km from the entrance, but indicated it was present further upstream, from Sugarloaf Bay about 7 km from the entrance, to Echo Point approximately12 km from the entrance. The upstream expansion of cover in the Parramatta River as well as Middle Harbour might suggest better capacity to map seagrass as methods have evolved over past years, or could also be interpreted as a generalised upstream migration. One explanation for the latter is the progressive improvement of water quality over the recent past with the introduction of the NSW Clean Waters Act in the 1970s.

The current distribution of seagrass in all NSW estuaries, as well as the Parramatta River, as well as other plants living in and around estuaries, will change with the forthcoming rise of sea level (Vanderzee 1988, Williams 1990). Terrestrial vegetation, such as Swamp She-oak (*Casuarina* spp.) and Paperbark (*Melaleuca* spp.), and intertidal vegetation, such as saltmarsh and mangrove will migrate further upstream and upslope with the rise in mean sea level. However, the expansion will be limited by natural topography or by structures such as roads and buildings. The fate of seagrass is less predictable, being dependent not only on topography but also on water clarity.

Table 3. Comparison of upriver extent of seagrass between West *et al*. (1985) and West *et al*. (2004).

	Survey	**Most upstream location: north or east side and distance from heads**	**Most upstream location: south or west side and distance from heads**
Parramatta River	West *et al*. (1985) West *et al*. (2004)	Henly: 17 km Morrisons Bay: 19 km	Elizabeth Bay: 7 km Hen and Chicken Bay: 18 km
Middle Harbour	West *et al*. (1985) West *et al*. (2004)	Bantry Bay: 10 km Bantry Bay: 10 km	Sugarloaf Bay: 7 km Echo Point: 12 km

Unlike other Australian states, where seagrass can be found in offshore waters (Kirkman 1997), seagrass in NSW is almost exclusively found in estuaries. It is generally limited to the central and lower portions of estuaries depending on growth factors including water velocity and sediment type. Water depth *per se* is not a factor, with the depth limit determined by light penetration (Dennison 1993). Studies of Botany Bay (Watford and Williams 1998) and Georges River (Pickthall *et al*. 2004) confirm this model of distribution. In both estuaries, seagrass was mostly found in the lower parts of the estuary. In a geomorphic context (*sensu* Roy 1984), seagrasses grow mainly in the Marine Tidal Delta and the Central Mud Basin portions of an estuary.

The geomorphic zones of Roy (1984) are simple to delimit with the assistance of aerial photographs, topographic maps and bathymetric contours, and once designated have the potential to be used in assessing the natural distribution of seagrass. For conservation and management purposes it becomes advantageous to know where within an estuary seagrass is present, whether species are spread across what might be their natural range, and the extent of any human disturbance.

One of the objectives of this project is to create a predictive model of the distribution of seagrass in the Parramatta River. Such a model would build on our understanding of the distribution of seagrass generally, but would be augmented by features specific to the Parramatta River. Our existing understanding of the distribution of seagrass is predicated on various physical, chemical and biological factors (Table 14). The foremost of the physical factors is sea level, given that it has risen and fallen of the order of 130 m during glacial intervals. Sediment type is important as seagrasses are rooted plants and do not grow on a rock substrate. Topography, or more specifically bathymetry, is a contributing factor in terms of area of available soft substrata on which seagrass can grow (Butler and Jernakoff 1999). A gently sloping shoreline can be covered with seagrass whereas no seagrass will grow on a steeply shelving rock face or vertical sheet installed for infrastructure.

Wave energy is important, as almost no seagrass is found in near shore coastal waters. The sole exception appears to be Broughton Island (off Port Stephens) where small patches are located in the sheltered waters of Esmeralda Cove, Coal Shaft Bay and Providence Beach. We assume that the high energy NSW coast prohibits any colonisation due to regular sand movement caused by storm waves. In the estuaries, ocean swell is moderated by the width, depth and orientation of the entrance and so some shorelines within estuaries show lower wave energy climates than others. The impact of wave energy is further expressed in relation to fetch, i.e., some sites will be consistently on a lee shore and so favour the growth of seagrass in relation to other sites that are more exposed. This would mean that northeast winds generated daily in the summer months would have an unfavourable impact on seagrass growing on the southern or western sides of estuaries.

Depth, in relation to the ambient wave energy and irregular pulses of wind or storm waves, is an important factor in relation to the establishment or growth of seagrass (Butler and Jernakoff 1999). Given that all other conditions are appropriate for the growth of seagrass (stable sea level, soft sediment, topography), the natural wave climate can still be so extreme as to prohibit growth of any kind. Furthermore, pulses of waves, either of a short term nature from storms, or of a longer duration in the form of small wind waves, can erode seagrass growing at the upper margin of distribution.

The depth to which seagrass grows and its upstream extent, are influenced by chemical as well as biological features (Butler and Jernakoff 1999). These features are listed in Table 4 specifically in relation to the Parramatta River. Other disturbances that can affect the distribution of seagrass include wave energy caused by the wakes of boats and ships, and reflection and refraction of waves caused by hard structures installed as part of transport infrastructure.

Tidal range, being variable along the long axis of an estuary, is another factor influencing the distribution of seagrass. A maximum of two metres at the entrance to NSW estuaries, it is reduced naturally, but to varying degrees depending on entrance condition, as well as being modified by entrance dredging or the installation of training walls. Neither of these types of engineering works are significant in the Parramatta River, there are no training walls, and dredging is limited to a relatively small entrance channel near Sow and Pigs Reef.

Table 4. The factors most likely to influence the distribution of seagrass in the estuary of the Parramatta River.

Disturbance type	**First order features**	**Natural (second order) features**	**Third order features**	**Type of disturbance[#]**		**Occurrence of disturbance**			
				Pressure	**Pulse**	**Up-stream**	**Up-slope**	**Down-slope**	**Down-stream**
Physical	Sealevel			X		X	X	X	X
	Sediment								
	Topography		Dredging	X		X	X	X	X
			Reclamation	X		X	X	X	X
	Wave energy	Ocean swell		X			X		X
		Fetch		X	X	X	X		
		Shoreline storm waves			X		X		
		Storm surge			X	X	X		
			Boat wake	X	X	X	X		
			Infrastructure refraction	X			X		X
	Tidal range		Entrance deepening	X		X	X	X	X
			Training walls	X		X	X		X
	Scour	Bank erosion			X	X	X	X	X
			Effluent discharge	X	X	X	X		
			Stormwater discharge	X	X	X	X		
	Sediment deposition	Erosion products							
			Effluent sediments	X	X	X	X	X	X
			Stormwater sediments	X	X	X	X	X	X
Chemical		Chemical Oxygen Demand (C.O.D.)	C.O.D.	X	X	X	X	X	X
		Nutrients*	Nutrients*	X	X	X	X	X	X
			Oil spills		X	X	X		X
			Dispersants		X	X	X	X	X
Biological		Biological oxygen Demand (B.O.D.)		X	X	X	X	X	X
			Increased algal density*	X		X	X	X	X
			Increased epiphyte density*	X		X	X	X	X
		Disease			X	X	X	X	X
Total				**18**	**15**	**21**	**24**	**14**	**18**

*Increased algal and epiphyte density are oftentimes factors associated with an increase in nutrient levels.
#After Glasby and Underwood 1995.

1.3. Objectives

Phase 1 (completed 2004)

1. Conduct PC-based GIS analysis of ortho-rectified aerial photographic images of the Parramatta River taken in 2000 and delimit the boundary of seagrass in the study area.
2. Conduct field checks to confirm seagrass boundaries.
3. Create ArcView shape files and associated data tables to indicate the area of cover for seagrass.
4. Provide a report to NSW Maritime (West *et al*. 2004).

Phase 2 (this project)

5. Update the data on cover of seagrass by analysing ortho-rectified aerial photographic images of the Parramatta River taken in 2003.
6. Provide an historical component to the project by analysing aerial photographs from earlier decades.
7. Create a predictive map of the distribution of seagrass.
8. Provide a report to NSW Maritime.

2. METHODS

2.1. Study site

The catchment of the Parramatta River has a surface area of approximately 217 km^2 and a waterway area of 49.7 km^2 (Department of Natural Resources, online). The estuarine portion of the river is defined by NSW Maritime as all the tidal waters below the eastern-most weir at Parramatta, the weir on the Lane Cove River and the natural tidal limit in Middle Harbour at the suburbs of St. Ives and Davidson (Appendix 1). For ease of planning and management, NSW Maritime has divided the estuary into five subunits. Three of these are riverine in nature: the Parramatta River (from the most downstream Parramatta weir to a line joining Manns Point to Yurulbin Point), the Lane Cove River, and Middle Harbour. The lower portion of the estuary includes Sydney Harbour and North Harbour. Collectively, the latter two sections are known as Sydney Harbour. While the water surface area of the estuary has changed over time, most notably over the past 200 years due to dredging and reclamation of parts of the foreshore, it presently stands at nearly 5300 ha (NSW Maritime 2004; Appendix 2). The whole of the tidal shoreline from the north headland to the Parramatta weir and back to the south headland, including the foreshores of islands, exceeds 300 km in length.

Roy (1984) set out principles by which the estuaries of southeast Australia could be classified into three major types: drowned river valleys, barrier estuaries and intermittently open estuaries. Within the Sydney metropolitan area all of the large estuaries, including the Parramatta River, are drowned river valleys (Roy *et al*. 2001).

Another facet of Roy's (1984) scheme is that when sealevel stabilised 6500 years ago, four geomorphic zones were created in any given estuary. These zones are known, from upstream to downstream, as the Riverine Channel, Fluvial Delta, Central Mud Basin, and Marine Tidal Delta. Mesley (2003) mapped the extent of these four zones in the Parramatta River (Figure 1). To a limited degree, the geomorphic zones correspond with the management subunits set out by NSW Maritime.

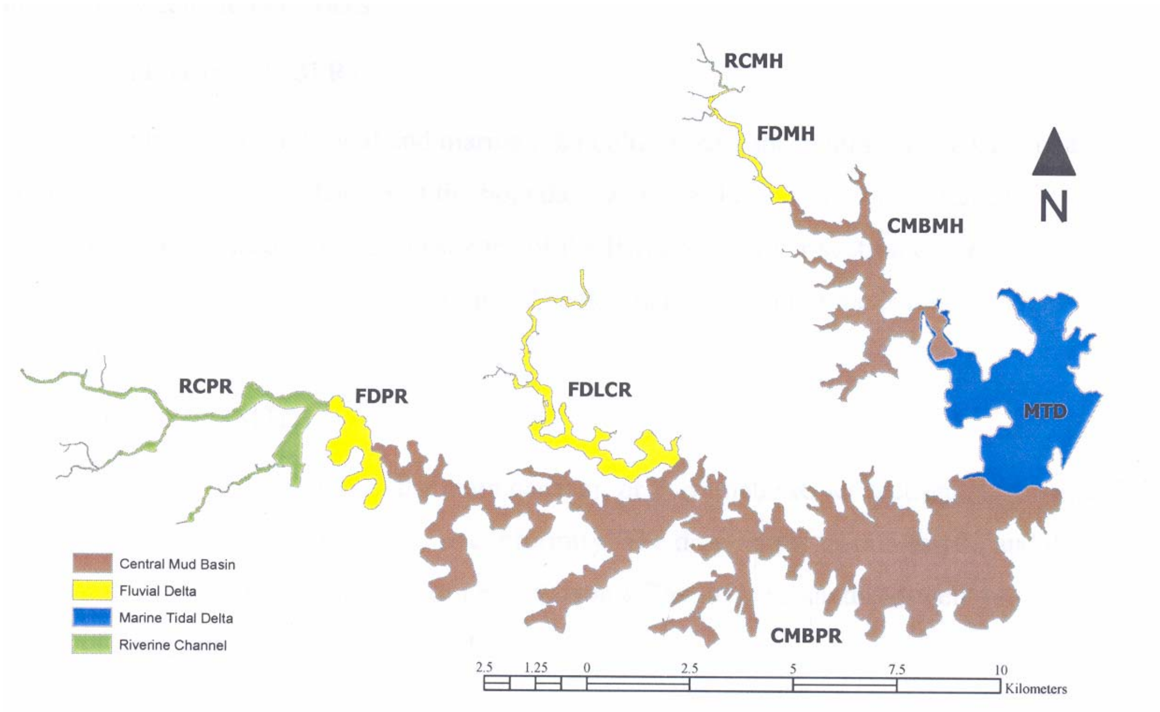

Figure 1. Geomorphic zones in the Parramatta River/Sydney Harbour estuary (Mesley 2003).

2.2. Mapping of seagrass

Seagrass in Middle Harbour and the Parramatta River was mapped for four time periods: 1978, 1986, 2000, and 2003. Black and white contact prints for 1978 and colour contact prints for 1986 were obtained from NSW Department of Lands, scanned and ortho-rectified. For 2000, ortho-rectified images of the study site were obtained by the then NSW Fisheries as part of a consortium of state and local government agencies co-ordinated by the then Office of Sydney Harbour Manager. Ortho-rectified images for 2003 were obtained by NSW DPI as part of a consortium with NSW Planning.

All mapping was done at a scale of 1:1 500 via onscreen digitising using the GIS software package ArcMap 9.1. The number of patches, area of cover, and distance from the most upstream patch to the tidal limit was calculated for each sample year. These distances were determined with reference to the entrance to Sydney Harbour (the entrance being defined as commencing at a line drawn from North Head to South Head). In Middle Harbour the tidal limit is about 400m upstream of Rocky Creek in Garigal National Park, and in the Parramatta River it is at the most downstream weir in Parramatta River.

Seagrass is variable in its cover, with extent expanding or contracting over time (Meehan and West 2000, Williams and Meehan 2004) and/or disappearing from one site and being found at an adjacent one. While persistence in cover has been assessed for some NSW estuaries (e.g., in the Hacking River, Williams and Meehan 2004), it has not been determined for the Parramatta River. To identify persistence, as well as unique occurrences, data for cover of seagrass for 1978, 1986 2000, and 2003 were overlayed and the 15 combinations (n^2-1) were delineated. Calculations of change in cover are presented in terms of the entrance to the estuary (Marine Tidal Basin), Middle Harbour and the Parramatta River, each with their respective geomorphic zones (Central Mud Basin, Fluvial Delta, Riverine Channel).

2.3. Prediction of future growth of seagrass

A computer model was used to estimate the location of seagrass in the estuary under the most favourable conditions that could be described with available data. Unfortunately, data relating to light penetration, one of the most important determinants of seagrass growth, is not readily available for the Parramatta River. It was beyond the scope of this project to collect these data, and the ensuing model is a first approximation of distribution.

Several methods have been successfully used in the development of predictive models of seagrass. These include Generalised Additive Models (Lehmann, 1998), Logistic Regression and Boolean Logic Models (Kelly *et al*. 2001) and Optical Models based on light attenuation and water depth (Lathrop *et al*. 2001). An alternative approach to the modelling of species distributions is through the use of GARP (genetic algorithm for rule-set prediction) (Stockwell and Noble 1991, Stockwell 1999, Stockwell and Peters 1999). GARP has been shown to be very robust and successful in the modelling of terrestrial plant and animal distributions (Pearson *et al.* 2003, Illoldi-Raggel *et al*. 2004), as well as fish (Wiley *et al*. 2003, Kolar 2004) and pests (Iguchi *et al*. 2004, Peterson and Vieglais 2001, Drake and Bossenbroek 2004). GARP was used as it can cater for presence-only data, can utilise GIS data directly, is freely available and can readily be applied to the modelling of other species, or in other estuaries.

The modelling package used in this study is Desktop GARP 1.1.6. This package provides a simple user-interface for the GARP modelling environment. The Mesley 2003 map was converted to a grid file and the individual zones were separated out to be used as a mask in Desktop GARP.

