Land subsidence and sea level rise in the Port Adelaide estuary: Implications for monitoring the greenhouse effect

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Land subsidence and sea level rise in the Port Adelaide estuary: Implications for monitoring the greenhouse effect

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The historic tide gauge records from Port Adelaide and Outer Harbour are one of the more important datasets from the Australian region purporting to show a significant rate of local sea level rise. However, geological evidence including radiocarbon dated palaeosea level indicators, indicates that most of this rise is due to subsidence of the land. The subsidence is significant but localized, and can be largely attributed to human activities associated with port development, reclamation and industrialization. Two principal contributing factors are reclamation of Holocene wetlands and groundwater extraction from deeper Tertiary aquifers. Wetland reclamation has caused surficial soil compaction as a result of artificial lowering of the water table, oxidation of peat and pyrite, and leaching of the substrate by soil acidification. Surficial subsidence at rates of up to 10 mm/year has occurred in reclaimed mangrove woodlands as a result of these processes. Extraction of groundwater from deeper aquifers over the past 50 years has created a potentiometric cone of depression in excess of 20 m beneath the Port Adelaide estuary. Land subsidence estimated at 2.8 mm/year is associated with the central zone of depressed groundwater levels.

The tide gauge data from Port Adelaide and Outer Harbour have been used in global sea level rise calculations without adequate local neotectonic correction. Although outside the zone of greatest land subsidence, three-quarters of the secular rise in mean sea level of 2.5–2.9 mm/year indicated by the tide gauge records can be attributed to land level changes. Hence the local sea level trend is a rise of ~0.7 mm/year. As many of the world's historic tide gauge sites are expected to be affected by similar anthropogenic effects, it is imperative that local neotectonic corrections be applied to all tide gauge data before drawing any conclusions regarding global or local eustatic sea level change.

Key words: coastal geology, geomorphology, greenhouse effect, land subsidence, sea level change.

INTRODUCTION

Estimates of present global or 'greenhouse' sea level rise are mostly based on averaging data from a number of tide gauges around the world (Gornitz *et al.* 1982; Barnett 1984; Warrick & Oerlemans 1990). However, the secular sea level trend as measured by individual tide gauges varies widely around the globe (± 10 mm/year), due mainly to variable rates of land subsidence or uplift operating at a range of spatial and temporal scales (e.g. Emery *et al.* 1988; Gornitz & Seeber 1990; Peltier & Tushingham 1991). In order to identify a global eustatic trend, effects of vertical land movements, whether geological or human-induced, must be removed from the data. Ideally, this should be achieved by high-resolution geodetic monitoring of tide gauge sites or by establishing site-specific subsidence curves. In the absence of such site-specific information for most of the world's historic tide gauge sites, corrective measures have been adopted based on regional neotectonics (e.g. Gornitz & Lebedeff 1987) or geophysical modelling to identify long wavelength crustal movements caused by isostatic adjustment (e.g. Peltier & Tushingham 1989, 1991). In neither case are local geological or recent anthropogenic effects adequately addressed.

Though localized, ground subsidence > 10 mm/year associated with human activities is common in large cities and their attendant ports that developed on coastal lowlands (e.g. Venice, London, Bangkok, Houston-Galveston, New Orleans); the principal causes are drainage, reclamation and construction on coastal wetlands, groundwater withdrawal and hydrocarbon extraction (Carbognin 1985). The net effect is that estimates of the rise in the global eustatic sea level obtained by averaging tide gauge records with only regional tectonic or isostatic corrections (typically quoted values of between 1.0 and 1.5 mm/year) are overestimates, possibly by as much as two or three times (Pirazzoli 1989).

The port of Adelaide in southern Australia provides a microcosm of the geological factors that affect historic tide gauge data. Large tracts of intertidal wetlands peripheral to the Port Adelaide estuary have been progressively reclaimed and masked by urban and industrial encroachment over the past 150 years (Figs 1, 2). Two tide gauges within the estuary have records of variable quality extending back to 1882 and 1944, respectively; both indicate a rise of sea level (2.5 and 2.9 mm/year). These have been used in various studies of regional and global sea level change without adequate local neotectonic correction (Barnett 1984; Aubrey & Emery 1986; Gornitz & Lebedeff 1987). Although land subsidence has been recognized as a potentially important factor (Belperio 1989), its relative contribution and causes have not been quantified. In this paper, land subsidence at Port Adelaide

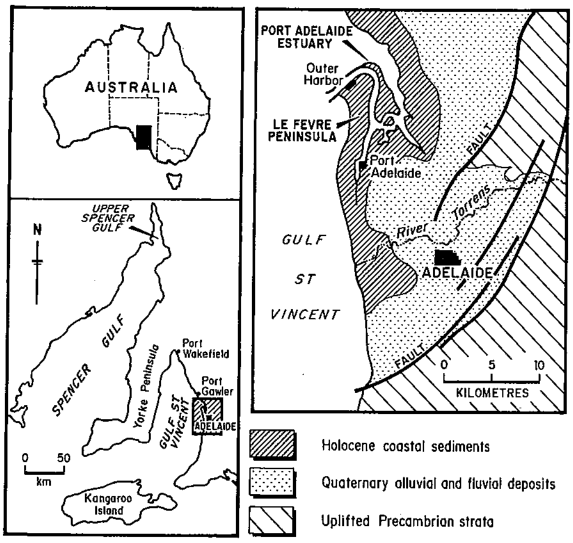

Fig. 1 Location map and geological setting of Port Adelaide estuary, South Australia.

is interpreted from the Holocene sedimentary record and from other available data, contributing factors are assessed, and implications for sea level change are discussed.

