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26/7/01

Impacts of River Regulation on the Terminal Lakes and Mouth of the River Murray, South Australia

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The River Murray is a highly regulated, low gradient stream. Prior to barrage construction near the Murray Mouth saline water was present sporadically far upstream. Barrage completion by 1940 has had geomorphic and ecological impacts. Estuarine Lakes Albert and Alexandrina became permanent freshwater bodies with elevated water levels. Exposed lake margins have eroded by up to 10 m yr^{-1}, whereas along sheltered shorelines, sedimentation has accompanied reed growth. Upstream weirs have inhibited coarse sediment from reaching the lakes. In the Goolwa Channel, sedimentation changed from bioclastic sands to muds, accumulating at up to 4.5 mm yr^{-1} over the past 50 years. Regulation has also transformed a migrating flood tidal delta at the Murray Mouth into a permanently vegetated island.

Encounter Bay in South Australia is the discharge point for the drainage waters of the Murray-Darling catchment, which covers almost 14 per cent (1.073 x 10^6 km^2) of the Australian continent. The Murray-Murrumbidgee-Darling River system is the world's fourth longest, stretching over 5,300 km. However, the mouth of this river system is so insignificant that neither Matthew Flinders nor Nicholas Baudin noticed it during their 1802 voyages, and Captain Charles Sturt could not reach the sea in 1830 after his epic voyage down the River Murray due to shallow water in channels near the mouth. These observations are not surprising as the River Murray has only 16 per cent of the River Nile discharge, 3.5 per cent of the Mississippi and 0.24 per cent of the Amazon; one day's flow from the Amazon equals the yearly discharge of the Murray (Eastburn, 1990).

The terminal lakes and Coorong originally comprised a large estuarine system covering almost 75,000 hectares (Fig. 1), characterised by mixing of fresh and brackish water with very variable flows. Under natural conditions, Lake

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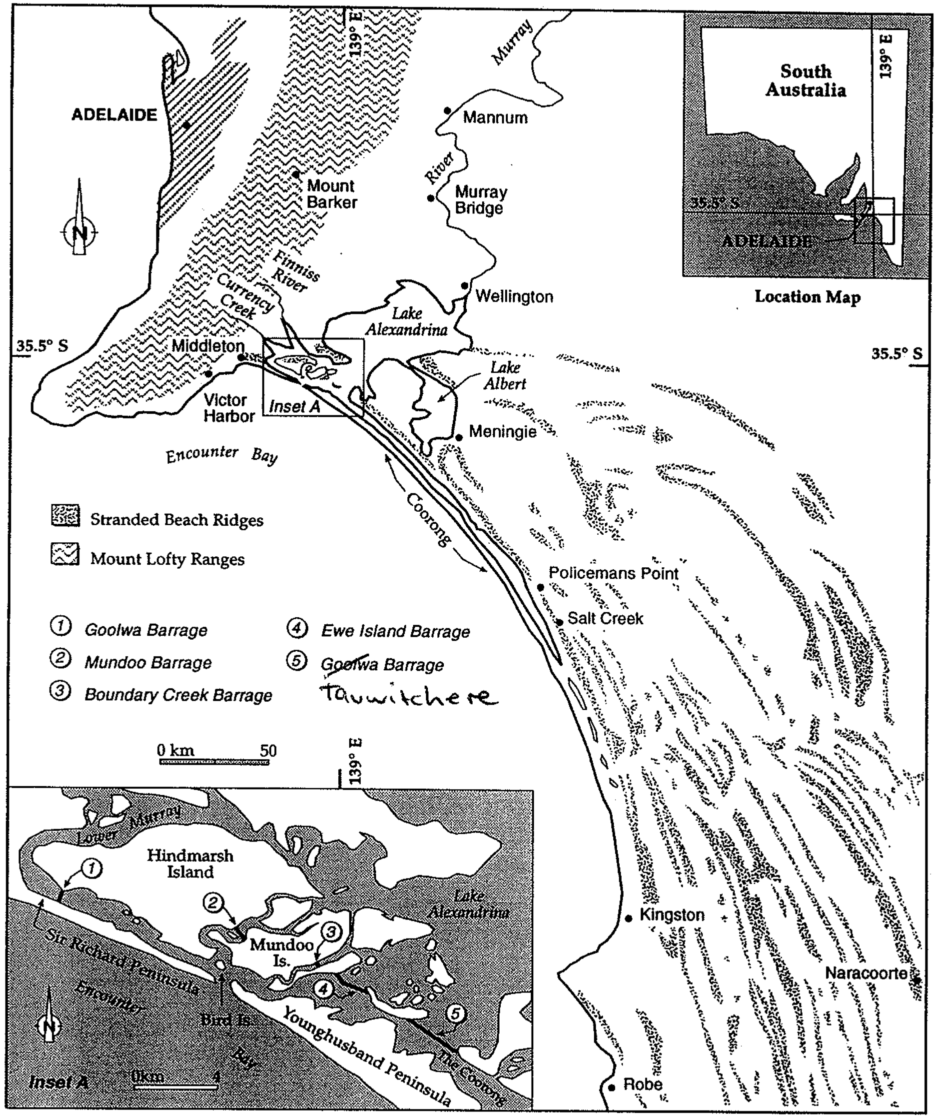

Fig. 1 Location map of Lower River Murray. Inset shows positions of barrages

Alexandrina was probably fresher than at present, except at times of low flows and high tides when elevated salinities resulted from seawater incursions (Close, 1990). This is corroborated by the dominance of the freshwater diatom, *fragilaria pinnata*, in Lake Alexandrina from about 6,000 yr B.P. onward (Barnett, in press).

