CHAPTER
7

LAKE-AQUIFER INTERACTION

7.0 INTRODUCTION

The historical development of lake-aquifer interaction concepts are reviewed. Field techniques used to identify flow regimes at Perry Lakes are presented and results discussed. Concepts of lake-aquifer coupling are presented. Historic and current field data is used to address possible lake 'detachment' from the aquifer over summer and explore the long term effects of water extraction near wetlands. Practical issues surrounding summer maintenance of wetlands is discussed with particular reference to Perry Lakes.

7.1 FLOW REGIMES AROUND SHALLOW LAKES

7.1.1 History

Hubbert (1940) showed the theoretical relationship between upland recharge of an isotropic homogeneous unconfined aquifer and valley discharge into streams. Tóth (1962), by developing an analytical solution to the Laplace equation, was able to mathematically define equipotentials and recharge-discharge areas for the case of an unconfined aquifer forming a ground water basin with impermeable base and sloping water table. Extending this solution to include an undulating water table Tóth (1963) demonstrated how near surface 'local' flow systems and larger, deeper intermediate and regional flow systems might coexist within the same low-order sedimentary basin[1] . The unconfined aquifer on the Swan Coastal Plain qualifies as such a 'basin'. The local flow systems include local groundwater mounds below hills which discharge into lakes or streams in the valleys. Significantly Tóth showed how some flow from these local mounds becomes part of the larger and deeper more regional flow systems, bypassing the adjacent discharge area and ultimately discharging much further down gradient. Much of the field identification of groundwater flow systems which validate Tóth's ideas was done in the post glacial 'hummocky moraine' terrain of North America. It is important to remember that glacial drift is clay rich with hydraulic conductivity typically

[1] Later attempts to apply this model to regional sedimentary basins (Tóth 1995 & 1996) have been criticised (Mazor 1996) because of divergence from real world conditions in regional basins, particularly abundance of shale and clay, which effectively partition these systems into separate aquifers.

many orders of magnitude less than the sands encountered on the Swan Coastal Plain (Freeze & Cherry 1979, p151). In such terrains water tables frequently display high relief. Local mounds can persist close to lakes for extended periods. On the Swan Coastal Plain relatively much greater average hydraulic conductivity results in a topographically subdued water table. Hills form recharge areas and the loci of local mounds in the glacial terrain examples whereas on the Swan Coastal Plain upland areas are more likely to be reduced (or nil) recharge areas (McFarlane 1984). Perry Lakes demonstrates that mounds (in this case artificially induced) are very transient under local hydraulic conditions, persisting for days rather than months.

Flow-through lakes represent the mid point in a continuum from recharge lakes such as hydraulically mounded ombrotrophic lakes (Moore & Bellamy 1974) to groundwater discharge lakes and playas (Jacobson & Jankowski 1989). The origins of the term 'flow-through' to describe lakes with a distinct groundwater flux is unknown. The term was used as early as 1973 in regard to the Perth Coastal Plain (Balleau 1973) and later to describe some lakes in Wisconsin (Novitzki & Devaul 1978, cited Rinaldo-Lee & Anderson 1980) and as part of a primary classification scheme by Born *et al* 1979 who identified three basic configurations (Figure 7.1a) for groundwater flow around lakes:

Discharge lakes:	receive groundwater over the entire lake bed
Recharge lakes:	release lake water to the aquifer over the entire lake bed
Flow-through lakes:	receive and release water over different parts of the lake bed

Meyboom (1967) identified what he termed local and intermediate flow systems around Saskatchewan 'kettle holes' (Figure 7.1b) which received groundwater from local and regional systems. In spring local groundwater mounds flow into adjacent discharge lakes. As summer progresses, the local mounds decay and complex interlake flow is established, involving discharge and flow-through lakes. Locally, daily and seasonal seepage reversals were defined around some lakes due to local water table depression by phreatophytes. Using combined mass/phosphorous budgets Brown (1986) was able to show that the net direction of groundwater flow changed seasonally in small Minnesota lakes. Using lumped parameter modelling Crowe (1993) showed that recharge to groundwater in Wabamun Lake, Alberta was typically an order of magnitude greater than discharge to the lake, varying annually and seasonally depending on climatic variables with recharge to groundwater typically comprising 36% of water loss from the lake.

A significant feature of Tóth's flow systems is the presence of stagnation points where the sum of the magnitude and direction of the flow field vectors cancel to zero. Here groundwater paths diverge. In Meyboom (1967) for example, a stagnation point occurs (but is not shown) below the temporary spring snow melt mound and the deeper flow system (Figure 7.1b). Similarly a stagnation point is implicit below the flow-through lake of Born *et al* (1979) in Figure 7.1a. Nield *et al* (1994) note that such stagnation points are critical to understanding the flow regime. Using numerical modelling Winter (1976 & 1978) demonstrated that where an encircling water table is everywhere higher than the lake, then groundwater will discharge to the lake from all sides. Where there is also a deeper flow system which bypasses the lake, a stagnation point will exist within the aquifer below the lake. If the stagnation point occurs at the base of the lake and the piezometric head at the stagnation point exceeds lake stage, discharge will occur over the entire lake bed. Using two-dimensional transient simulations of observed seasonal changes in flow, Anderson and Munter (1981 & 1984) were able to simulate the development and migration of a stagnation point during the transition from flow-through to discharge conditions (Figure 7.1c). At their field site a temporary groundwater mound developed as a result of snow melt and spring rain on the down gradient side of a flow-through lake.

