CHAPTER
3

PHYSIOGRAPHY

3.0 INTRODUCTION

This chapter is a summary of all the basic physical and biological characteristics of Perry Lakes. The botanical and geological characteristics of the wetlands are reviewed followed by an overview of field experiments completed to measure the basic hydrological parameters of the superficial aquifer and lacustrine sediments. Depth-area-volume relationships are constructed from field surveys.

3.1 VEGETATION

3.1.1 Background

No formal assessment of vegetation has ever been undertaken at Perry Lakes. Passing references include Alexander (1919), Watson (1958), Riggert (1966), Keighery *et al* (1990), Dames & Moore 1992, Mitchell McCotter & Ecoscape (1993). Arnold (1987) includes sketch maps of the distribution of open water and principal vegetation communities within the lake basins *circa* 1986. Surveys undertaken here describe in detail the distribution of vegetation communities and in particular the distribution of the dominant fringing emergent macrophytes *Baumea articulata* (R. Br.) S. T. Blake (Cyperaceae) and *Typha orientalis* C. Presl (Typhaceae), commonly referred to as jointed twig-rush and bulrush (Chambers *et al* 1995). These species dominate the littoral zone at Perry Lakes and are highly responsive to short term changes in water regime (Froend *et al* 1993, Froend & McComb 1994). Mapping also differentiated the distribution of the naturally occurring species *Bolboschoenus caldwellii* (common name marsh club-rush) and the small sumpland plant *Villarsia*. Naturalised introduced sedges *Cyperus eragrostis* and *Cyperus tenuiflorus* were also mapped as their distribution also appears linked to water regime.

Depth to water table is a function of the elevation of the lake bed, the local water table gradient and the regional water table level. The distribution of emergent macrophytes is controlled by three principal factors (Froend *et al* 1993, Chambers *et al* 1995):

- Annual range (minimum-maximum water level)
- Period of inundation at any particular RL within the lake basin
- Sediment type (typically sand, peat or clay)

Within the shallow saucer like form of Perth Coastal Plain wetlands, these three criteria define concentric zones around the shore where sand grades to silt-clay substrate and where the degree and duration of seasonal waterlogging and inundation vary. Dredging and reclamation of the shorelines has resulted in extensive areas of sandy substrate around portions of both lakes (Figures 3.6 a&b). At Perry Lakes the principal factors controlling the distribution of *Baumea* and *Typha* appears to be their differing preferred range and mean annual water levels (Table 3.1). Therefore *Baumea* occurs in the deeper portions of the basins where there is a longer or permanent period of inundation while *Typha* occurs on higher ground where inundation is sporadic.

Table 3.1 Water level criteria, dominant emergent macrophytes

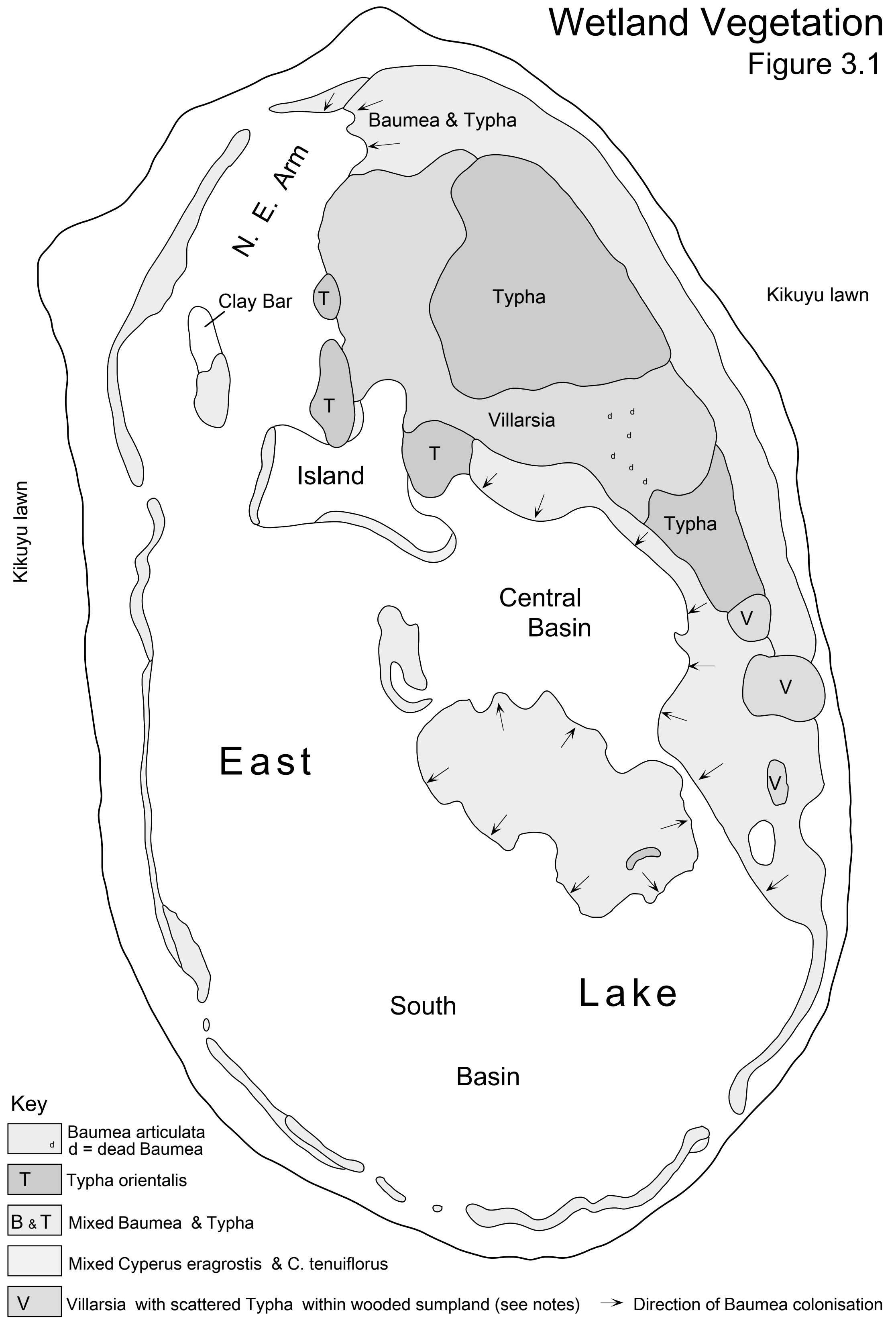
	Tolerable WL Range	Preferred Mean WL
Baumea articulata	+400 to -400mm	+250mm
Typha orientalis	+100 to -300mm	0 *i.e.* waterlogged

Mapping was controlled using 10x20m surveyed grids established for topographic and sediment isopach surveys. In East Lake, mapping was completed simply to document the vegetation distribution as it existed at the completion of the water balance field work in early 1998. In West Lake mapping was completed during the summers of 1995, 1996 and 1997 specifically to document the vegetation changes associated with the transition from permanent to seasonal innundation.

3.1.2 East Lake

Prior to dredging in 1962, East Lake appears to have been dominated by extensive stands of *Baumea articulata*, but with open permanent water always present in the South Basin. Since about 1970, water levels have declined and there has been a steady progression from permanent open water over the entire basin to permanent open water (artificially maintained over summer) in the South Basin only. Figure 3.1 shows the distribution of vegetation and open water or seasonal mud flats as of January 1998. *Baumea* is now actively expanding into the South, Central and N. E. Arms while *Typha* is expanding in the higher northeast quarter of the basin where there is only occasional inundation. Remnants of dead *Baumea* are common in the *Villarsia* sumpland (Figure 3.1) reflecting a recent site of *Baumea* colonisation. These colonies have probably died within the past five years.

Wetland Vegetation
Figure 3.1



Notes

1: Outer margin of lake basin defined by the 5m AHD contour

2: Kikuyu lawn grass (Pennisetum clandestinum) occupies steep bank between 5m contour and outer margin of wetland vegetation

3: Typha and Villarsia in N.E. quadrant of basin occur within wooded sumpland of Flooded gum (Eucalyptus rudis) and paperbark (Melaleuca spp.)

4: Bolboschoenus caldwellii not identified in East Lake

Scale: 1:2000

Mapped January 1998

3.1.3 West Lake

West Lake dried completely (apart from the small sump adjacent to the staff gauge) for the first time in recent years in the summer of 1995. Anecdotal evidence (Chapter 2) suggests that within historic times occasional summer drying had occurred previously, but probably not to the same extent. Since 1995, West Lake has been dry every summer from approximately January until June or July. It has become a seasonal wetland or 'sumpland' as defined by Semeniuk (1987). Vegetation distribution was mapped in detail in February of 1995, 1996 and 1997. During this period:

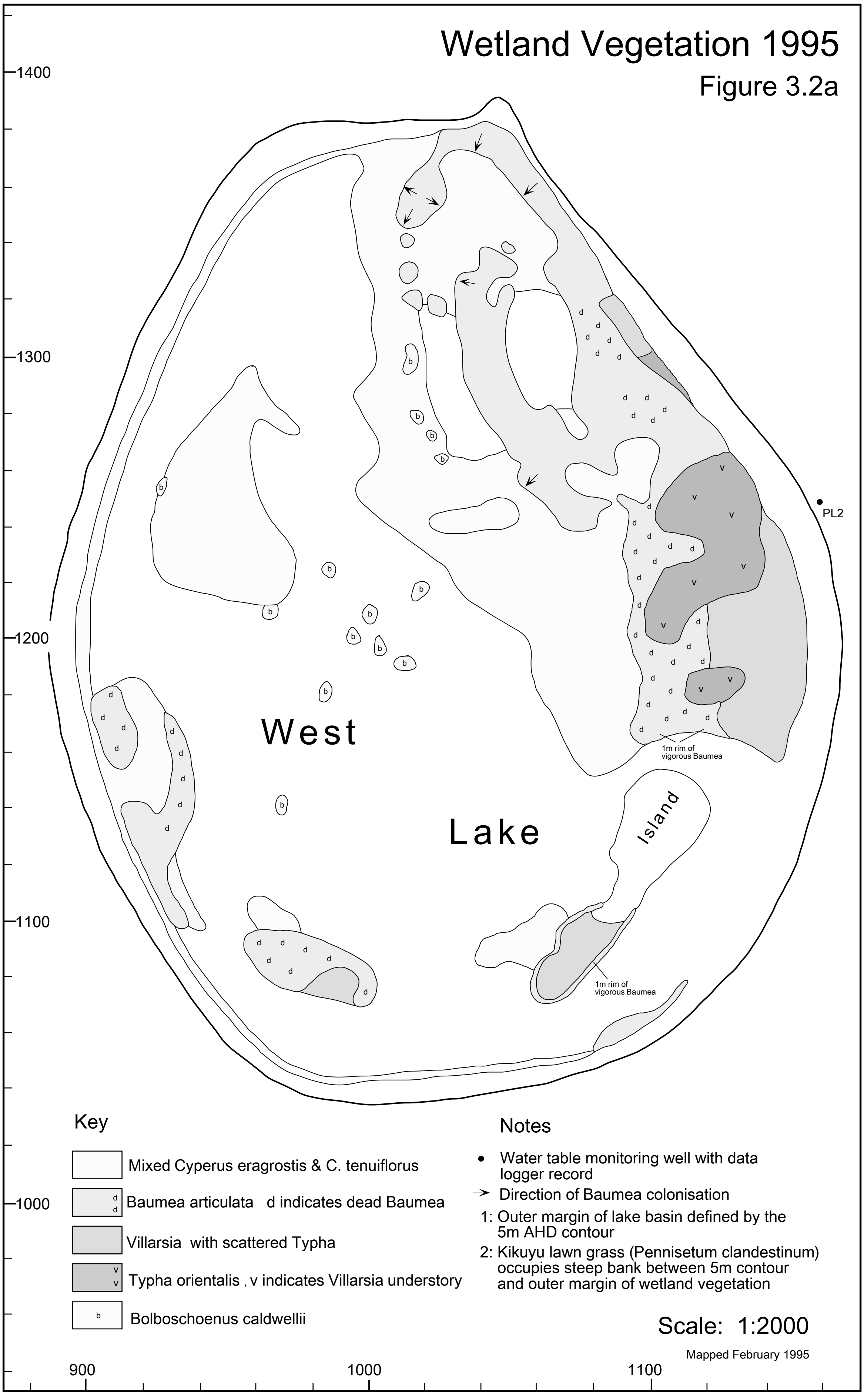
- Mean depth and period of winter inundation decreased
- Depth to water table over the summer increased

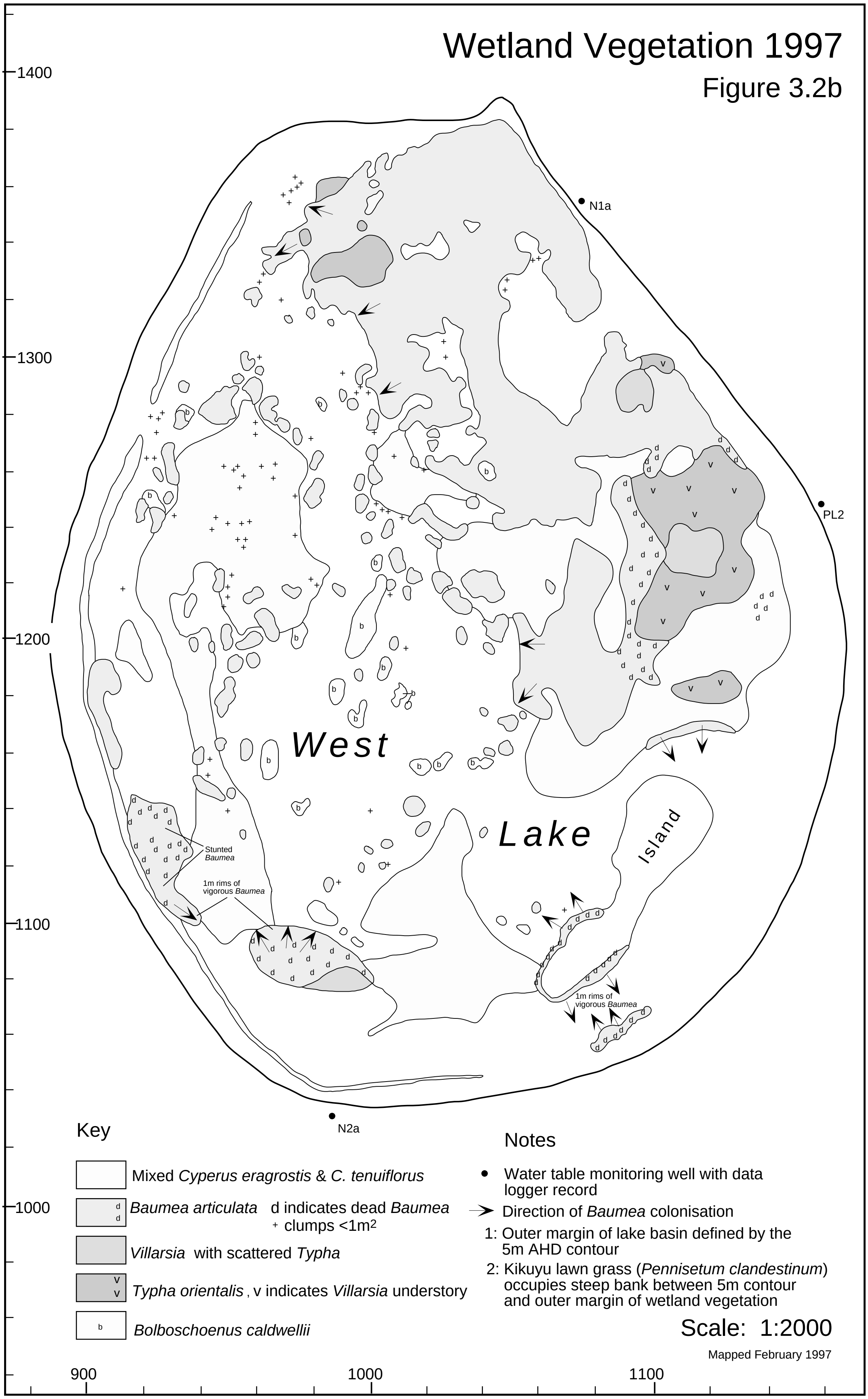
In a lake the piezometric head at the lake bed is everywhere equal to the elevation of the water surface. The water surface constitutes a horizontal water table. When a lake dries out however, the regional water table gradient is re-established beneath the lake bed. Therefore despite having the same elevation, different points around the lake bed will be at differing vertical distance to the water table. In West Lake, the regional gradient traverses the lake from northeast to southwest (Figure 3.3). Therefore over summer when the lake is dry, distance to the water table in the southwest corner of the lake basin will be greater than in the northeast corner.