A suite of barrages was constructed by the 1940s to assure water supplies for irrigation and to improve water quality and conditions for navigation. Together with the locks and weirs upstream they transformed the River Murray into a highly regulated system (Thoms and Walker, 1992; 1993). Although successful in providing reliable water supplies, there have been many accompanying adverse side effects.

Geological and geomorphological background

The geological and geomorphological setting of the lower River Murray lakes area has been discussed by many authors including Taylor and Poole (1931), Hossfeld (1950), Tindale (1959), de Mooy (1959a, 1959b), Blackburn *et al.* (1965), Jessup (1967), Cook *et al.* (1977), Schwebel (1978; 1983), Sprigg (1952; 1959; 1979),von der Borch (1975; 1976) von der Borch and Altmann (1979), Bourman (1979), Bourman (1986), Bourman and Harvey (1983), Bourman and Murray-Wallace (1991), Barnett (1993) and Belperio (in press).

Lakes Albert and Alexandrina are essentially Holocene features, occupying Quaternary interdune areas and formed in response to eustatic sea level rise following the maximum of the Last Glaciation ca. 18,000 years ago. Their location also reflects ongoing subsidence of the lakes region in relation to the Mount Lofty Ranges and the Robe-Naracoorte area in the South East of South Australia (Sprigg, 1952). The River Murray is incised through Tertiary sediments where it enters Lake Alexandrina, and through the Pleistocene calcreted Alexandrina Range between Points Sturt and McLeay, and at the Narrung Narrows (Fig. 2). This range has been equated with the Bruhnes/Matuyama magnetic reversal by Bourman and Murray-Wallace (1991), indicating that this has been the position of the lower Murray channel for at least the last 780,000 years or so. The lower reaches of the River Murray, Lakes Albert and Alexandrina and the Coorong are separated from the open ocean by the Holocene sand barriers of Sir Richard and Younghusband Peninsulas, which flank the Murray Mouth.

The barrages

By 1940, five barrages with a total length of 7.6 km, and associated causeways of 2.45 km, were built across the tidal channels of the lower Murray lakes system (Fig. 1). Barrage construction provided information on the channel dimensions and the underlying materials (Lawrie, 1939). The foundations of the Goolwa Barrage were built on fine sand and silt into which timber piles were driven about 19 m to provide support, while Mundoo, Boundary Creek, Ewe and Tauwitchere Barrages were built in shallower water on 'limestone reefs'. Descriptions of the sediments as calcareous sandstone and 'limestone reefs' suggest that they are aeolianite and calcrete, probably of the Pleistocene Coomandook Formation (Brown and Stephenson, 1989). The main lower Murray channel is the Goolwa Channel, which during low sea levels had a depth of over 19 m. Oliver and Anderson (1940) estimated that during maximum flows up to 70 per cent discharged through it, 10 per cent through Mundoo Channel and 20 per cent through the remainder.

The barrages were designed to maintain water quality in the lower river and lakes by excluding ocean water, to facilitate gravity irrigation and to ameliorate shoreline erosion by reducing winter water levels before the necessary rise in lake levels in spring (Radock and Stefanson, 1975). Radock and Stefanson (1975) illustrated the effectiveness of the barrages in reducing salinities: salinity at Murray Bridge was 6929 ppm during the 1914 drought, but during the 1945 drought when no freshwater passed over the barrages for a year, the salinity at Murray Bridge was only 833 ppm.

In order to achieve the management aims it was considered necessary to maintain the pool level at 0.75 m AHD (Australian Height Datum) and to surcharge the lakes to 0.85 m (AHD) prior to barrage closure to offset evaporation losses[1] and increased demands and to undertake opportunistic 'empty/fill' cycles to reduce salinity in Lake Albert when river flows are sufficient. For example, with a flow of 15,000 ML day^{-1} at Blanchetown (274 km upstream from the Murray Mouth) the barrages are lowered to 0.64 m AHD to flush out salty water. This procedure has stabilised salinity in Lake Albert, which had been increasing before 1986. An estimated 595,000 tonnes of salt per annum are precipitated in the terminal lakes, thus highlighting the importance of freshwater flushing (Coulter, 1992).