Winter's work showed that the presence of a local mound down gradient does not preclude some recharge from the lake. If the height (or other factors such as hydraulic conductivity) weakens the effect then discharge from the mound to the lake can occur as a local flow cell. Cherkauer & Zager (1989) provide a field example showing how such a system can vary seasonally (Figure 7.1d). As the local groundwater mound forms and enlarges, a reverse flow zone is established. Cherkauer & Zager show the boundary between mound discharge and lake recharge as a dashed 'hinge zone'. In fact it also defines a stagnation zone which migrates along the base of the lake. Using in lake piezometers Cherkauer & Zager were able to plot the expansion of the reverse flow zone into the lake.

7.1.2 Recent Research on the Swan Coastal Plain

Over the past decade numerical models have been developed which address specifically the hydrology of shallow lakes on the Swan Coastal Plain. In their natural state these were generally flow-through lakes with no surface flows. Groundwater therefore was the dominant water balance component. Many, like Perry Lakes, are now hydrologically modified, principally through winter storm water inputs.

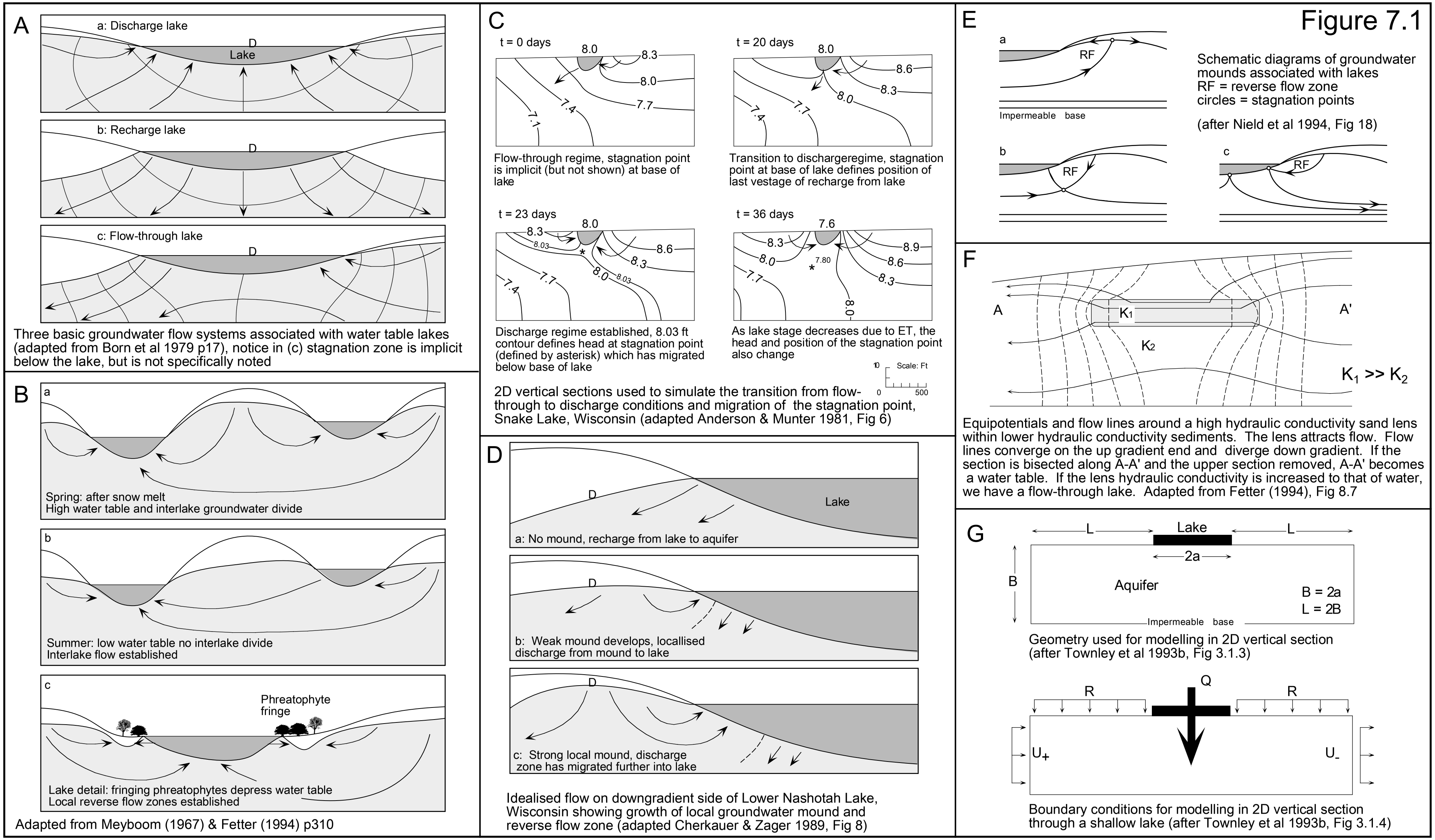


Figure 7.1
A
a: Discharge lake
D
Lake
b: Recharge lake
D
c: Flow-through lake
D
Three basic groundwater flow systems associated with water table lakes (adapted from Born et al 1979 p17), notice in (c) stagnation zone is implicit below the lake, but is not specifically noted
B
a
Spring: after snow melt
High water table and interlake groundwater divide
b
Summer: low water table no interlake divide
Interlake flow established
c
Phreatophyte fringe
Lake detail: fringing phreatophytes depress water table
Local reverse flow zones established
Adapted from Meyboom (1967) & Fetter (1994) p310
C
t = 0 days
8.0
8.3
8.0
7.7
7.4
7.1
Flow-through regime, stagnation point is implicit (but not shown) at base of lake
t = 20 days
8.0
8.6
8.3
8.0
7.7
7.4
Transition to dischargeregime, stagnation point at base of lake defines position of last vestage of recharge from lake
t = 23 days
8.0
8.3
8.03
8.6
8.3
8.0
8.03
7.7
7.4
Discharge regime established, 8.03 ft contour defines head at stagnation point (defined by asterisk) which has migrated below base of lake
t = 36 days
7.6
8.3
8.0
7.80
8.9
8.6
8.3
8.0
7.7
As lake stage decreases due to ET, the head and position of the stagnation point also change
Scale: Ft
10
0
500
2D vertical sections used to simulate the transition from flow-through to discharge conditions and migration of the stagnation point, Snake Lake, Wisconsin (adapted Anderson & Munter 1981, Fig 6)
D
D
Lake
a: No mound, recharge from lake to aquifer
D
b: Weak mound develops, locallised discharge from mound to lake
D
c: Strong local mound, discharge zone has migrated further into lake
Idealised flow on downgradient side of Lower Nashotah Lake, Wisconsin showing growth of local groundwater mound and reverse flow zone (adapted Cherkauer & Zager 1989, Fig 8)
E
a
RF
Impermeable base
b
RF
c
RF
Schematic diagrams of groundwater mounds associated with lakes
RF = reverse flow zone
circles = stagnation points
(after Nield et al 1994, Fig 18)
F
A
A'
K1
K2
K1 >> K2
Equipotentials and flow lines around a high hydraulic conductivity sand lens within lower hydraulic conductivity sediments. The lens attracts flow. Flow lines converge on the up gradient end and diverge down gradient. If the section is bisected along A-A' and the upper section removed, A-A' becomes a water table. If the lens hydraulic conductivity is increased to that of water, we have a flow-through lake. Adapted from Fetter (1994), Fig 8.7
G
L
Lake
L
2a
B
Aquifer
B = 2a
L = 2B
Impermeable base
Geometry used for modelling in 2D vertical section (after Townley et al 1993b, Fig 3.1.3)
R
Q
R
U+
U-
Boundary conditions for modelling in 2D vertical section through a shallow lake (after Townley et al 1993b, Fig 3.1.4)