Figures 3.2 a&b demonstrate the principal changes delineated over the two years from February 1995 to February 1997. These fringing emergent macrophytes constitute dynamic communities which respond quickly to exploit a modified water regime. The principal changes observed over 24 months were:

- an explosive expansion of *Baumea articulata* into the deeper western and southern portions of the basin including the establishment of numerous isolated outliers
- expansion of *Typha orientalis* into the northern section of the basin
- a decrease in vitality or death of *Baumea* and *Typha* at various locations around the higher periphery of the basin
- death of *Villarsia* along the higher eastern margin of the basin
- rapid expansion of *Cyperus* and *Bolboschoenus* into the deeper portions of the basin

Examining the vegetation distributions in conjunction with the lake bed topography (Figure 3.10b) demonstrates the effects of topography combined with seasonal re-establishment of a water table gradient beneath a seasonally dry lake. In 1995 vigorous *Baumea* tended to occur between the 3.2 and 3.0m RL while plants situated between 3.2


Wetland Vegetation 1995
Figure 3.2a
1400
1300
1200
1100
1000
900
1000
1100
PL2
West
Lake
Island
1m rim of vigorous Baumea
1m rim of vigorous Baumea
Key
Mixed Cyperus eragrostis & C. tenuiflorus
Baumea articulata d indicates dead Baumea
Villarsia with scattered Typha
Typha orientalis , v indicates Villarsia understory
Bolboschoenus caldwellii
Notes
Water table monitoring well with data logger record
Direction of Baumea colonisation
1: Outer margin of lake basin defined by the 5m AHD contour
2: Kikuyu lawn grass (Pennisetum clandestinum) occupies steep bank between 5m contour and outer margin of wetland vegetation
Scale: 1:2000
Mapped February 1995



Wetland Vegetation 1997
Figure 3.2b
1400
1300
1200
1100
1000
N1a
PL2
N2a
West
Lake
Island
Stunted *Baumea*
1m rims of vigorous *Baumea*
1m rims of vigorous *Baumea*
Key
Mixed *Cyperus eragrostis* & *C. tenuiflorus*
Baumea articulata d indicates dead *Baumea*
+ clumps <1m2
Villarsia with scattered *Typha*
Typha orientalis, v indicates *Villarsia* understory
Bolboschoenus caldwellii
Notes
Water table monitoring well with data logger record
Direction of *Baumea* colonisation
1: Outer margin of lake basin defined by the 5m AHD contour
2: Kikuyu lawn grass (*Pennisetum clandestinum*) occupies steep bank between 5m contour and outer margin of wetland vegetation
Scale: 1:2000
Mapped February 1997
900
1000
1100

and 3.4m were stunted and in part dead (Figure 3.2a). This was largely a topographic effect only representing annual differences in range and period of inundation. Between 1995 and 1997 *Baumea* expansion was largely confined to the northern half of the lake basin between 2.9 and 3.0m RL. Despite the fact that large portions of the southern half of the basin lay within the same elevation range these remained uncolonised, due to the water table gradient effect. *Baumea* cannot colonise these southern portions of the basin because the depth to water over summer is too great. The data demonstrate the rapidity of vegetational response to major changes in wetland water regime.

3.1.4 Aquatic Flora

Watson (1958) describes *Potamogeton pectinatus* in East lake in 1957 and *Nitella sp* in flood ponds on present day Alderbury Flats. Lantzke (1986 unpublished) noted abundant submerged aquatic plants in 1974 including *Najas marina*, *Triglochin procera* and *Potamogeton pectinatus*. Approximately two decades later Dames and Moore (1992) reported only sparse distributions of *Chara sp* and possible *Nitella sp* with abundant epiphytic growths. No aquatic flora were noted over the period 1996-1998.

3.1.5 Algae

The available historic evidence suggests that algae are a natural part of the Perry Lakes ecology. Seasonal growth of algae appears to be a natural part of Swan Coastal Plains wetland ecology and possibly precedes European occupation. Hodgkin & Vicker (1987) for example make such a suggestion in respect to the Swan River. Watson (1958) noted a heavy growth of filamentous green alga in East Lake over winter 1957. Lantzke (1986 unpublished) reported similar alga in both lakes over the period 1975-1984 as did Dames & Moore (1992) in 1991 along with abundant *Chara sp* in West Lake.

Samples of alga collected from East Lake in October 1995 were identified as *Zygnema sp* (J. Nowell pers com), a filamentous non branching green alga. Blooms of this species were observed each October during 1995 to 1998. Each year blooms grew slowly over several weeks and then collapsed quickly suggesting nutrient limiting in either nitrogen or phosphorous. Blooms of blue-green algae have been reported during 1976-77 (Lantzke 1986 unpublished) and in West Lake only in 1991 by Dames & Moore (1992). None were observed over the period 1995 to 1998.

3.2 AQUIFER GEOLOGY

3.2.1 Geomorphology

Perry Lakes are situated within the Pleistocene Spearwood Dune System of McArthur & Bettenay (1960). Immediately to the west within Bold Park, calcareous coastal dunes of the Holocene Quindalup system (McArthur & Bettenay 1960, Semeniuk, Cresswell & Wurm 1989) encroach as far east as Camel Lake.

Sands of the Spearwood Dune System while principally yellow, include white, light grey and brown sands. They are predominantly quartz, with colour derived from a coating of kaolin and goethite (Glassford & Killigrew 1976). These siliclastic sands overlying the Tamala Limestone have been generally interpreted to represent *in situ* decalcified Tamala Limestone (Prider 1948, Lowry 1977). The Spearwood Dune System has generally been accepted to represent an aeolian reworking of this material from the west (McArthur & Bettenay 1960). Petrographic data (Glassford & Killigrew 1976) and stratigraphic evidence (Glassford & Semeniuk 1990) suggest an aeolian continental provenance for these yellow quartz sands representing extensive desert phases co-incident with periods of middle Pleistocene glaciation in higher latitudes. Interdigitating deposits of limestone and yellow sand may therefore represent alternating periods of coastal aeolian and continental desert aeolian sedimentation (Semeniuk & Glassford 1987).

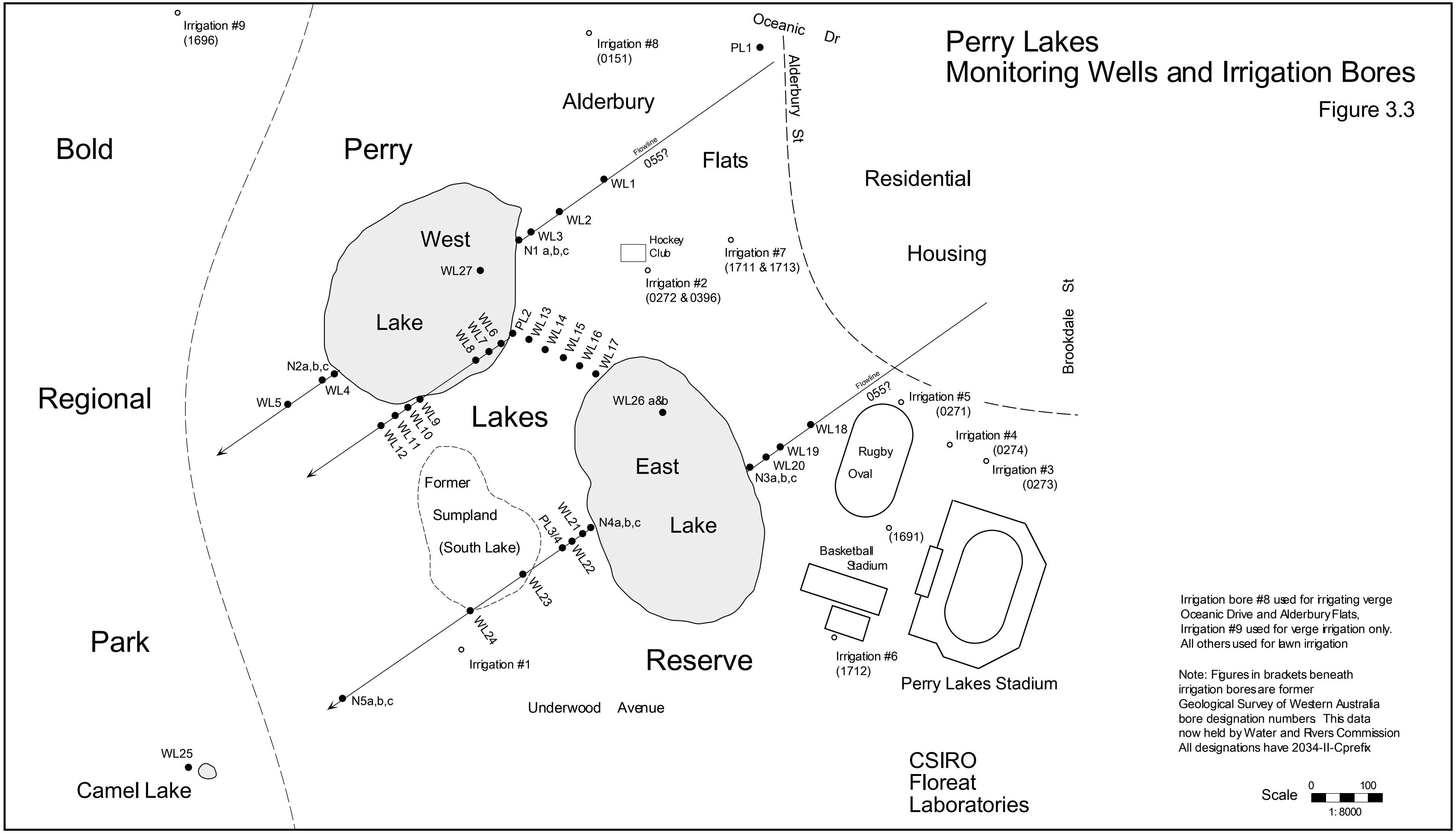
Perry Lakes are probably of Holocene age. The lakes occupy small interdunal depressions. Their shape (and distribution of palaeo-sediments within them) suggests that they formed in deflation basins of the style described by Hutchinson (1975) associated with extreme aridity at the end of the Pleistocene. Lake basin sediments are therefore Holocene to Recent in age. Lacustrine geology is described in detail in Section 3.3.

3.2.2 Hydrogeology

Superficial aquifer geology and hydrogeology is based on data from three sources:

- production bore hydrogeological records
- CSIRO drilling conducted for this project
- geophysical records

Hydrogeological records (now held by the Water and Rivers Commission) were located at the Geological Survey of Western Australia (GSWA) for some of the current and former production bores within Perry lakes Reserve. Production bores for lawn irrigation were first drilled in 1962 (Somerford pers com). The situation is confusing because all bores



Perry Lakes
Monitoring Wells and Irrigation Bores
Figure 3.3

have been periodically replaced, some have been relocated and bore designations have changed. Available logs commence in 1971. The interpreted locations (Figure 3.3) are based on street location, Perth City Council (PCC) bore designation and depth to static water level. Most were drilled by cable tool, which provides uncontaminated samples and accurate depth information. These logs therefore provide the stratigraphic framework for the aquifer sections (Figures 3.4 a&b). Drill logs are included as Appendix 3.1. Nested piezometers N1c-N5c drilled for this project using hollow stem augers provide good contact definition between sand or weakly consolidated calcarenite and hard limestone.

A local stratigraphy has been erected comprising 'Upper Sand', 'Limestone' and 'Lower Sand':

Upper Sand:

> Medium grained yellow to white quartz (plus minor carbonate), 8-15m thick. Grain size analysis and detailed logs (Appendix 3.2) from the nested piezometers provide additional detail. The Upper Sand thins to the west of both lakes where it forms a thin veneer over the limestone. The Upper sand is principally a residual weathering product of the underlying limestone. Thin bands and fragments of limestone are common within this unit.

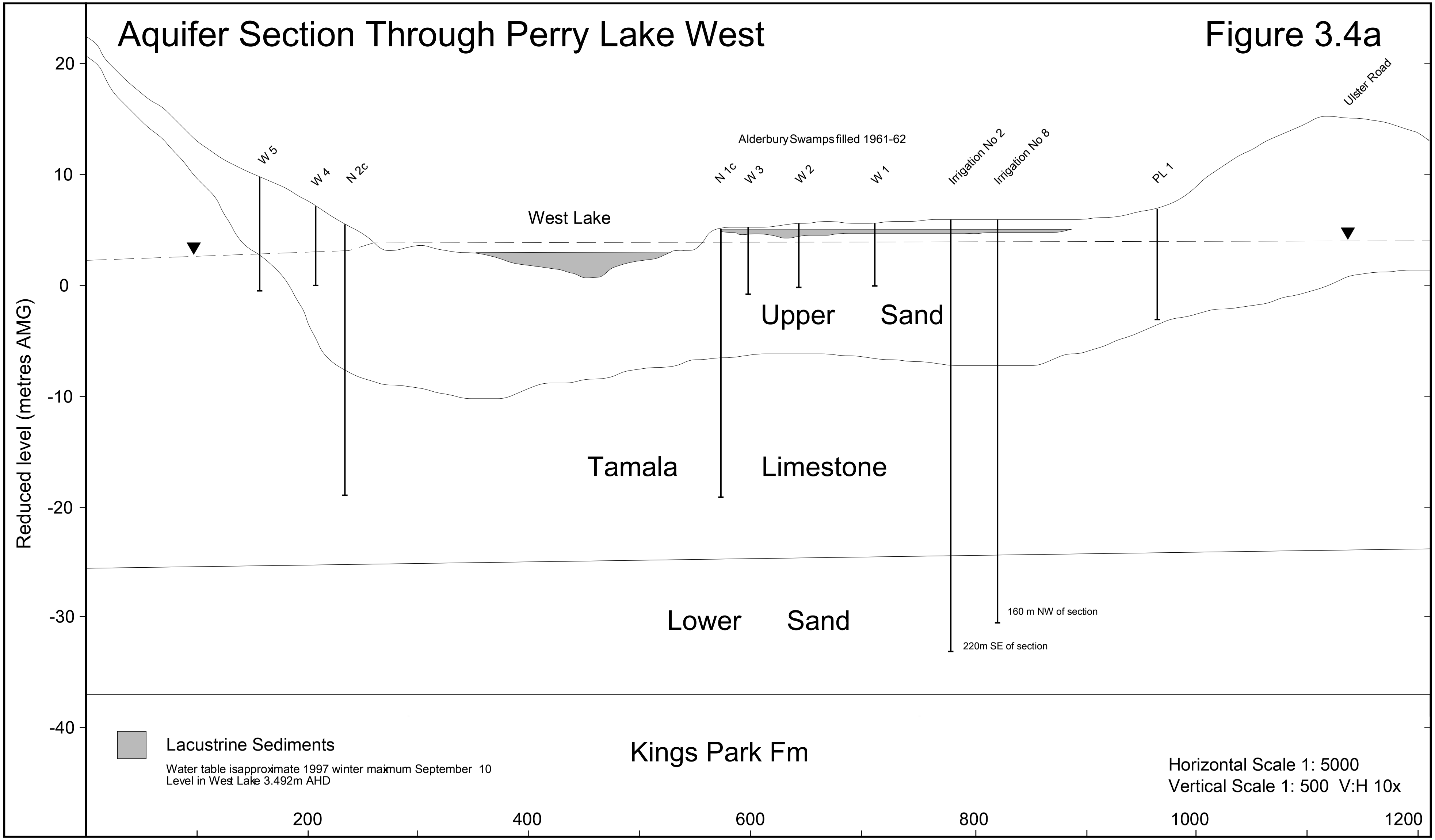
Limestone:

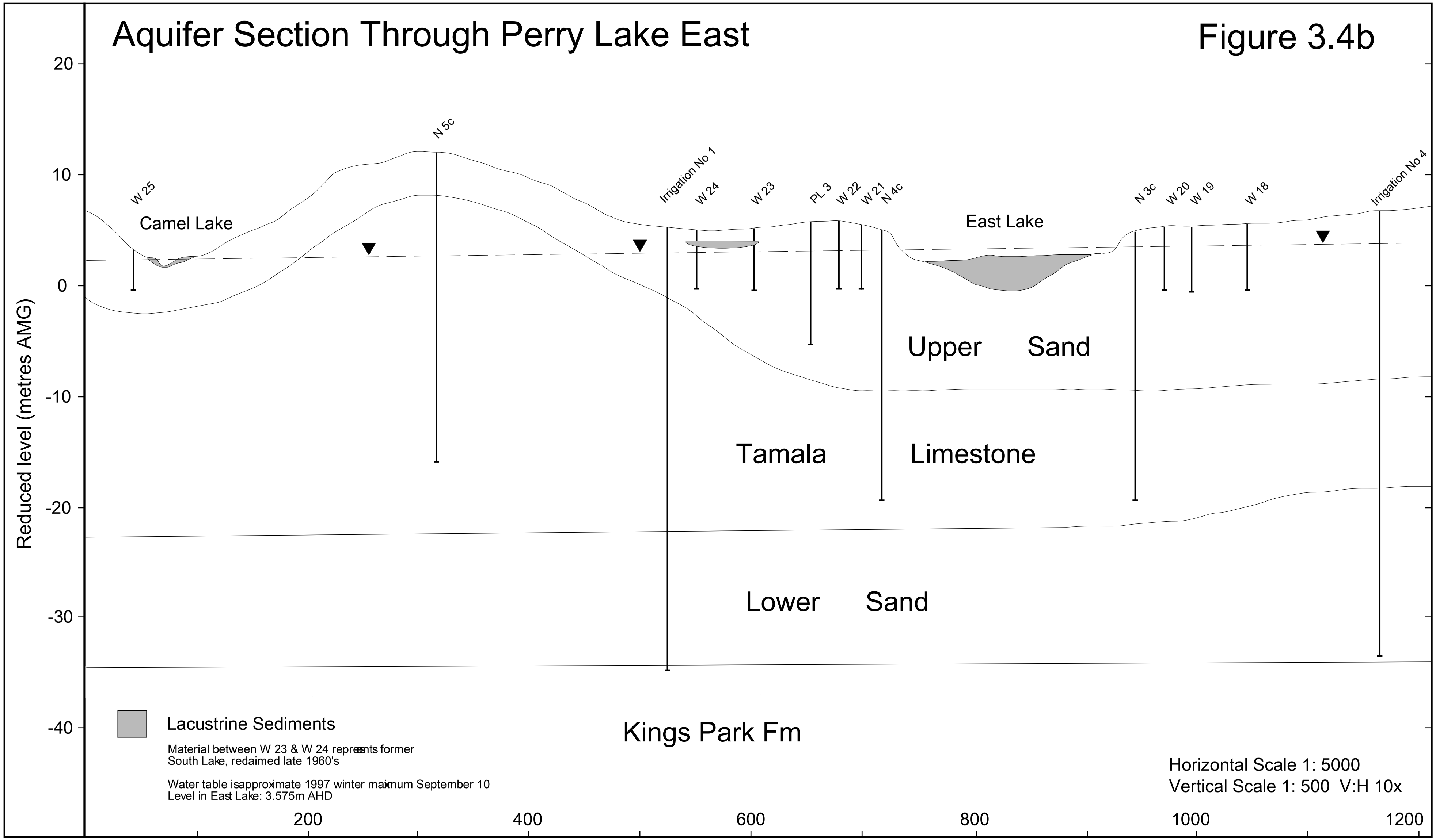
> Sheet like, 10 to >20m thick beneath the lakes, thickening to the west where it outcrops within Bold Park. The upper surface is irregular reflecting varying degrees of degradation to quartz-carbonate sand. The limestone is principally a weakly cemented quartz carbonate sand interspersed with harder centimetre to metre scale bands of grainstone (quartz grains in carbonate matrix), extremely hard vuggy calcrete and centimetre scale bands of beige to grey carbonate rich clay. The lower portions of the limestone frequently contain shells. The grainstone and calcrete bands are often impenetrable using an auger drill.

Lower Sand:

> This unit is known only from driller's logs which suggest a predominantly coarse, well sorted sand with occasional limestone rubble. All irrigation bores at Perry Lakes are screened within this unit. Gray clay representing degraded shale and siltstone of the Kings Park Fm. forms an aquitard and base to the superficial aquifer.

Total saturated thickness of the superficial aquifer is 35 to 39m below Perry Lakes Reserve.


Aquifer Section Through Perry Lake West
Figure 3.4a
Ulster Road
Alderbury Swamps filled 1961-62
W 5
W 4
N 2c
N 1c
W 3
W 2
W 1
Irrigation No 2
Irrigation No 8
PL 1
West Lake
Upper Sand
Tamala Limestone
Lower Sand
160 m NW of section
220m SE of section
Kings Park Fm
Reduced level (metres AMG)
20
10
0
-10
-20
-30
-40
200
400
600
800
1000
1200
Lacustrine Sediments
Water table is approximate 1997 winter maximum September 10
Level in West Lake 3.492m AHD
Horizontal Scale 1: 5000
Vertical Scale 1: 500 V:H 10x


Aquifer Section Through Perry Lake East
Figure 3.4b
Reduced level (metres AMG)
20
10
0
-10
-20
-30
-40
W 25
Camel Lake
N 5c
Irrigation No 1
W 24
W 23
PL 3
W 22
W 21
N 4c
East Lake
N 3c
W 20
W 19
W 18
Irrigation No 4
Upper Sand
Tamala Limestone
Lower Sand
Kings Park Fm
Lacustrine Sediments
Material between W 23 & W 24 represents former South Lake, redaimed late 1960's
Water table isapproximate 1997 winter maximum September 10
Level in East Lake: 3.575m AHD
Horizontal Scale 1: 5000
Vertical Scale 1: 500 V:H 10x
200
400
600
800
1000
1200

3.2.3 Bore Hole Geophysics

Natural gamma ray logging can be used to detect layers of clay within the aquifer (Guyod 1975, Telford *et al* 1976). Gamma emitting radioisotopes normally found in sediments are potassium 40 and the myriad daughter products of the uranium and thorium decay series (Killeen 1975). Potassium is abundant in feldspars and micas. These weather to clays which in general have a much higher natural gamma activity than sands and carbonates (Keys & MacCarey 1971). Sands and carbonate comprise the principal lithologies within the superficial aquifer.

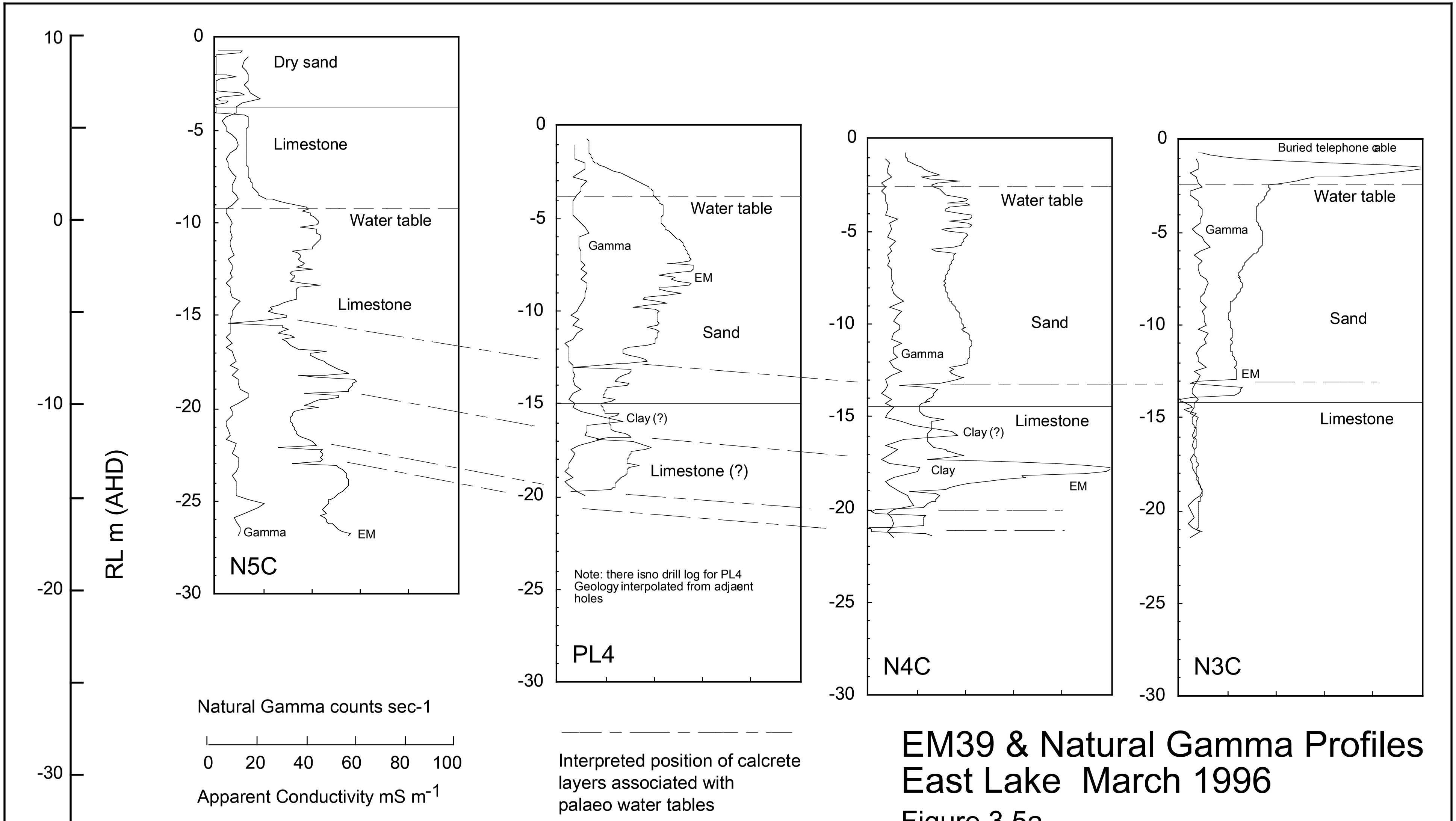
Frequency domain inductive electromagnetic (EM) methods utilise probes with two coils. The transmitter coil induces eddy currents in conductive formations. These generate secondary EM fields which are detected in the receiver coils, this induced signal being proportional to the conductivity of the formations surrounding the borehole, conductivity being the reciprocal of resistivity (Keys & MacCarey 1971). Highly resistive material will display low conductivity and vice versa. In the superficial aquifer clays will display high conductivity and strongly lithified material such as grainstone or calcrete will display low conductivity. These responses will be superimposed on a background level which varies in response to the conductivity of the pore water.

Bore hole logging was carried out in piezometer nests N1c-N5c and PL4 to test for clay units and resistive lithologies. Instrumentation comprised:

Natural gamma logging:	Mt Sopris 1000 total count natural gamma logger and probe
Apparent conductivity:	Geonics EM39 borehole conductivity logger and probe

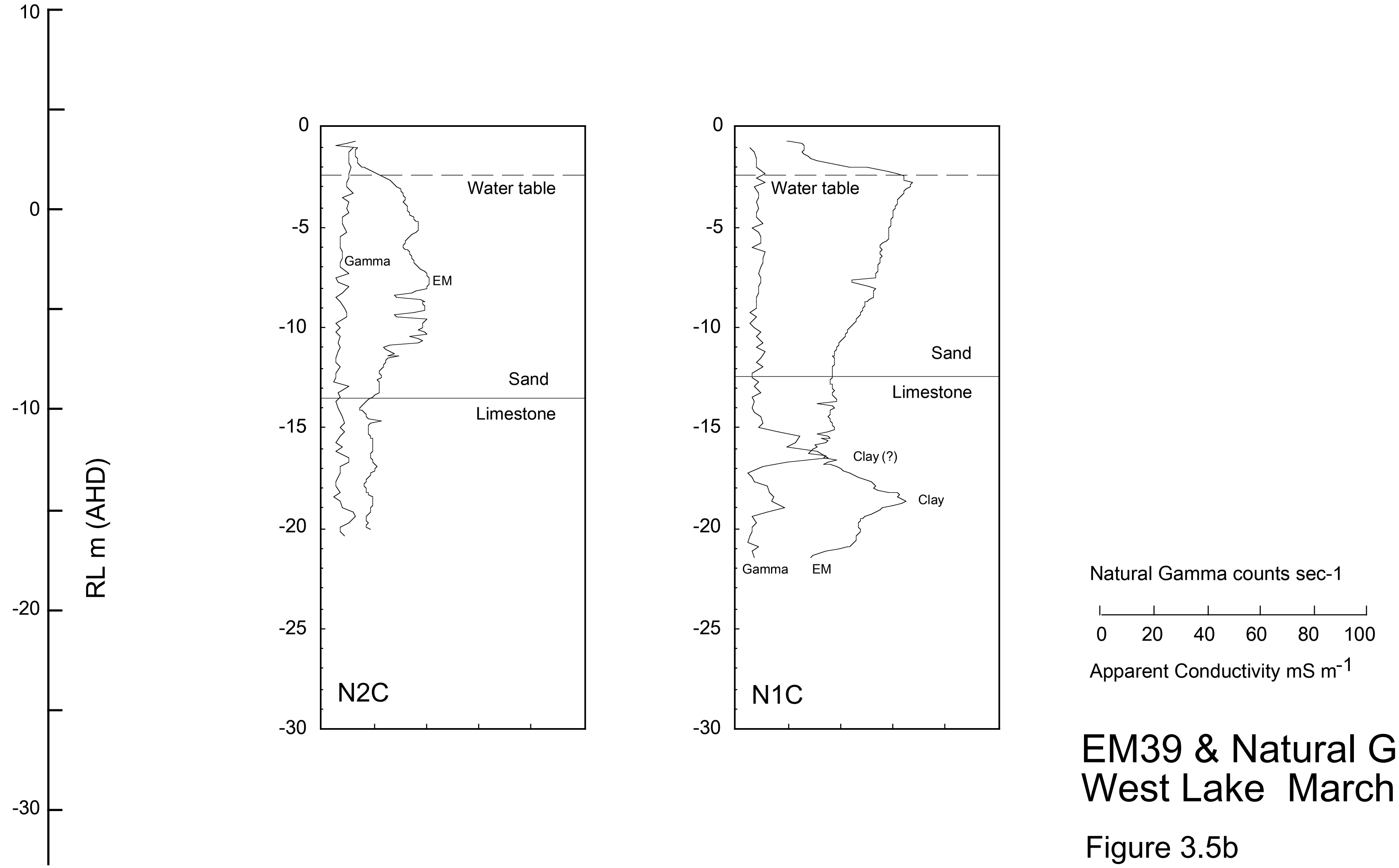
Gamma, apparent conductivity and simplified geology are compiled as profiles in Figures 3.5 a&b. Geological logging and grain size analysis located organic rich lacustrine sediments to the east end of both lakes (piezometers N1c and N3c). These are plotted on the cross sections. The grain size analysis (Appendix 3.2) shows that these sediments contain only 12-30% silt and clay, the remainder being sand. Neither returned a gamma or conductivity response. All holes on the East Lake profile display a narrow (<1m) sharp conductivity low between approximately RL -5 to -9m AHD. Similar features are apparent at other levels, particularly in N5c. Two such features 1m apart may correlate with similar features in N4c.