METHODS

The morphostratigraphy within the Port Adelaide estuary was established from 51 vibrocores taken across both reclaimed and undisturbed portions of the tidal wetlands, supplemented with data from pre-existing drill holes (Fig. 2). Historical records and air photographs provided additional information on the former extent of wetland environments and rate of migration of mangroves. The vibrocores provided information on and samples of the subsurface strata from which palaeosea levels could be established. Samples for radiocarbon dating (shell or mangrove peat) were extracted, washed and cleaned, and submitted for pretreatment and analysis by commercial dating laboratories (Table 1). Radiocarbon ages, corrected for the marine reservoir effect (–450 ± 35 years; Gillespie & Polach 1979), provide the chronological framework for interpreting the geohistory of the site. Core sites were surveyed to local geodetic and low water datums, and measurements made of groundwater level and acidity. Vibrocore lithologies and stratigraphic interpretations, and detailed data relating to facies isopachs, structure contours, groundwater levels, pH and permeability, are described in site investigation reports by Belperio (1985b) and Belperio and Rice (1989).

MORPHOLOGICAL DEVELOPMENT OF THE PORT ADELAIDE ESTUARY

After the Holocene sea reached present level some 6600 radiocarbon years BP, a broad tidal embayment developed beneath the study site as a result of progressive northward migration of LeFevre Peninsula, a major coastal sand barrier (Fig. 2). Subtidal, intertidal and back-barrier sedimentation within this embayment has generated a thick and complex but coherent facies architecture dominated by saturated and unconsolidated mud, sand and organic-rich sediments (Fig. 3). Overall, the Holocene

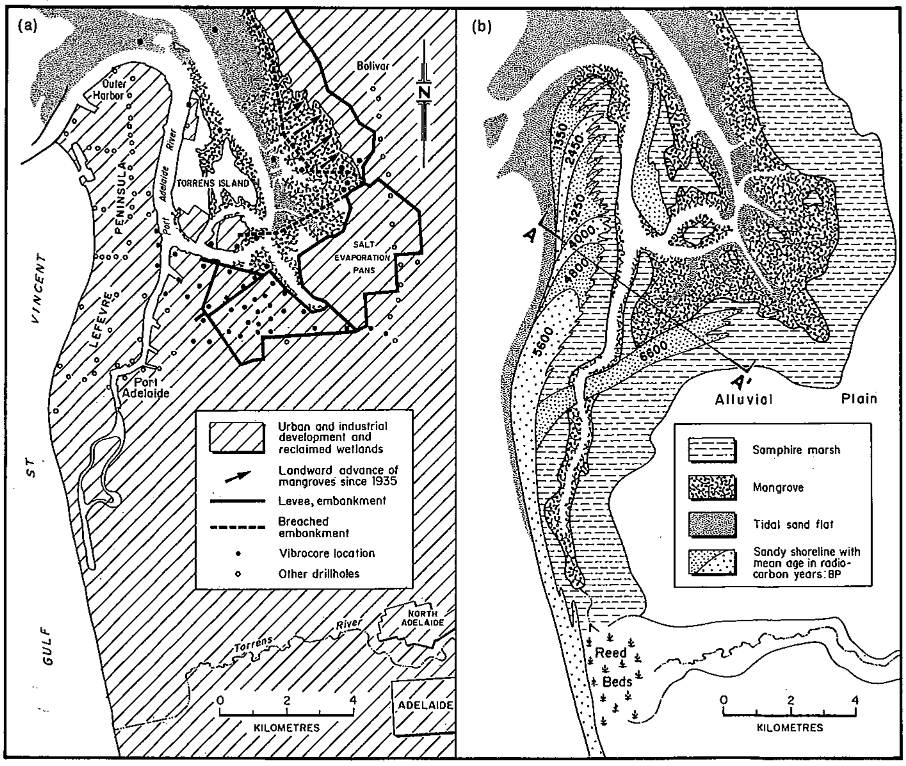

Fig. 2 Morphology of the Port Adelaide estuary showing the current extent of urban and industrial encroachment (a) and the pre-European morphology (b) as interpreted from vibrocore and bore information and historical air photographs. Mean radiocarbon ages for the coastal sand barriers include data from Bowman and Harvey (1986).

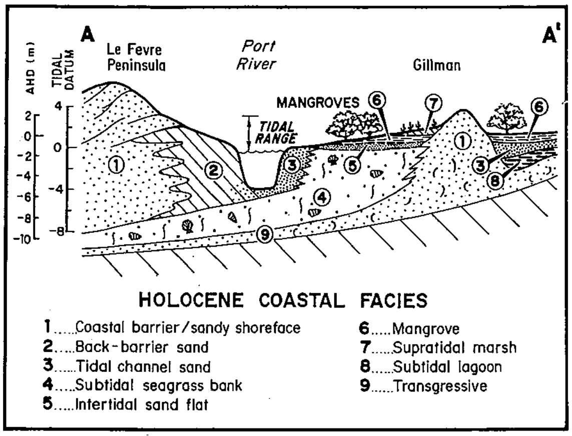

Fig. 3 Schematic cross-section from Le Fevre Peninsula to Gillman (A–A′ on Fig. 2) showing the interrelationships of Holocene coastal sedimentary facies.