The Geological Survey of Western Australia carried out early field studies of lacustrine hydrology at Jandabup Lake (Allen 1979), Marijiniup Lake (Hall 1985) and Bibra Lake (Davidson 1983). Allen (1979), using salinity differences demonstrated a groundwater flux and identifiable release zone through such lakes. McFarlane (1984) identified similar plumes down gradient of Mason Gardens and Shenton Park Lake, prompting further investigations by Oo (1985) and Townley & Davidson (1988). Advances in the identification and modelling of flow patterns including the chemical and isotopic identification of lake release zones are reported in Townley *et al* (1991). Nield (1990) addressed the question of lake bed seepage distributions. This work is expanded in Townley *et al* (1993a) and Nield *et al* (1994) who also provide a general framework for examining surface water-groundwater interaction. Townley *et al* (1993a) presents the results of a three year study on the interaction between lakes, wetlands and unconfined aquifers with particular emphasis on numerical modelling. It includes field validation from a number of wetlands in the Perth area and a concise review of pertinent international and Western Australian literature. Townley *et al* (1993b) is a readable summary of this work, aspects of which are further expanded in Townley & Trefry (2000) and Townley & Smith (2002).

7.1.3 Models of Surface Water-Groundwater Interaction

Simple models of recharge and discharge lakes such as Born *et al* (1979) (Figure 7.1a) are readily understood. Intuitively it is easy to see why water seeps from a recharge lake. Flow-through lakes on the other hand are not intuitively obvious. They interrupt the normal horizontal groundwater flow and, by inducing zones of upward and downward flow, divert significant quantities of groundwater through the lakes themselves. Townley *et al* (1993b) use the analogy of an electrical short circuit where it is easier for water at the base of an aquifer to rise a few metres into a lake, travel possibly many hundreds of metres in the water body and then descend back to the bottom of the aquifer rather than travel the entire distance through the more resistive pore spaces of the aquifer sediments. The lake represents a low resistance 'conductor' in parallel with high resistance sediments. Where lakes intersect an unconfined aquifer there is effectively no horizontal gradient because the lake surface is horizontal and the piezometric head at the lake bed is everywhere equal to lake stage. Therefore groundwater beneath the lake tends to stagnate while groundwater approaching on the up gradient side tends to rise over this stagnant zone, discharging into the lake close to the lake shore (Townley *et al* 1995). Another way to visualise the flow-through mechanism is to consider a sand lens of high hydraulic conductivity within lower conductivity clays (Figure 7.1f). Flow converges on the lens. If the section above A-A' is removed, the pattern is identical to the flow-through lake of Born *et al* (1979).

Figure 7.10 illustrates schematically the principal components of a flow-through lake. The 'capture zone' is that area within which any surface recharge will eventually flow through to the lake while the 'release zone' contains water which has passed through the lake. High evaporation relative to precipitation and groundwater flux means that release zone water will be enriched both in salts and stable isotopes. Nield *et al* (1994) characterised the fundamental differences between types of water bodies using simple geometric ratios. Their work extends that of Townley & Davidson (1988) who found that the ratio of horizontal hydraulic gradients up and downstream of a lake defines the position of the stagnation point separating regions of recharge and discharge through the lake boundary and determines capture zone width and depth. This approach provided a foundation for the systematic study of the shape of capture and release zones as a function of the physical properties of the lake and aquifer plus nearby aquifer flows and net groundwater recharge. Nield *et al* (1994) present a non dimensional hierarchy of models for the three basic lake-aquifer flow regimes (recharge, discharge and flow-through). These also permit quantitative predictions to be made of capture and release zone geometry.