2.3.1. Mapping of depth and slope

Sounding data were provided by NSW Maritime (D. Buttigeig, pers. comm.) in point form as an ESRI shapefile (Figure 2). The reference point was the 0 datum at Fort Denison which conforms to Indian Springs Low Water (0.925 m below Australian Height Datum). The shapefile, with a total of 180,832 soundings, was imported into the software program Surfer 8 and converted into a grid that conformed to the spatial distribution of the substrata data with a resolution of 10 m. Due to the irregular but close spacing of the latter, the natural neighbour method of grid generation was used to derive the final gridded data set. The sign of the depth data was inverted to conform with the format of the sediment data. Consequently, shallow water occurrences of seagrass appear in the text as small positive numbers (e.g., 1.25) whereas deep occurrences of seagrass are denoted as a negative number (e.g., -6.99).

Substrata and depth data layers were clipped to conform to the study area. The derived bathymetric depth layer was then used as input in Spatial Analyst in ArcGIS to generate bathymetric slope (Figure 3).

The depth at which seagrass is currently growing was then determined. For this task, the bathymetric model was converted to a point shapfile with a point representing the centre and value of each pixel in the original bathymetric model. Data for the seagrass patches were then overlaid and the intersecting points were selected for the calculation of the depth statistics.

The data were set out in relation to Roy’s (1984) geomorphic zones. Should the need arise, the dataset can be reconfigured to identify cover in other ways, such as for the five subunits of estuary set out by NSW Maritime (2004): Parramatta River, Lane Cove River, Sydney Harbour, Middle Harbour, and North Harbour.

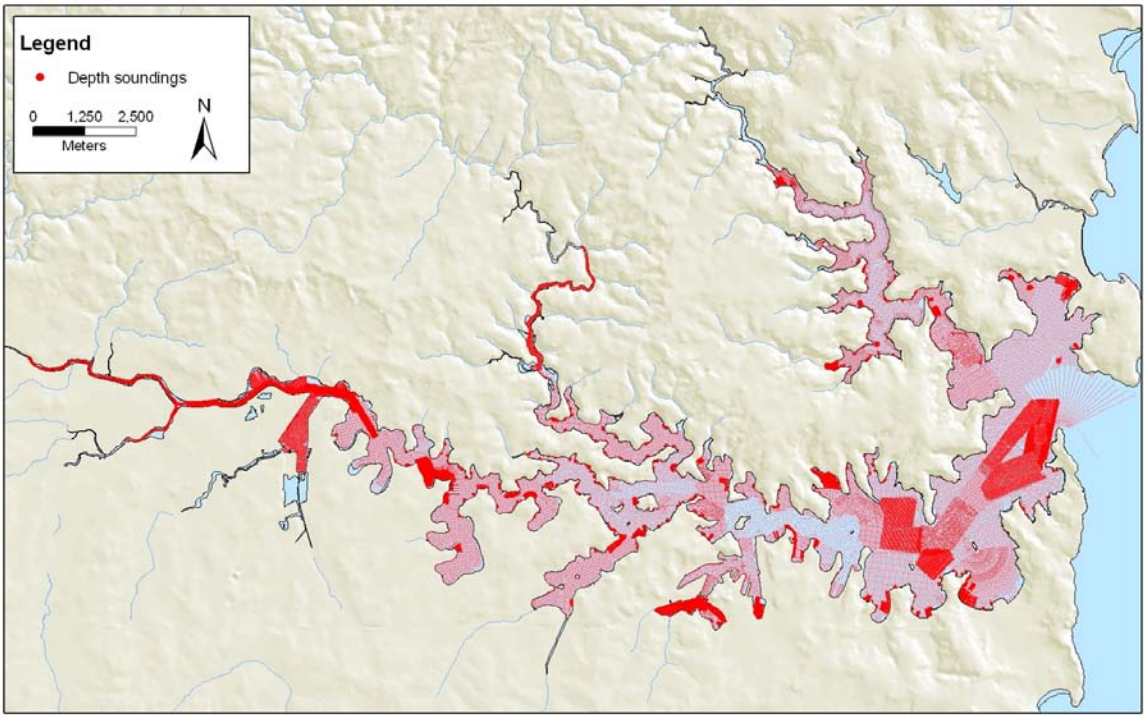

Figure 2. Distribution of the depth soundings (NSW Maritime 2004) used in the derivation of the bathymetric layer.

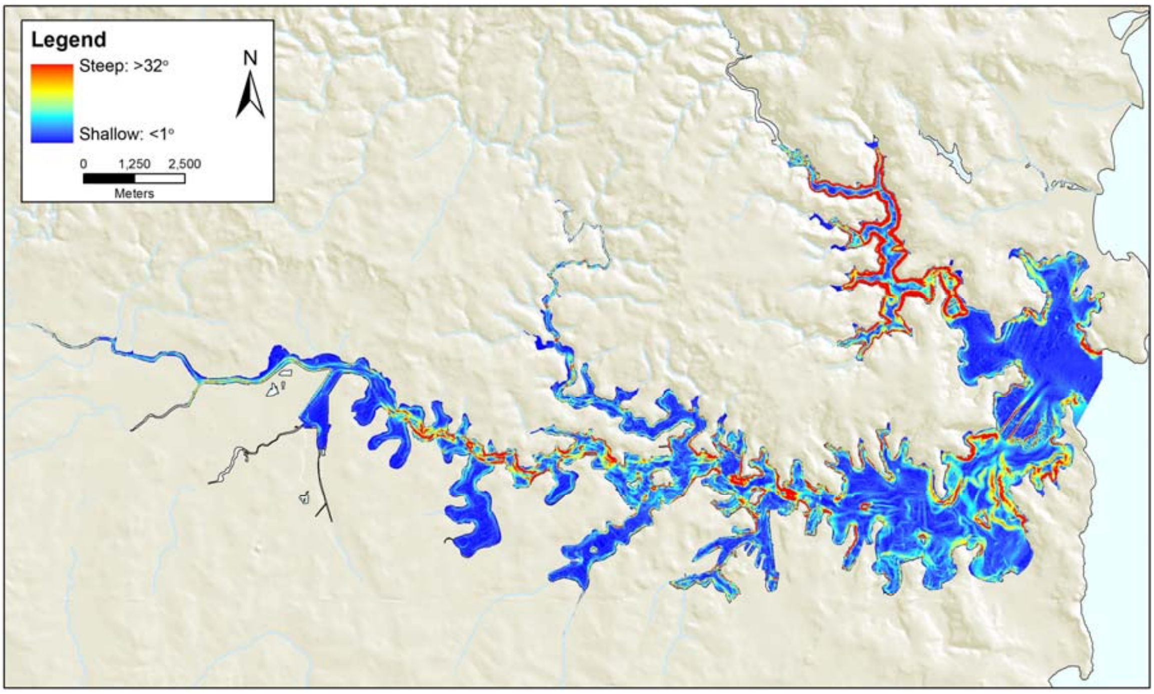

Figure 3. Derived bathymetric slope for Sydney Harbour, calculated using Spatial Analyst in ArcGIS 9.1.

2.3.2. Mapping of substrata

The sediments of the Parramatta River/Sydney Harbour are well described, particularly at depth (Birch and Taylor 2004). To map the substrata, a file containing data for 569 sample locations was provided by Stuart Taylor (pers. comm., 2005). Locations used to determine type of substrata are shown in Figure 4. Percent composition of sand, mud and gravel were extracted from the point files and put into the software package Surfer 8 to generate surface grids covering the study area. As sample locations were limited to the estuarine water body there was a need to use a gridding method that limited the grid derivation to the estuary but also considered the coastline as a barrier. This barrier effect prevents the derivation of values across adjacent arms of the estuary. Given these restrictions, the minimum curvature gridding method was selected. This method utilises what is called a "fault line" to limit the flow of data to within the selected area. In this instance the fault line was a simplified version of the coastline. Three layers were derived: percent mud, percent sand and percent gravel at a spatial resolution of 10 m.

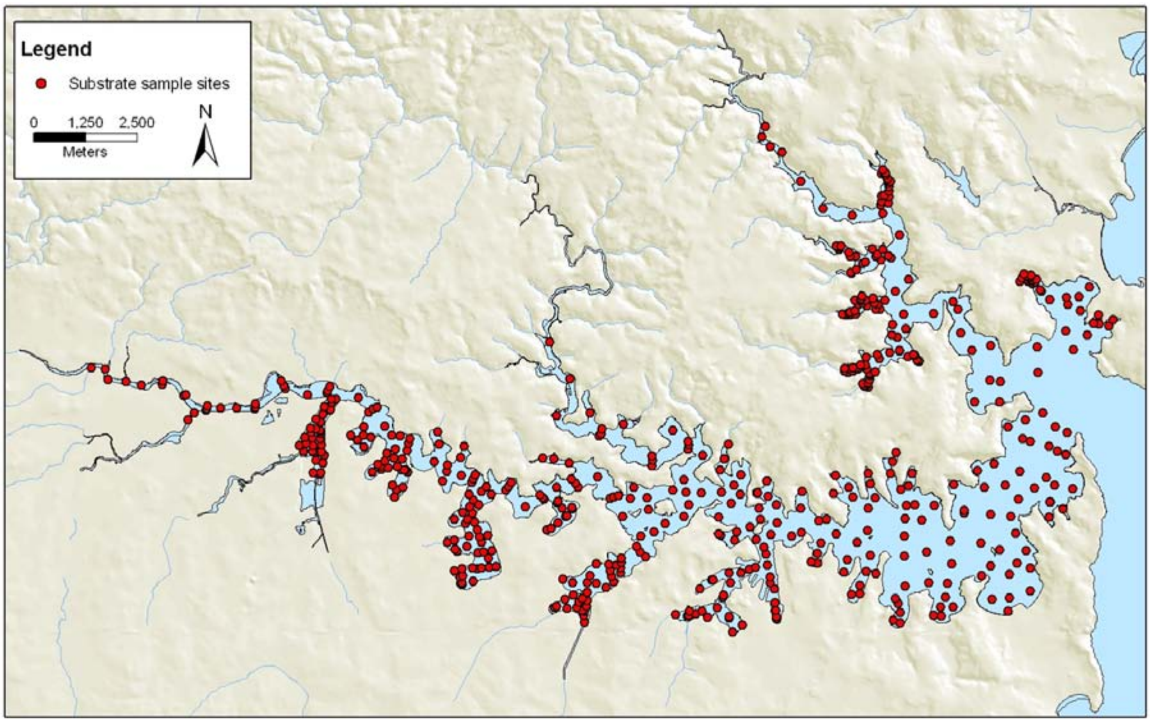

Figure 4. Locations of samples (S. Taylor pers. comm) used to develop the mud, sand and gravel substrata layers.

2.3.3. *Mapping of fetch*

Wind and wave exposure were calculated for the eight principal compass directions. Several methods have been devised to calculate fetch for a given location (Puotinen 2005, Ekebom *et al*. 2003, Ruuskanen *et al*. 1999). Given the size and resolution of the grid data and the need to generate fetch for all points within the study area, the method described in Lathrop *et al*. (2006) was used. This method generates nine fetch calculations for each of the eight main directions that are centred on the selected bearing, i.e. for each of the eight directions there are nine values at three degree intervals with the main bearing being the centre. Fetch was derived using the UWWaves Toolbox for ArcGIS 9.0 Version: 1.0.2. However in this initial form all fetch directions have an equal weighting and do not take the effects of wind frequency into account. To account for this the annual average wind frequency was estimated from a wind rose chart downloaded from the Bureau of Meteorology website (BOM online; Figure 5). Each of the fetch grids was multiplied by the derived wind frequency values (Table 5). This provided eight grids with the derived fetch for each of the selected bearings (Figure 6).

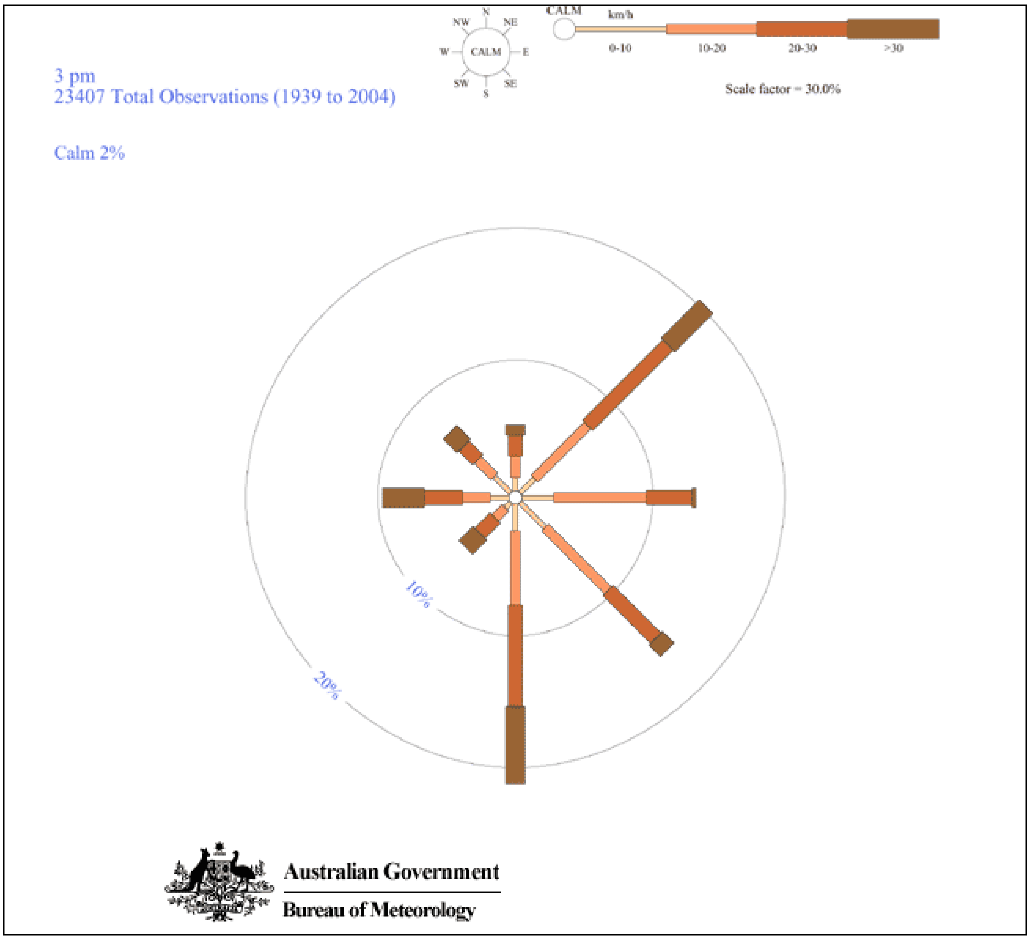

Figure 5. Wind rose depicting annual average wind frequency and strength for Sydney Harbour, for measurements made at 1500hrs.

Table 5. Relative frequency of wind directions as derived from the wind rose for the annual average wind direction information for Sydney Harbour at 1500hrs.