The Tamala Limestone is of late Pleistocene age. Radiometric dating suggests that initial deposition commenced about 140 000 years ago, with further deposition and reworking continuing into the early Holocene (Teichert 1967, Playford *et al* 1976, Playford 1988). The conductivity features may define thin calcrete layers developed through the process of



EM39 & Natural Gamma Profiles East Lake March 1996

Figure 3.5a



EM39 & Natural Gamma
West Lake March 1996

Figure 3.5b

capillary rise (Semeniuk & Meagher 1981) associated with a Pleistocene palaeo-water table under arid conditions. The Pleistocene was a period which included intense high latitude glaciation coupled with widespread aridity in southwest Western Australia (Glassford & Killigrew 1976, Wyrwoll 1979, Semeniuk & Glassford 1987, Glassford & Semeniuk 1990). This interpretation is consistent with driller's records which indicate predominantly soft limestone with interspersed thin hard bands. Gamma and co-incident conductivity peaks are interpreted to be carbonate clays.

3.3 LACUSTRINE GEOLOGY

3.3.1 Lacustrine Sediment Isopachs

Sediment thickness was measured by probing with a 6mm diameter brass rod 3.5m long. The rod was found to penetrate clays easily. At the clay-sand contact penetration becomes difficult. The technique, checked by hand auger was found to be accurate to within 5cm. Typical station spacing was 10x20m (Appendices 3.3 a&b).

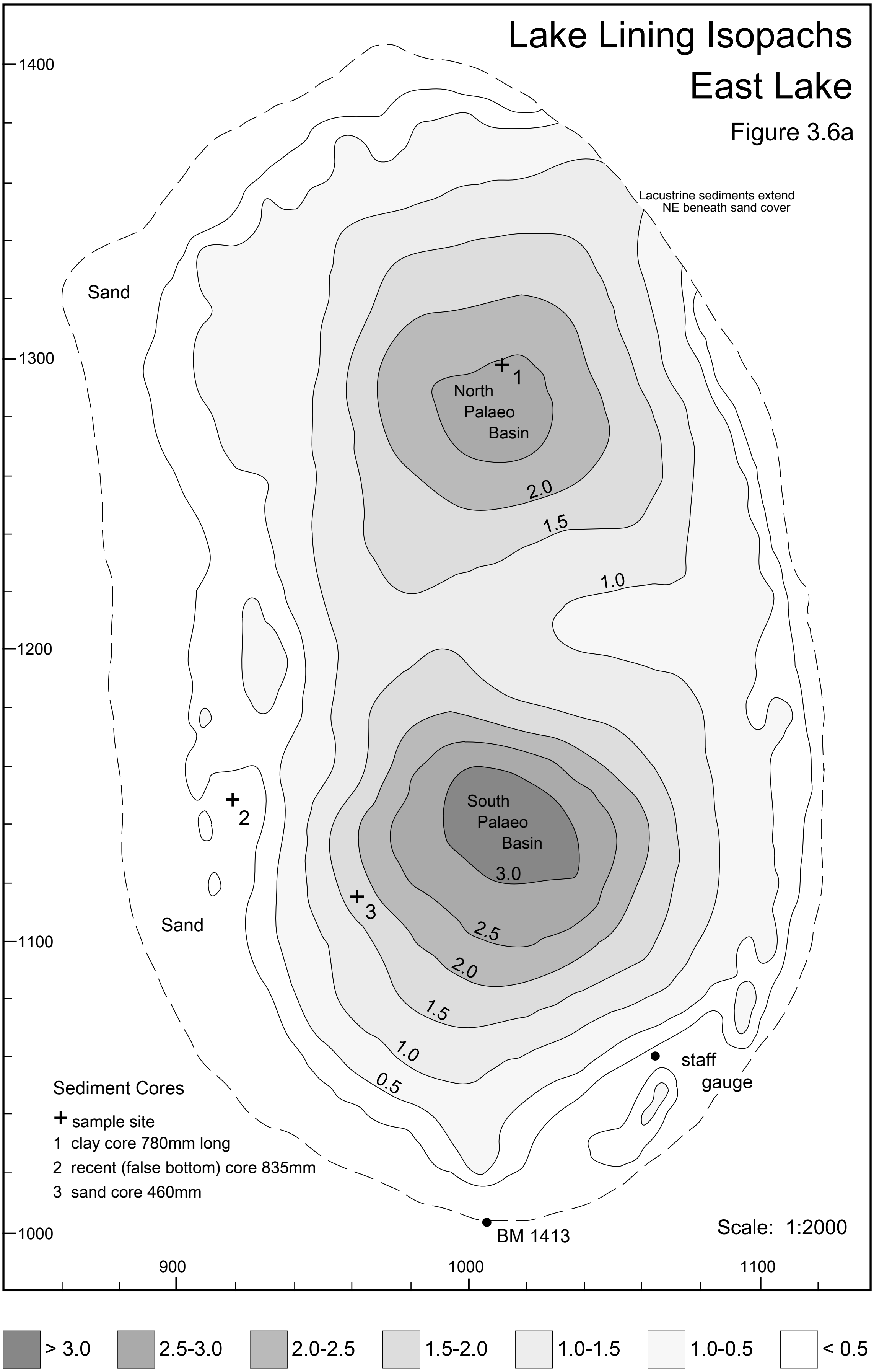
East Lake (Figure 3.6a)

The north, west and south margins of the basin have a sand floor (this includes sand with less than 20cm of false bottom sediment). The bird nesting island (Figure 3.10a) comprises sand and limestone fill dumped over the original lacustrine lining. The palaeo-lake was originally two separate ponds. As sedimentation continued, these palaeo-basins coalesced. Megirian (1982) found a similar pattern at Bibra Lake which coalesced from three smaller lakes. The data suggests that later stages of the lake extended to the northeast beneath what is now sand cover. In the South Basin, recent false bottom material comprises up to 0.5m of the sediment thickness.

West Lake (Figure 3.6b)

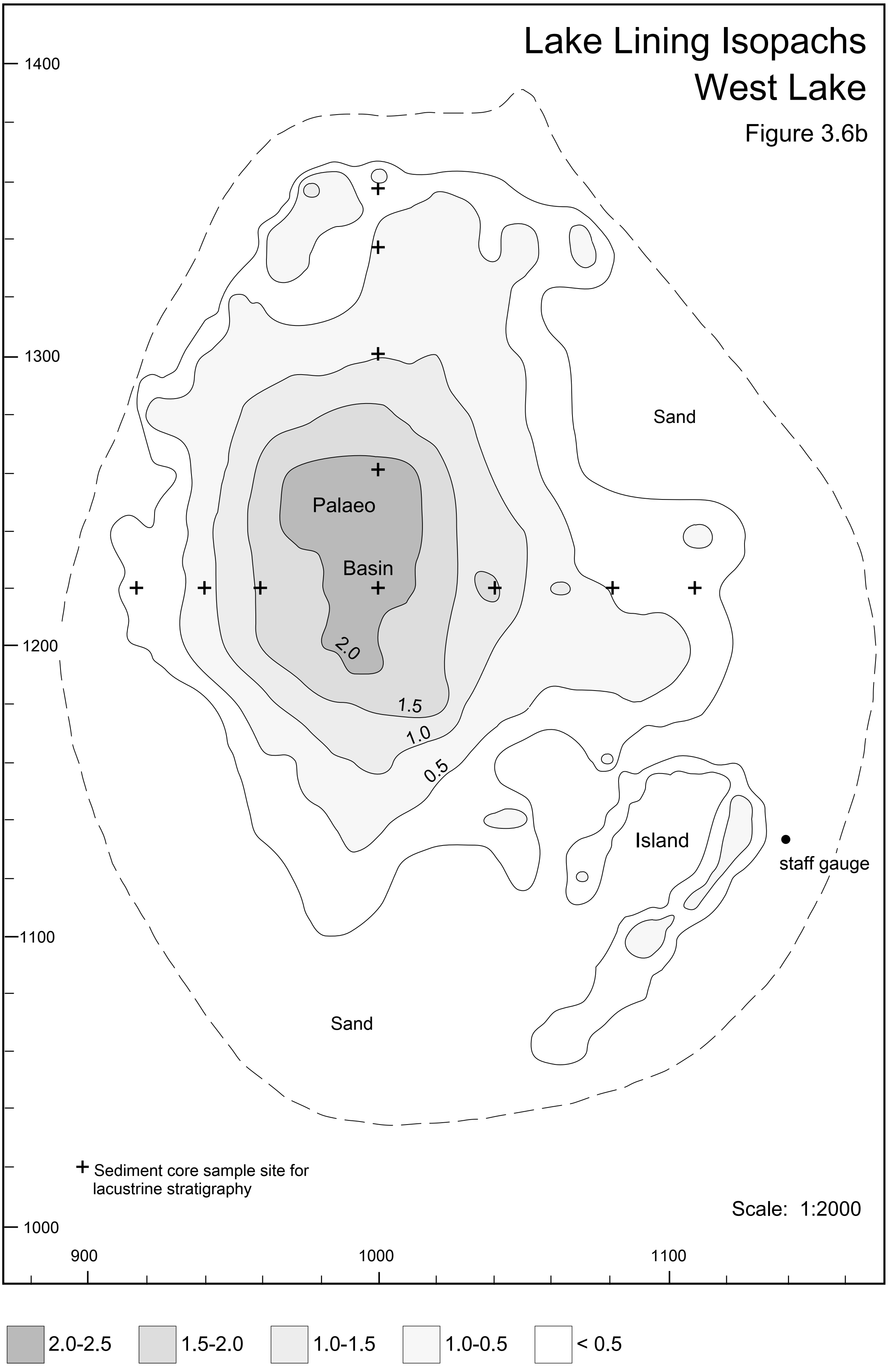
The palaeo-lacustrine sediments are concentrated in one palaeo-basin. The bird nesting island was formed by bulldozing a deep arcuate basin along the south shore. Recent false bottom sediments fill this basin. The island is not therefore underlain by older lacustrine sediment. Recent sediment also fills elongate basins along the north and east margins of the lake formed when the lake was deepened and the banks extended in the early 1960's. Approximately 30% of the basin floor consists of sand with no lacustrine sediment lining.

At Perry Lakes the areas of permanent water that existed prior to modification in 1962 (Figure 2.2), did not overlie the deepest portions of the palaeo-basins which contain most of the sediment and must therefore have been the principal flooded portion of the lakes for



East Lake lacustrine sediment isopach contours generated from 497 soundings (Appendix 3.3a)

Dashed line is 5m surface contour (approximate limit of lake basin)



West Lake lacustrine sediment isopach contours generated from 646 soundings (Appendix 3.3b)
Dashed line is 5m surface contour (approximate limit of lake basin)

most of their history. These palaeobasins are the original wind deflation hollows which became flooded as the water table rose.

3.3.2 Lacustrine Stratigraphy and Palaeo-geography

A framework for lake basin lacustrine stratigraphy was compiled using a combination of coring and hand augering. Cores were collected specifically for the purpose from West Lake which was dry and readily accessible from the summer of 1995 onwards. Observations from hand augering were also compiled during lacustrine sediment isopach mapping on both lakes. Cores representing partial sections were collected from East Lake for vertical hydraulic conductivity and specific yield measurements and studies on the recent sediments within the South Basin.

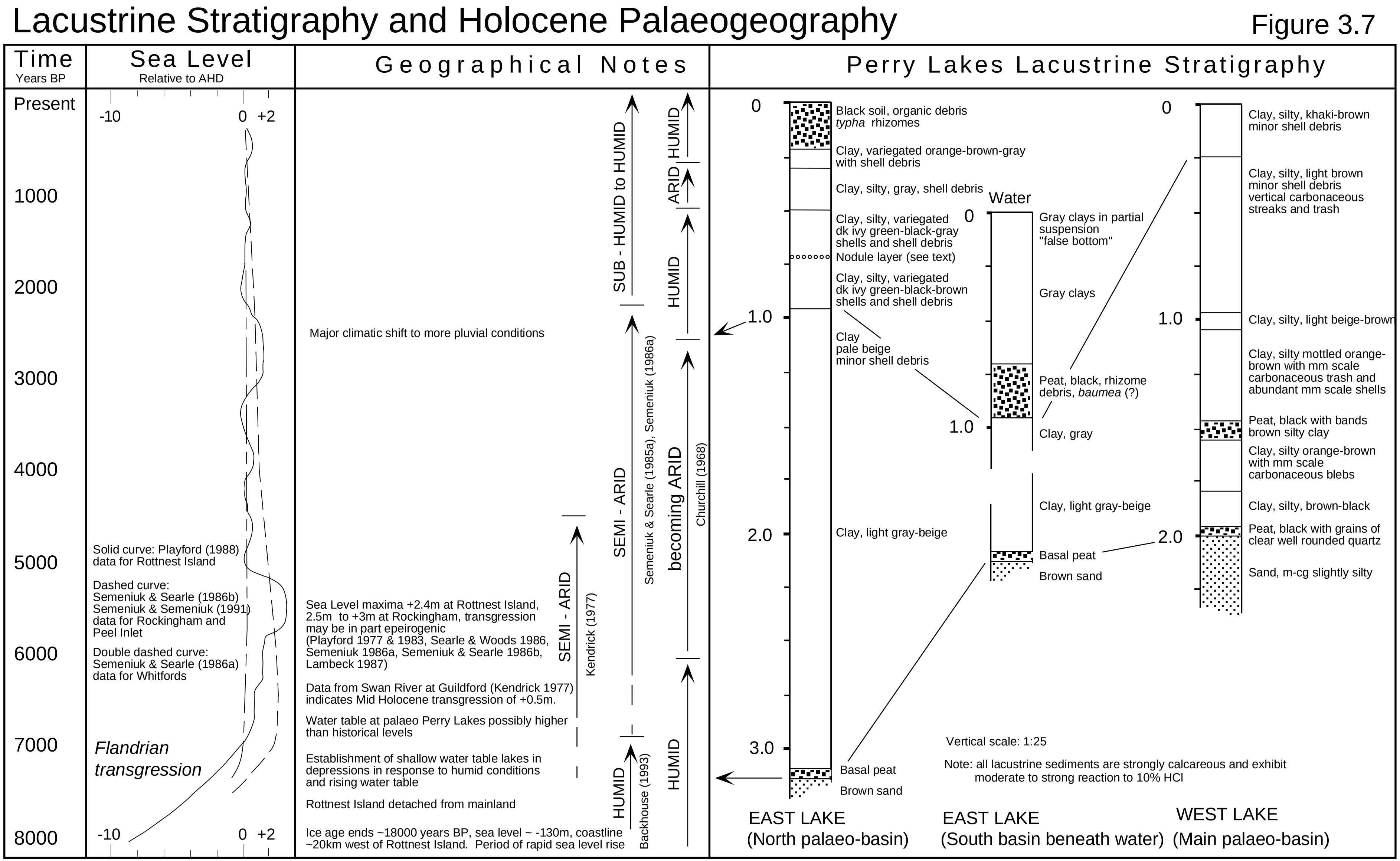
In West Lake 11 cores were collected (Figure 3.6b). Lengths of 40mm PVC were bevelled inwards and driven to the lacustrine sediment-sand contact and then withdrawn using a tripod and hand winch. Inward bevelling forces an oversize sample into the tube, ensuring that the sample core is not partially withdrawn by suction when the PVC is removed. The technique is essentially that of Megirian (1982). The tubes were opened by cutting longitudinally using an angle grinder. Cores were sectioned lengthwise as stratigraphically younger material is dragged over older material around the pipe periphery, obscuring contacts. The lacustrine sediments have a low specific gravity, and compress when driven into the PVC. In the deepest holes, sample length was about 42% of original. Megirian (1982) found the compaction rate to be variable depending on depth and sediment type (maximum compression in clays and minimum compression in sands). In this case sediments were all clays. Contacts were adjusted assuming a uniform compaction rate. Due to the short lengths involved, compaction rate of all West Lake cores was assumed to be constant. Cores collected from East Lake at W26 and the South Basin were uncompressed. Sampling methods are described elsewhere in this chapter.