Figure 7.1g shows the co-ordinate system used to describe their model. The lake (defined by the solid bar) has a 'length' (parallel to groundwater flow) of $2a$, aquifer thickness B and distance from the model boundary to lake edge L. Fluxes through the boundaries of the modelled domain are U_+, U_- (uniform horizontal groundwater flux), R (uniform recharge flux) and Q (flux per unit width from lake to aquifer).

Eight independent parameters a B D K_x K_z U_+ U_- and R control flow within the model domain. The first five are physical characteristics of the lake and aquifer while the remainder are components of the water balance. Flow geometry is expressed using seven non dimensional ratios (Table 7.1).

Table 7.1 Ratios defining flow geometry

Ratio	Dimensionless Flow Parameter
$2a / B$	lake length
D / B	lake lining resistance
L / B	distance to boundary
K_x / K_z	anisotropy ratio
U_+ / K_x	slope of the phreatic surface
U_- / U_+	horizontal flux ratio
RL / U_+B	recharge (net recharge/net horizontal flux)

Anisotropy

The aquifer is assumed to be anisotropic with respect to horizontal and vertical hydraulic conductivity K_x and K_z. An equivalent isotropic system is obtained by stretching the vertical coordinate z with a new coordinate z' defined as:

$$z' = \left(\frac{K_x}{K_z}\right)^{0.5} z \qquad \text{(Nield } et\ al \text{ 1994 eqn 5b)} \qquad (7.1)$$

The lake lining is similarly defined as an equivalent sediment depth D, this being the equivalent thickness of aquifer material with the same resistance to vertical flow. Therefore a lake with a continuous low conductivity lining behaves like a lake with no lining but much smaller length (expressed as $2a/B$).

Winter (1983) initially demonstrated and Nield *et al* (1994) further illustrate how small changes in anisotropy have very large effects on domain geometry (Table 7.2).

Table 7.2 Relationship between anisotropic and equivalent isotropic domains

Model Parameter	Anisotropic Domain K_x/Kz = 100	Equivalent Isotropic Domain $x' = x/10$*	Equivalent Isotropic Domain $z' = 10z$*
a	250m	25m	250m
B	50m	50m	500m
D	5m	5m	50m
L	1000m†	100m	1000m
K_x	100m d^{-1}	10m d^{-1}	10m d^{-1}
K_z	1m d^{-1}	10m d^{-1}	10m d^{-1}
U_+	0.01m d^{-1}	0.01m d^{-1}	0.001m d^{-1}
U_-	0.01m d^{-1}	0.01 d^{-1}	0.001m d^{-1}
R	0.0001m d^{-1}	0.001 d^{-1}	0.0001m d^{-1}
$2a/B$	10	1	1
D/B	0.1	0.1	0.1
L/B	20†	2	2
K_x/K_z	100	1	1
U_-/U_+	1	1	1
RL/U_+B	0.2	0.2	0.2

Data from Nield *et al* (1994), Table 1
* scaling factor $[(K_x / K_z)^{0.5}] = 10$ is calculated using the physical values in the anisotropic domain
† L in the anisotropic domain chosen such that L/B in equivalent isotropic domain is 2

Table 7.2 illustrates the extreme effect anisotropy plays in the effective dimensions of a lake-aquifer system. A lake of physical size a = 250m behaves like a lake of only a = 25m at K_x / K_z of 100. Modelling requires such simplifications, as anisotropy renders the real world infinitely more complex. Freeze & Witherspoon (1967) for example suggest that where the hydraulic conductivity of adjacent aquifer beds differs by 10:1 or greater, the bed having the lower conductivity may be considered impermeable relative to the other.

Flow regime designations

In total Nield *et al* (1994) define 39 flow regimes in three basic categories: flow-through (FT), discharge (D) and recharge (R). These are further subdivided into partially penetrating (where water interacting with the lake flows within the aquifer), and fully penetrating (where interacting water extends to the base of the aquifer). Those theoretically most pertinent to Perry Lakes are partially penetrating. These are summarised in Figures 7.2 a-c and have been annotated to aid understanding. Water which interacts with the lake is shaded and each model (originally presented by Nield *et al* (1994) only in 2D vertical section) is also shown in plan. The shaded and non shaded areas in section are defined by dividing streamlines which separate regions of water with different source or destination. By convention Nield *et al* (1994) use a left to right groundwater flux. Figures 7.2 are mirror images (designated with an asterisk), which allow the reader to visualise lakes as they would exist on the Swan Coastal Plain, viewed looking north as per cartographic convention. Each 2D section includes information which provides clues about the relative magnitudes of the principal water balance components lake flux Q and precipitation (or irrigation) recharge R.

Where $Q<0$: groundwater discharged to the lake exceeds groundwater recharged to the aquifer. Flow-through or discharge regimes occur characterised by high evaporative or surface flow losses.

Where $Q>0$: groundwater discharged to the lake is less than groundwater recharged to the aquifer. Flow-through or recharge regimes occur characterised by high precipitation or surface flow inputs (such as storm drains).

Where $R<0$: there is little or no precipitation (summer conditions), FT regime designations are even numbers.

where $R>0$: recharge is occurring, (winter precipitation or summer irrigation), FT regime designations are odd numbers.