Direction	Frequency(%)
North	6
North-East	20
East	14
South-East	16
South	22
South-West	5
West	10
North-West	7

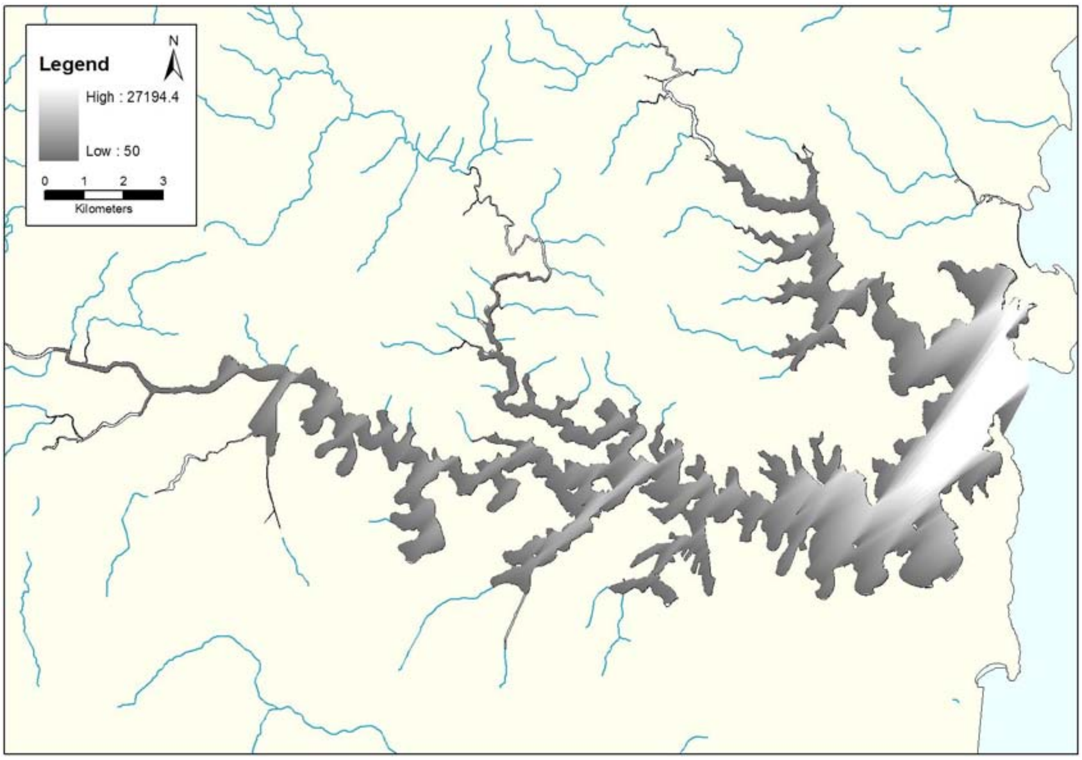

Figure 6. Derived annual NE fetch length weighted by the average wind frequency for Sydney Harbour.

2.3.4. Mapping of distance from the entrance

Distance from the entrance of the estuary was calculated. A point midway along a line from Quarantine Head to South Head was used as the origin, and distance from that point upstream was measured in metres (Figure 7).

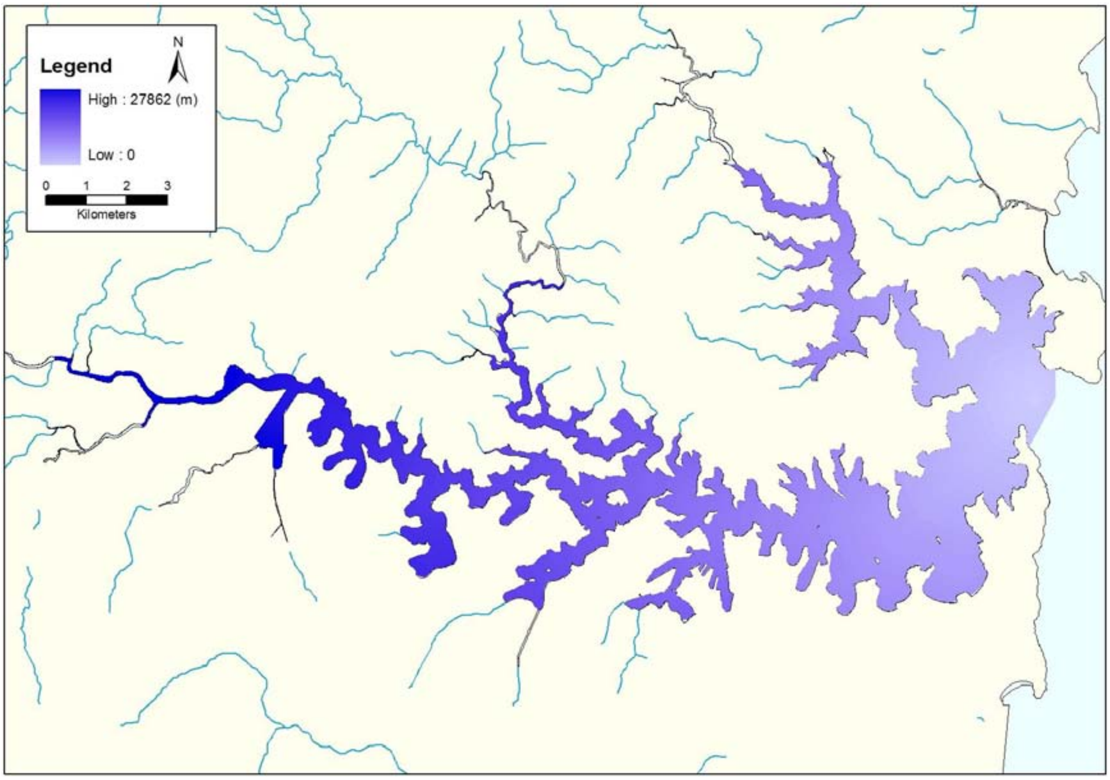

Figure 7. Derived distance in metres from the estuary entrance.

2.3.5. Data preparation for GARP

To standardise the layer files to have the same coverage and dimensions, all layers were recoded to a value of 1 or 0. They were then added together to create a composite layer. The maximum value on this layer is the area that layers have in common. This layer was then recoded so that all other values were removed keeping only this common area. This layer was then used to clip all of the environmental layers to the same region. To simplify the model generation the estuary was divided up into the respective geomorphic zones (Figure 1). To limit the model generation to only those areas within the zones, each zone was exported to an individual grid file and used as a mask in the Desktop GARP software package (DG). All layers were exported as ASCII grids for import into DG via the GARP Dataset Manager.

2.3.6. Model settings

Seven models for seagrass distribution were generated. One was for the entire estuary and another was for the entrance only. The others were based on the two tributaries and the geomorphic zones within which seagrass was present in 2004. The Parramatta River Fluvial Channel was not modelled as there is no seagrass present in that zone. The first set of models was developed as follows:

Harbour Entrance: Marine Tidal Delta (HE_MTD)
Parramatta River: Central Mud Basin (PR_CMB)
Parramatta River-Lane Cove: Fluvial Delta (PR_LC_FD)
Middle Harbour: Central Mud basin (MH_CMB).

The lack of adequate training points for some sectors meant that a subsequent stage of modelling was required for:

Parramatta River Fluvial Delta (PR_FD)
Middle Harbour: Fluvial Delta (MH_FD).

To model the distribution of seagrass in PR_FD and MH_FD, these sectors were joined to their respective downstream Central Mud Basins, thereby extending the number of training points for the model generation.

Desktop GARP was setup with the following settings for each of the model runs.

Use 50% of the seagrass locations as training and 50% for testing.
Generate 500 runs with a convergence value of 0.01 and 2000 iterations.

The best subset option was selected (based on Anderson *et al*. (2003)) with a specification to use extrinsic omission measures with a hard threshold of 50 models and a commission threshold of 50%. This selects 10% of the 500 runs that have an extrinsic omission of less than 10%. The best 25 of these models were selected around the median of this subset to be used in the model generation.

2.3.7. Seagrass sample locations

The map of seagrass for the year 2000 (SG2K) was chosen for the modelling input. This dataset is the most accurate, as it was checked in the field. Sample points of the seagrass were selected by creating a point file from the Grid mask (as above), and generating a point grid with a 10 m interval that coincided with the environmental data. This point file was intersected with the SG2K data to leave only the points that coincided with the seagrass distribution. All attributes for the seagrass layer were then transferred to the selected points for inclusion in the model if required. The total number of points selected and generated was 5065.

The seagrass locations and associated environmental data were input to DG for analysis. Models were run for each of the geomorphic zones that had adequate seagrass locations present, as well as for the entire estuary as a whole. No model was generated for PR_FC as no seagrass has been found in this section of the estuary. Table 6 lists the number of seagrass locations that were included in each of the models that were generated. PR_FD and MH_FD were not modelled individually due to the lack of seagrass or the small number of locations. To enable prediction in these two sectors they were combined with their respective Central Mud Basin zones.

Table 6. Training data for each zone. Unmasked points are the points available for inclusion in the model (* indicates that no model was created).

Zone	Unmasked	Masked	Total
All zones	5062	3	5065
HE_MTD	1609	3456	5065
PR_CMB	3103	1962	5065
PR_FD*	0	5065	5065
PR_LC_FD	124	4941	5065
MH_CMB	220	4845	5065
MH_FD*	6	5059	5065
PR_CMD & PR_FD	3103	1962	5065
MH_CMB & MH_FD	226	4839	5065

2.3.8. Model output

The 25 best subsets for each zone were added together to create a predictive layer for each zone. This layer had values ranging from 0 to 25 indicating areas where each of the predictions overlapped. The value of 25 indicates agreement between all of the models and is the final product for the model outcomes. The final models for each zone were then merged together to create the final composite predictive layer for the study area.

3. RESULTS

3.1. Mapping of historical and present distribution of seagrass

3.1.1. Area, number of patches, and distance upstream

The area of seagrass in the Parramatta River, based on aerial photographs taken in 2000 and 2003 is of the order of 50 ha (Table 7). However, cover was even greater in the mid 1980s when 87.4 ha were mapped, and in 1978 when 59.2 ha was mapped. The amount recorded by West *et al*. (1985) from photos taken in 1978 and field inspection in 1981 was 128.6 ha, but the amount we determined for the 1978 photos was less than half that determined by them (Table 7).

Table 7. Estimated area of seagrass in Sydney Harbour over recent decades.

Aerial photo	Photo interpretation	Field survey	Area (ha)
1978	West *et al*. (1985)	Jan. 1981	128.6
1978	This study	Not possible	59.2
1986	This study	Not possible	87.4
2000	West *et al*. (2004)	Sydney Harbour: May 2002 Parra. River: March – June 2003	51.9*
2003	This study	Not done	49.5

*initially reported by West *et al*. (2004) as 51.7ha, but modified in a *corrigendum*.

Through all four sampling dates the entrance to Sydney Harbour (Marine Tidal Delta (MTD)) accounted for 15 – 20% of the cover of seagrass (Table 8). The Parramatta River had the greatest cover, of the order of 70 – 80% of the total, with the amount greatest in the Central Mud Basin (CMB) and then decreasing further upstream. The tendency for the CMB to have more cover than the Fluvial Delta (FD) or Riverine Channel (RC) was also seen in Middle Harbour. The large increase in cover from 1978 to 1986 was, with the exception of the FD in Middle Harbour, seen across the whole estuary. Middle Harbour showed no seagrass in its Riverine Channel (RC).

The number of patches showed a similar geographic pattern to that of total area, with most of patches in the two tributaries being in the CMB (Table 8). The number of patches was, with the exception of the CMB of the Parramatta River, greater in 1986 than in the other years. The increase in number of beds, coupled with the increase in area, suggests an overall expansion rather than a breaking up of the beds.

In relation to the tidal limit, the most upstream occurrence of seagrass in Middle Harbour has consistently been of the order of 12 km from the Entrance (Table 9). The Parramatta River showed variation in extent: the furthest upstream penetration occurred in 1986 when seagrass was found over 23 km from the heads, considerably further than the values shown in Table 3, but in the periods before and after 1986, the upstream limit of seagrass was found further downstream.

Figures 8, 9, 10 and 11 show the recent history of the estimated cover of seagrass for the Parramatta River and Middle Harbour.

Table 8. Estimated seagrass area (ha) and number of patches for each year for each estuarine section and each geomorphic zone in Sydney Harbour. Data are from aerial photographs analysed during this study.

Year	Data type	Middle Harbour			Parramatta River			Harbour Entrance	Total
		Riverine Channel	Fluvial Delta	Central Mud Basin	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta	
1978	Area covered	0.0	0.058	2.683	0.016	3.278	42.529	10.674	59.237
1986	Area covered	0.0	0.023	3.159	0.141	5.060	49.866	29.178	87.426
2000	Area covered	0.0	0.035	2.236	0.0	1.264	31.530	16.796	*51.861
2003	Area covered	0.0	0.054	2.452	0.0	1.087	30.651	15.207	49.451
1978	No. of patches	0	7	152	1	66	595	231	1052
1986	No. of patches	0	12	270	2	141	591	497	1513
2000	No. of patches	0	9	186	0	57	569	465	1286
2003	No. of patches	0	8	213	0	72	618	306	1217

*initially reported by West *et al*. (2004) as 51.7ha, but modified in a *corrigenda*

Table 9. Penetration distance for seagrass in Middle Harbour and Parramatta River estuaries.

Year	Middle Harbour Distance from Entrance to tidal limit = 16.1km		Parramatta River Distance from Entrance to tidal limit = 31.0km	
	Distance from Entrance of most upstream seagrass bed (km)	% of distance from Entrance	Distance from Entrance of most upstream seagrass bed (km)	% of distance from Entrance
1978	11.4	70.8%	21.6	69.7%
1986	12.1	74.5%	23.4	75.5%
2000	12.2	75.8%	18.9	61.0%
2003	12.2	75.8%	18.9	61.0%

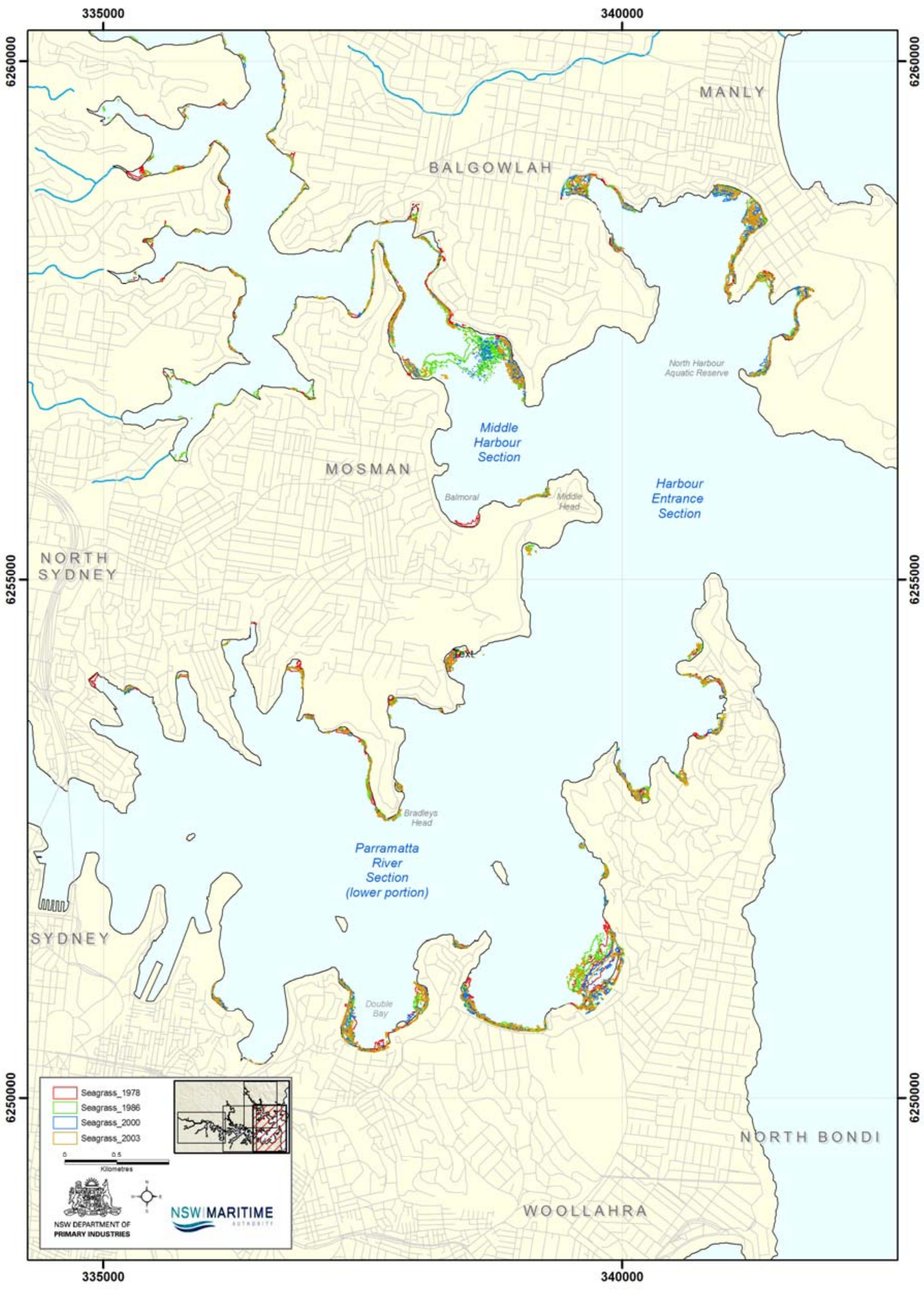

Figure 8. Historical distribution of seagrass in the Parramatta River, Harbour Entrance, 1978 – 2003.