Problems associated with these management practices include accelerated wave erosion of the north and northeastern lake shorelines. The increased water level is exacerbated by wind set-up effects, which cause rapid and considerable changes in water levels on different sides of the lakes, with a variation of up to 600 mm being documented over a two hour period (Noye and Walsh, 1976). Furthermore, lowering of water levels during flooding may mobilise highly saline water from adjacent lagoons and backwaters into the lakes as well as facilitating the access of slugs of sea water through overflow of causeways or barrages during storm surge conditions. Radock and Stefanson (1975) suggested that the barrages should be replaced by a system that would automatically control lake levels in response to severe meteorological tides.

There is apparently no set preference of order for opening the barrages, this being influenced by the ease of the operation and wind and tide conditions. The barrages are now quite antiquated and their operation is labour intensive. This is particularly the case for Mundoo Barrage, which has discouraged flushing through the Mundoo channel, thereby encouraging the growth of Bird Island (Fig. 1). In essence the flushing management practices appear to be dominated by the aim of reducing salinity levels in the lakes rather than clearing channels near the mouth.

Effects of barrage construction on the lakes

Accelerated lake shoreline erosion has been a major impact of barrage construction (Fig. 2). In some localities shoreline erosion has reached a maximum of 10 m yr^{-1}, with an average of 1.0 m yr^{-1} (Coulter, 1992). Evidence of transgressing lake shorelines is provided by fence lines and property boundaries originally on dry land, but now situated in the lakes. The costs of land and production losses since the barrages were built has been calculated at $4.2 million (Coulter, 1992). Not only has productive land been lost, but many wetland and wildlife habitats have been destroyed, while water quality has deteriorated with increases in salinity, turbidity and nutrients.

A management strategy designed to minimise foreshore erosion was to lower lake water levels in winter, while taking into account the amount of upstream water available to raise the lake level in the following spring (McIntosh, 1949). However, this option has sometimes been prevented by winter high tides restricting river discharge and strong winds producing lake set-up effects.

Factors affecting shoreline erosion

Various factors affecting shoreline erosion include soil type, shoreline aspect, wind and wave approach, currents, land management and regulation management (Coulter 1992). The most extensive erosion has occurred where shores face south or southwest, and have soils with a sandy subsoil (Fig. 2). The four main soil types surrounding the lakes (de Mooy, 1959a) are closely related to the geology of the area and have different responses to shoreline erosion. Limestone-based soils formed on aeolianites capped with calcrete suffer negligible erosion, and Black Swamp Soils and Border Association Soils on the eastern side of Lake Alexandrina are moderately susceptible to erosion. However, soils of the Poltalloch Association comprised of heavy clay soils over sandy subsoils are highly erodible, especially when water levels coincide with the sandy subsoil horizon. These soils are the most difficult to stabilise.

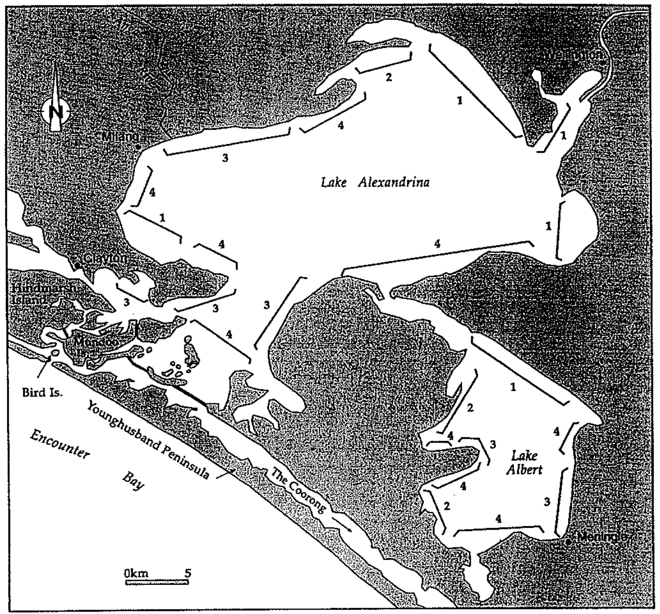

Fig. 2 Shoreline erosion potential map of Lakes Alexandrina and Albert (After Coulter, 1992).

(1) Extremely high: >1.0 m yr^{-1};
(2) Very high: 1.0 m yr^{-1};
(3) High: 0.5 - 1.0 m yr^{-1};
(4) Moderate: 0 - 0.5 m yr^{-1}

Lake set-up effects and wind-generated waves related to wind strength, duration, fetch and lake depth are responsible for much of the shoreline erosion. Maximum water depths are only 4.5 m and 2.5 m for Lakes Alexandrina and Albert respectively, influencing the short wave lengths and maximum wave heights of only 1 m. The wind regime is dominated by winds from the south, southeast and west (Kotwicki, 1994), with prolonged windy periods and squalls up to 50 km hr^{-1}, so that the impact is most prevalent on northern and eastern shores. Wind roses constructed from five years of data from the Engineering and Water Supply Department weather stations at Mundoo, Milang and Tauwitchere illustrate wind direction as a percentage of time (Fig. 3). Dominant wind durations are from the south, west and north. All winds are considered significant because, although single extreme events can cause land losses of up to 2 metres, breezes of 5-10 km hr^{-1} for over 15 minutes can generate waves which are effective in eroding the shoreline (Coulter, 1992).