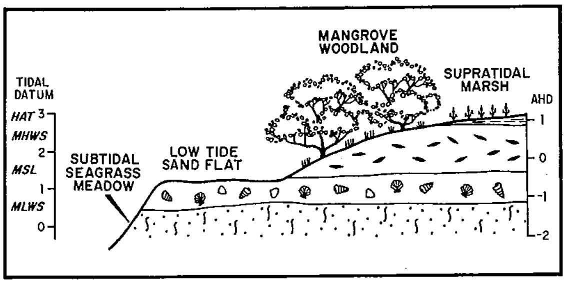

Fig. 4 Elevation and zonation of sedimentary facies relative to tidal levels and Australian height datum (AHD). HAT = highest astronomical tide; MHWS = mean high water spring tide; MSL = mean sea level; MLWS = mean low water spring tide.

strata form a northwestward thickening wedge, from < 1 m in the south to 10 m beneath Torrens Is. and 12–14 m beneath Outer Harbour and LeFevre Peninsula.

In southern Australia, the most significant constructional Holocene coastal facies are the subtidal seagrass, intertidal sandflat and intertidal mangrove woodland environments (Cann & Gostin 1985; Belperio *et al.* 1988). These environments baffle, trap and bind the sediments, creating distinctive shore-parallel, seaward-prograding sedimentary biofacies. In addition, the intertidal flora and fauna, and their preserved sediment facies, are sensitive indicators of sea level change as seen in other coastal settings within the South Australian gulfs (Belperio *et al.* 1984).

Accumulation of bioclastic sediment in subtidal *Posidonia* seagrass meadows within the former embayment created the shoaling necessary for subsequent intertidal facies development and coastal progradation. The seagrass facies comprise poorly sorted, muddy bioclastic sands that are weakly bound by decomposing cellulose residue of *Posidonia* rhizomes. Sediment is highly calcareous with abundant foraminifers and small molluscs, and soft to firm with an increasing mud content with depth below the surface.

Intertidal sandflat facies have developed as a thin sheet over the seagrass facies. They comprise a characteristic coarsening-upward coquina that is poorly sorted, unconsolidated, porous and permeable. Fossil bioclasts consist predominantly of gravel-size bivalves and gastropods (*Katelysia* and *Batillaria*) and the unit, though generally < 1 m thick, forms an important surficial saline aquifer because of its porosity and proximity to mean sea level.

Mangrove facies have formed a similarly thin but laterally extensive surficial sheet characterized by soft and spongy muddy or sandy peat. Contemporary mangroves are sensitive sea level indicators, growing only within specific tidal limits (Fig. 4). Preserved mangrove strata can similarly be used as a palaeosea level indicator. In particular, the lower contact of the mangrove facies with the underlying intertidal sandflat facies is a sharp and distinctive boundary that can be related to a specific tidal or palaeotidal level. With decreasing frequency of inundation at higher elevations, the mangrove woodland is replaced by a very low gradient supratidal-marsh association of *Sarcocornia*, *Halosarcia* and *Sclerostegia*.

Following European colonization in 1836, progressive reclamation of tidal wetlands occurred through the construction of levees and sluices, and placement of landfill. Urban and industrial development now masks large areas (Fig. 2), though a significant portion of the estuary remains in its natural state and provides valuable information against which human-induced ecological and geological changes can be assessed.

EVIDENCE FOR SEA LEVEL CHANGE

Previous observations

Historic tide gauge data from Port Adelaide, extending back to 1882, indicate a secular rise in sea level of 2.5 mm/year (Culver 1970). More recent and reliable data from the Outer Harbour tide gauge indicate a long-term rise of 2.9 mm/year over the past 50 years (Allan 1989). Associated with this relative rise of sea level has been a marked landward migration of the mangrove woodland on the eastern side of the estuary (Burton 1982). Inland advance of the mangroves over the low-gradient supratidal marsh commenced soon after the abortive construction of an embankment in 1894 (Fig. 2). Historical air photographs show the rate of advance from 1935 to 1981 to be 17 m/year. Just 18 km to the north of Port Adelaide, however, mangroves are actively prograding seaward (Cann & Gostin 1985), as they are for the remainder of the gulf coastline. This indicates that the apparent sea level rise in the Port Adelaide estuary is a geographically restricted phenomenon.

Relevelling of bench marks across Adelaide in 1969 provided direct evidence of changes in land levels. From the relevelling data, Culver (1970) estimated that land subsidence of 1.8 mm/year was occurring at Port Adelaide. Belperio *et al.* (1983) and Belperio (1985a) inferred local subsidence from the low level of key intertidal facies relative to their contemporary levels in the Port Adelaide estuary. They concluded that the region had potentially undergone 0.5 m of ground subsidence, but little evidence was available on the duration over which this had occurred.

Morphostratigraphic evidence

Contemporary peritidal facies display a zonation of biota and sedimentary constituents that are closely related to tidal elevations (Cann *et al.* 1988 and Fig. 4). Where preserved in the subsurface, the ages and elevations of these facies provide reliable data on palaeosea levels. Within the Port Adelaide estuary, the contact between mangrove and low tide sandflat facies is preserved in most vibrocores as a sharp and distinctive change from coquina to peat. In a number of cores, this interface is well below (up to 0.7 m) contemporary levels in the tidal waterways, indicating relative ground subsidence (Fig. 5). The elevation differential, however, shows a spatial variability that includes both positive and negative deviations. This is resolved when the data are redrawn as a time–depth plot (Fig. 6 enlargement). The palaeosea level indicators define a regressive sea level curve typical of the southern Australian coast, but with a superimposed subsidence effect. The spatial variability in the elevation of the coquina/peat contact is thus an artefact of the time-transgressive nature of sedimentation. The greatest values of apparent ground subsidence coincide with the reclaimed mangrove woodland south of Torrens Is., although these also coincide with the youngest radiocarbon ages. Negative values are also associated with some cores outside the reclaimed areas, indicating that ground subsidence is not solely a result of wetland reclamation (Table 1).