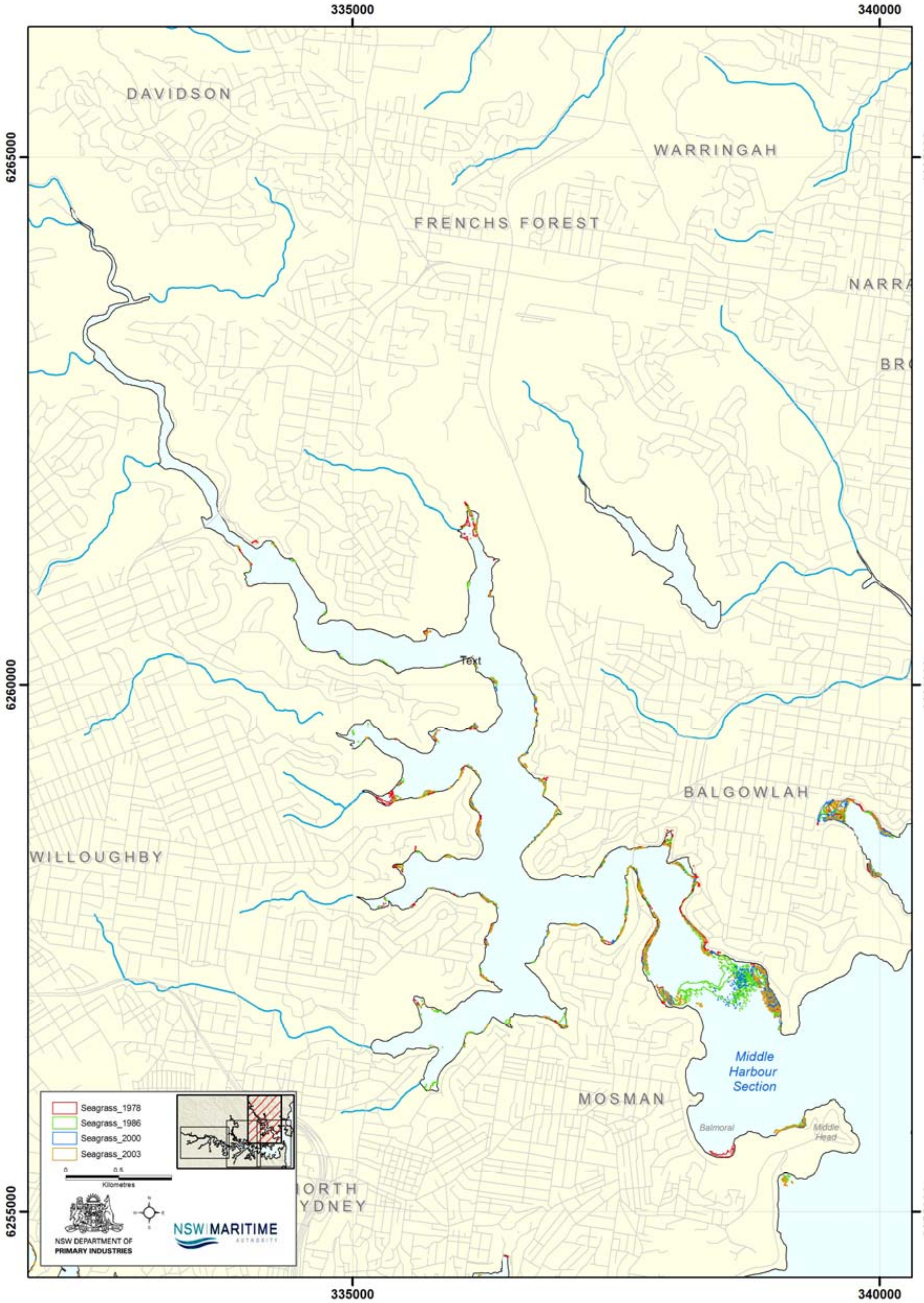

Figure 9. Historical distribution of seagrass in the Parramatta River, Middle Harbour, 1978 – 2003.

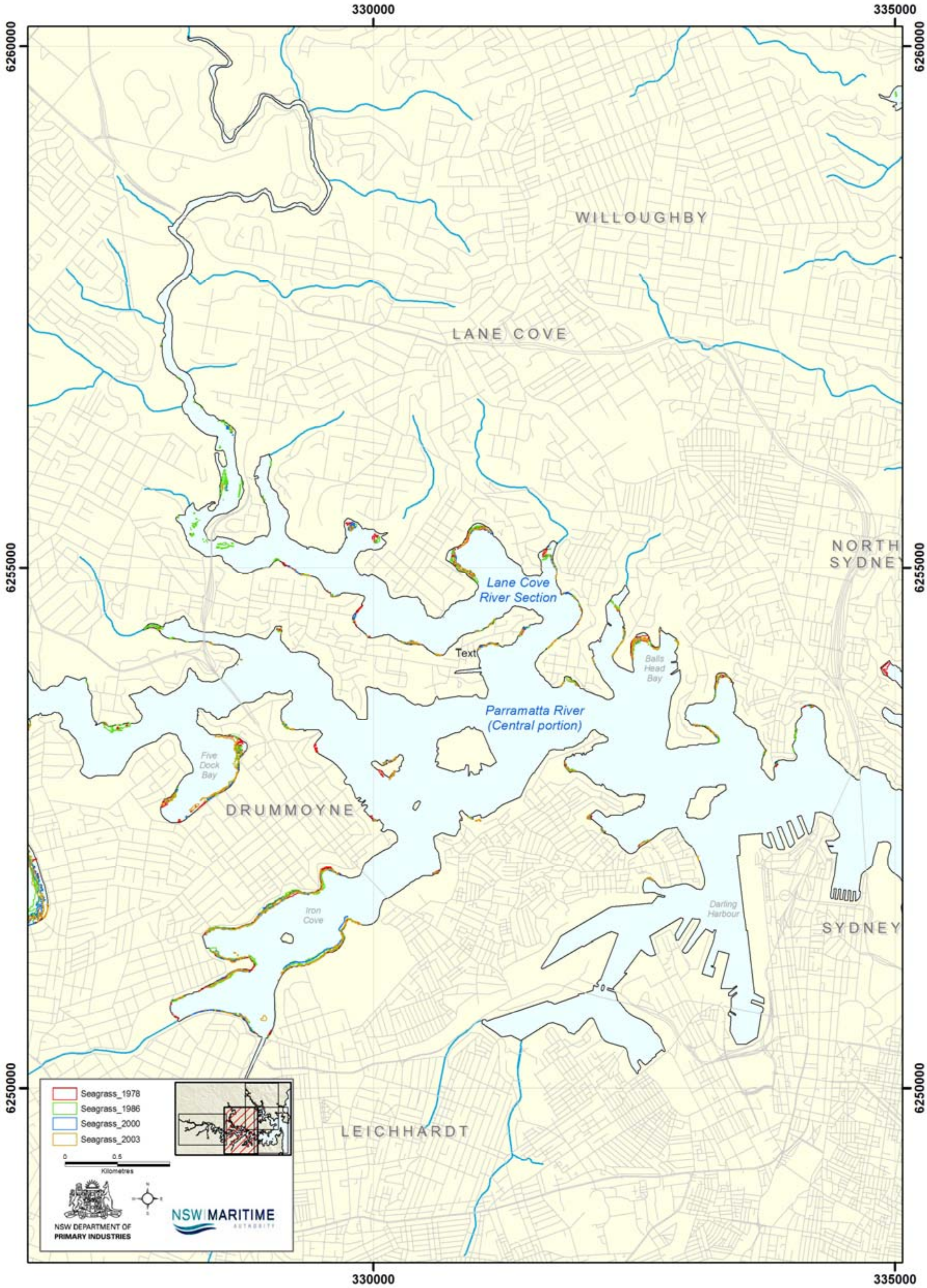

Figure 10. Historical distribution of seagrass in the Parramatta River, Central Portion, 1978 – 2003.

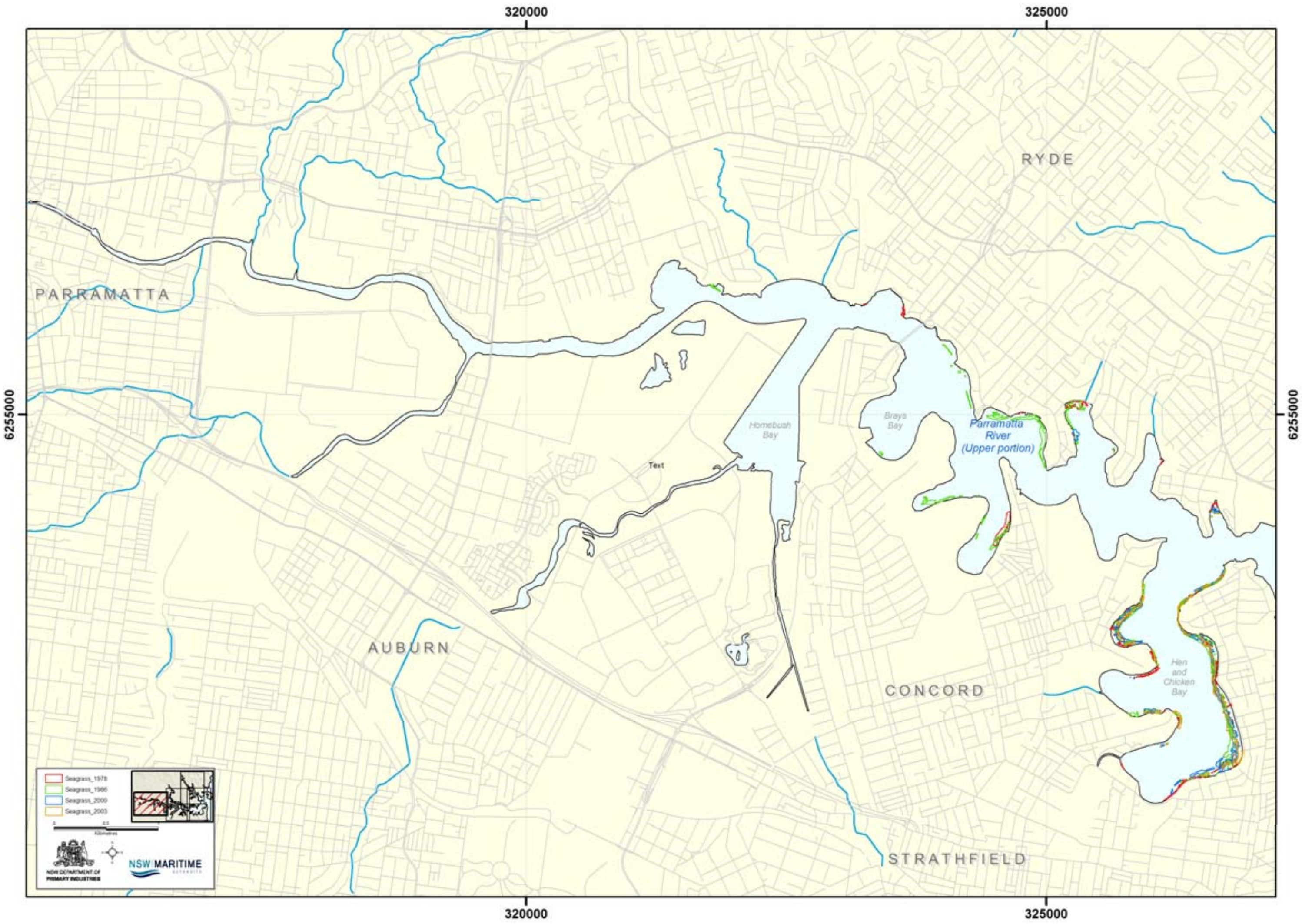

Figure 11. Historical distribution of seagrass in the Parramatta River, Western Section, 1978 – 2003.

3.1.2. Persistence of seagrass

Some seagrass beds were consistently found in the same location over the period from 1978 to 2003, but their extent varied over time. Other beds were ephemeral, appearing only on one of the four sample years. Data sets were produced in which occurrence in a single year, as well as combinations of years, were identified. For example, the total cover of seagrass in 1978 is obtained by adding data sets 1, 2, 3, 4, 5, 6, 7 and 15 (Table 10). Only about 25% of the seagrass (almost 13 hectares – Data set 15) was consistently present from 1978 through to 2003. Most of this grew in the CMB of the Parramatta River.

Total amounts of seagrass for any one year can be determined by adding the eight data sets for that year. The summary calculations for each year appear in Appendix 3, and the aggregated data can be cross-tabulated with Table 10.

Table 10. The persistence of cover (ha) of seagrass in Middle Harbour and the Parramatta River by year group for each section of the estuary and each geomorphic zone.

Data set	Years	Middle Harbour		Parramatta River			Harbour Entrance	Total
		Fluvial Delta	Central Mud Basin	Fluvial Delta	Riverine Channel	Central Mud Basin	Marine Tidal Delta	
1	1978	0.077	1.961	1.918	0.016	12.971	2.989	19.932
2	1978, 1986		0.259	0.697		9.085	1.482	11.523
3	1978, 1986, 2000		0.031	0.070		3.746	1.570	5.416
4	1978, 1986, 2003	0.000	0.060	0.037		1.859	0.471	2.426
5	1978, 2000	0.000	0.035	0.093		1.700	0.406	2.234
6	1978, 2000, 2003	0.001	0.132	0.102		1.840	0.782	2.857
7	1978, 2003	0.001	0.080	0.145		1.418	0.406	2.050
8	1986	0.021	1.897	3.632	0.141	16.905	15.121	37.717
9	1986, 2000	0.000	0.155	0.157		2.842	1.787	4.942
10	1986, 2000, 2003	0.001	0.404	0.168		2.979	4.411	7.961
11	1986, 2003	0.001	0.228	0.084		2.539	1.768	4.621
12	2000	0.012	0.580	0.355		5.544	3.027	9.520
13	2000, 2003	0.021	0.775	0.104		2.969	2.244	6.111
14	2003	0.030	0.648	0.231		7.137	2.557	10.603
15	1978, 1986, 2000, 2003		0.125	0.215		9.912	2.569	12.820

An example of the wide variation in cover that can occur is at Rose Bay (Figure 12). The area shaded dark green represents the core area that was covered with seagrass in each of the four survey years. Note that in 1986, the peak year of cover (blue-green), there was considerable expansion down slope (offshore) augmented with some upslope (onshore) increase.