Radio carbon dating of wetlands on the Swan Coastal Plain suggests that lacustrine sedimentation commenced around 8000 years B.P. (V. Semeniuk pers com) with initiation of the present interglacial and associated Flandrian transgression (Flint 1967). Sea level rose rapidly to levels at and exceeding its current level accompanied by and in response to a significant global warming (Sturman & Tapper 1996). The previous 100Ka were characterised by extensive high latitude glaciation and in southwest Western Australia widespread aridity and high winds (Glassford & Killigrew 1976, Wyrwoll 1979, Semeniuk & Glassford 1987, Glassford & Semeniuk 1990). The driest conditions and lowest sea level (-130m AHD) occurred about 15-20Ka (Sturman & Tapper 1996) when the coast was approximately 50km west of Perry Lakes (present distance 2.5km). At this time groundwater levels would have been much lower than at present. Calcrete layers (Section 3.2.3) may define fossil water table levels during this arid climatic regime. Wetlands associated with a regionally homogeneous aquifer on a narrow coastal plain will be intimately linked to climate, principally rainfall and recharge (Allen 1981), vegetation and evapotranspiration (Congdon 1985) and sea level (Semeniuk 1986).

Proposed Holocene climate regimes on the Swan Coastal Plain are summarised in Figure 3.7. There is a general consensus that there was a rapid climatic amelioration at the beginning of the Holocene. Botanical evidence (Churchill 1968) suggests rainfall may have been similar to the present climate, with a trend towards aridity about 6000 years B.P. This is corroborated by peat radiocarbon dated at 7200 years B.P. and pollen and aquatic mollusc data from Barker Swamp, Rottnest Island (Backhouse 1993). However pollen data for Loch McNess (Newsome & Pickett 1993) indicated Eucalyptus woodland interspersed with wetland sedge communities and showed little change in vegetation from 9000 years B.P. to the present. Kendrick (1977) using radiocarbon dated mollusc data from the Swan River advocates a period of semi-arid climate (saline conditions in the Swan up stream to at least Guildford and little winter flooding) from at least 6700 years B.P. to at least 4500 years B.P. Mid Holocene aridity from at least 7000 to about 3500 years B.P. is also advocated by Semeniuk (1986) on the basis of water table related calcrete in beach and dune sands. Rainfall increase to modern era values may have occurred only in the past 2000-3000 years (Semeniuk (1986). Churchill (1968) suggests a recent dry phase from about 1300-500 years B.P.

Figure 3.7 includes sea level curves. In a regionally homogeneous aquifer on a narrow coastal plain sea level and the water table will be intimately linked (Semeniuk 1986). The sea forms a nearby constant head boundary and changes in sea level will be reflected in nearby groundwater levels . There is a marked variability in Holocene sea level curves for areas close to Perry Lakes. Local curves, (Figure 3.7) have been constructed from coastal geology (fossil platforms and notches) and radiocarbon dating. They include Rottnest Island (Playford 1988), Whitfords (Semeniuk & Searle 1986a), Rockingham (Semeniuk & Searle 1986b) and Peel Inlet (Semeniuk & Semeniuk 1991). These differences are ascribed to local epeirogeny (Playford 1977 & 1983, Searle & Woods 1986, Semeniuk 1986, Semeniuk & Searle 1986b, Lambeck 1987). The data however are similar to regional curves for Holocene sea level change for much of the southern hemisphere and southeast Asia (Bird 1993).

In summary, Perry Lakes are considered to be Holocene features, formed when sea level stabilised and climate approached modern era conditions about 8000 years B.P. During much of their history however a somewhat more arid climate may have prevailed.



Lacustrine Stratigraphy and Holocene Palaeogeography
Figure 3.7
Time
Years BP
Present
1000
2000
3000
4000
5000
6000
7000
8000
Sea Level
Relative to AHD
-10
0 +2
Solid curve: Playford (1988) data for Rottnest Island
Dashed curve: Semeniuk & Searle (1986b) Semeniuk & Semeniuk (1991) data for Rockingham and Peel Inlet
Double dashed curve: Semeniuk & Searle (1986a) data for Whitfords
Flandrian transgression
Geographical Notes
Major climatic shift to more pluvial conditions
Sea Level maxima +2.4m at Rottnest Island, 2.5m to +3m at Rockingham, transgression may be in part epeirogenic (Playford 1977 & 1983, Searle & Woods 1986, Semeniuk 1986a, Semeniuk & Searle 1986b, Lambeck 1987)
Data from Swan River at Guildford (Kendrick 1977) indicates Mid Holocene transgression of +0.5m.
Water table at palaeo Perry Lakes possibly higher than historical levels
Establishment of shallow water table lakes in depressions in response to humid conditions and rising water table
Rottnest Island detached from mainland
Ice age ends ~18000 years BP, sea level ~ -130m, coastline ~20km west of Rottnest Island. Period of rapid sea level rise
SEMI - ARID
Kendrick (1977)
SUB - HUMID to HUMID
SEMI - ARID
HUMID
Semeniuk & Searle (1985a), Semeniuk (1986a)
Backhouse (1993)
HUMID
ARID
HUMID
becoming ARID
HUMID
Churchill (1968)
Perry Lakes Lacustrine Stratigraphy
0
1.0
2.0
3.0
Black soil, organic debris typha rhizomes
Clay, variegated orange-brown-gray with shell debris
Clay, silty, gray, shell debris
Clay, silty, variegated dk ivy green-black-gray shells and shell debris
Nodule layer (see text)
Clay, silty, variegated dk ivy green-black-brown shells and shell debris
Clay pale beige minor shell debris
Clay, light gray-beige
Basal peat
Brown sand
Water
Gray clays in partial suspension "false bottom"
Gray clays
Peat, black, rhizome debris, baumea (?)
Clay, gray
Clay, light gray-beige
Basal peat
Brown sand
Clay, silty, khaki-brown minor shell debris
Clay, silty, light brown minor shell debris vertical carbonaceous streaks and trash
Clay, silty, light beige-brown
Clay, silty mottled orange-brown with mm scale carbonaceous trash and abundant mm scale shells
Peat, black with bands brown silty clay
Clay, silty orange-brown with mm scale carbonaceous blebs
Clay, silty, brown-black
Peat, black with grains of clear well rounded quartz
Sand, m-cg slightly silty
Vertical scale: 1:25
Note: all lacustrine sediments are strongly calcareous and exhibit moderate to strong reaction to 10% HCl
EAST LAKE (North palaeo-basin)
EAST LAKE (South basin beneath water)
WEST LAKE (Main palaeo-basin)

Lacustrine sedimentary records for Swan Coastal Plain wetlands are scarce. Megirian (1982) obtained cores from Bibra and North Lakes (part of the East Beeliar chain of wetlands) and was able to define a coherent stratigraphy comprising 3 sedimentary cycles defining eutrophication and rejuvenation, with the present lakes comprising part of Cycle 3. Maximum sediment thickness recovered was about 3m (exclusive of recent ooze). The base of the deepest portions of each lake basin were not tested. The predominant lithology in each cycle was white-light grey clay, variably diatomaceous. Each cycle terminates in a thin peat layer. Perry Lakes and the East Beeliar wetlands are considered to be of a similar age and have similar thicknesses of preserved sediment.

In Perry East a 2cm thick sheet of ferruginous nodules underlies part of the basin (Figure 3.7). These nodules are 2-3cm in diameter, somewhat irregular in shape and yellow-brown in colour. They comprise principally clay and silt and include mm scale bivalves and gastropod shells. They may represent a period when most of the basin was uniformly vegetated. Nodular 'bog iron' (impure hydrous iron oxides) is a common wetland phenomenon forming through atmospheric oxidation or the oxidising action of algae and iron bacteria (Hackett & Lehr 1985). Nodules or plaques may form around the roots of wetland plants with well developed aerenchyma (such as *Typha*) where oxygen diffusion to the roots is sufficient to oxidise adjacent anoxic sediment containing reduced iron (Taylor *et al* 1984, Crowder & Macfie 1986).

Small wetlands typically exhibit sedimentation patterns reflecting progression from an oligotrophic to eutrophic state. In extremely shallow wetlands within a homogeneous aquifer close to the ocean progression from open water to swamp will occur in response to:

- sedimentation alone
- a lowered water table brought about by climatic change
- a lowered water table brought about by sea level decline or a combination of all these factors

Closed lakes accumulate sediments readily but have no mechanism for sediment removal. Therefore sediment cyclicity in Swan Coastal Plain wetlands is most likely a climatic feature superimposed on a more or less steady rate of sedimentation. If climate (and hence water table level) remain more or less constant, the lakes will tend towards a eutrophic state on the basis of sedimentation alone. Rejuvenation can only occur if the water table rises or sediment is removed. The high water levels of the 1950's were a natural climatic rejuvenation brought about by increased rainfall (augmented artificially through the introduction of storm drains). A second totally artificial sedimentological rejuvenation occurred when the lakes were dredged in 1962. The current rapid transition to eutrophication involves natural climatic changes (reduced rainfall) and artificial climatic changes (reduced groundwater levels through bore extraction). The sediment record suggests that since early Holocene wetland initiation there have been at least two cycles of eutrophication (probably reflecting aridity) followed by rejuvenation. It is important to note however that each rejuvenation requires a more extreme climatic change (higher water table) to overcome the build up of sediment in the basin.

In summary the palaeo-sea level, climate and sedimentary record suggests that:

- maximum water levels may have occurred shortly after wetland initiation in response to sea level and climate
- the lakes have oscillated between predominantly open water and vegetated sumpland in response to sediment accumulation and climate
- the lakes are now approaching a eutrophic state brought about by water table decline in response to natural (rainfall decline) and artificial (groundwater extraction) climatic change

3.4 AQUIFER HYDROLOGY

3.4.1 Grain Size Analysis

Unlike pumping tests which can provide large scale values of aquifer characteristics integrated over large volumes of an aquifer, grain size methods rely on small, disturbed samples to provide point source data. Where no other aquifer information is available however they can provide useful estimates of hydraulic conductivity (Kresic 1997).

Aggregate 1m samples were collected from surface to the upper contact with limestone in piezometers N1-N4. Samples were dried and sieved after the method of Allman & Lawrence (1972). Hydraulic conductivity was calculated using grain size distributions calculated from cumulative frequency curves (Folk 1966). Average values for samples below 2m (the wetted section of the aquifer) are summarised in Table 3.2. Details regarding methodology and results are included as Appendix 3.2.

Table 3.2 Hydraulic conductivity Upper Sand (m day^{-1}) surface to 7m

Method	d_{10}	d_{50}	σ_I	Sk_I	K_G	-1-	-2-	-3-	-4-	-5-	-6-	-7-
N1c	0.084	0.212	1.13	+0.26	1.40	6.2	4.0	6.0	7.2	3.7	11.1	4.8
N2c	0.101	0.207	0.80	+0.03	0.93	8.9	5.7	7.0	10.7	5.4	10.7	8.3
N3c	0.086	0.231	1.22	+0.37	1.65	6.6	4.2	6.1	7.6	4.0	12.8	6.5
N4c	0.132	0.331	0.71	+0.44	1.05	15.3	9.8	13.7	17.8	9.2	23.1	14.9

Key

1: Hazen (1893)
2: Harleman *et al* (1963)
3: Masch & Denny (1966)
4: Breyer cited Kresic (1997)
5: Uma *et al* (1989)
6: Shepherd (1989)
7: Alyamani & Sen (1993)

d_{10}: grain size(mm) at 10 cumulative percent (effective grain size)
d_{50}: grain size(mm) at 50 cumulative percent (median grain size)
σ_I: Inclusive graphic standard deviation (Folk & Ward 1957)
Sk_I: Inclusive graphic skewness (Folk 1968)
K_G: Graphic kurtosis (Folk 1968)

The upper sand unit in N4 is sedimentologically and hydrologically different to sands encountered in the other 3 piezometers. It has a larger effective and median grain size and is better sorted (smaller σ_I). Material on the east side of both lakes (N1 and N3) are poorly sorted while those on the west side (N2 and N4) are better sorted, N2 being moderately sorted and N4 moderately well sorted using the classification of Folk (1968). Skewness is a measure of curve asymmetry. The sands tend to be positively skewed indicating tails of fine material. Kurtosis measures the ratio between sorting in the tails and central portion of the grain size distribution. Material from N2 and N4 have average kurtosis values which approach unity, the value for a normal Gaussian distribution whereas N1 and N4 are >1 indicating better sorting or 'peakedness' in the central portion of the distribution curve. The differences are clearly evident in the histograms (Appendix 3.2). Sorting, skewness and kurtosis as measures of how closely the grain size distribution approaches the normal Gaussian probability curve provide geological clues regarding a sediment's genealogy (Folk & Ward 1957). For example dune sands tend to be positively skewed and beaches negatively skewed (Friedman 1961). The characteristics of the upper sand are consistent with its derivation from an aeolianite.

The grain size analyses (Table 3.2) suggest that the hydraulic conductivity in the upper sand unit around N4 is about double that measured else where around Perry Lakes. Grain size methods which take into account the overall grain size distribution are more likely to provide useful estimates of hydraulic conductivity for heterogeneous poorly sorted sediments (Appendix 3.2). The data (Table 3.3).suggest (but due to limited sample distribution do not prove) there is a significant difference in the hydraulic conductivity of the upper sand west of East Lake.

Table 3.3 Hydraulic conductivity range (m day^{-1}), Upper Sand

Piezometer	N1	N2	N3	N4
Hydraulic conductivity range	6-11	7-11	6-13	14-23

3.4.2 Pump Test Analysis

Pump tests are considered the most accurate measure of aquifer parameters because they provide *in situ* measurements averaged over a large aquifer volume (Freeze & Cherry 1979). In unconfined aquifers, analysis of pumping test data, particularly at early times is complicated by the delayed drainage of unsaturated material above the receding water table and vertical flow components (Webb & Watson 1979). Measurement of hydraulic conductivity is also highly scale dependent. Experiments by Rovey & Cherkauer (1995) using effective test radii of <1 to >10 000m show that hydraulic conductivity increases approximately linearly with test radius to a range between 20 and about 200m after which it is constant with scale. Small scale field methods such as slug tests will typically under estimate regional hydraulic conductivity by up to an order of magnitude (Bredehoeft *et al* 1983) while laboratory tests such as permeameters may yield values a further order of magnitude smaller (Ptak & Teutsch 1994, Millham & Howes 1995).

Results from Pump Tests on the Swan Coastal Plain

Pump tests provide the best estimates of horizontal hydraulic conductivity (K_h) within the superficial aquifer in the Perth metropolitan area. These are summarised in Table 3.4. In all cases the superficial aquifer is strongly anisotropic. Data from these tests fit solutions for semi-unconfined to semi-confined aquifers as defined by Kruseman & de Ridder (1990). Pump tests generally provide an averaged estimate of hydraulic conductivity over the entire aquifer section. Martin & Baddock (1989), using pump tests on the Jandakot Mound, estimated K_h in five units with distinctly different hydraulic properties (Table 3.4). Further resolution on the basis of grain size and the degree of sorting, suggested at least 12 layers with estimated K_h in the range 0.1-150m d^{-1}. This sort of variability is probably typical of the superficial aquifer. Anisotropy results from differing grain size, sorting, orientation, packing of framework grains, cementation and sedimentary bedding (Pettijohn *et al* 1972). In situ samples of sands from the superficial aquifer typically exhibit 10-15 visually recognisable layers per vertical metre (M. Martin, Water Corporation, pers com). In the Gnangara sands, individual bedding is recognisable down to the mm scale (S. Appleyard, Water and Rivers Commission pers com). Estimates of vertical hydraulic conductivity calculated using the solution of Walton (1962) are included in Table 3.4. They suggest that within the Superficial aquifer K_z:K_h is in the range 0.002 to 0.0004. Aquifer characteristics appear to be strongly influenced by the hydrogeology of the Tamala Limestone:

- limestone comprising unconsolidated to weakly cemented carbonate and quartz sand will display aquifer characteristics similar to other sand units within the superficial formations but with generally greater hydraulic conductivity.
- where initial porosity has been destroyed or reduced through duricrusting or vadose zone processes, the limestone may act as an aquitard, inhibiting vertical groundwater movement. Where such limestone comprises a significant portion of the aquifer section overall transmissivity of the aquifer will decrease.
- limestone containing karst features may exhibit cavernous flow conditions and extremely high transmissivities. At Kwinana (25km south of Perry Lakes) transmissivities of up to 20,000m^2 d^{-1} have been reported (Layton Groundwater Consultants 1979). These high transmissivities are believed to reflect zones of karst development and cavernous flow conditions.