The time–depth plot of radiocarbon-dated sea level indicators (Fig. 6) defines a local palaeosea level curve that includes both long-term (isostatic rebound) and recent (anthropogenic subsidence) effects. The commonly observed transgressive/regressive elements for Holocene sea level behaviour around the southern Australian coast (Peltier 1988; Lambeck & Nakada 1990; Belperio 1993) include present sea level being first reached ~6600 years BP, subsequent isostatic adjustment generating an apparent mid-Holocene highstand (h*), followed by sea level regression to the present low water datum. The

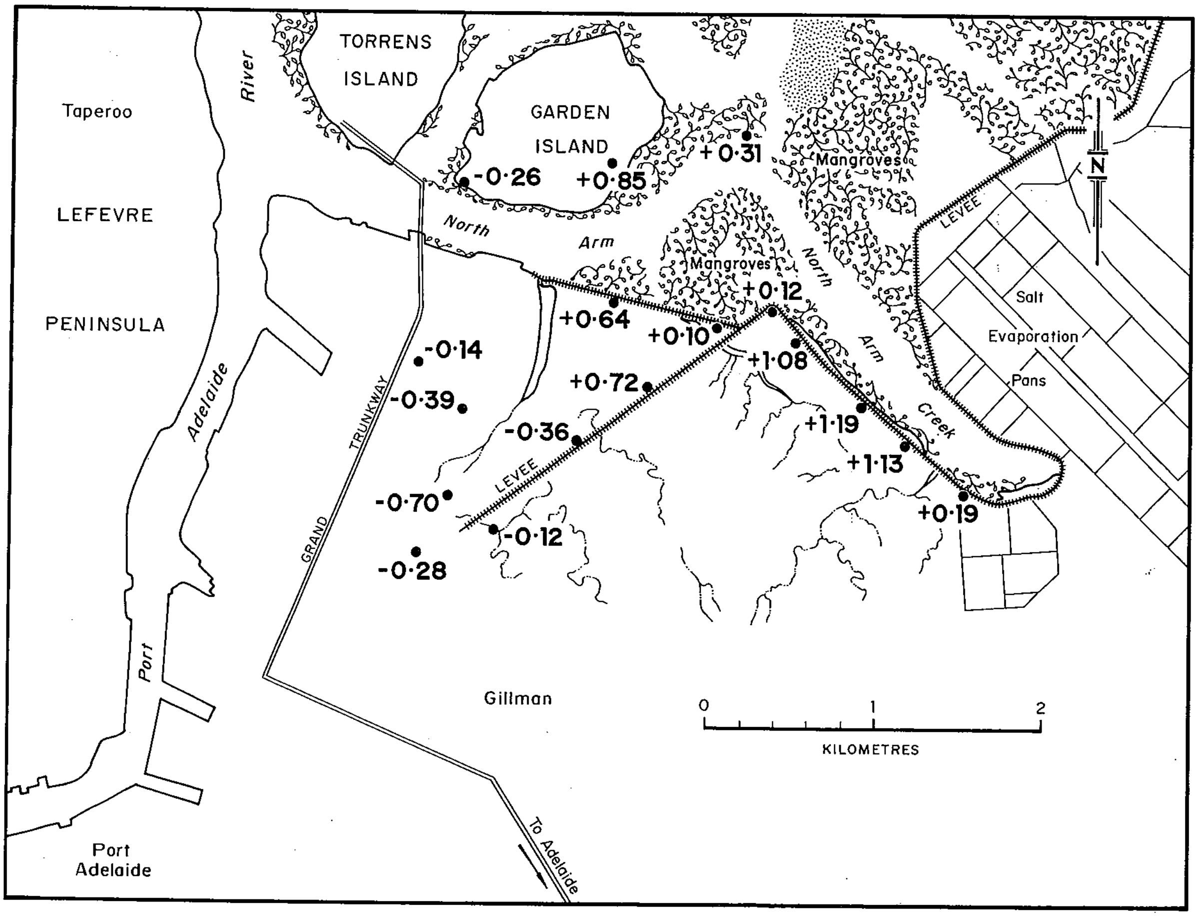

Fig. 5 Elevations of the mangrove/coquina contact intersected in vibrocores from the Gillman area in metres relative to the contemporary level in the tidal estuary.