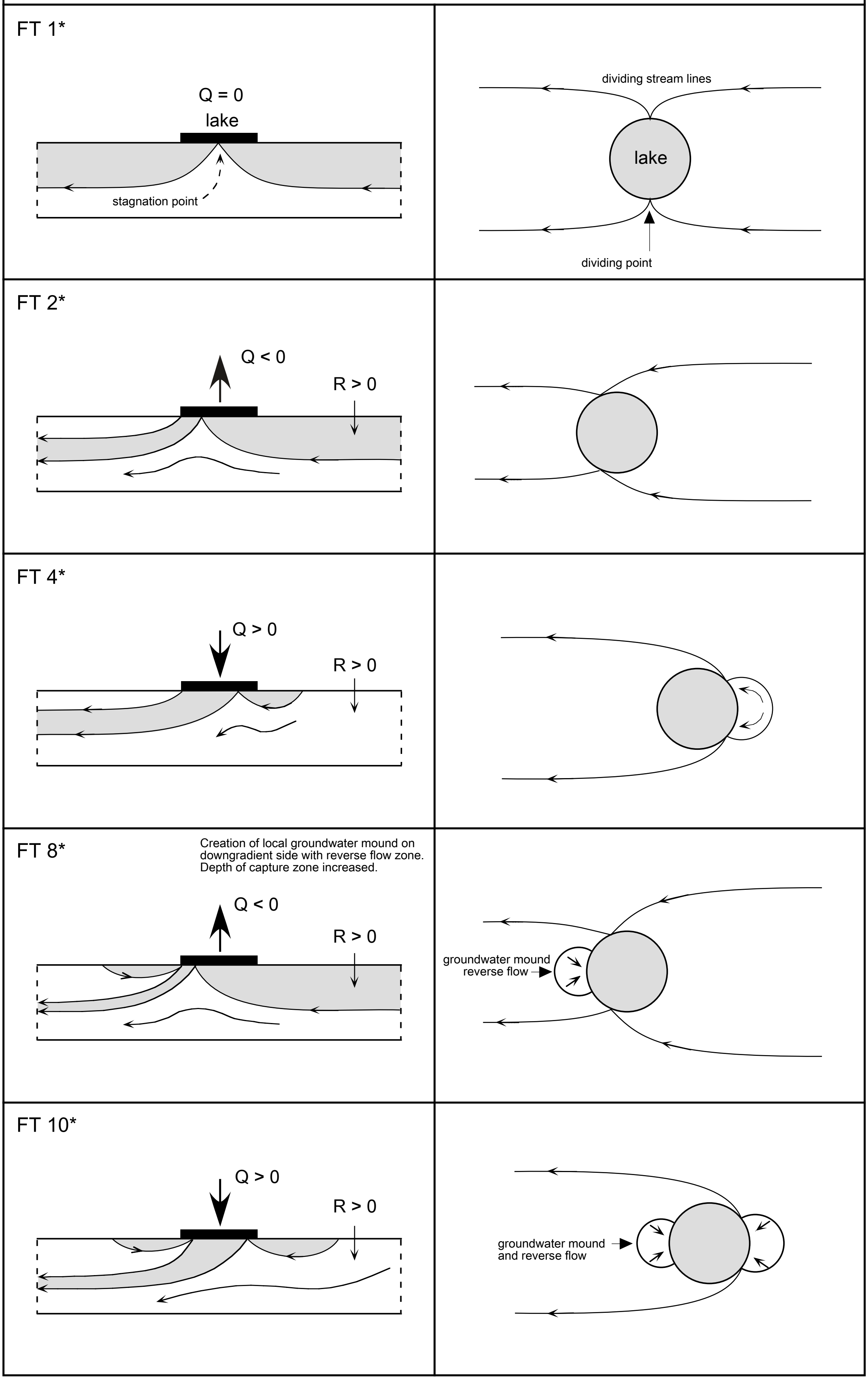
Reverse flow and stagnation Zones

Many of the flow-through regimes contain one or two reverse flow zones. Reverse flow zones identify the presence of a local groundwater mound (Nield *et al* 1994). Implicitly, these must also include stagnation points at the base of the lake (Cherkauer & Zager 1989). Figure 7.1e demonstrates three local groundwater mound configurations (all partially penetrating) and their associated reverse flow zones and stagnation points. Figure 7.1e panel a includes discharge regimes D1 and D2, where some groundwater