On a regional scale, transmissivity within the superficial aquifer is estimated to rise sharply from 600 to 1000m^2 d^{-1} in a narrow band along the coast commencing with the appearance of outcropping Tamala Limestone (Davidson 1995). Perry Lakes are situated on this transitional zone. The range of regional transmissivities equate to expected hydraulic conductivities of approximately 16-27m d^{-1} at wetted thickness of 37m. A

Pumping Test Summaries Perth Metropolitan Area — Table 3.4

Area (Reference)	Aquifer Geology: Formation	Depth (m)		Lithology	Aquifer Characteristics	T ($m^2 d^{-1}$)	K_h ($m d^{-1}$)	K_z ($m d^{-1}$)	S
					Semi-unconfined				
Lake Jandabup	Bassendean Sand	0.0	27.0	sand, fine-coarse	Lower portion of aquifer initially responds as	328-541	18-27		
(Wharton 1981a)		27.0	27.5	clay, carbonaceous	a confined aquifer, as gravity drainage occurs				
	Gnangara Sand	27.5	54.0	sand, fine-medium, minor gravel	response follows type curves for unconfined	av: 410	av: 23		
		54.0	58.5	limestone, calcareous sand	aquifer with delayed yield (Boulton 1963) or				
	Poison Hill			-unconformity-	leaky artesian aquifer (Hantush & Jacob, 1955)				
Lake Gnangara	Bassendean Sand			15 bores, Bassendean sand to max	Unconfined with delayed yield	271-1100	5.3-22		
(Balleau 1971)				51.8m, with persistent layers of	Analysed using methods of Theis (1935)				
				clay and limestone	Cooper & Jacob (1946), Boulton (1963)	av: 544	av: 11.6		
	Poison Hill			-unconformity-					
Thompson Lake	Bassendean Sand	0.0	31.5	sand, fine-coarse	Unconfined to semi-unconfined	270-312			
(Wharton 1981b)	Guildford Clay	31.5	34.5	clay, dark grey					
	Gnangara Sand	34.5	43.5	sand, medium-coarse	groundwater is unconfined in the upper sands	av: 300	av: 19		$2.6x10^{-4}$
		43.5	45.0	sand, fossiliferous, very coarse	but is semi-unconfined beneith the clay at				
	Ascot Fm	45.0	48.0	limestone, with gravel	31.5m. The lower sands display drawdown				
		48.0	51.0	sand, fossiliferous, fine-v. coarse	response for leaky artesian aquifers				
	Osborne Fm			-unconformity-	(Hantush & Jacob, 1955)				
Thompson Lake	Bassendean Sand	0.0	5.0	sand, fine-coarse	Semi-unconfined to semi-confined				
(Deeney 1985a)	Gnangara Sand	5.0	41.0	sand, fine-coarse clay/silt at base					
				sand and gravel, poorly sorted &	lower sands fit solution of Walton (1962) for	170-214	8-15	$1.0x10^{-3}$	$4.0x10^{-4}$
	Ascot Fm	41.0	67.0	highly fossiliferous, minor clay	semi-confined aquifers, K_z is for mid level silt			to	
				and limestone	which forms an aquitard			$2.0x10^{-3}$	
	Osborne Fm			-unconformity-	Estimated K_z for entire aquifer $1.3x10^{-2}$ to $6.0x10^{-3}$				
Forrestdale Lake	Bassendean Sand	0.0	5.0	sand, fine to coarse	Semi-unconfined overall				
(Deeney 1985b)	Gnangara Sand	5.0	33.0	sand, fine to coarse, clay base	Aquifer comprises 4 distinct units, 1-4 from top			$1.1x10^{-2}$	
	Ascot Fm	33.0	42.0	sand and gravel with limestone,	units 1 & 3 are aquitards			to	
				highly fossiliferous	Unit 4 forms a semi-confined aquifer and fits	172-200	16-20	$8.5x10^{-3}$	
	Osborne Fm			-unconformity-	solution of Walton (1962)				
Jandakot	Bassendean Sand	0.0	5.0	sand, fine to coarse	Highly anisotropic, unconfined	Unit 1	20	Bassendean Fm	
(Martin & Baddock 1989)	Gnangara Sand	5.0	23.0	sand, fine to very coarse	Aquifer comprises 5 units with distinctly	2	5	Coffee Rock	
	Ascot Fm	23.0	44.0	fine sand to gravel, thin limestone	different hydraulic conductivities, analysed	3	10	Gnangara Fm	
				highly fossiliferous	using the method of Neuman (1975)	4	50	Gnangara Fm	
	Osborne Fm			-unconformity-		5	8	Ascot Fm	

summary of the geological and hydrogeological character of the Tamala Limestone is included as Appendix 3.4.

Tracer Tests on the Swan Coastal Plain

Bromide tracer tests in sands from two locations 12-15km northeast of Perry Lakes indicated groundwater velocities varying from 40-100 m yr^{-1} to 100-150m yr^{-1} (Salama *et al* 1989, Thierrin *et al* 1993). Within the Tamala Limestone velocities of 85-335m yr^{-1} have been reported (Barber *et al* 1990 cited Davidson 1995).

Description of the Pump Test

A 50 hour pump test was carried out using irrigation bore No.1. This utilises a submersible pump, with a rated *irrigation* capacity of about 900m^3 d^{-1}. Output from the bore was routed via the 6 inch (150mm ID) irrigation ring main into East Lake through the south (100mm ID) flow meter (Figure 5.1a). Figure 3.8 shows well locations and measured drawdown. The pumping rate rose slowly from 1.842m^3 min^{-1} (2652m^3 d^{-1}) at the start of the test to 2.011m^3 min^{-1} (2896m^3 d^{-1}) at the end. These figures are about three times the rated irrigation capacity and reflect the fact that output was restricted only by the flow meter. The low initial rate probably reflects filling within the extensive irrigation ring main system. Dataflow capacitive water level loggers operating at 1 minute intervals were installed in observation wells W22, W23 and W24. These are spaced about 1, 2 and 4 aquifer thicknesses from the pumped well as recommended by Lohman (1972) and Hazel (1975), details in Table 3.5 and Figure 3.8a. W22, W23 and W24 are water table monitoring wells, screened over 1m approximately 2m below the water table (Figure 3.8b). The pumped well is believed by the Town of Cambridge to be screened over 18m representing about 48% of aquifer thickness.

Table 3.5 Observation well locations

Observation Well	W24	W23	W22	N5c
Distance to pumped well (m)	38.2	81.7	153.5	205.0
Distance as aquifer thicknesses	1.0	2.2	4.1	5.5

The test was carried out May 27-29 1997, one week after all lawn irrigation and lake maintenance pumping had ceased (Figure 3.8c). Total test time was limited by the Town of Cambridge (on the basis of electricity costs) to 2 days. Total pumping time was 2916 minutes (2.025 days). Loggers were operated for a further 2.5 days to record recovery. During the recording period, 14mm of rain was recorded at Perry East. Combined with water from the pumped well, this produced a 150mm rise in lake level. The rain event is evident in the drawdown curve for W22, but was not recorded in W23 or W24.

Aquifer Geology of the Test Site

Aquifer geology in the test area is summarised in Figure 3.8b, based on sieve analysis of the upper sand from N4 and the driller's log for irrigation bore No.1. In N4, distinctive dark green (possibly glauconitic) silty sands were intersected from 12-15m and 0.5m calcareous clay from 18.5-19.0m. N4c was drilled to bit refusal at 24m after passing through alternating bands of hard and soft limestone. Little is known of the lower sand unit. Driller's logs for irrigation bores around Perry Lakes generally describe it as coarse grained sand with occasional shells and limestone. It almost certainly represents sandy units within the Tamala Limestone but may also include Bassendean Sand (Figure 1.2). In summary the aquifer would be expected to be highly anisotropic. The limestone in particular varies from weakly cemented calcareous silica sand to strongly indurated grainstone and calcrete which is impenetrable using a light rotary auger drill rig. These units may form local aquitards.

Results

Approaches using non-steady and steady state solutions produced widely differing results. This test satisfied few of the basic assumptions underlying pumping test solutions. Neither the pumped well nor any of the observation wells were fully penetrating and no observation well was screened at the same depth, or within the same lithology as the screen within the pumped well. Pump test analysis of unconfined aquifers, even under ideal well configurations is complicated, particularly at early times, by delayed drainage and vertical flow components. Type curves for partially penetrating pumping and observation wells in unconfined aquifers developed by Moench (1993) suggest that for the range of K_h and K_z typically reported for the superficial aquifer, early time drawdowns will be much greater than the Theis type curve. Therefore we would expect that transient solutions will produce unrealistically high estimates of transmissivity. It is important to remember that pump test solutions are non-unique. Pump test data may match a theoretical curve, but that alone is meaningless unless the aquifer fits the assumptions used to generate the curve (Freeze & Cherry 1979).

Up to approximately t = 720 minutes (12 hours) curves exhibit very rapid initial drawdowns and the sigmoid pattern typical of delayed yield. Late stage curves however approach Theis type curves for unconfined aquifers exhibiting no delayed yield (Boulton 1963). Therefore reliable estimates of transmissivity might be expected only from the late time steady state results since they represent a much larger volume of the aquifer, sampled over a much longer period of time, and where the early time complexities induced by partial penetration are minimised.

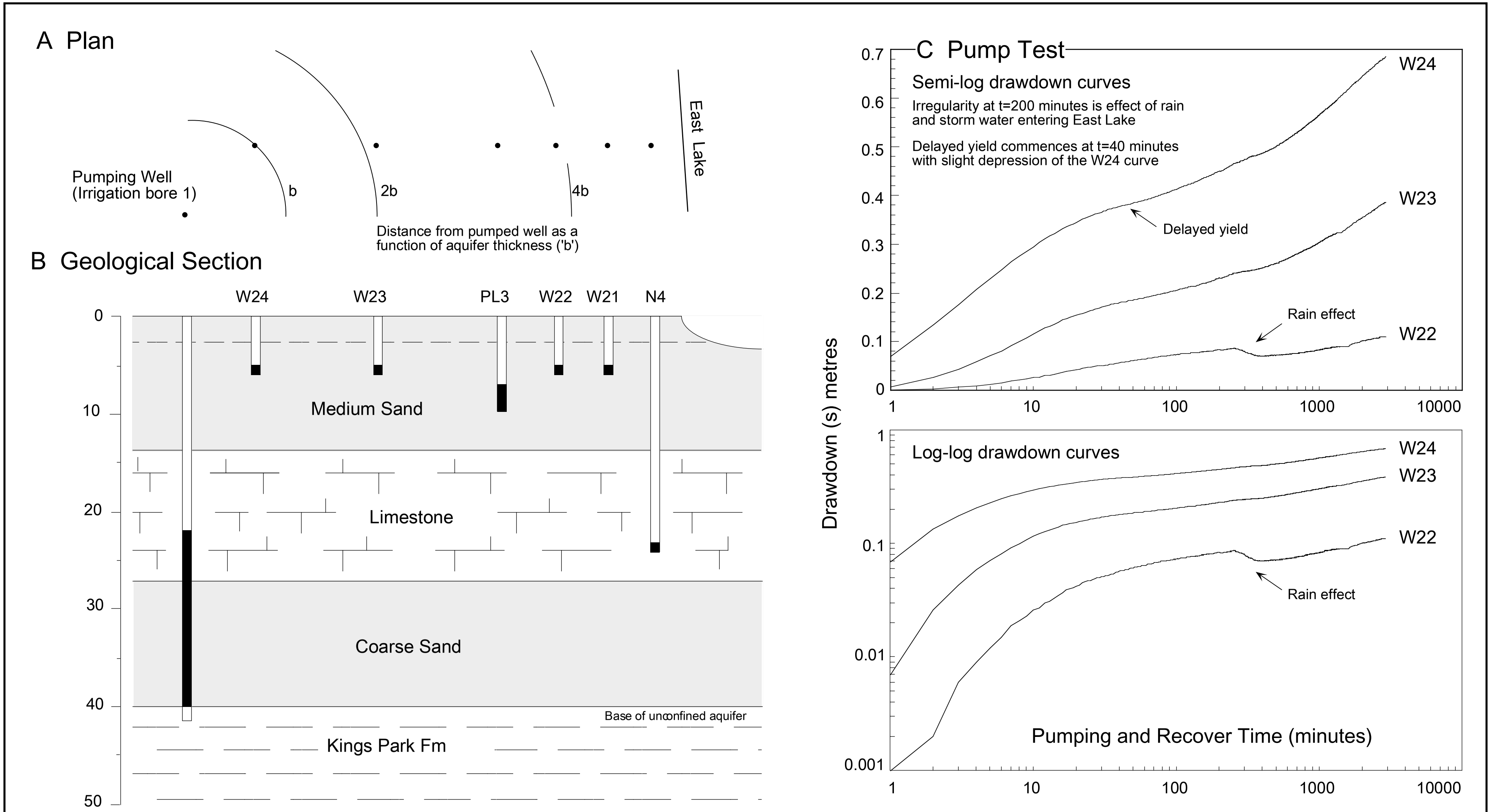

A Plan
Pumping Well
(Irrigation bore 1)
b
2b
4b
East Lake
Distance from pumped well as a function of aquifer thickness ('b')
B Geological Section
W24
W23
PL3
W22
W21
N4
0
10
20
30
40
50
Medium Sand
Limestone
Coarse Sand
Base of unconfined aquifer
Kings Park Fm
Screened intervals shown as solid shading
Vertical scale 1:600, Horizontal scale 1:2500
C Pump Test
Semi-log drawdown curves
Irregularity at t=200 minutes is effect of rain and storm water entering East Lake
Delayed yield commences at t=40 minutes with slight depression of the W24 curve
Delayed yield
Rain effect
Log-log drawdown curves
Drawdown (s) metres
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
0.1
0.01
0.001
1
10
100
1000
10000
Pumping and Recover Time (minutes)

Figure 3.8

Transient Methods

Experiments using partially penetrating observation bores at Jandakot showed that anisotropy results in calculated transmissivities which increase with increasing distance from the pumped well (Martin & Baddock 1989). At Perry Lakes (Table 3.6) similar results were obtained using both the Boulton and Cooper-Jacob methods (where pumping and observation bores are assumed to be fully penetrating) and the Moench method (for partially penetrating wells). The apparent transmissivities however are unreasonably high when compared to other superficial aquifer pump test data (Table 3.4).

Table 3.6 Pump test results using transient methods

Method	Technique	Transmissivity $m^2\ d^{-1}$			Hydraulic Conductivity $m\ d^{-1}$		
		W24	W23	W22	W24	W23	W22
Boulton	Manual curve match	2176	2857	7620	58	77	205
Cooper-Jacob	Manual curve match	1975	2628	7100	53	71	192
Moench	Computer	2995	4377		81	118	
Recovery[1]		2628			71		

Note: aquifer thickness *b* taken as 37m
1: method of Theis (1935)

The Moench type curve method (Moench 1993, Hall 1996) generates type curves for partially penetrating pumping and observation wells including observation piezometers. Field data is curve matched to the type curves, generated using computer software (Hall & Chen 1994).