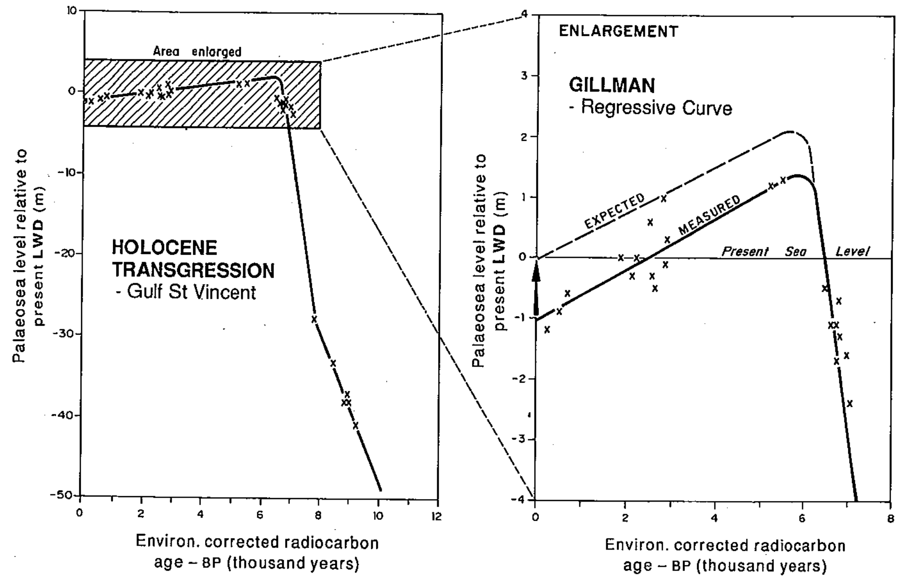

Fig. 6 Time–depth plot of radiocarbon-dated palaeosea level indicators (x) for the Port Adelaide estuary and deeper waters of Gulf St Vincent. The line of best fit through the regressive data points from the Gillman wetlands ($r = 0.88$) has a negative intercept indicating 1.0 m of recent subsidence has affected this region. As the sea level curve should have a zero intercept corresponding with present day low water datum, the subsidence effect is interpreted as a very recent phenomenon that has occurred since the youngest dated mangrove peats were deposited (<260±50 years BP). Correcting the curve for this amount of subsidence results in a curve that more closely matches the expected curve for this area (the Port Gawler curve in Fig. 7).

Table 1 Radiocarbon dated palaeosea level indicators from vibrocores from the Gillman tidal wetlands and adjacent Gulf St Vincent.

Sample	Facies	Lab. code	Environment corrected sample age (years BP)	Sample level (m LWD)	Palaeosea level (m LWD)
Gulf St Vincent					
GLEN	Mangrove	CS-568	6610±140	0.71	-1.1±0.6
GLEN	Mangrove	CS-396	6990±150	0.21	-1.6±0.6
GLEN	Mangrove	CS-395	6730±110	0.71	-1.1±0.6
SV23	Subtidal	SUA-2713	8840±105	-37.7	>-37.7
SV23	Subtidal	SUA-2711	8940±105	-37.2	>-37.2
SV23	Subtidal	SUA-2712	9010±95	-37.6	>-37.6
SV38	Intertidal	B-30178	7800±135	-26.9	-27.8±0.3
SV39	Intertidal	B-30179	8460±95	-32.2	-33.1±0.3
SV49	Intertidal	B-30181	9230±185	-39.9	-40.8±0.3
VC284	Subtidal	WK-1117	7070±450	-2.44	>-2.4
VC284	Subtidal	WK-1118	6820±240	-1.27	>-1.3
Gillman wetlands					
†VC146	Coquina	WK-784	2530±80	1.45	0.6±0.3
†VC154	Coquina	WK-785	1890±70	0.93	0±0.3
†VC156	Coquina	WK-786	2650±80	0.36	-0.5±0.3
*VC242	Samphire	WK-1968	6740±70	1.04	-1.7±0.3
*VC245	Intertidal	WK-1969	6800±80	0.76	-0.7±1.0
†VC248	Mangrove	WK-1971	2140±100	1.49	-0.3±0.6
*VC305	Coquina	WK-2142	5230±80	2.02	1.2±0.3
*VC307	Coquina	WK-2143	5500±80	2.12	1.3±0.3
*VC312	Coquina	WK-2144	2830±70	1.83	1.0±0.3
*VC313	Coquina	WK-1974	2880±70	0.8	-0.1±0.3
*VC315	Coquina	WK-1976	2580±60	0.53	-0.3±0.3
*VC315	Mangrove	WK-1975	260±50	0.57	-1.2±0.6
*VC327	Mangrove	WK-1977	530±50	0.9	-0.9±0.6
*VC327	Coquina	WK-1978	2230±60	0.84	0±0.3
*VC334	Mangrove	WK-1979	6490±60	1.34	-0.5±0.6
*VC337	Coquina	WK-1981	2920±70	1.12	0.3±0.3
*VC337	Mangrove	WK-1980	710±60	1.2	-0.6±0.6

* Core from reclaimed wetland. † Core from natural wetland. LWD = low water datum.

magnitude of the highstand has been shown both theoretically (Lambeck & Nakada 1990) and from site-specific field studies (Belperio 1993) to vary systematically and predictably with distance up the gulfs from the continental margin (Fig. 7). The notable difference between sea level curves for Port Adelaide and other sectors of the South Australian coast, is the subdued highstand of 1.3 m *vs* an anticipated value of 2.0 m and its negative intercept at time zero (Figs 6, 7). Within the resolution provided by the radiocarbon data, stratal subsidence of ~1.0 m is indicated since the youngest dated substrate (260 ± 50 years BP) was deposited. Correcting the palaeosea level curve for recent subsidence of 1 m eliminates the negative intercept and results in a curve that closely matches the expected curve based on theoretical considerations and field measurements from Port Gawler to the north (Fig. 7).