The maximum fetch on Lake Alexandrina is 35 km east-west and 12 km on Lake Albert . The greatest amount of lake set-up caused by wind-piled water is 1.1 m (Noye and Walsh, 1976), but the shallowness of the lakes restricts

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[1] The annual evaporation from the lakes, calculated at 900 GL (gigalitres), represents 50 per cent of South Australia's water allocation of 1,850 GL (Close, 1990).

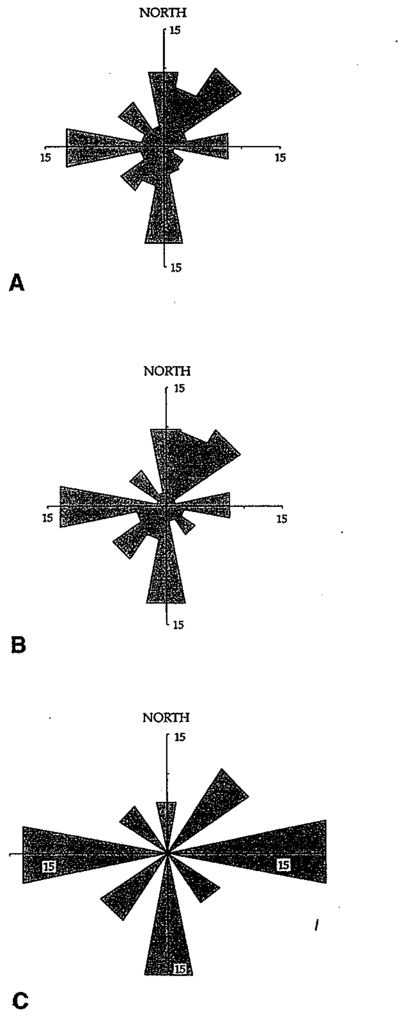

Fig. 3 Wind roses derived from weather stations at Mundoo, Milang and Tauwitchere weather stations showing wind direction as a percentage of time

seiching effects. Wind-generated lake set-ups impact on shoreline erosion in that they can create multiple swash levels which can override lowered lake levels. Regulation of the lake levels impacts on shoreline erosion in that during the summer surcharge and empty/fill cycles, the higher lake levels impact directly on erodible soils causing accelerated erosion.

There is little information available on currents within the lakes and water stratification is minor due to the shallowness of the lakes. The main currents are most likely generated by oblique wave action at the shore. Wind-generated up-river currents occur occasionally and strong currents occur through the Narrows at Narrung (Coulter, 1992).

The destabilisation of the shoreline has been accelerated by land clearance and cultivation, the replacement of samphire, lignum and paper barks with pasture grasses, and the introduction of livestock to foreshores. Exclusion of stock from lakeshores to assist shoreline stabilisation has been advocated (McCord, 1979). Bulrush (*Typha angustifolia*) and bamboo reed (*Phragmites communis*) have been found to be the most successful controllers of shoreline erosion, but only survive well in semi-sheltered waters (McCord, 1979), whereas reeds, rushes, grasses, shrubs and trees are unsuccessful on exposed shorelines.

Structural options for erosion control have included stakes, rock fill, revetments, gabions, breakwaters, tyre walls, groynes, off-shore breakwaters and steel star droppers (Coulter, 1992). These have had various degrees of success and, apart from the tyre walls, generally the most expensive techniques appear to be the most successful.

Increases in lake sedimentation

A notable feature of the River Murray is the absence of a delta off the coast, indicating that only a small amount of fluvial sediment reaches the coast, where it is rapidly dispersed by waves and currents. Much of the sediment transported by the River Murray is deposited in the upstream reaches behind weirs (Thoms and Walker, 1992; 1993) or within the settling basins of Lakes Alexandrina and Albert, and does not reach the coast.

The amount of clastic sediment reaching the coast in the past may have been much greater than at present. For example, Sprigg (1952) discounted the role of significant longshore transport along the Younghusband Peninsula coastline and attributed higher quartzose contents in beach sediments near the Murray Mouth to terrestrial sediment inputs from the river. On the other hand, the source of the barrier sand may have derived from offshore during the Holocene Transgression (Belperio, in press). Regardless of the source of the sandy sediments, since construction of weirs along the River Murray, much sediment has been trapped upstream, thereby reducing the amount of coarse sediment reaching the terminal lakes (Thoms and Walker, 1992, 1993).