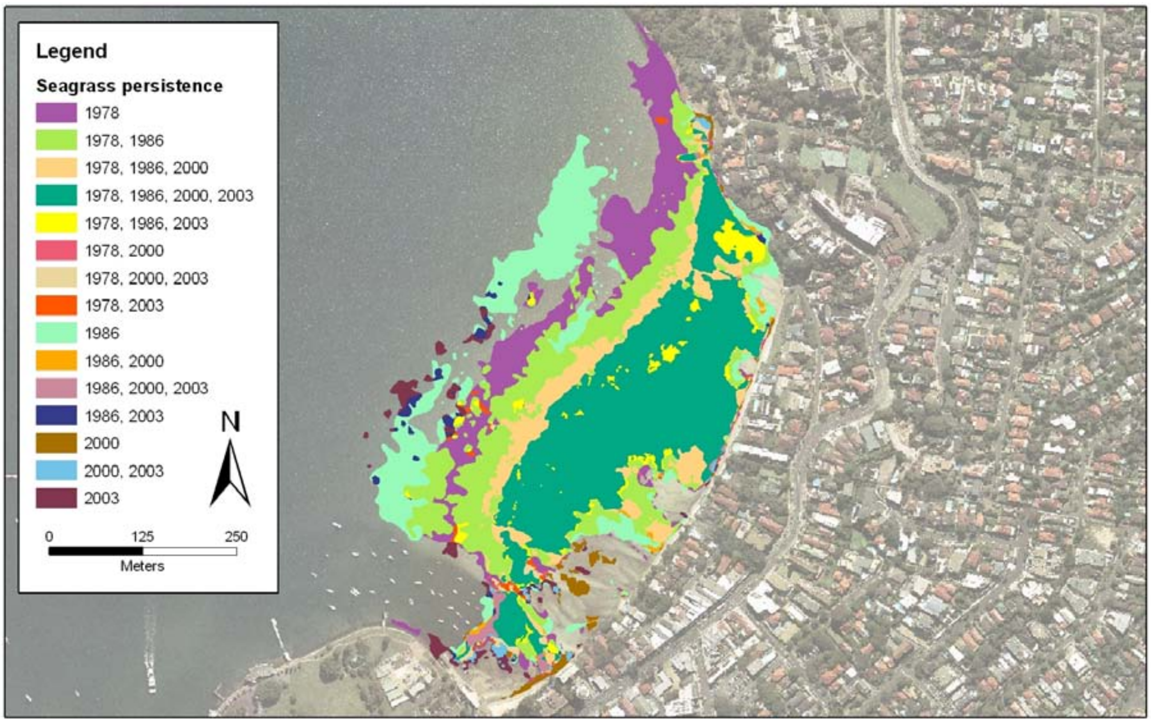

Figure 12. Persistence of seagrass at Rose Bay. Dark green indicates seagrass that was in the same location for all time periods.

3.1.3. Depth of seagrass

Variability in depth at which seagrass occurred was examined in terms of shallowest, deepest, and mean depth over the four sample years. Variation over time was seen at all three depth levels. For example, there was over a metre and a half difference between the deepest seagrass at the Entrance in 2000 compared to 2003 (Table 11).

Table 11. Summary data for the depth (m below Mean Tide) of seagrass for each year for Middle Harbour and the Parramatta River for each geomorphic zone. Data derived from Appendix 4a. All values are relative to the Australian Height Datum for Fort Denison.

Year	Depth Range	Middle Harbour			Parramatta River			Harbour Entrance
		Riverine Channel	Fluvial Delta	Central Mud Basin	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
1978	Shallowest	0.0	-0.32	0.91	0.48	0.65	1.00	0.65
1986	Shallowest	0.0	-0.64	0.82	0.63	0.90	1.00	0.68
2000	Shallowest	0.0	-1.45	0.97	0.0	0.47	1.10	0.74
2003	Shallowest	0.0	-1.45	0.97	0.0	0.58	0.81	0.45
Overall	Shallowest	0.0	-0.32	0.97	0.63	0.90	1.10	0.74
1978	Mean	0.0	-0.81	-0.98	0.31	-0.12	-0.55	-1.09
1986	Mean	0.0	-1.91	-1.66	0.52	-0.12	-0.55	-1.79
2000	Mean	0.0	-2.49	-1.57	0.0	-0.27	-0.44	-1.53
2003	Mean	0.0	-2.03	-1.54	-0.32	-0.50	-1.67	-0.32
Overall*	Mean	0.0	-1.92	-1.50	0.48	-0.15	-0.63	-1.75
1978	Deepest	0.0	-1.74	-7.33	0.10	-2.56	-8.52	-7.85
1986	Deepest	0.0	-3.18	-8.70	0.44	-2.88	-8.81	-6.29
2000	Deepest	0.0	-3.92	-7.84	0.0	-2.88	-7.86	-5.49
2003	Deepest	0.0	-3.14	-7.77	0.0	-3.91	-7.58	-6.77
Overall	Deepest	0.0	-3.92	-8.70	0.44	-3.91	-8.81	-7.85

* Mean of total data set.

Figure 13 illustrates the relationship between depth of seagrass and geomorphic zone. The greatest depth range is found in the CMBs of both Middle Harbour and Parramatta River, with a range of approximately 1 to - 9m. The seagrass depth range is slightly reduced in the Harbour Entrance, from 0.74 to – 7.85m. The lower depth in the two FDs is similar: -3.92 in Middle Harbour and -3.91 in the Parramatta River. As would be expected, the range is shallowest in the RC of the Parramatta River, 0.63 to 0.10m. No seagrass was recorded in the RC in Middle Harbour. The shallowest, mean and deepest depths are greater in the Parramatta River than in Middle Harbour.

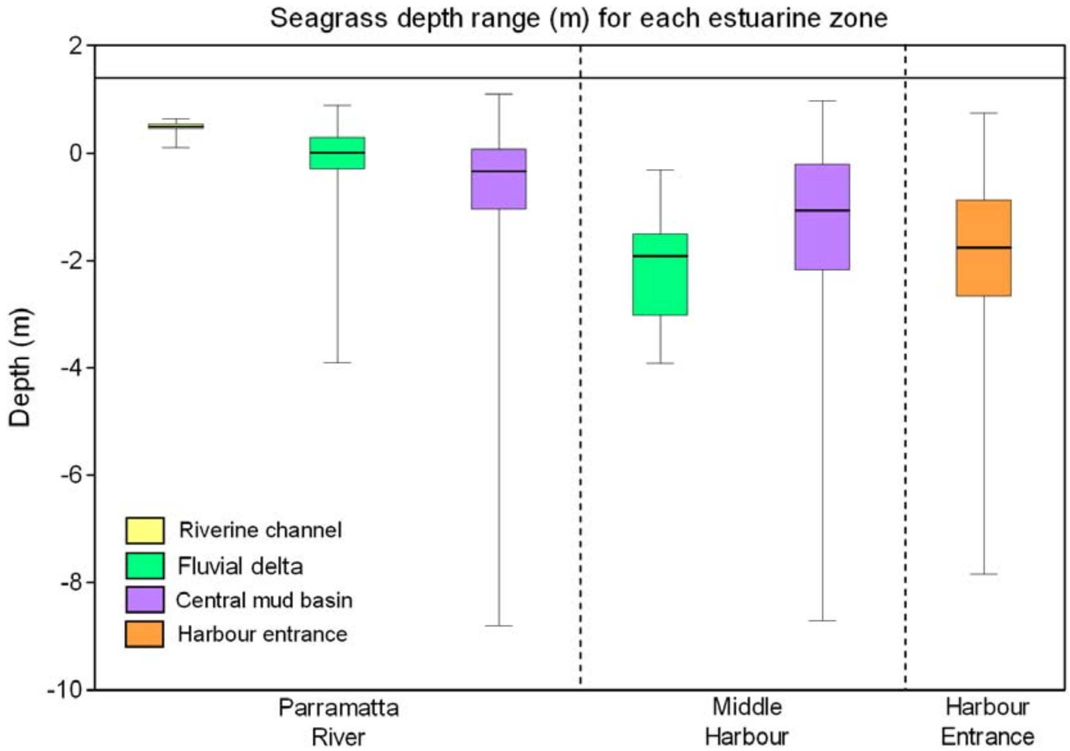

Figure 13. Boxplot of median, quartiles and extreme values showing depth characteristics of seagrass for the Entrance, Middle Harbour and Parramatta River for all years of mapping combined.

3.2. Prediction of future growth of seagrass

3.2.1. Mapping of substrata

Map layers were created from the sample data for each of three substrata types: percent mud (Figure 14), percent sand (Figure 15) and percent gravel (Figure 16). Mud was absent from some sample sites (MTD, CMB) and was the sole material at others (CMB, FD, RC; Table 12). Sand was absent from some sites (CMB, FD, RC) but was the only constituent at others (MTD, CMB). Gravel was sometimes absent from all zones, and when present, was restricted in amount.

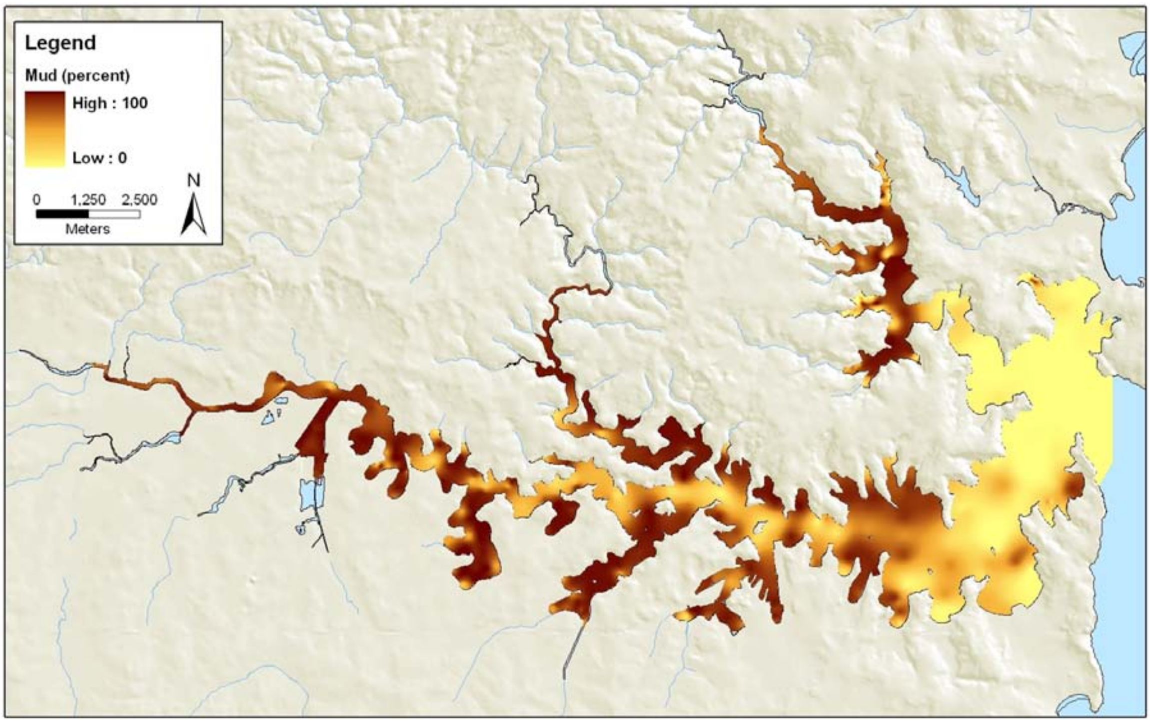

Figure 14. Distribution of the derived mud values as a percentage of the three substrata components: mud, sand and gravel.

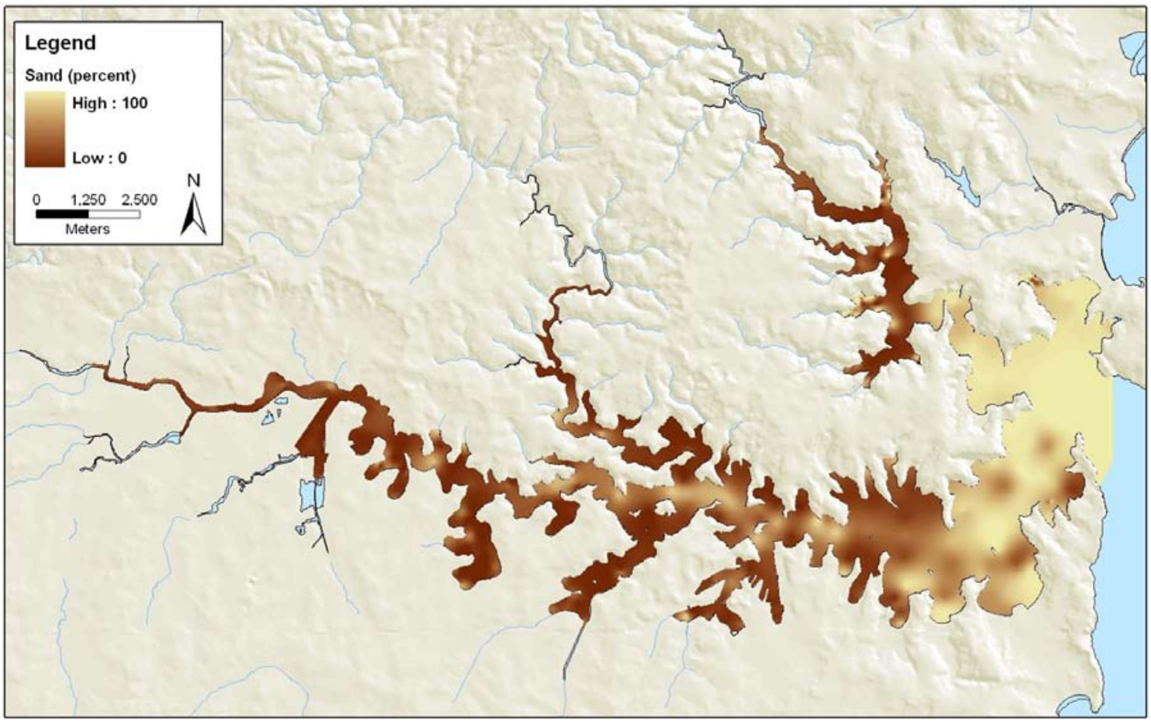

Figure 15. Distribution of the derived sand values as a percentage of the three substrata components: mud, sand and gravel.

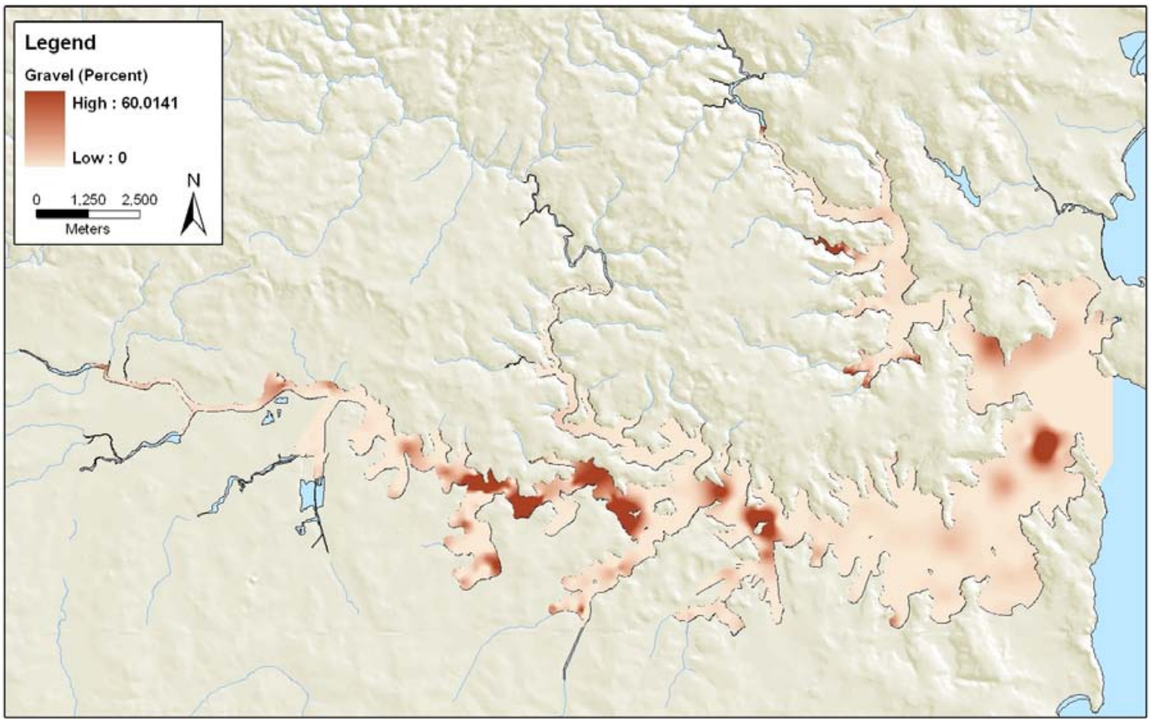

Figure 16. Distribution of the derived gravel values as a percentage of the three substrata components: mud, sand and gravel.