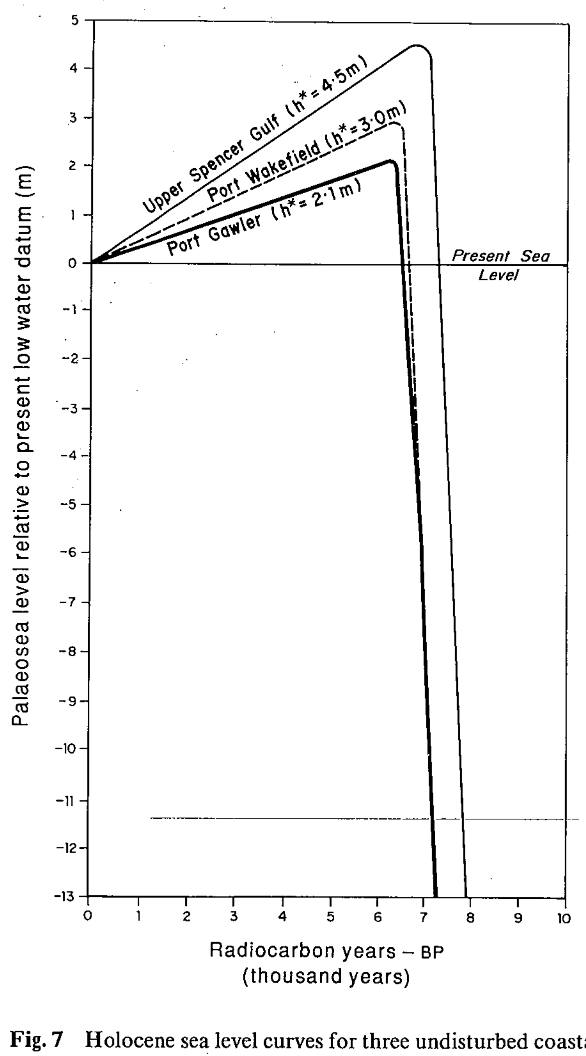

Fig. 7 Holocene sea level curves for three undisturbed coastal locations within the South Australian gulfs showing the systematic change in the mid-Holocene highstand (h*). Data from radiocarbon-dated palaeosea level indicators (Belperio 1993). Locations are indicated on Fig. 1. The Port Gawler site, 18 km north of Port Adelaide, reveals the expected pattern of relative sea level change for the study site if it were not perturbed by recent anthropogenic influences.

Data from tide gauges, mangrove migration patterns and the subsurface stratigraphy all indicate a contemporary relative rise in sea level within the Port Adelaide estuary. The geographic restriction of these effects to the Port Adelaide estuary, together with available geodetic evidence, indicate that the apparent rise in sea level is a local phenomenon, resulting chiefly from land subsidence.

Within the resolution provided by radiocarbon-dated palaeosea level indicators (Figs 5, 6), subsidence of 0.7–1.0 m has occurred since 260 ± 50 years BP. That is, the changes in land level can be reasonably assumed to be anthropogenic, associated with the increasing urban and industrial utilization of the estuary and wetland reclamation over the past 150 years.

FACTORS CONTRIBUTING TO LOCAL SUBSIDENCE

A number of short- and long-term geological and anthropogenic effects have been recognized world-wide as contributing to relative changes in sea levels (Emery & Aubrey 1991). The following are relevant to the Port Adelaide estuary.

Long-term basin subsidence

The Port Adelaide estuary occurs within the St Vincent Basin, an Early Tertiary to Holocene graben containing more than 500 m of sediment. Long-term subsidence within the basin has been estimated at 0.01 mm/year with a slightly higher rate of 0.02–0.03 mm/year during the Quaternary (Belperio & Bateman 1986). These rates for long-term basin subsidence are insignificant in comparison with the contemporary rate of land subsidence.

Glacio- and hydro-isostatic adjustment

The waxing and waning of continental glaciers and the associated addition or subtraction of meltwater to the ocean basins and continental shelves is accompanied by isostatic adjustments of the earth's crust (Chappell 1974; Clark *et al.* 1978). The Australian coast is in the 'far field' of crustal rebound associated with the last deglacial cycle, with mid-Holocene highstands being characteristic (Peltier 1988; Lambeck & Nakada 1990). Significant spatial variability is exhibited in the magnitude of the highstand and subsequent fall of sea level. However, these essentially isostatically driven mechanisms cannot explain the sea level rise at Port Adelaide. The preserved coastal record at Port Adelaide is clearly anomalous when compared with either measured or predicted palaeosea level trends for the gulfs (Belperio 1989, 1993 and Lambeck & Nakada 1990, respectively).

Sediment compaction due to wetland reclamation

Sediment compaction and ground subsidence invariably accompany drainage and reclamation of wetlands, with the greatest subsidence associated with peat and organic-rich soils (Carbognin 1985). World-wide, measured subsidence rates for reclaimed organic soils vary from <10 to >80 mm/year. Compaction resulting from placement of fill is one obvious cause of land settlement, but subsidence also results from several other factors associated with the artificial drainage process. Lowering of the water table causes consolidation, compaction and densification of exposed, previously saturated, sediments. Settlement is directly related to the magnitude of water table lowering and occurs at faster rates in warmer regions. Aeration of peat and organic soils additionally results in a loss of mass from irreversible microbial (biochemical) oxidation of organic matter (Stephens *et al.* 1984) and chemical oxidation of sulphide minerals (Postma 1983). Microbial and chemical oxidation of the substrate are longer-term processes that continue as long as temperature, pH and meteoric aeration are conducive to biological and chemical change.

Each of these effects has accompanied reclamation of the Port Adelaide tidal wetlands. Construction of levees and sluices to artificially drain mangrove and samphire marshes and to prevent further marine inundation commenced in 1894 and continued in stages to 1974. Other forms of reclamation have included a variety of landfill operations (that continue today) and fill from the dredging of tidal waterways.

The most notable ground subsidence coincides with an area of reclaimed mangrove woodland at Gillman, where some 400 ha of mangrove peat up to 1.5 m thick has been exposed to meteoric infiltration and aeration. Levees and sluice gates constructed to prevent marine flooding and allow low-tide discharge of ponded stormwater have artificially lowered the water table by 1.0 m relative to the unconfined marine water table that formerly characterized the site (Fig. 8). Empirical relations established by Schothorst (1977) and Stephens *et al.* (1984) suggest that densification and biochemical oxidation of peat may be responsible for 0.45 m of land subsidence. Actual field measurements indicate a lowering of 0.7 m has occurred, suggesting additional factors are operating in the reclaimed Gillman wetlands.