Nevertheless, an increase in the sedimentation rate in Lake Alexandrina over the past 100 years is apparent, most likely resulting from lake shoreline erosion, European settlement and associated land clearance. The long term net mass accumulation rate of 0.023 g cm^{-2} yr^{-1} (0.5 mm yr^{-1}) in the central channel region of the lake determined from ^{14}C dating is substantially less than the shorter term rate determined by ^{210}Pb dating of 0.063 gm^{2} yr^{-1} (1.7 mm yr^{-1}) (Barnett, in press). Further evidence of an accelerated sedimentation rate is given for the lower channel region just upstream from the Goolwa Barrage where a change in facies from bioclastic sands to muds in the upper sediments has recently occurred; a number of similar facies changes in the lower tidal channels are also apparent (Barnett, 1993). The most plausible explanation for this depositional change in the lower channel reaches is that restriction to flow by the barrages since the 1940s has altered the environment, and in so doing initiated rapid deposition of mud over the past 50 years, in the order of 4.5 mm yr^{-1}. Such an increase in sediment deposition, whether due to a general increase in the amount of sediment or sediment redistribution, could have wide ranging repercussions for the future operation of the barrages.

Accelerated sedimentation in Lake Alexandrina has been accompanied by minor increases in organic carbon, total phosphorous and copper concentrations (Barnett, 1993). While these can mostly be related to either early diagenic processes or fluctuating algal populations in the lake, the addition of organic matter, nutrients and trace elements due to European settlement cannot be overlooked.

The construction of the barrages and the raising of water levels by up to 0.75 m AHD have transformed Lakes Alexandrina and Albert into permanent freshwater bodies, encouraging the replacement of estuarine communities with freshwater vegetation, especially in sheltered areas, prior tidal channels and at entry points of streams. This has facilitated sediment deposition along portions of the lake margins, and digitate deltas have developed at the mouths of the Finniss River and Currency Creek, at the entrance of the River Murray into Lake Alexandrina and in the Narrows of Lake Albert. Consequently, while there has been widespread and significant shoreline erosion elsewhere along exposed lake margins, shoreline progradation has actually increased in the sheltered and vegetated areas.

Sedimentation of the lower channels by aeolian coastal sands has occurred and in some locations along Younghusband Peninsula aeolian sands are currently spilling into the waters of the Coorong. This process has taken place over long periods of time as backwater lagoonal muds have, at times, been exposed on the beach faces due to landward migration of the dunes (Bourman and Murray-Wallace, 1991).

Matthew Flinders noted occasional bare and drifting sand dunes along the Coorong Coast in 1802 (Bourman, 1979) and these were either natural or enhanced by Aboriginal occupance. However, after European settlement in the area, but prior to barrage construction, Sir Richard Peninsula was essentially a mass of drifting sand due to the effects of rabbit and stock graz-

Fig. 4 Oblique aerial view looking to the southeast along Sir Richard Peninsula during construction of the Goolwa Barrage. Note the extensively degraded vegetation on the spit. (*Source*: Atkins Photographers)

ing. Figure 4, taken during construction of the Goolwa barrage, shows a highly degraded vegetation cover and large areas of drifting sand. Johnston (1917) noted the shallow nature of the southern side of the Goolwa Channel downstream from Reedy Island and attributed it to sand dune encroachment from Sir Richard Peninsula. Following barrage construction, approximately 300 hectares of Sir Richard Peninsula were resumed with a view to preventing sand from drifting into the river between the barrages and the mouth (Lawrie, 1939). Extensive areas of mobile sand were planted with marram grass, pip grass and bushy shrubs, and stock were removed from the reserve to assist sand stabilisation.

Impacts at the Murray Mouth - the Growth of Bird Island

The regulation of the River Murray has reduced freshwater outflows at the Murray Mouth by 8,100 GL yr^{-1}, or almost two thirds of the natural flows (Close, 1990), as well as altering their seasonality. Decreased oceanic discharges occur, especially at times of low and modest flows (Geddes and Hall, 1990). Furthermore, barrage construction has markedly reduced the size of the estuary. The most obvious impact of these factors has been at the Murray Mouth, transforming a perpetually migrating flood tidal delta consisting of coastal sands into Bird Island, which is now permanently vegetated, approximately 1 km in diameter and up to 5 m high (Fig. 14).

Although the present barrages were not completed until 1940, the Mundoo Channel immediately upstream from Bird Island was closed by a barrage with timber sluiceway in 1915 to restrict salt water ingress into Lake Alexandrina. At present, freshwater flow from the lakes to the sea is controlled largely by opening the Goolwa and Tauwitchere barrages while Mundoo Barrage is rarely opened. This has favoured the growth of Bird Island in the absence of flow from the Mundoo Channel.

Fluvial processes clearly affect the shoals of the flood tidal delta and the mouth, although there has been some disagreement concerning the role of river erosion in influencing mouth migration (Thomson, 1975; Walker, 1990). A severely restricted Murray Mouth is substantially cleared by an outflow of 20,000 ML day^{-1} for one month or more, highlighting the need for provision of sufficient water for flushing the mouth (Harvey, 1988). Not only has regulation reduced river discharge but it has markedly restricted the tidal prism, which is important in maintaining the mouth during periods of no river flow. Thus the barrages have serious implications with respect to the potential permanent closure of the Murray Mouth.