Flow-Through Regimes
Characterised by Increasing Recharge

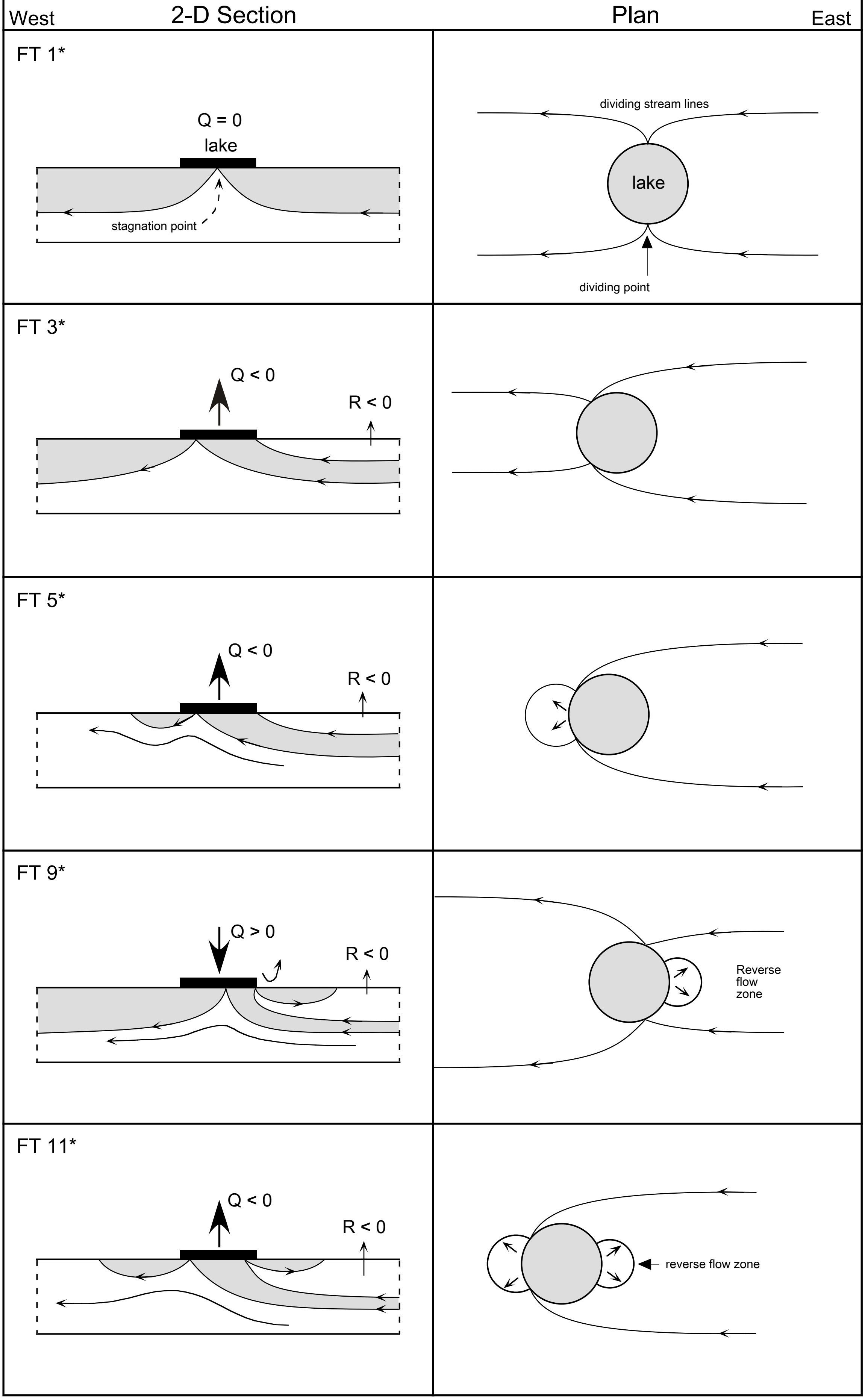
Figure 7.2a

West 2-D Section Plan East