Steady State Methods

Hantush (1956 & 1964) presented a solution for leaky aquifers utilising the final drop of the piezometric surface s_f (the equilibrium drawdown) in a number of observation wells located at different distances r from the pumped well. The pumped well is located within the lower sand unit which may be thought of as a leaky confined aquifer receiving water from the overlying limestone and sand units. Using data from W22-W24, s_f was calculated at the end of the pumping test t = 2916 minutes (2.025 days) and with t extrapolated to 10 000 minutes (6.95 days). The Hantush method also allows the limits of the radius of influence to be estimated ($s_f = 0$). Results are tabulated as Table 3.7.

Table 3.7 Pump test results using the steady state method of Hantush

Time (d)	$s_f = 0$ (m)	Transmissivity $m^2\ d^{-1}$			Hydraulic Conductivity $m\ d^{-1}$		
		W24	W23	W22	W24	W23	W22
2.025	262	1256	1364	1492	33.9	36.8	40.3
6.950	280	1096	1124	1365	29.6	30.4	36.8

Aquifer thickness b taken as 37m

Similar results were obtained using the Thiem and Thiem-Dupuit equations for steady state flow in an unconfined aquifer (Hazel 1975, Bouwer 1978). These methods utilise ratios of drawdown and distance to the pumped well in adjacent observation bores. Results are tabulated as Table 3.8.

Table 3.8 Thiem and Thiem-Dupuit steady state pump test results

Method	Time (d)	Transmissivity $m^2 d^{-1}$		Hydraulic Conductivity $m d^{-1}$	
		W23/24	W22/23	W23/24	W22/23
Thiem	2.025	1121	1303	30.3	35.2
	6.950	1053	1010	28.5	27.3
Thiem-Dupuit	2.025	1119	1302	30.2	35.2
	6.950	1051	1009	28.4	27.3

Aquifer thickness *b* taken as 37m

Summary Comments

Estimates of transmissivity decrease with increasing time and increase with increasing *r*. This suggests that true steady state was not achieved and that the effects of aquifer anisotropy are still present. Mean horizontal hydraulic conductivity of the aquifer at Perry Lakes is estimated to be somewhat less than the estimates determined from the pump test and probably lies in the range 20-30m d^{-1}.

3.4.3 Specific Capacity Tests

Specific capacity data from irrigation bores No. 2 and 8 was used to provide estimates of transmissivity and hydraulic conductivity (Table 3.9) using the method of Razack & Huntley (1991) where

$$T = 15.3 \left(\frac{Q}{h_0 - h} \right)^{0.67} \qquad (3.1)$$

Table 3.9 Transmissivity estimates from specific capacity

Bore	Q $m^3 d^{-1}$	Drawdown (m)	T $m^2 d^{-1}$	K $m d^{-1}$
Irrigation No 2	2094	12.20	480	13.0
Irrigation No 8	1309	1.72	1300	35.1
	1702	2.44	1230	33.2
	2291	3.66	1144	30.9

Aquifer thickness *b* taken as 37m

Well logs (Appendix 3.1) suggest a similar aquifer geology in both wells. The excessive drawdown in No 2 bore suggests that the well was not sufficiently developed when the test was conducted at the time the bore was constructed. These estimates are for the Lower Sand unit and are similar to the steady state pump tests for irrigation bore No 1.

3.5 LAKE LINING HYDROLOGY

3.5.1 Physical Character of the Recent Sediments

The lake lining consists of three sediment types:

- Sand (the exposed top of the Pleistocene Upper Sand unit)
- Clays (lacustrine sediments of Holocene age)
- Recent sediments comprising a false bottom over the older clays and sand

Transition from false bottom sediments to clay appears to be completely gradational. The false bottom consists of a suspended soupy mass of carbonate rich mud, colloidal sludge and organic material. A worker standing bare foot in this material typically sinks about 0.6m. When exposed at low lake stages, these bottom sediments shrink producing mud cracks. In recent years all of West Lake and much of East Lake have been dry for extended periods each summer. Where the false bottom sediments have dried and shrunk over an entire summer, the false bottom does not re-establish during winter inundation. West Lake first dried up completely over the summer of 1994-95. The bottom then remained firm over the following winters.

Bulk density is defined as the oven dried mass of a sample W_d divided by its field volume V_t. Bulk density may also be expressed as

$$(1 - n)\rho \qquad (3.2)$$

where n is the porosity and ρ is the density of the solid phase, taken to be 2.65g cm^{-3} for most clays (Deer, Howie & Zussman 1967). Clays typically have porosities of 40-70% (Freeze & Cherry 1979) which equates to a bulk density range of 1.59-0.79.

Bulk density measurements were made on an uncompressed core of this material from East Lake collected at 1120N 960E (Table 3.10 & Figure 3.6a). The core was collected by vibrating a 0.9m length of 90mm ID PVC pipe into the lake bed. The base of this sample tube was fitted with a 10m length of sash cord. Water depth was only about 5cm which allowed the height of sediment in the sampler to be compared with the undisturbed lake bed, thereby ensuring no compression of the sample. When fully inserted, the top was capped, and the base rotated to the surface by pulling on the sash cord from a distance of about 5-6m. This sheared the contained sample flush with the bottom of the sampler, with no loss of sample. After capping, the sample was frozen and cut into 10cm lengths then oven dried at 105° to constant weight.

Table 3.10 Bulk density measurements, false bottom sediments

Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-83.5
Bulk density	0.199	0.238	0.249	0.255	0.264	0.304	0.241	0.217
Geology	mud	mud	mud	mud	mud	mud	mud & peat	mud & peat

The bulk density increases by about 50% from the sediment water interface to 60cm depth where it is still 50% or less than that of typical clays. Analysis of similar material in Figure 3.9 by Carbon *et al* (1988) confirms that organic material comprises up to 52% (dry weight) of these sediments.

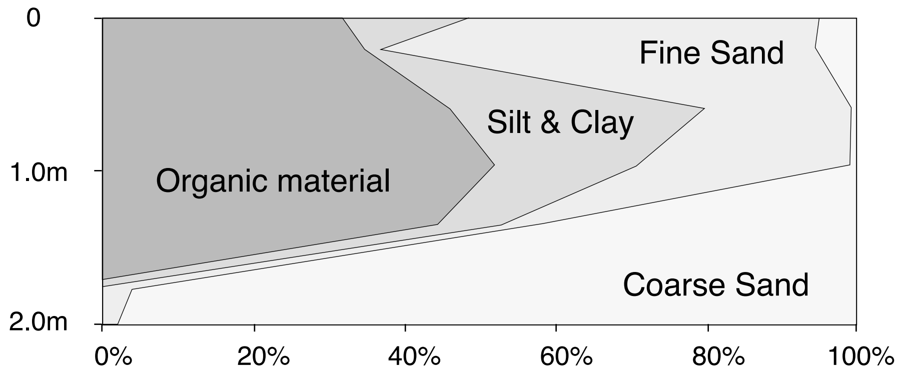


Figure 3.9 Sediment composition in lake lining core, East Lake. Initial dry weight determined by drying at 105°C, organic material determined by weight loss after further drying at 600°C. Sand fractions determined by sieve analysis, silt and clay by difference. Adapted from published and unpublished data of Carbon *et al* (1988).

Where the lake is permanently inundated, the water-sediment interface is therefore a transitional zone. Where the lake is seasonally inundated, the false bottom sediments shrink and compact forming a well defined sediment-water interface.

3.5.2 Hydraulic Conductivity of Lake Lining

Permeameter Tests

Vertical *in situ* cores of lake bed sand and clay were collected from East Lake. These were run as permeameters and estimates of vertical hydraulic conductivity (K_z) determined.

Sand Core: L: 460mm D: 100mm Location : 1150N 920E
Mean of 6 falling head tests: 9.5m day^{-1} (run times 1 to 10 hours)

Clay Core: L: 780mm D: 100mm Location: 1300N 1017E
Mean of 43 fixed head tests: 1.08cm day^{-1} (run times 12 to 72 hours)

The clay core was run in an unheated building during winter. Data were corrected for absolute water viscosity by logging day and night time water temperature. Methodology, geology of the cores and detailed results are summarised in Appendix 3.5.

3.5.3 Specific Yield of Lake Lining

Specific yield was determined on the saturated sand and clay cores using the methods modified from Johnson *et al* (1963) and Prill *et al* (1965). Principal modification was the use of undisturbed cores collected *in situ* as opposed to cores comprising repacked sediment. True specific yields can only be estimated using temperature controlled columns and test runs of hundreds of days, however Piper (1939) cited Prill *et al* (1965) found that increasing the time to hundreds of days increased specific yield by only 1 to 3 percent. The data presented here is therefore considered to represent reasonable estimates of specific yield.

Columns were allowed to drain until flow ceased. Specific yield at t = 24 hr was calculated for use in evapotranspiration estimates using water table fluctuations (Chapter 11).

Sand core: S_y 0.136 S_y at t = 24 hr: 0.134

Clay core: S_y 0.0243, S_y at t = 24 hr: 0.0069

Details are included as Appendix 3.6.

3.6 DEPTH-AREA-VOLUME RELATIONSHIPS

Stage-area-volume curves define the relationship between lake stage (easily measured) and lake area and lake volume (difficult to measure directly). Area and volume are essential to water balance studies. In very small, shallow wetlands where area and volume vary by several hundreds of percent over a season, accuracy in these relationships is crucial.

3.6.1 Methods

Methodology was similar for both lakes. Local metric grids with central baseline were established (Appendix 3.7 a&b) using wooden survey pegs on 10x20m centres. Surveyed points were typically 10m apart, decreasing to 5m or 1m where additional detail was required Grid orientations were:

East Lake:	baseline (1000E) bearing 350° true (surveyed January 1998)
West Lake:	baseline (1000E) bearing 040° true (surveyed February 1995)

Standard optical levelling techniques (Bannister & Raymond 1984) were employed with each station levelled to ±1mm. All levels are in metres AHD, tied to the following bench marks:

WEMBLEY 7 (Corner Oceanic Drive & Ulster Road)	12.790m
MWB 1413 (Perry East flood remediation pump station)	5.518m
Australian Survey Office Plan A0-495 control point 27 (West Lake)	6.127m

Water and Rivers Commission staff gauges were checked against these bench marks. The East Lake gauge is considered accurate to ±1mm. The West Lake gauge was checked twice. A 12mm discrepancy was recorded with control point 27 in February 1995 and a 16mm discrepancy in January 1998, (gauge reads low). This suggests that the West Lake gauge is slowly sinking. Recorded water levels in West Lake have been corrected by adding 14mm.

West Lake was completely dry when surveyed apart from a 20x50m pool around the staff gauge. East Lake was dry apart from the south basin which contained a pool of water measuring approximately 100x100m. The submerged portion of the lake bed was surveyed by measuring water depth to the water-sediment interface. This interface (which appears optically to be clearly defined), is in reality a gradational or 'false bottom' (see Section 3.5). Depth measurements were converted to AHD by subtracting from the lake stage height. Readings accurate to 1 mm were possible as the maximum water depth was only 26cm (lake stage 2.938m). Stations at the periphery of the submerged area were also surveyed optically a few days later. Elevations for these duplicate stations were typically 20mm lower, reflecting compaction of the sediment upon draining and partial drying. Elevations at these tie points, obtained using both survey methods, were averaged.

3.6.2 Historical Note

The basic morphology of the lake basins appears similar to that inferred from aerial photographs prior to the 1962 dredging (Chapter 2). East Lake generally sloped from shallow in the northeast (N. E. Shelf in Figure 3.10a) to deep in the southwest. This general form remains. A distinct trough immediately adjacent to the eastern bank was created during bank reclamation. The deepest water still occurs in the South Basin, just as it did prior to dredging (Plate 2.1). A central, southeast trending curvilinear ridge colonised by *Baumea* remains today just as it did in the 1940's and 1950's. This combined with the fossil tree stump and old fence data (Chapter 2) suggest that the dredging probably removed false bottom 'muck' but very little of the denser clay lining. Somerford (pers com) believes that very little dredging was actually carried out in the northeast section of the basin and suggested that the present basin contours (apart from the bank reclamation) closely mimic the original lake basin.

In West Lake the effects of bank reclamation are also evident around most of the lake perimeter. The overall morphology however mimics that evident in 1942 (Plate 2.1). The S.W. Basin remains the deepest natural portion of the lake with deeper artificial sections close to the island. The shallow east - west trending bar immediately to the south is a remnant of the original south basin margin, the present bank having been dug out south of it. The gentle sloping shelf forming the eastern margin of the lake basin is largely natural and is evident in Plates 2.1 and 2.2.

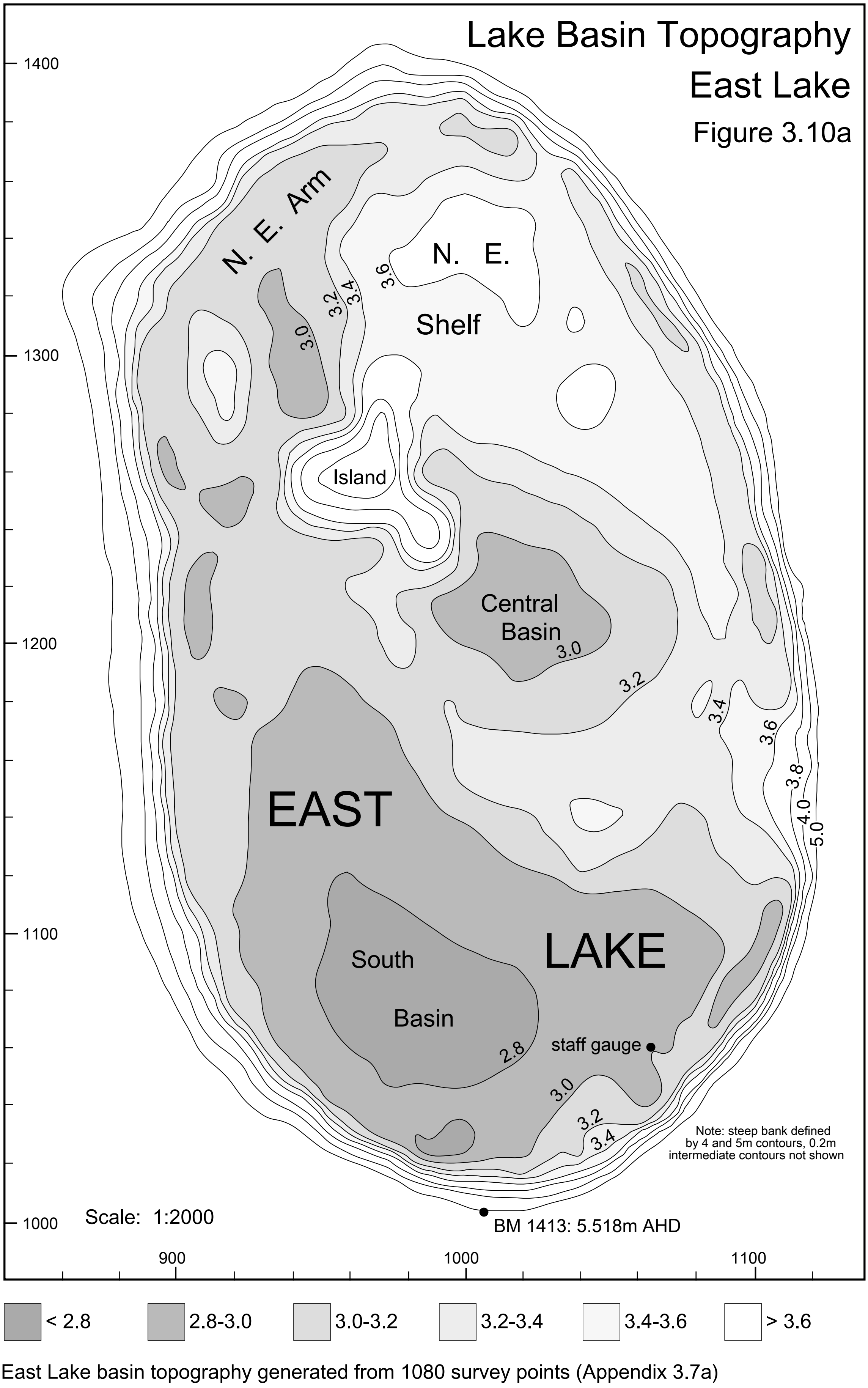
3.6.3 Generation of Contour Maps and Depth-Area-Volume Curves

Lake basin contours, and stage-area -volume relationships were computer generated for both lakes using SURFER. The underlying grid was generated by kriging using 2x2m nodes. Stage-area-volume data was generated directly from this grid. Smoothing routines have been applied to produce the presentation contour maps Figures 3.10 a&b. Stage-area-volume tables were computed for both lakes at 1mm stage intervals and are presented in graphical form as Figures 3.11 & 3.12 and as tables in Appendices 3.8 a&b. Volume calculations were checked manually using the formula of Welch (1948)

$$Volume = \frac{h}{3}(a_1 + a_2 + \sqrt{a_1 a_2}) \qquad (3.3)$$

where a_1, a_2 are top and bottom area of frustra, and h its height. Manual calculations were within 1% of the computer generated values.