The origin of Bird Island as a flood tidal delta was documented by Bourman and Harvey (1983) following the closure of the Murray Mouth in 1981. They concluded that the island had formed after barrage construction, that parts of the island had established well above the level of the highest historical flood of 1956 and that it had become progressively colonised by vegetation, the succession of which has been recorded by Carruthers (1992).

Records of early surveys of the mouth, including plumes of flood tidal deltaic sediments, were examined and superimposed by Johnston (1917). Surveys from 1839 to 1914 indicated a constantly changing flood tidal delta morphology, with the sediments being devoid of vegetation. Oblique aerial photographs taken during barrage construction in the late 1930s (Figs. 5 and 6) reveal a large unvegetated recurved spit, extending from the distal end of Sir Richard Peninsula, occupying the present location of Bird Island. Figure 5, showing the construction of the Mundoo Barrage also reveals that the small peninsula immediately landward of the present Bird Island was unvegetated.

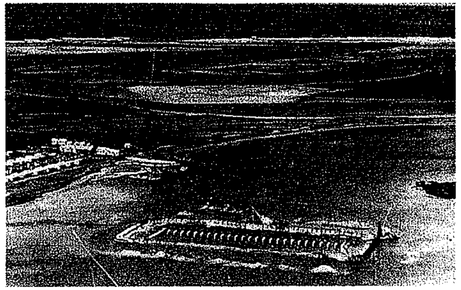

Fig. 5 View along the Mundoo Channel towards the sea during construction of the Mundoo Barrage. (*Source*: Atkins Photographers)

Fig. 6 Oblique aerial photograph of the Murray Mouth during the time of barrage construction. At this time the distal end of Sir Richard Peninsula (Pullen Spit) is arecurved spit which occupies the current location of Bird Island (*Source:* Atkins Photographers)

Fig. 7 Aerial photograph (24/2/45) of partly vegetated flood tidal deltaic sediments at the Murray Mouth after 250 days of no river flow (*Source*: S.A. Department of Lands). Scale of all vertical photographs approximately 1; 40,000

Fig. 8 Flood tidal delta at 23/3/49 after 90 days of no river flow (*Source*: S.A. Department of Lands)

Sequential aerial photographs (Figs. 7 to 15) reveal the progressive changes of Bird Island and the Murray Mouth. On the earliest available vertical aerial photographs taken after no flow periods of 250 days and 90 days respectively (Fig. 7: 24/4/45 and Fig. 8: 23/3/49), an extensive flood tidal delta and the development of a small patch of vegetation can be seen. In 1945, the small peninsula north of Bird Island was still essentially vegetation-free, but by 1949 it had been colonised. Between the time of the 1945 and 1949 photographs the mouth migrated about 400 m to the southeast and was near the base of Barkers Knoll, the high sand dune on Younghusband Peninsula.

During the highest flood (1.43 m AHD) since European occupance, the photograph in

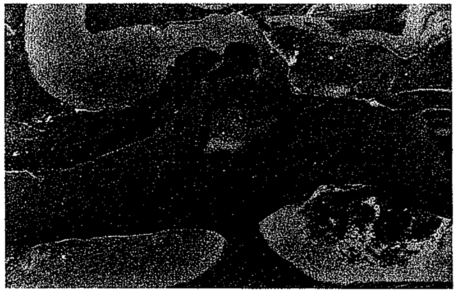

Fig. 9 Bird Island and Murray Mouth during the highest recorded flood (14/9/56).(*Source:* S.A. Department of Lands)

Fig.10 Murray Mouth and Bird Island on 18/11/65 showing extensive vegetation on the island. (*Source:* S.A. Department of Lands)

Fig.11 Bird Island and the Murray Mouth 20/10/67 (*Source*: S.A. Department of Lands)

Fig. 12 Oblique aerial view of Murray Mouth showing Bird Island linked to Sir Richard Peninsula, April, 1974 (Photograph: R.P. Bourman)

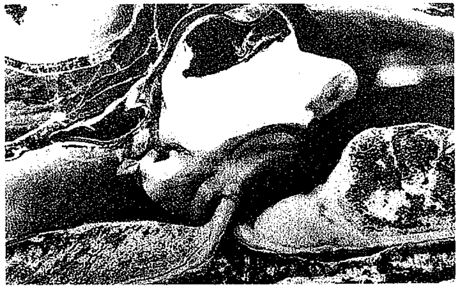

Fig. 13 Photo taken on 25/3/80 showing constriction in the Murray Mouth and sands clogging channels (*Source:* S.A. Department of Lands)

Fig. 14 Closure of the mouth of the River Murray (30/4/81).