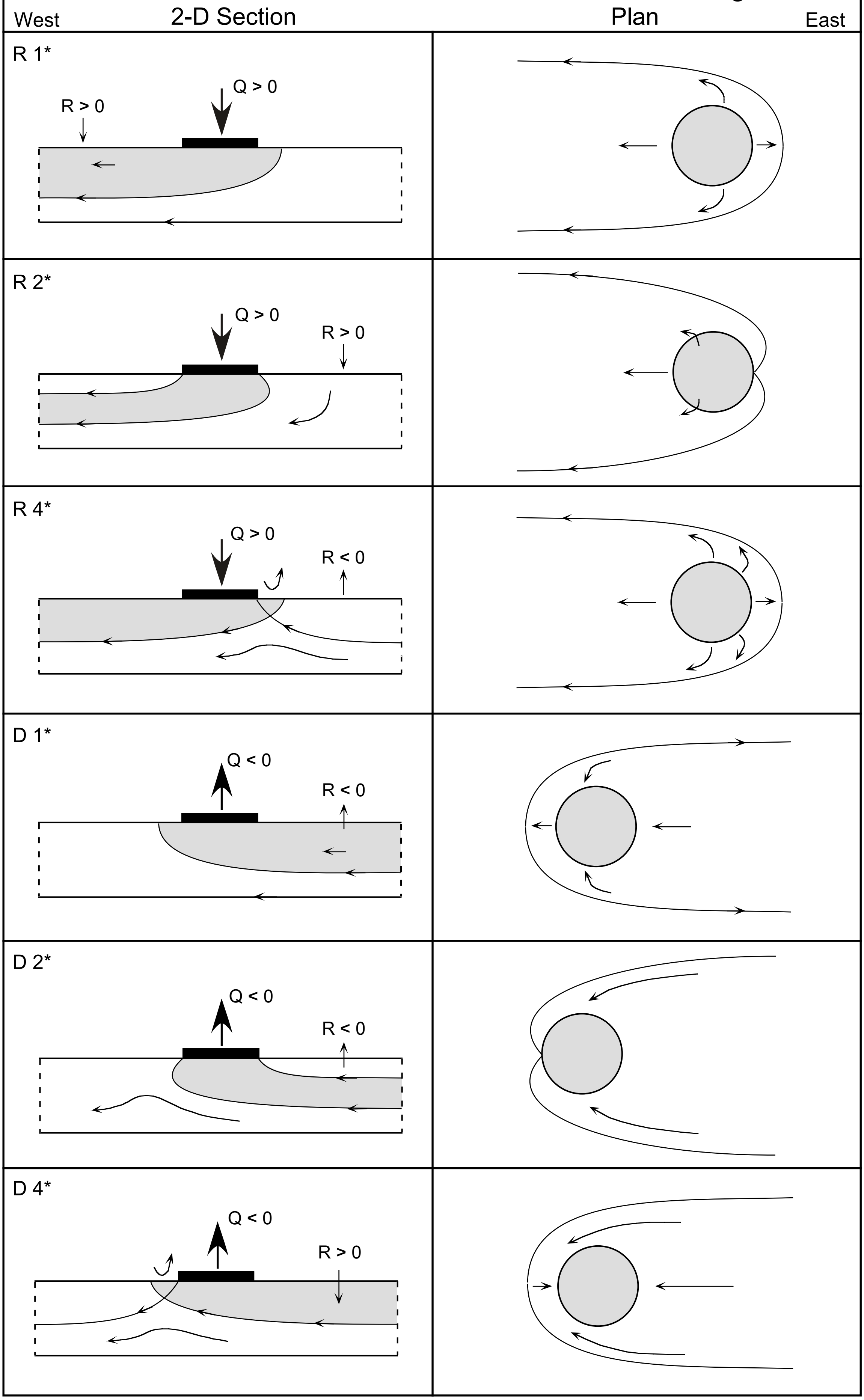


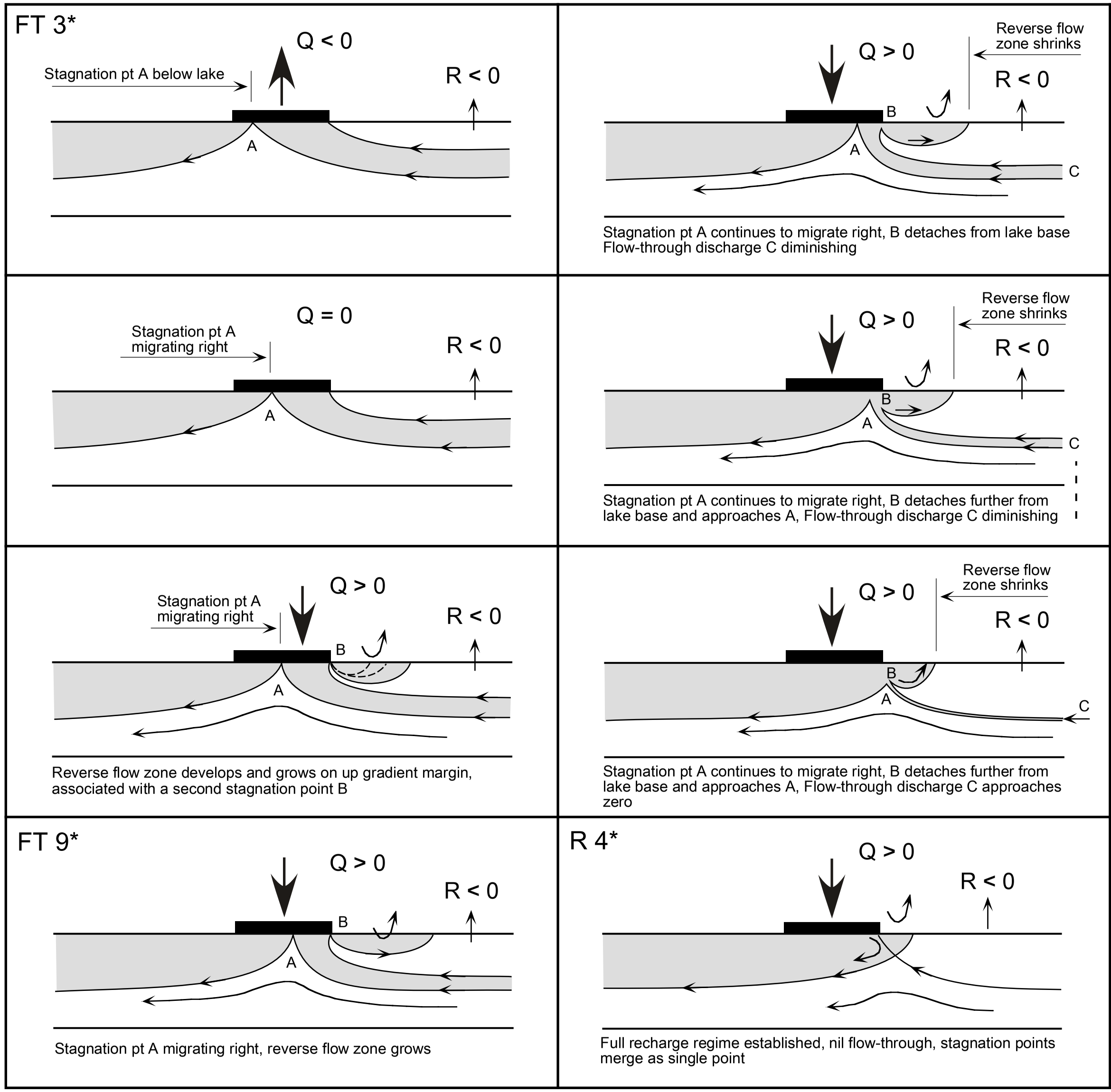
Flow-Through Regimes
Characterised by Decreasing Recharge