Bacterial sulphate reduction with precipitation of elemental sulphur and iron sulphide are inherent characteristics of mangrove sediments in their natural state (Harbison 1986). Exposure of mangrove peats allows oxidation of the sulphur and sulphide minerals, generating low-pH groundwaters. Dissolution of carbonate minerals by the acid groundwater results in mass loss within the shallow substrate. Rates of sulphur and sulphide oxidation and acid generation are enhanced in the presence of *Thiobacillus* bacteria and if pyrite is present in a fine framboidal form in permeable sediments (Pye & Miller 1990). Within the exposed peat land of the Gillman area, oxidation of sulphide minerals has generated highly acid groundwaters with pH values of 3.5–5.0. Extensive decalcification of sediments has occurred to depths >2 m within and beneath the mangrove peat layer (Belperio 1985b; Belperio & Rice 1989). Decalcification is greatest beneath the oldest reclaimed areas. Authigenic gypsum is locally present at the sharp redox front between decalcified and unaltered marine sediment. However, the almost complete removal of dissolution products has probably been aided by the use of the reclaimed land as stormwater ponding basins. With typical carbonate contents of 20% in the unaltered strata, this process is thought to be responsible for additional subsidence of 0.2. m in the reclaimed mangrove swamp at Gillman. Thus the combined effects

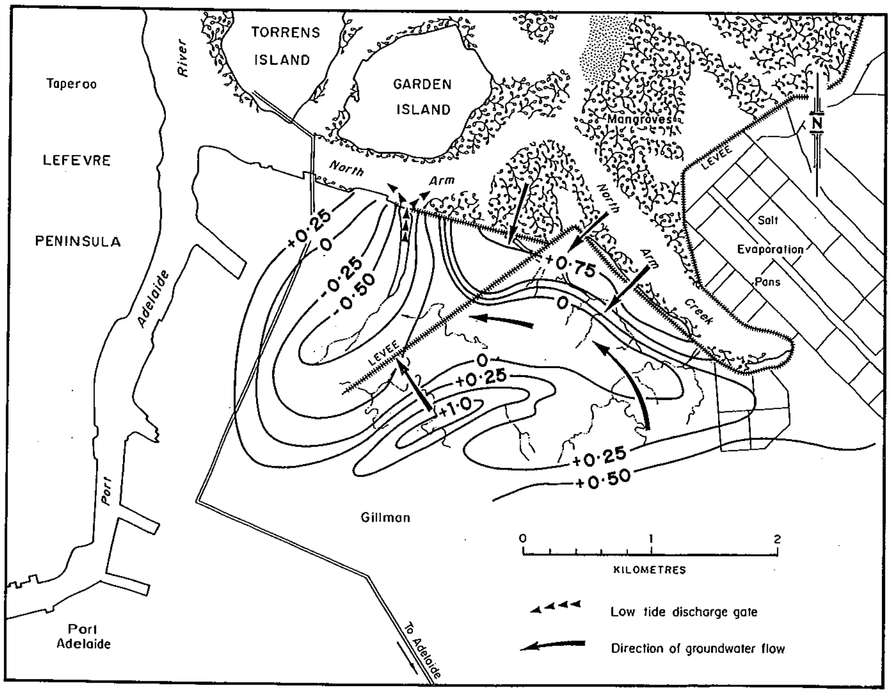

Fig. 8 Unconfined groundwater levels in metres relative to mean sea level within the reclaimed Gillman wetlands for August 1989. Note the infiltration of marine groundwater beneath the North Arm levee, and the north-west gradient towards low-tide sluices.

of processes associated with artificial drainage of the tidal wetlands are anticipated to have caused 0.65 m of land settlement (Table 2). This compares closely with the value of 0.7 m indicated by the subsurface stratigraphy (Figs 5, 6).

Reclamation by dumping of fill results in additional lowering of the Holocene substrate as the weight of overburden compresses buried low density layers. Known areas of fill were avoided in the vibrocore study so that the effects of overcompaction do not bias palaeosea level measurements obtained from radiocarbon analyses. However, the tide gauge sites at Outer Harbour and Port Adelaide are underlain by 10 and 5 m, respectively, of soft and compressible organic mud, over which has been placed 4–5 m of fill. Depending on the structural integrity of the tide gauge foundations (which are probably in a very poor condition), ongoing compaction and settlement due to overloading effect of fill may well be an additional factor to be considered at these sites.

Groundwater withdrawal

Many spectacular examples exist around the world of human-induced ground subsidence resulting from the withdrawal of fluids, principally groundwater and hydrocarbons (Poland & Davis 1969; Chi & Reilinger 1984). Ground subsidence is the surface manifestation of consolidation of subsurface strata accompanying declining head and pore pressures in aquifers.

Within the study area, extraction of groundwater from deeper confined aquifers has increased over the past 50 years. As a result, the potentiometric surface of the main Tertiary aquifer has been severely modified by excessive pumping (Gerges 1987). A major cone of depression has developed under the Port Adelaide estuary, mainly as a result of large-scale pumping of groundwater for industrial purposes (Fig. 9).