Table 12. Mean, maximum and minimum values of substrata type for each geomorphic zone in the estuary of the Parramatta River.

	Data	**Riverine Channel (%)**	**Fluvial Delta (%)**	**Central Mud Basin (%)**	**Marine Tidal Delta (%)**
Mud	Min.	24.51	12.47	0.00	0.00
	Mean	84.66	83.42	57.48	2.50
	Max.	100.00	100.00	100.00	89.60
Sand	Min.	0.00	0.00	0.00	10.40
	Mean	14.02	16.27	40.21	95.58
	Max.	67.44	85.32	100.00	100.00
Gravel	Min.	0.00	0.00	0.00	0.00
	Mean	1.33	0.32	2.31	1.92
	Max.	12.14	20.17	60.01	39.59

3.2.2. *Mapping of depth*

Bathymetry of the estuary is shown in Figure 17. Depths range from 0.18 m to a maximum depth of -45.63 m. If the data are sorted by geomorphic zone (Table 13), the two CMBs, as expected, show the deepest parts of the estuary. The MTD follows, at -27.34 m, and is in turn followed by the FD environments (-8.93 m to -13.90 m). The RC is the shallowest zone (1.34 m to -4.82 m). The RC of Middle Harbour is much constrained due to a rock sill.

Table 13. Range of depths (m) relative to datum at Ft. Denison for each geomorphic zone.

	Middle Harbour			Parramatta River			Entrance
	Riverine Channel	Fluvial Delta	Central Mud Basin	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
Min	NA	0.18	1.31	1.34	1.47	1.47	1.13
Mean	NA	-3.79	-13.89	-0.85	-1.66	-9.60	-10.67
Max	NA	-8.93	-32.69	-4.82	-13.90	-45.63	-27.34

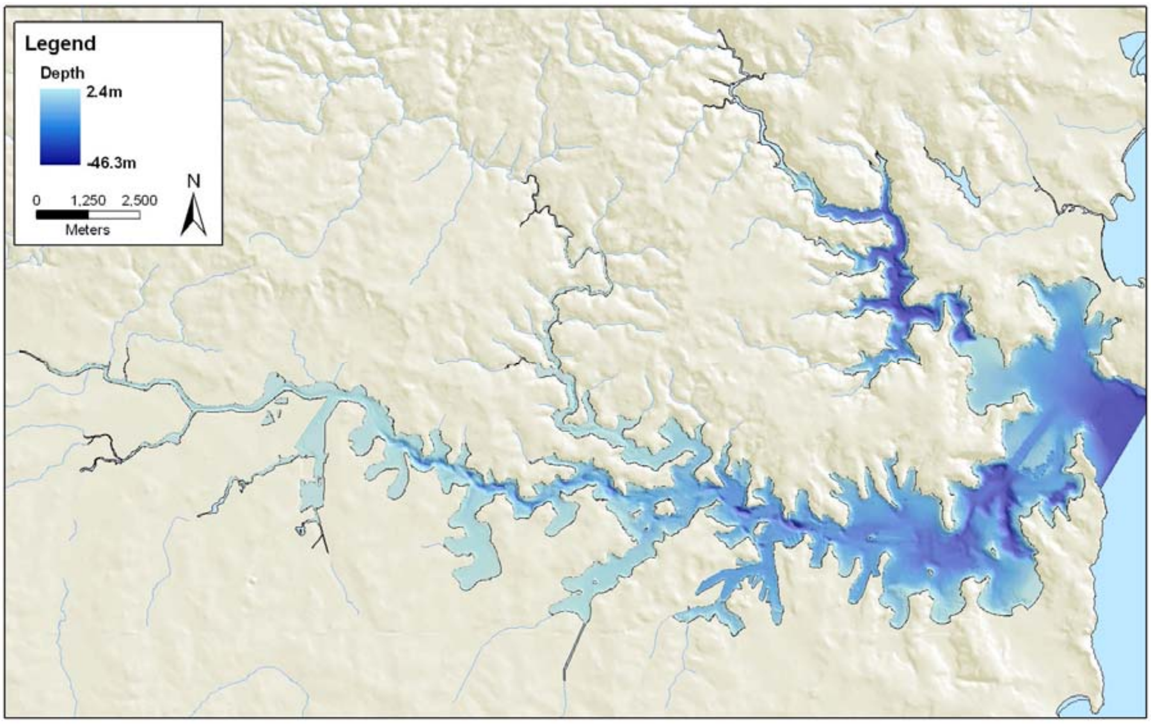

Figure 17. Bathymetry for the Parramatta River Estuary.

3.3. Area predicted suitable for seagrass

An area of 343.42 ha at 789 locations was predicted as suitable for the growth of seagrass (Table 14). These numbers compare with the actual area and count of polygons, as checked in the field in 2000, of 51.86 ha and 1286 polygons. The large number of mapped polygons suggests fragmentation has taken place. Figures 17, 18, 19 and 20 show respective portions of the estuary with the potential for seagrass growth.

In terms of geomorphic zone, predicted area was greater in every situation, particularly for the two CMBs (Table 14). The CMB of the Parramatta River has the largest mapped and predicted areas, as well as largest mapped and predicted counts. However, the count of predicted patches at the CMB and MTD of the Parramatta River were considerably lower than the mapped counts, suggesting these as the prime zones in which fragmentation had taken place.

Table 14. Area of seagrass mapped in 2000 compared to the area predicted to be suitable for seagrass for each geomorphic zone.

Estuarine section	**Zone**	**Area (ha)**		**Count**	
		Mapped	**Predicted**	**Mapped**	**Predicted**
Harbour Entrance	Marine Tidal Delta	16.80	78.25	465	41
Middle Harbour	Central Mud Basin	2.24	46.78	186	213
	Fluvial Delta	0.03	7.66	9	10
Parramatta River	Central Mud Basin	31.53	203.93	569	488
Parramatta River – Lane Cove River	Fluvial Delta	1.26	6.80	57	37
Total		**51.86**	**343.42**	**1286**	**789**

A comparison of the areas predicted to be suitable for seagrass with the areas where seagrass has been mapped is shown in Table 15. Of the total 789 locations at which seagrass was predicted to occur, 145 have been confirmed to have seagrass within them, but 644 are devoid of mapped seagrass. Predicted locations with actual cover show 270.55 ha, whereas the locations predicted to be suitable but that are devoid of mapped seagrass comprise an area of 72.86 ha.

Table 15. Comparison of areas predicted suitable for seagrass that have seagrass already present, compared to predicted areas where seagrass is not present.

Estuarine section	**Zone**	**Mapped Area**		**Unmapped Area**		**Predicted**	
		Count	**Area (ha)**	**Count**	**Area (ha)**	**Count**	**Area (ha)**
Harbour Entrance	Marine Tidal Delta	20	72.77	21	5.48	41	78.25
Middle Harbour	Central Mud Basin	49	32.73	164	14.05	213	46.78
	Fluvial Delta	1	7.07	9	0.59	10	7.66
Parramatta River	Central Mud Basin	62	151.93	426	52.00	488	203.93
Parramatta River – Lane Cove River	Fluvial Delta	13	6.06	24	0.74	37	6.80
Total		**145**	**270.56**	**644**	**72.86**	**789**	**343.42**

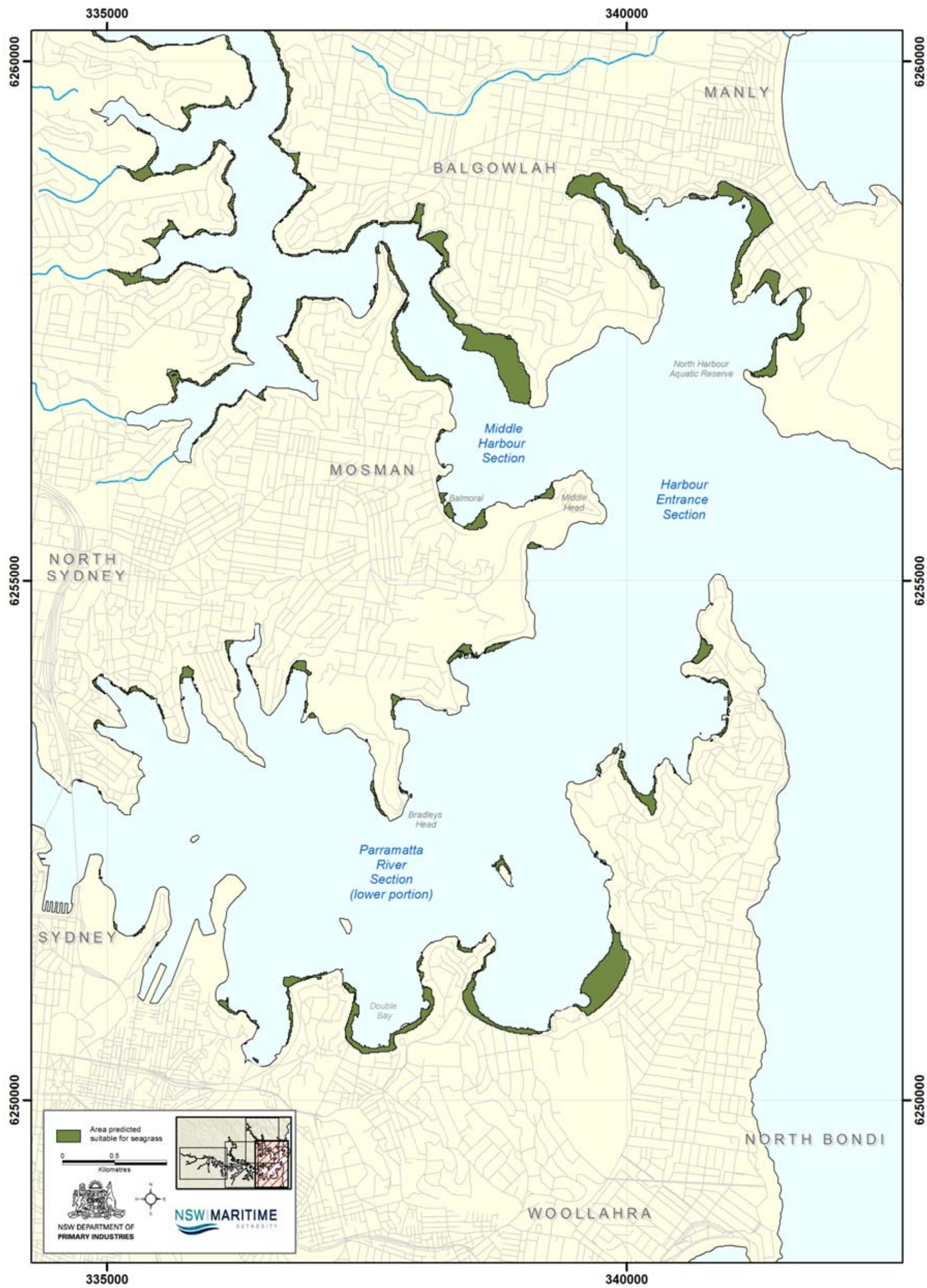

Figure 18. Locations predicted as suitable for seagrass, Harbour Entrance.

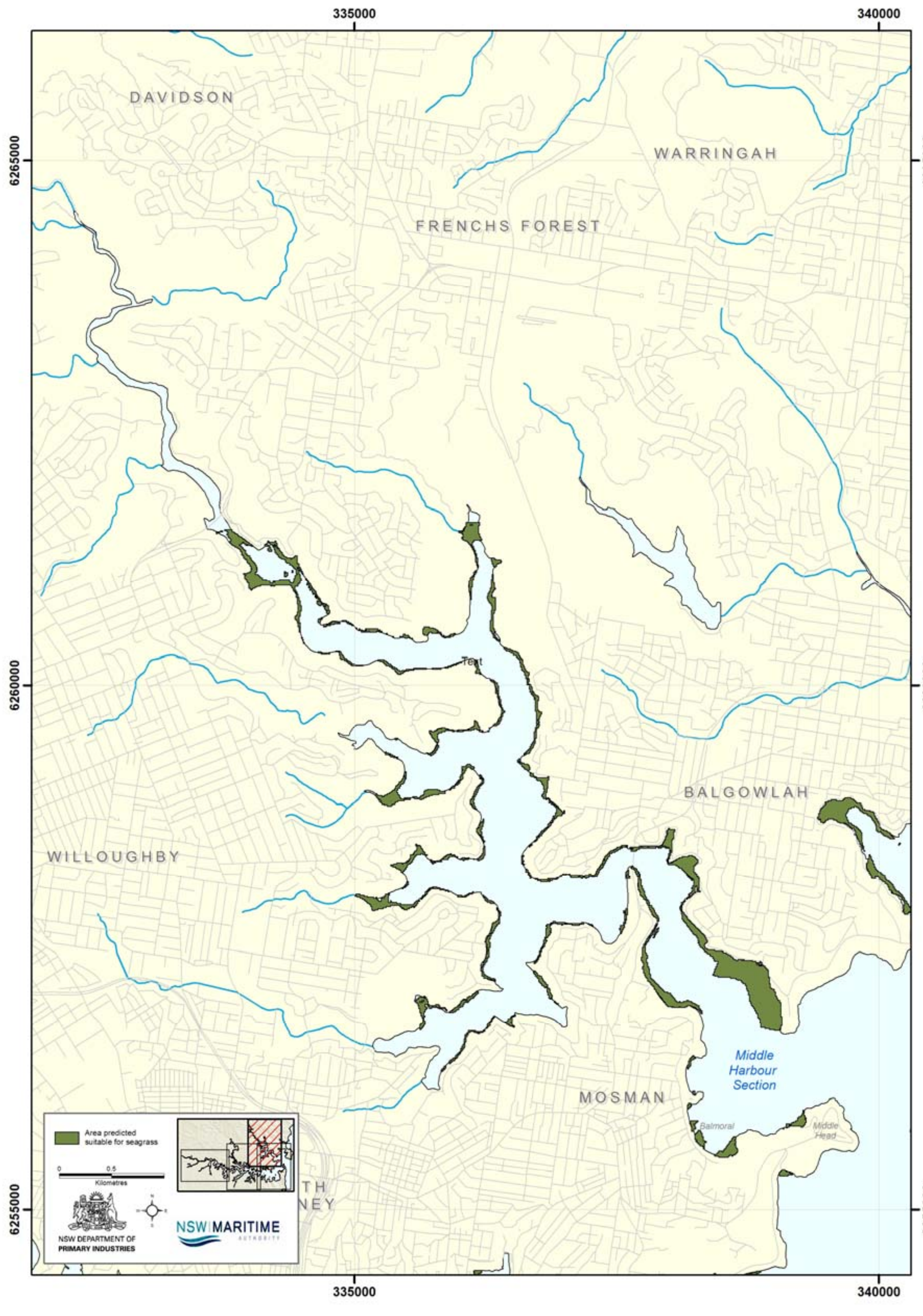

Figure 19. Locations predicted as suitable for seagrass, Middle Harbour.