Fig. 15 Aerial photograph of Murray Mouth and Bird Island (28/9/93) during high river flow. The Murray Mouth is 1.2 km from its position in 1949. X marks position of dunes constructed and vegetated within a twelve month period; Y marks position of older sequence of jumbled sand dunes on Hindmarsh Island. (*Source:*S.A. Department of Lands)

Figure 9 (14/9/1956) reveals that the highest part of the island, including the patch of vegetation, stood above the floodwater level. In the 1960s little had changed apart from a slight extension to and thickening of the vegetation cover in the core of the island. However, by 18/11/1965 (Fig. 10) the dune in the core of the island was larger, additional sand dunes had built out from the centre, the landward side of the island was vegetated with samphire, the position of the mouth had migrated several hundred metres back to near its 1945 position and hooks had formed on the opposed spits.

By 20/10/1967, during drought conditions when the mouth almost closed up, a complex flood tidal delta formed between the mouth and the now vegetated Bird Island (Fig. 11), and by 25/1/1972 sand from this delta had apparently shifted to Bird Island forming the semblance of a foredune on its seaward side. The mouth almost closed again in April 1974 (Fig. 12) after low flow conditions, and at this time Bird Island was accessible by vehicles as it was linked by a sand spit to Sir Richard Peninsula.

The island was divided during flood conditions in December 1974, but by this time the frontal dune had built up sufficiently to protect the older higher dune in the core of the island. During high water conditions in December 1978 the frontal dune was even larger, although it was not yet vegetated, while the seaward side of the island exposed above the water level exhibited samphire on its flanks. This samphire has probably been eroded and regenerated several times since then; it was not present on 25/3/80 when the area between the mouth and Bird Island was becoming severely clogged with sand (Fig. 13), and finally closed by 30/4/81 (Fig. 14). Following the artificial opening of the mouth it almost closed again, but high river water in 1983 cleared the channels.

Since the opening of the mouth in 1981 it has been migrating in a northwesterly direction towards Goolwa, with ramifications for the further growth of Bird Island. Walker (1990) reported that the most recent aerial photographs indicated a continuing movement in this direction of the order of 100 m yr^{-1} and by 1993 the mouth had migrated about 1200 m from its 1945 position (Fig. 15). Strong water flow from the river initially eroded the landward side of Sir Richard Peninsula at its distal end, but coastal processes subsequently became more important in the migration, especially with respect to high energy waves approaching from the southeast. It has also been noted that some of the waves entering the Murray Mouth reflected from the southern shore of Hindmarsh Island and eroded the landward side of Sir Richard Peninsula (Roger Callen - personal communication, March 1992). At about this time part of Scab Channel on the south side of Hindmarsh Island filled in and permanently became land.

The migration of the Murray Mouth has implications for the continued accretion of Bird Island, which is now protected from oceanic waves by Younghusband Peninsula. Sand blown from the exposed flood-tidal deltaic sediments is currently creating a new foredune on the island, reinforcing its seaward progradation. In addition, during the progressive migration of the mouth a rapid build up of dunes followed erosion on the southern shore of Hindmarsh Island as the mouth migrated. Dunes up to 2 m high were constructed and vegetated within a twelve month period at this location (X on figure 15). There is a much larger and older sequence of jumbled sand dunes (Y on figure 15) on Hindmarsh Island and these may be analogues of the current dunes, perhaps having formed in the past during Murray Mouth migrations when the mouth was larger than at present.

Vegetation colonisation of Bird Island

Bird Island has been progressively colonised by vegetation (Carruthers, 1992). The distribution of vegetation associations reflects the progressive evolution of the island and broadly coincides with the following geomorphic units:

(1) frontal samphire vegetation on a low sand dune (0.5 m high) and in a shallow depression behind it on the seaward side of the island;
(2) a 2 m high frontal sand dune;
(3) an interdune rush-swamp area;
(4) a central dune, up to 5 m high; and
(5) a repetition of the interdune rush-swamp area on the landward section of the island.

Management Issues

Several ecological impacts can be attributed to construction of the barrages and the build up of sand bars at the Murray Mouth. For example, the migration of fish and other organisms between the sea, the Coorong and the lakes is inhibited or prevented; the former estuary upstream of the barrages is now a lacustrine environment without the essential mix of fresh and salt water, and the remaining estuarine area has reduced productivity due to restriction of freshwater and nutrient inputs that are considered vital for the life cycles of estuarine-dependent species (Geddes and Hall, 1990). Furthermore, the reduced freshwater flows may increase salinities in the Coorong beyond the tolerance levels of some species (Geddes and Hall, 1990).