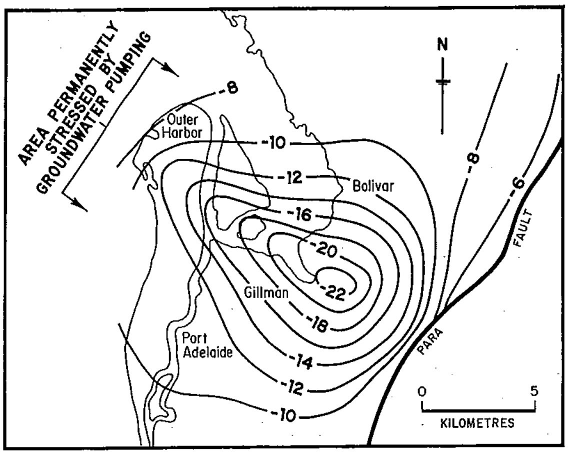

Fig. 9 Decline in water levels in metres over the past 50 years for the upper Tertiary aquifer beneath the Port Adelaide estuary (modified after Gerges 1987). Tide gauges are located at Outer Harbour and Port Adelaide.

Table 2 Summary of contributing factors to land subsidence for four sections of the Port Adelaide estuary.

Wetland reclamation	Groundwater withdrawal	Net subsidence	Rate of land subsidence (mm/year)	Rate of sea level rise (mm/year)
Gillman				
Anticipated settlement of 650 mm total from compaction, oxidation and decalcification	Anticipated 140 mm of ground subsidence in the zone of maximum groundwater head decline	Between 700 and 1000 mm of subsidence over the past 70–100 years indicated by core and C14 data	10	Not resolved
Bolivar				
Not applicable	Anticipated 140 mm of ground subsidence due to groundwater withdrawal	Equivalent 150–200 mm of relative sea level rise indicated by the rate of migration of mangroves	2.8	0.2–1.2
Port Adelaide				
Unknown effect from 4-5 m of fill over 5 m of Holocene coastal sediments	Geodetic relevelling indicates 1.8 mm/year of ground subsidence; Tide gauge indicates 2.5 mm/year of net sea level rise	Ground subsidence of 180 mm over the past 100 years	1.8	0.7
Outer Harbour				
Unknown effect from 4-5 m of fill on 10 m of Holocene marine sediment	Tide gauge indicates 2.9 mm/year of sea level rise; three-quarters (2.2 mm/year) attributed to ground subsidence	Ground subsidence of 110 mm over the past 50 years	2.2	0.7

Davis (1987) has developed empirical relationships between aquifer-head decline and subsidence of the land for stressed aquifer systems on coastal plains. Non-recoverable compaction occurs when a preconsolidation stress, equivalent to ~20 m of head decline is exceeded, and proceeds while the induced drawdown is maintained. A relationship between subsidence and head decline established by Davis (1987) for stressed groundwater systems in coastal plain settings indicates potential subsidence in the study area of up to 0.14 m over the past 50 years. At Bolivar, on the eastern side of the estuary, the landward advance of mangroves onto the samphire marsh of 850 m over the past 50 years is equivalent to an effective sea level rise of 3–4 mm/year. This part of the estuary should be subject mainly to the effects of groundwater withdrawal, indicating that the method of Davis (1987) is a useful means of determining such land subsidence effects.

Spatial variability of the subsidence attributable to groundwater withdrawal is expected to mimic the hypsometric pattern of depressed water levels (Fig. 9), but only limited data are available for detailed assessment. The tide gauges at Outer Harbour and Port Adelaide are outside the zone of maximum head decline. Here, maximum values for ground subsidence are 2.9 and 2.5 mm/ year respectively; that is, if all the secular signal recorded by the tide gauges is attributed to land subsidence. Third-order relevelling in 1969 indicates land subsidence at Port Adelaide of ~1.8 mm/year, implying actual sea level rise of 0.7 mm/year; that is, three-quarters of the tide gauge signal at this site can be attributed to the effects of land subsidence.

Net effect

The available data have been geographically devolved (Table 2), and indicate highly variable rates of land subsidence (1.8–10.0 mm/year) over the study area. The magnitude and extent of land subsidence are determined by the superposition of tidal wetland reclamation and the zone of stressed groundwater. The effects of wetland reclamation are most pronounced where mangrove woodland has been drained and reclaimed and the sediment subjected to exposure and oxidative processes. These effects can continue for in excess of 100 years. The effects of groundwater extraction are more subtle, extending for a 10–15 km radius of Gillman, and including both tide gauge sites within the Port of Adelaide. At the two tide gauge sites, three-quarters (1.8 and 2.2 mm/ year) of the apparent sea level rise can be attributed to anthropogenic land settlement effects, with the remainder (0.7 mm/year) attributable to actual rise of sea level. Subsidence due to groundwater withdrawal will continue while the groundwater regime remains under stress.

CONCLUSIONS

(i) The Port Adelaide estuary is undergoing significant land subsidence at rates that vary from 1.8 to 10 mm/year over different parts of the region.

(ii) The major causes of land subsidence are surficial soil compaction associated with wetland reclamation and groundwater withdrawal from deeper Tertiary aquifers.

(iii) Maximum subsidence (up to 10 mm/year) is occurring where these two effects coincide. Subsidence is also occurring in the remaining natural wetlands within the estuary, as a result of the regionally depressed groundwater potentiometric surface. Groundwater withdrawal has a noticeable effect over a radius of ~10–15 km.

(iv) Three-quarters of the secular rise in sea level recorded by the local tide gauges can be attributed to land subsidence. The neotectonically corrected local sea level trend is a rise of 0.7 mm/year rather than the figures of 2.5–2.9 mm/year previously used.

(v) As similar anthropogenic effects are expected to affect most coastal plain tide gauge sites, it is imperative that all tide gauge data used to infer regional or global changes in sea level are corrected for local land level changes.

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