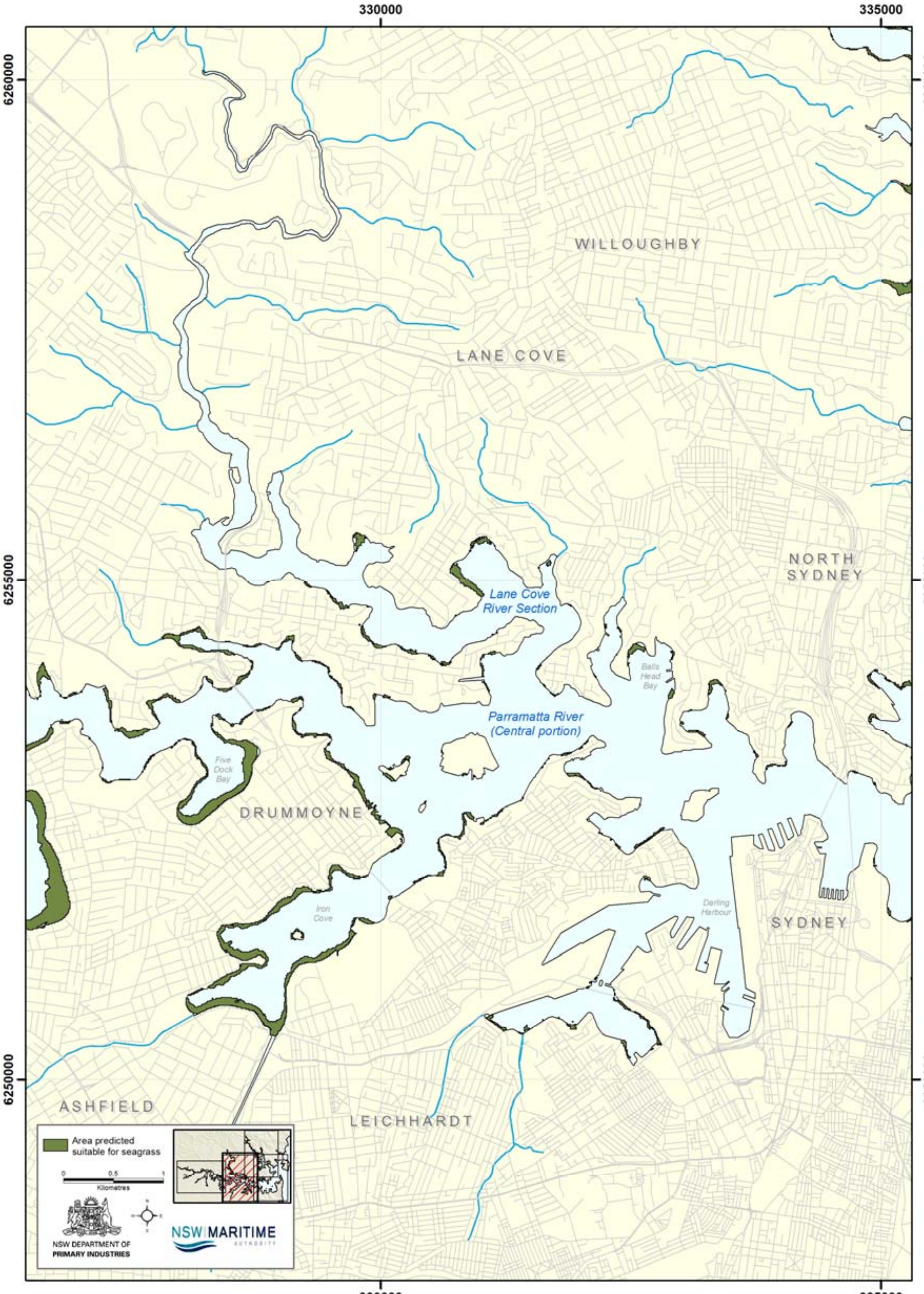

Figure 20. Locations predicted as suitable for seagrass, Central Section.

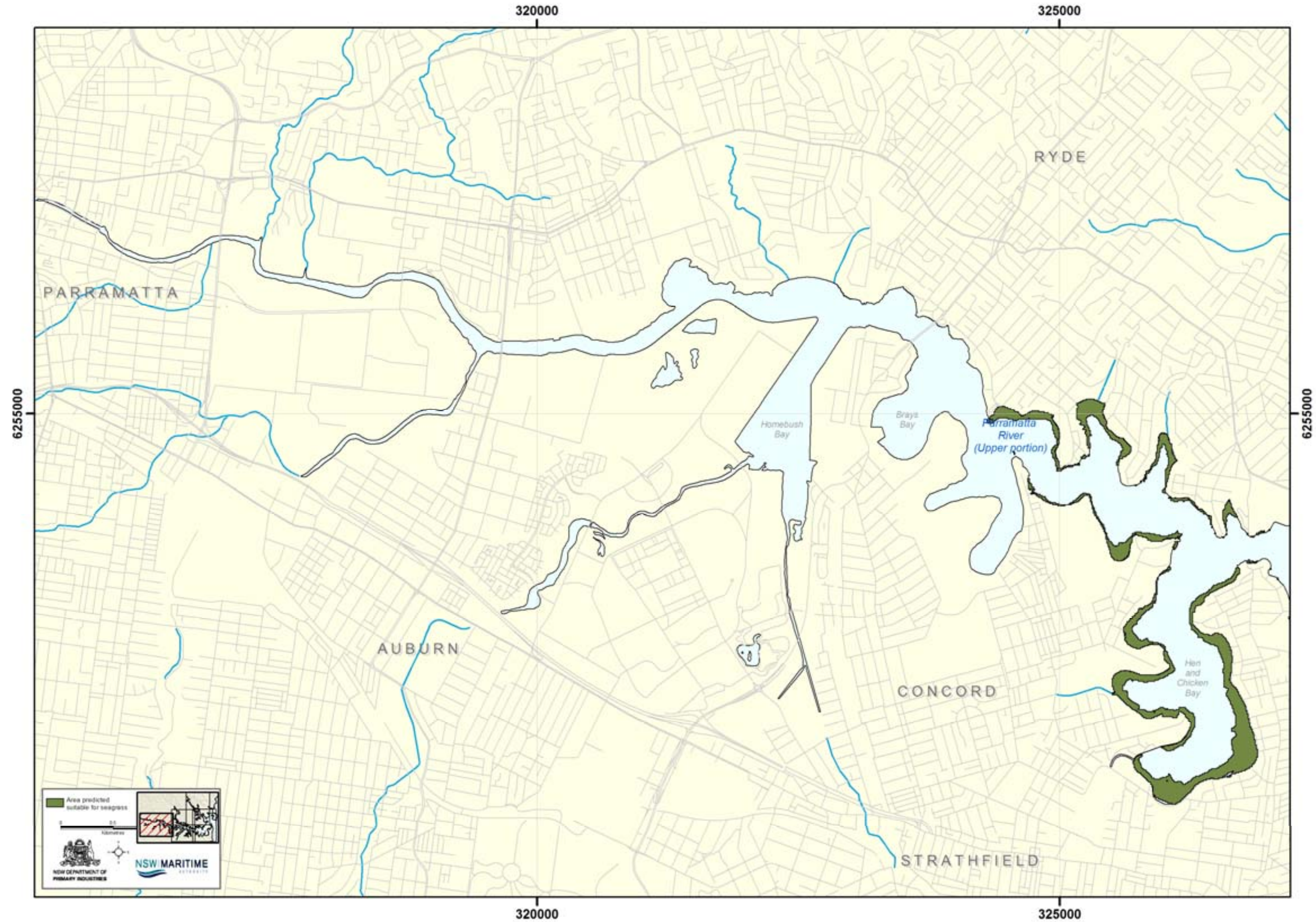

Figure 21. Locations predicted as suitable for seagrass, Western Section.

4. DISCUSSION

4.1. Technical covenants on mapping seagrass in the Parramatta River

Ideally, estimates of the cover of seagrass should be done regularly, and aerial photographic interpretation (API) complemented with field checks is one cost effective method of generating data on the distribution of beds. The presumptive estimates made for 1978, 1986 and 2003 were not confirmed in the field and there is no way to determine the accuracy of the cover estimate for these years are artefacts. Nevertheless, the values derived for these years suggest that there has been of the order of 50 ha of seagrass in the estuary over the past three decades.

4.2. Depth and geomorphic zones

The lowest depth to which seagrass will grow is primarily a function of the penetration of light through the water column, and light penetration is determined by water clarity (Dennison *et al*. 1993). It is not unreasonable to assume that as the upstream portions of estuaries are more susceptible to turbid waters due to runoff, stormwater discharge and reduced flushing, the depths at which seagrass can grow at upstream sites are restricted compared to downstream locations. Water clarity will be better maintained at downstream locations, being influenced by tidal flushing, particularly in estuaries with wide entrances. This relationship is borne out in the Parramatta River. Seagrass is little present in the upstream sectors represented by the Riverine Channel or Fluvial Delta, instead being predominant in the downstream Central Mud Basin and Marine Tidal Delta (Table 8).

4.3. Seagrass model

Our model predicted areas suitable for seagrass based on five environmental variables (depth, slope, substrata, fetch and distance from the entrance). There is good concordance between the model and presence of seagrass mapped and confirmed in the field in 2000 and 2003. However, there is considerably more area predicted suitable than is actually colonised. The modelling technique is reliant upon the observed locations being able to provide adequate information relating to the actual distribution of the seagrass and the degree to which the environmental variables actually define the seagrass environmental limits (Pearson and Dawson 2003). Further, other factors not included in the model, such water clarity, proximity to disturbances such as pollutant inputs and sediment movement, mean that the actual cover of seagrass may not occupy all areas that we have modelled as suitable (Anderson *et al*. 2002). The accuracy of the model is limited by the available information or lack thereof and the interpretation of the model needs to be done with care (Pearson and Dawson 2003).

4.4. Management implications

The GIS-based historical analysis shows consistency in extent of cover over the past 30 years (at least 50 ha and up to 87 ha, Table 7), but a high degree of variability in number, size and shape of beds was seen. Some beds showed intermittent appearances and disappearances, complementing the presence of beds that have remained in place over several decades. These findings indicate that seagrass can not be effectively managed on the basis of any single assessment, but that an understanding of both the current and historical distributions is mandatory.

This study also indicates that the present distribution of seagrass represents only a small portion of the bed of the estuary that could be colonised. Hence, seagrass could be even more effectively managed on where it might be found in the future. Furthermore, this study did not endeavour to discriminate between species or assemblages of seagrass. Ideally, mapping should be stratified by species because due to their variability in abundance and other biotic characteristics over time (e.g., Larkum *et al*. 1984).

Prior to the construction of the three Parramatta weirs in the 1800s to create a source of freshwater, the tide would have intruded further up the river than at present. Hence, the salinity regime within the estuary has been modified by these structures. Furthermore, engineering works to infill the heads of bays, most notably Homebush Bay, would also have had an influence on tide and salinity. The cumulative hydraulic effect of these works would have been considerable, and it is unlikely the estuarine communities subsequently re-established would have replicated the communities there previously. In effect, the character of some, if not all of, the estuarine portion of the river is now extensively modified compared to what it was 150 – 200 years ago. As it is not possible to reconstruct the environment that was present prior at that time, current and future management approaches need to recognise and endeavour to conserve remnants of the original ecosystem as well as enhance the extent of seagrass and other estuarine macrophytes where possible.

Any forthcoming rises in sealevel will have a significant impact on the distribution of estuarine macrophytes along the NSW coast including the Parramatta River. Seagrass will move further upriver as well as upslope when existing shorelines are inundated, and some other assemblages such as mangrove will also move. Saltmarsh will move upstream and upslope but its distribution will be limited by topography and structures such as roads and buildings. It is therefore important that planning measures are implemented to create buffers that will provide upslope refuge for estuarine plants throughout the estuary.

While there is less seagrass in the estuary of Parramatta River than has been previously reported, the amount when mapped with a consistent technique has remained relatively stable over the last 30 years with a peak in the 1980s. The cover present in the 1980s should be used as a management target. Threats to seagrass remain, in the form of exposure to stormwater and/or physical damage, and they need to be managed appropriately. It is important that areas of seagrass in good or excellent condition be maintained, and those of poor or average condition be managed in such a way that their ecological function and integrity improves. Most importantly, there is a need to assess modifications to the shoreline and/or bed of the estuary in the context of potential, rather than actual, growth of seagrass.

5. CONCLUSIONS AND RECOMMENDATIONS

In context of the present

- This study updates previous meso-scale depictions of the cover of seagrass in the estuary of the Parramatta River.
- The area of seagrass is estimated to be at least of the order of 50ha.
- Only about 25% of the seagrass mapped between 1978 and 2003 was consistently present, indicating that the distribution of seagrass within the estuary is highly variable over time.
- The model predicted an overall area of 343.42 ha suitable for the growth of seagrass. While there is good concordance between the modelled area and the 2003 distribution of seagrass, the inclusion of other factors including water clarity, proximity to disturbances and sediment movement may significantly reduce the predicted area.

In context of the past

- Human disturbances that have impacted on the estuarine portion of the Parramatta River over the past 150 years and that have affected estuarine vegetation include catchment clearing, construction of the Parramatta weirs and foreshore modification (e.g. Homebush Bay). The role of any one of these in modifying the estuarine structure, and hence the estuarine vegetation of the river, is not well understood.
- This study was able to quantify extent of change in the cover of seagrass of the Parramatta River over recent decades by means of a GIS-based historical assessment. This assessment considerably enhances our understanding of the locations at which seagrass grows and the loss and regrowth of these plants.
- The area of seagrass of the early 1980s determined by West *et al.* (1985) has been refined by the study of West *et al.* (2004) and this study. The large difference between the first study and the subsequent investigations is, in large part, due to the difference in methods used by that (*camera lucida*) and this (GIS) study.
- Legislation enacted by the NSW Government in the early 1970s provided a framework for progressive increases in the water quality of the estuary.

In context of the future

- Water quality of the estuary might continue to improve in future and if so it is possible that the upstream extent and amount of seagrass will increase.
- Rise of sea level can be expected to have a significant impact on the distribution of estuarine plants in the Parramatta River and other NSW estuaries. Some assemblages such as seagrass (mangrove and saltmarsh) will move further upriver as well as upslope as existing shorelines are inundated.
- Given the ongoing rise in sea level, it is not yet possible to forecast some ultimate condition of seagrass or the rate at which change will take place.
- The seagrass model did not predict the actual distribution of seagrass but instead modelled the areas considered suitable for seagrass based on the variables used.
- Incorporation of additional variables, specifically water clarity, would enhance the robustness of the predictive model.

Recommendations

- An analysis of aerial photographs from the 1990s is needed to complement this investigation, but specifically to assist in interpreting the unusual increase in area of seagrass from 1978 to 1986 and the decrease thereafter.
- To put the dynamics of change in seagrass over the past 30 years in context, a chronology of land-use activities along the river that have impacted on water flow, depth, nutrient and sediment input and other relevant factors should be constructed.
- The dynamics of change should be put into a larger context by analysing aerial photographs from the 1940s, 1950s and 1960s.
- To better manage seagrass, meso-scale monitoring by analysis of aerial photographs should be undertaken at no more than three-year intervals. Future assessments must be able to distinguish upslope, downslope and along-shore migration as well as seagrass species.
- Fine-scale assessments of seagrass should be initiated.
- The model should be revised to incorporate other data sets that may be better indicators of the extent, type and condition of seagrass including; water quality, water currents, and the locations of stormwater outlets sewer overflows.
- Alternative modelling techniques should be investigated, including Maxent, OpenModeller and other statistical methods that may provide additional insight into the potential distribution of seagrass in the estuary of the Parramatta River.
- Many local government authorities as well as state government agencies have responsibility for the management of seagrass in the Parramatta River. Because of differences in distribution of seagrass and local government priorities it would seem appropriate that a regional scale management approach be adopted by the Sydney Metropolitan Catchment Management Authority.
- The NSW Maritime Authority can assist with the management of seagrass as it is a landholder for much of the intertidal land around the estuary of the Parramatta River.