Fish stocks and recruitment in the Coorong and Murray Mouth area are influenced by the operation of the barrages, with potentially adverse effects for fish. Spawning and recruitment depend on changes in water temperature and salinity gradients in estuarine environments so that the rate of change and the volumes of freshwater flows through barrages have enormous impact on fish population dynamics (Coulter, 1992). For example, high productivity of juvenile mulloway and flounder has been associated with high freshwater flows accompanied by high nutrient levels and high freshwater plankton densities. At these times there is greater survival of post-larval and juvenile fishes in the Coorong (Geddes and Hall, 1990). Consequently, for the health of the system to be maintained, increased allocations of freshwater should leave the system at the Murray Mouth. The estuarine fish species, dependent on brackish water at some time in their life cycles, include mulloway, greenback flounder, black bream, river garfish, congolli (or tupong) and bridled goby. Construction of fish ladders, which would allow access into the lakes would certainly benefit some of these species. Apparently, some fishermen have had different views concerning the effect of freshwater on the habits of butterfish and mullet. They have requested that no freshwater be released from the beginning of November until the end of February, claiming that these are the months when butterfish may be likely to enter the river mouth. However, irrigation requirements have not been subjugated to other interests (McIntosh, 1949).

The region is also very important for bird sanctuaries. Two species of birds, the Australian pelican and the crested tern, breed in the area (Geddes and Hall, 1990) and it is visited by many other birds including the red-necked stint, which migrates to Siberia and Alaska for breeding. These birds depend on fish stocks in the area for part of the year.

The outlet of Australia's largest river system is subject to great natural change. For example, the Murray Mouth has fluctuated through a range of 1.4 km since first surveyed in 1839 (Johnston, 1917; Thomson, 1975), and even greater fluctuation of up to 6 km in the past ca. 5,000 years (Bourman and Murray-Wallace, 1991). This natural dynamic character of the Murray Mouth, which breaches the barriers of Sir Richard and Younghusband Peninsulas, highlights the sensitivity of the area to further human-induced environmental change. The need to take this into account in proposing management plans for the area should be recognised.

As a severely restricted Murray Mouth would require an outflow of 20,000 ML day^{-1} for one month or more to be cleared (Harvey, 1988), upstream river management should be modified to provide sufficient water for this purpose. Tidal flushing of the mouth is also of great significance in maintaining the opening as there have been up to 529 days of no river flow when the mouth has been maintained solely by tidal processes. Storm surges are important in mouth maintenance; when these are minimal there is an increased likelihood of closure of the mouth. For example, prior to mouth blockage in 1981, when there were only 196 days of no river flow, meteorological conditions and associated storm surge effects were very subdued.

Various strategies to maintain the Murray Mouth were considered by Harvey (1988). These included using water stored in the terminal lakes to flush out the mouth, the construction of temporary or permanent groynes, the use of drift fencing to prevent wind-blown sand from entering the mouth and the dredging of a channel through the blocked mouth. Although the last option was considered to be the most cost effective method of clearing the mouth, a more desirable option would be to modify the upstream management to produce an outflow of 20,000 ML day^{-1} for one month or more prior to blockage.

The development of Bird Island and its colonisation by vegetation, the build up of a dune cap on the flood tidal deltaic sediments since barrage closure, and the progressive progradation towards the Murray Mouth needs to be considered in any long term management strategy. The present operation of the barrage system needs to be assessed in order to prevent further and more serious mouth blockages in the future.

The proximal end of Sir Richard Peninsula is of great significance as it forms the barrier between the sea and freshwater held back by the Goolwa Barrage. The possibility of a potential breakthrough in this section of the spit has been raised by various people. Under existing conditions Sir Richard Peninsula is affected by high energy waves, but the small tidal range and limited surge effects, together with the dissipative effect of the offshore topography, suggest that there is little likelihood of oceanic breaching of the barrier. Even during the 1981 blockage of the Murray Mouth when a storm surge resulted in washover of the barrier near the western end of Barkers Knoll on Younghusband Peninsula, a new channel was cut but silted up rapidly.

While there appears to be no immediate danger of a breakthrough of the Sir Richard Peninsula barrier upstream from the Goolwa Barrage, high priority should be given to the preservation of the stability at this site. This section of the spit has been subjected to a history of coastal erosion, which may lead to its further narrowing, thereby increasing the danger of oceanic breaching (Bourman and Murray-Wallace, 1991). A rise in sea level, related in part to enhanced 'Greenhouse' influences, or the continuance of the long-term tectonic subsidence of the Murray Mouth area (Sprigg, 1952) could exacerbate this problem.

Conclusion

The River Murray is of great significance to South Australia and provides up to 85 per cent of metropolitan Adelaide's summer water supply. It is a highly regulated river system, which drains a large area of land, but relative to other major river systems, has only a small discharge to the sea. The demands for water from the river for agriculture, industry and urban use have reduced flow to the sea by two-thirds. This could be greater in the future unless there are specific allocations for the maintenance of the remaining estuarine environment that would include diluting the saline waters in the Coorong Lagoon and flushing out of the Murray Mouth. At least half of the water allocation to South Australia is lost by evaporation from Lakes Alexandrina and Albert, a factor which may need to be addressed in the future.

Important management strategies relate to the timing, extent and location of water releases from the barrages in order to minimise lakeshore erosion, optimise the erosion of channels through sand bars near the mouth, facilitate fish recruitment and dilute salinities in the Coorong. Further studies of lakeshore erosion are required to assess potential long-term shoreline changes and to assess the benefits and costs of variably timed changes to water levels.

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