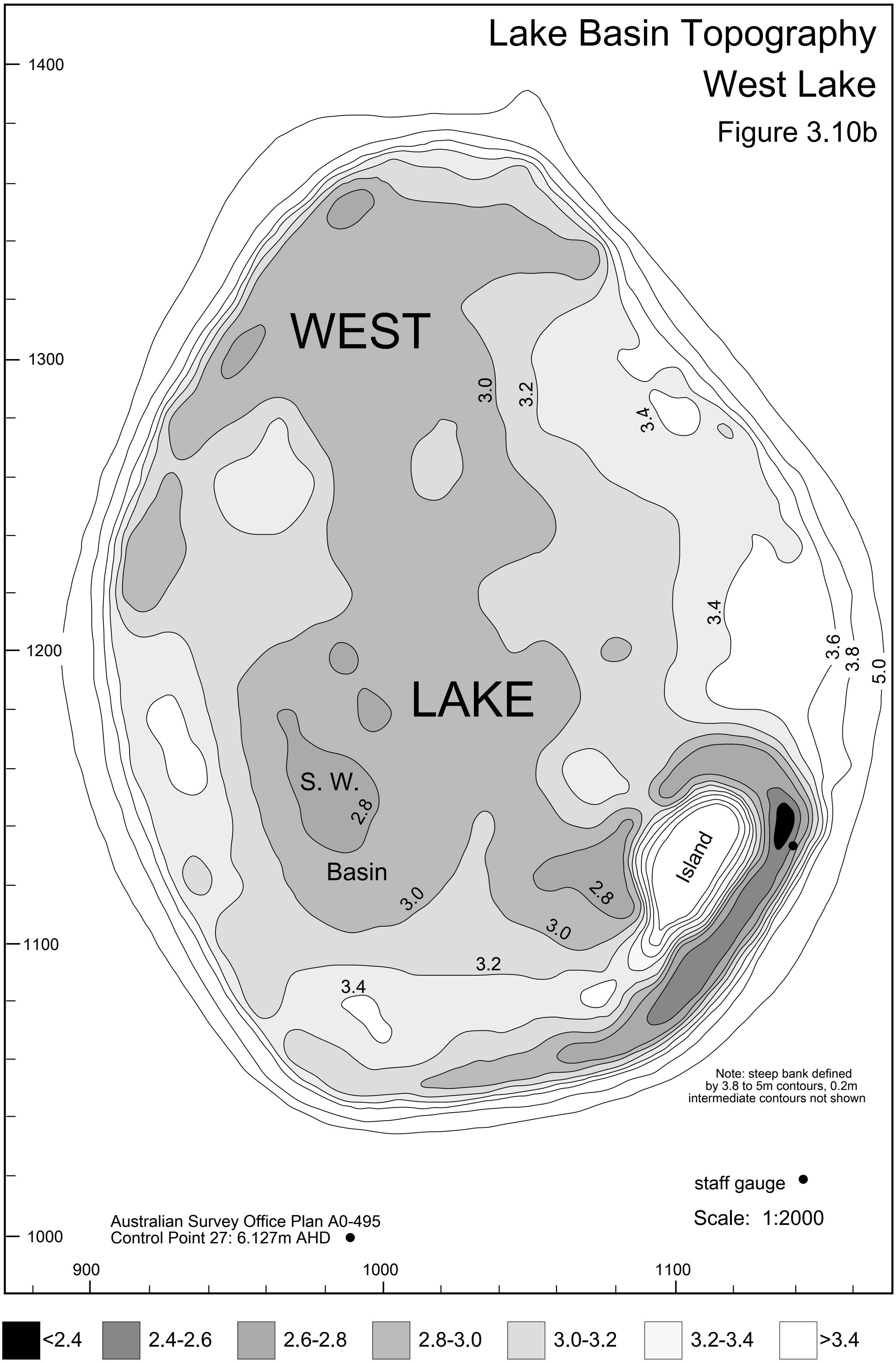
In water balance studies, stage is the quantity measured, area is required for quantifying rainfall, evaporation and heat (solar radiation) and volume is the mass of water or 'storage' in the lake. The stage-area (hypsographic) curves both have a distinct change of slope at the point where the irregular basin floor becomes completely flooded and the lake is contained by the steep basin walls. The curves are representative of concave lake basins using the classification of Hakanson (1981). During the course of this study, neither basin floor was ever completely flooded. The basin floors take the form of very shallow irregular saucers where small changes in lake stage produce large changes in lake area.



East Lake basin topography generated from 1080 survey points (Appendix 3.7a)

Outer basin margin defined by 5m contour

Contour interval: 0.2m.

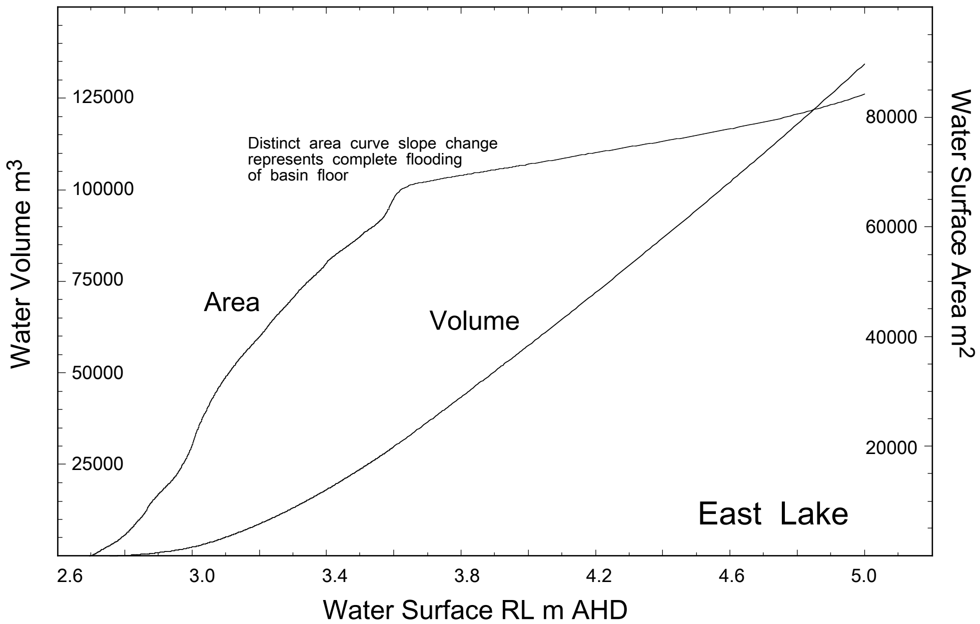


West Lake basin topography generated from 1086 survey points (Appendix 3.7b)

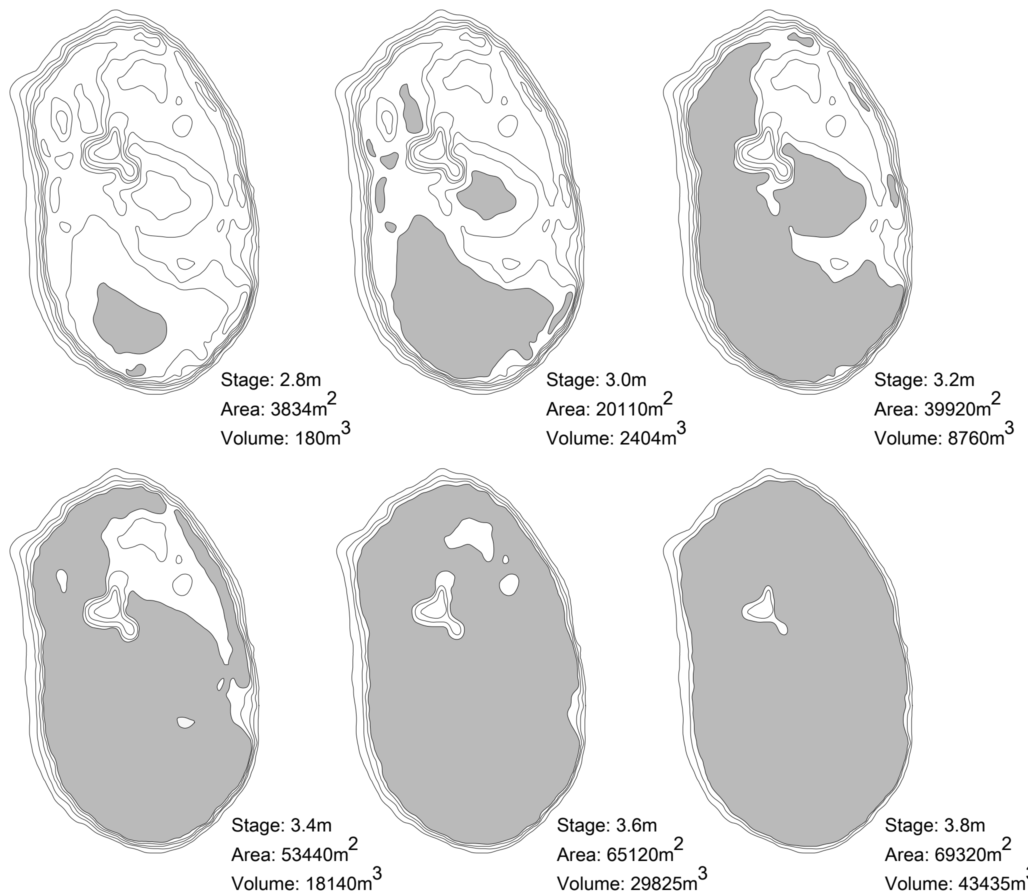
Outer basin margin defined by 5m contour

Contour interval: 0.2m.

Volume - Area Curves



Incremental Stage Flood Maps



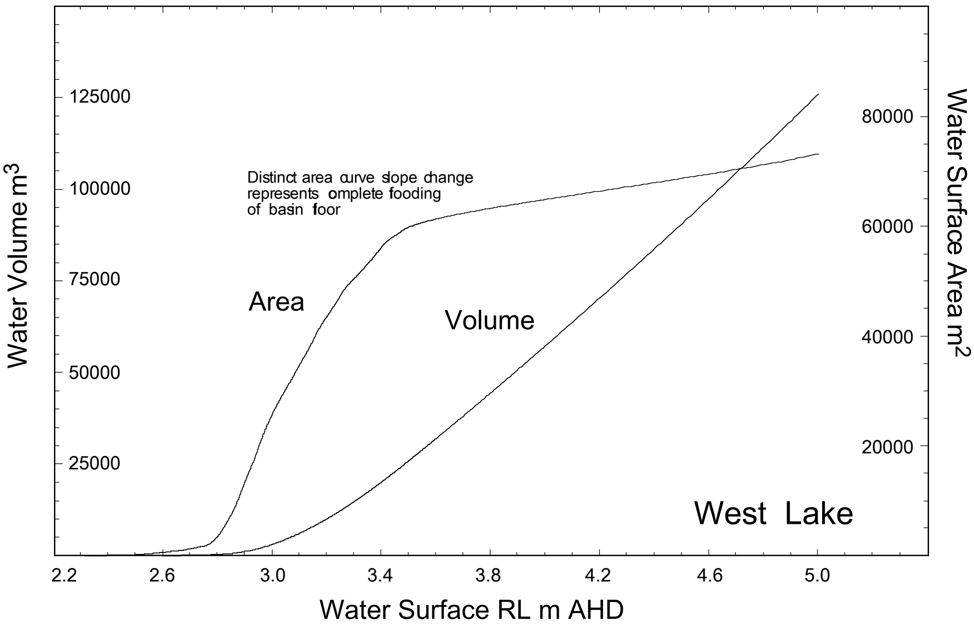
Notes

Lake stage-area and stage-volume curves for water surface stage 2.6 - 5.0m AHD
Flooding outside lake basin occurs above approximately 5m
Data plotted at 1mm stage resolution.
Thumbnail maps show water surface at stages between 2.8 - 3.8m AHD

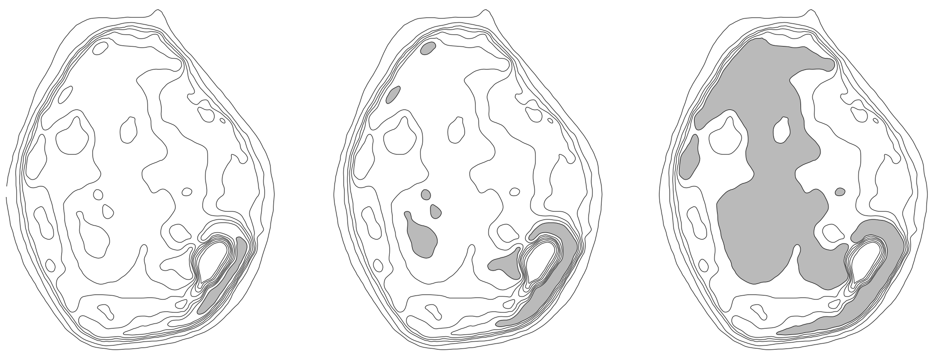
Area - Volume
East Lake

Figure 3.11

Volume - Area Curves



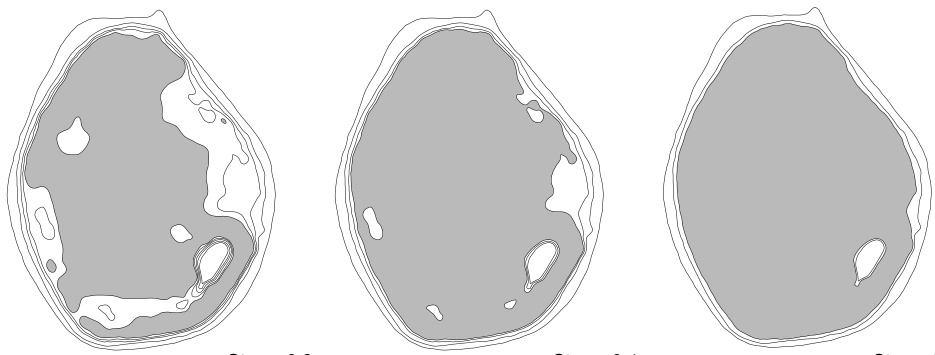
Incremental Stage Flood Maps



Stage: 2.6m
Area: 600m^2
Volume: 56m^3

Stage: 2.8m
Area: 3628m^2
Volume: 348m^3

Stage: 3.0m
Area: 25940m^2
Volume: 3145m^3



Stage: 3.2m
Area: 43660m^2
Volume: 10135m^3

Stage: 3.4m
Area: 56280m^2
Volume: 20200m^3

Stage: 3.6m
Area: 61295m^2
Volume: 32095m^3

Notes

Lake stage-area and stage-volume curves for water surface stage 2.2 - 5.0m AHD
Flooding outside lake basin occurs above approximately 5m
Data plotted at 1mm stage resolution.
Thumbnail maps show water surface at stages between 2.6 - 3.8m AHD

Area - Volume
West Lake

Figure 3.12