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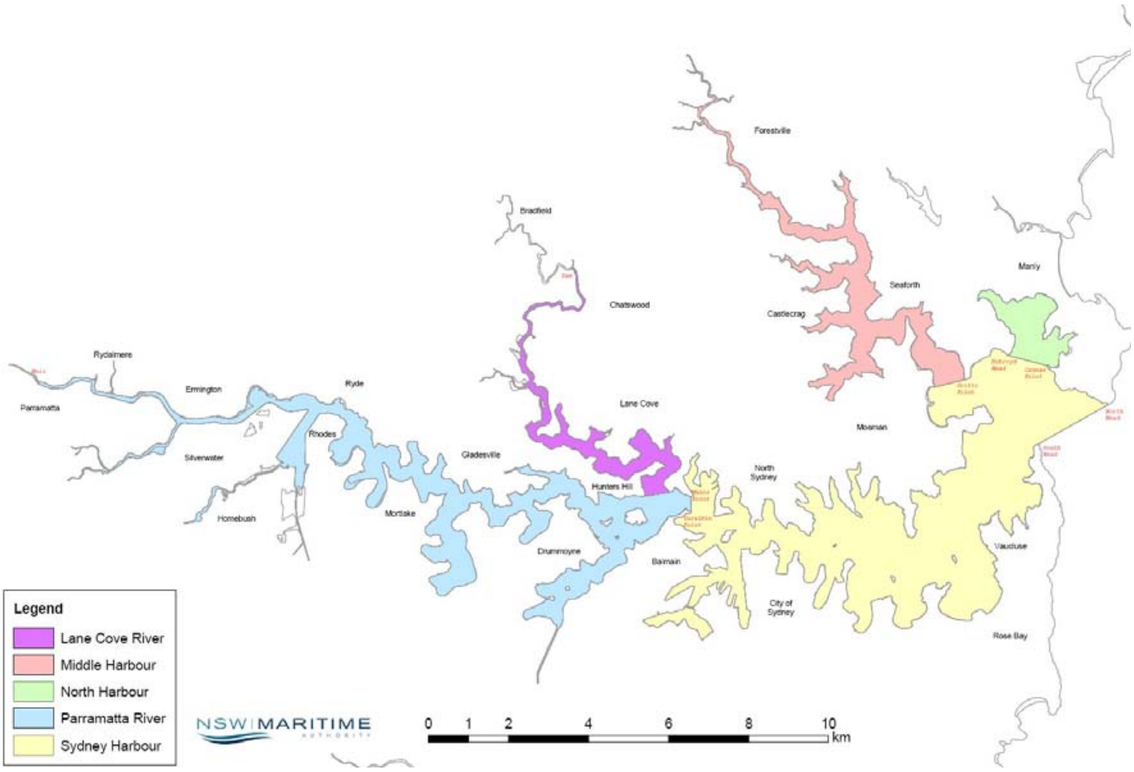
7. APPENDICES

Appendix 1. **Map of the Parramatta River/Sydney Harbour Estuary, including estuary sub-units as defined by NSW Maritime (2004).**



Appendix 2. **Area and foreshore length of the estuary of the Parramatta River. Data were extracted from NSW Maritime (2004). Mean High Water Mark (MHWM) is 1.48 m above zero level on the Fort Denison tide gauge.**

		Water area at MHWM		Perimeter at MHWM including island foreshore	
		(ha)	(%)	(km)	(%)
Parramatta River		1,344	26	114.8	36
Lane Cove River		291	6	39.3	12
Port Jackson	Sydney Harbour	2,756	52	91.6	29
	Middle Harbour	647	12	61.8	20
	North Harbour	217	4	9.2	3
Total		**5,255**	**100**	**316.7**	**100**

Appendix 3a. **Area of seagrass for the Parramatta River estuary in 1978 by geomorphic zone.**

Data set	Year group	RC	FD	CMB	MTD	Grand Total
1	1978	0.053	1.996	14.932	2.989	19.970
2	1978, 1986	0.007	0.697	9.344	1.482	11.530
5	1978, 2000		0.093	1.734	0.406	2.234
7	1978, 2003		0.146	1.498	0.406	2.050
3	1978, 1986, 2000		0.070	3.777	1.570	5.416
4	1978, 1986, 2003		0.037	1.919	0.471	2.426
6	1978, 2000, 2003		0.102	1.972	0.782	2.857
15	1978, 1986, 2000, 2003		0.215	10.036	2.569	12.820
	Total	**0.060**	**3.356**	**45.212**	**10.675**	**59.303**

Appendix 3b. **Area of seagrass for the Parramatta River estuary in 1986 by geomorphic zone.**

Data set	Year group	RC	FD	CMB	MTD	Grand Total
8	1986	0.168	3.652	18.802	15.121	37.743
2	1978, 1986	0.007	0.697	9.344	1.482	11.530
9	1986, 2000		0.158	2.997	1.787	4.942
11	1986, 2003		0.085	2.767	1.768	4.621
3	1978, 1986, 2000		0.070	3.777	1.570	5.416
4	1978, 1986, 2003		0.037	1.919	0.471	2.426
10	1986, 2000, 2003		0.168	3.382	4.411	7.961
15	1978, 1986, 2000, 2003		0.215	10.036	2.569	12.820
	Total	**0.175**	**5.082**	**53.024**	**29.179**	**87.459**

<u>Appendix 3c.</u> Area of seagrass for the Parramatta River estuary in 2000 by geomorphic zone.

Data set	Year group	RC	FD	CMB	MTD	Grand Total
12	2000		0.368	6.124	3.027	9.520
5	1978, 2000		0.093	1.734	0.406	2.234
9	1986, 2000		0.158	2.997	1.787	4.942
13	2000, 2003		0.125	3.743	2.244	6.111
3	1978, 1986, 2000		0.070	3.777	1.570	5.416
6	1978, 2000, 2003		0.102	1.972	0.782	2.857
10	1986, 2000, 2003		0.168	3.382	4.411	7.961
15	1978, 1986, 2000, 2003		0.215	10.036	2.569	12.820
	Total	**0.000**	**1.299**	**33.765**	**16.796**	**51.861**

<u>Appendix 3d.</u> Area of seagrass for the Parramatta River estuary in 2003 by geomorphic zone.

Data set	Year group	RC	FD	CMB	MTD	Grand Total
14	2003		0.261	7.785	2.557	10.603
7	1978, 2003		0.146	1.498	0.406	2.050
11	1986, 2003		0.085	2.767	1.768	4.621
13	2000, 2003		0.125	3.743	2.244	6.111
4	1978, 1986, 2003		0.037	1.919	0.471	2.426
10	1986, 2000, 2003		0.168	3.382	4.411	7.961
6	1978, 2000, 2003		0.102	1.972	0.782	2.857
15	1978, 1986, 2000, 2003		0.215	10.036	2.569	12.820
	Total	**0.000**	**1.139**	**33.102**	**15.208**	**49.449**

Appendix 4a. **Distribution of depth (m) for each year group. Due to datum considerations the numbers with the highest positive values show the shallowest depths.**

Years	Data	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
1978	Min	0.48	0.65	0.87	0.64
	Average	0.31	-0.13	-0.87	-0.96
	Max	0.10	-2.12	-8.52	-7.85
1978, 1986	Min		0.57	1.00	0.65
	Average		-0.12	-0.67	-1.07
	Max		-2.56	-7.03	-6.29
1978, 1986, 2000	Min		0.43	0.86	0.46
	Average		0.20	-0.23	-1.15
	Max		-0.20	-2.91	-3.61
1978, 1986, 2000, 2003	Min		0.32	0.59	0.35
	Average		0.01	-0.09	-1.22
	Max		-0.41	-6.56	-4.52
1978, 1986, 2003	Min		0.33	0.46	0.23
	Average		-0.02	-0.53	-1.21
	Max		-0.40	-6.09	-4.77
1978, 2000	Min		-0.30	0.75	0.40
	Average		-0.50	-0.83	-0.92
	Max		-0.70	-6.24	-4.83
1978, 2000, 2003	Min		0.04	0.91	0.45
	Average		-0.58	-0.75	-1.15
	Max		-2.08	-5.98	-4.33
1978, 2003	Min		0.58	0.60	0.07
	Average		0.24	-0.73	-1.15
	Max		-0.43	-7.00	-4.75
1986	Min	0.63	0.90	0.87	0.68
	Average	0.52	-0.11	-0.91	-2.13
	Max	0.44	-3.18	-8.81	-5.56
1986, 2000	Min		0.44	0.91	0.41
	Average		-0.43	-0.54	-1.46
	Max		-2.88	-7.86	-3.90
1986, 2000, 2003	Min		0.18	0.58	0.40
	Average		-0.43	-0.75	-1.57
	Max		-2.62	-6.08	-4.47
1986, 2003	Min		0.42	0.66	-0.34
	Average		-0.34	-0.80	-1.97
	Max		-2.10	-5.98	-5.35
2000	Min		0.47	1.10	0.74
	Average		-0.40	-0.76	-1.94
	Max		-3.92	-7.24	-5.49
2000, 2003	Min		0.41	0.97	-0.08
	Average		-0.82	-1.04	-1.81
	Max		-3.14	-7.77	-5.44
2003	Min		0.51	0.81	0.18
	Average		-0.87	-0.77	-2.23
	Max		-3.91	-7.58	-6.77
Absolute Min (shallowest)		**1986: 0.63**	**1986: 0.90**	**2000: 1.10**	**2000: 0.74**
Absolute Max (deepest)		**1978: 0.10**	**2000: -3.92**	**1986: -8.81**	**1978: -7.85**
Overall Average		**0.48**	**-0.18**	**-0.70**	**-1.75**

Appendix 4b. **Distribution of percent mud for each year group.**

Years	Data	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
1978	Max		98.87	100.00	43.30
	Average		89.60	43.75	9.14
	Min		53.90	0.00	0.00
1978, 1986	Max		98.85	100.00	44.04
	Average		95.41	23.42	5.46
	Min		69.66	0.00	0.00
1978, 1986, 2000	Max		98.81	100.00	38.19
	Average		97.94	29.91	3.62
	Min		95.95	0.00	0.00
1978, 1986, 2000, 2003	Max		98.87	100.00	44.65
	Average		95.73	15.64	4.89
	Min		48.73	0.00	0.00
1978, 1986, 2003	Max		98.62	99.88	33.19
	Average		97.43	28.02	4.40
	Min		92.25	0.00	0.00
1978, 2000	Max		86.99	100.00	42.55
	Average		78.74	46.12	7.07
	Min		57.30	0.00	0.00
1978, 2000, 2003	Max		98.86	99.27	36.61
	Average		93.69	43.13	7.14
	Min		55.88	0.00	0.00
1978, 2003	Max		98.72	99.27	42.19
	Average		98.55	50.50	11.06
	Min		98.25	0.00	0.79
1986	Max	82.60	98.85	100.00	38.96
	Average	80.60	78.42	56.33	2.60
	Min	77.83	14.46	0.00	0.00
1986, 2000	Max		96.98	100.00	41.99
	Average		93.00	70.95	3.14
	Min		55.41	0.00	0.00
1986, 2000, 2003	Max		98.87	100.00	44.33
	Average		95.52	63.94	4.15
	Min		65.89	0.00	0.00
1986, 2003	Max		98.50	100.00	42.76
	Average		82.17	63.67	4.35
	Min		40.24	0.61	0.00
2000	Max		98.88	100.00	46.18
	Average		91.33	66.71	4.14
	Min		58.87	0.00	0.00
2000, 2003	Max		98.86	100.00	46.03
	Average		82.33	60.08	5.63
	Min		46.47	0.00	0.00
2003	Max		98.73	100.00	41.34
	Average		86.20	67.36	6.22
	Min		40.50	0.30	0.00
Absolute Max		**82.60**	**98.88**	**100.00**	**46.18**
Absolute Min		**77.83**	**14.46**	**0.00**	**0.00**
Overall Average		**80.60**	**85.46**	**46.80**	**4.31**

Appendix 4c. **Distribution of percent sand for each year group.**

Years	Data	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
1978	Max		45.02	99.33	100.00
	Average		10.25	55.09	90.00
	Min		1.02	0.00	56.57
1978, 1986	Max		29.67	99.43	100.00
	Average		4.51	75.79	93.75
	Min		1.04	0.00	55.83
1978, 1986, 2000	Max		4.04	99.43	99.24
	Average		1.96	69.49	95.23
	Min		1.09	0.00	61.62
1978, 1986, 2000, 2003	Max		50.34	99.46	100.00
	Average		4.15	83.84	94.26
	Min		1.02	0.00	55.22
1978, 1986, 2003	Max		7.73	99.43	100.00
	Average		2.48	71.27	94.38
	Min		1.28	0.00	66.68
1978, 2000	Max		41.52	99.27	99.99
	Average		20.88	51.50	91.59
	Min		12.92	0.00	57.30
1978, 2000, 2003	Max		42.99	99.34	99.98
	Average		6.16	56.28	92.21
	Min		1.03	0.00	63.27
1978, 2003	Max		1.63	98.67	98.31
	Average		1.33	48.61	88.13
	Min		1.17	0.00	57.65
1986	Max	18.89	83.36	100.00	100.00
	Average	16.86	21.21	40.56	92.95
	Min	15.62	1.05	0.00	59.62
1986, 2000	Max		43.43	99.35	100.00
	Average		6.92	27.49	93.92
	Min		3.02	0.00	57.84
1986, 2000, 2003	Max		33.95	98.80	99.39
	Average		4.40	34.61	94.42
	Min		1.02	0.00	55.53
1986, 2003	Max		59.34	98.55	99.45
	Average		17.62	34.50	93.79
	Min		1.40	0.00	57.13
2000	Max		40.11	99.42	100.00
	Average		8.58	30.83	93.06
	Min		1.01	0.00	53.70
2000, 2003	Max		52.68	99.78	99.45
	Average		17.56	38.38	92.67
	Min		1.04	0.00	53.85
2003	Max		59.12	98.82	99.72
	Average		13.61	31.17	91.99
	Min		1.15	0.00	58.48
Absolute Max		**18.89**	**83.36**	**100.00**	**100.00**
Absolute Min		**15.62**	**1.01**	**0.00**	**53.70**
Overall Average		**16.86**	**14.30**	**51.60**	**93.05**

<u>Appendix 4d.</u> Distribution of percent gravel for each year group.

Years	Data	Riverine Channel	Fluvial Delta	Central Mud Basin	Marine Tidal Delta
1978	Max		1.08	43.03	10.74
	Average		0.15	1.16	0.86
	Min		0.00	0.00	0.00
1978, 1986	Max		0.68	25.61	11.31
	Average		0.08	0.79	0.80
	Min		0.00	0.00	0.00
1978, 1986, 2000	Max		0.13	10.13	11.30
	Average		0.10	0.60	1.16
	Min		0.01	0.00	0.00
1978, 1986, 2000, 2003	Max		0.93	9.76	9.57
	Average		0.12	0.52	0.85
	Min		0.02	0.00	0.00
1978, 1986, 2003	Max		0.12	11.85	11.22
	Average		0.09	0.71	1.21
	Min		0.02	0.00	0.00
1978, 2000	Max		1.18	42.88	11.27
	Average		0.38	2.38	1.35
	Min		0.08	0.00	0.00
1978, 2000, 2003	Max		1.13	17.06	11.22
	Average		0.15	0.59	0.66
	Min		0.00	0.00	0.00
1978, 2003	Max		0.12	17.11	11.12
	Average		0.12	0.89	0.81
	Min		0.11	0.00	0.00
1986	Max	3.28	2.18	42.97	11.93
	Average	2.54	0.37	3.10	4.46
	Min	1.78	0.00	0.00	0.00
1986, 2000	Max		1.15	15.31	11.87
	Average		0.09	1.56	2.94
	Min		0.00	0.00	0.00
1986, 2000, 2003	Max		0.15	15.13	11.72
	Average		0.08	1.44	1.43
	Min		0.00	0.00	0.00
1986, 2003	Max		0.93	14.82	11.50
	Average		0.21	1.83	1.85
	Min		0.00	0.00	0.00
2000	Max		1.02	43.08	11.86
	Average		0.09	2.46	2.81
	Min		0.00	0.00	0.00
2000, 2003	Max		0.86	22.98	11.80
	Average		0.11	1.54	1.70
	Min		0.00	0.00	0.00
2003	Max		0.98	43.67	11.25
	Average		0.19	1.48	1.79
	Min		0.00	0.00	0.00
Absolute Max		**3.28**	**2.18**	**43.67**	**11.93**
Absolute Min		**1.78**	**0.00**	**0.00**	**0.00**
Overall Average		**2.54**	**0.24**	**1.60**	**2.63**

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