Figure 7.2b



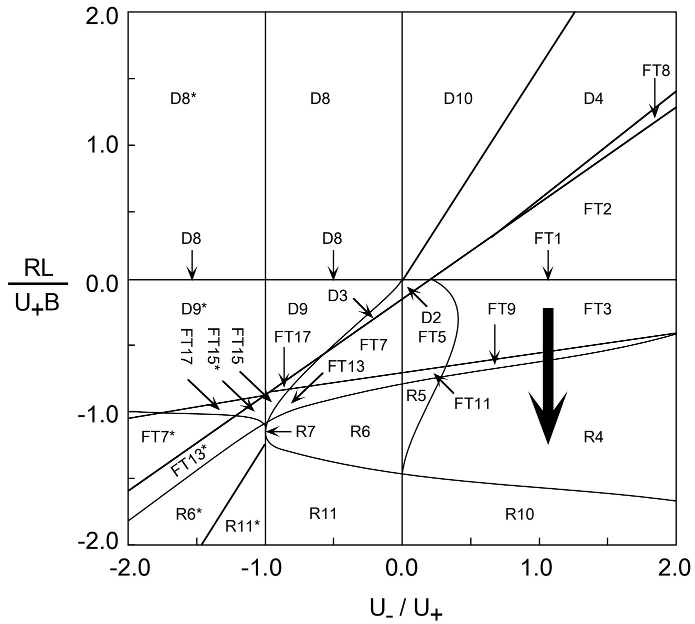
Recharge and Discharge Regimes
Figure 7.2c





Theoretical Transition Patterns between Flow-Through and Recharge Regimes

Figure 7.3



Transition diagram for U= > 0, 2a/B = 1 and D/B = 0 (adapted from Fig 17 of Nield et al 1994). Large arrow defines transition path from FT3-FT9-R4 shown in 2D sections. Flow regimes R1, R2, D5, FT4 & FT10 are off the diagram, occurring at U- / U+ > approximately 3

2D sections are flipped left to right to simulate conditions on the Swan Coastal Plain viewed looking north (denoted by asterisk), FT3* in section is equivalent of FT3 in transition diagram. Water which interacts with the lake is shaded.

initially bypassing the lake, discharges via a reverse flow zone on the left. Figures 7.1e panels b&c are analogous to the local down gradient recharge mounds of Meyboom (1967), Figure 7.1b panel a, Anderson & Munter (1981), Figure 7.1c (t = 23 & 36 days) and Cherkauer & Zager (1989), Figure 7.1d panels b&c.

Flow Regime Transitions

Nield *et al* (1994) provide a framework of flow regime types which effectively allow any regime to be 'pigeon holed' into a category which approximates its flow conditions. In reality there is an infinite continuum of regimes. Some are highly sensitive to changes in the water balance and/or the physical characteristics of the lake and aquifer. For example, using 'transition diagrams' plotted in RL / U_+B versus U_- / U_+ space Townley *et al* (1993a) and Nield *et al* (1994) demonstrate large changes in regime distribution when lake length (as $2a / B$) is increased from 1 to 4. Figure 7.3 illustrates the concept of a flow-regime continuum. The transition from FT3 to R4 must include the intermediate FT9 regime. The 2D vertical sections illustrate a few of the intermediate steps in the transition. A lake shrinking towards dryness is a similar case (Figure 7.10).

Capture Zone Depth and Width

Capture zone depth depends principally on lake length, expressed as $2a / B$ (Townley *et al* 1993b p27). Using the concept of 'equivalent isotropic domain' (Nield *et al* 1994 p2464), note that a lake with a continuous clay lining is the hydraulic equivalent of a lake with no lining but smaller length. Decreasing lake length and/or introducing a continuous low conductivity lining have the equivalent effect of decreasing capture zone depth (Figure 7.4a).

Capture zone width is less sensitive, depending largely on the degree of lake isolation from adjacent lakes (Townley *et al* 1993b, p28). Where a lake is isolated from adjacent lakes the capture zone width approaches double the lake diameter (Figure 7.4b). Nearby lakes have the effect of reducing capture zone width. Ignoring for a moment the possible effects of lake linings, we can estimate maximum (winter) capture zone widths at Perry Lakes, Table 7.3.

Table 7.3 Estimated capture zone widths

Parameter	East Lake	West Lake
$2W$ (distance between lake centres)	460m	460m
a (lake length/2)	120m	160m
$2a/B$ (B taken to be 37m)	~ 8	~ 8
a/W	~ 0.5	~ 0.7
Capture zone width w_+/a	1.6	1.3
Capture zone width	380m	420m

Lake Bottom Seepage Distribution

Field studies indicate that groundwater seepage into flow-through lakes is spatially highly variable but is generally most intense close to the up gradient shore (Lee 1977, Munter & Anderson 1981, Pfannkuch & Winter 1984). Seepage rates decrease rapidly from shore, decaying at a rate variously described as exponential (McBride & Pfannkuch 1975, Lee 1977) or rapid but non exponential (Townley *et al* 1993b p28). Seepage distribution is linked to aquifer anisotropy (Winter 1976, Lee *et al* 1980, Barwell & Lee 1981, Winter 1983) however in geologically complex multi-layered aquifer systems quite different seepage distributions can occur (Cherkauer & Nader 1989). Figure 7.4c summarises model simulations (Pfannkuch & Winter 1984, Townley *et al* 1993 a&b). The plots are symmetrical, with the distribution and intensity of discharge on the up gradient side matched by equal and opposite recharge down gradient.

In long lakes ($2a/B>4$), with no resistive lining, seepage is concentrated close to the shore, rapidly decreasing to nil just a short distance off shore. In very short lakes there is an almost linear distribution. As would be expected, the presence of a resistive lining and application of an equivalent isotropic system has the effect of reducing lake length, resulting in seepage distributions similar to those of very short lakes in isotropic domains. Figure 7.4c includes a purely diagrammatic representation of the discharge-recharge distributions in a lake of approximately similar length-width ratio as East Lake.

Non Uniform Lake Lining Distribution

Lakes on the Swan Coastal Plain typically contain resistive linings which are concentrated in the deepest part of the lake basin and thin towards the edges which may be devoid of lining. This is the general situation at Perry Lakes (Chapter 3). Townley *et al* (1993b) provide possible schematic lining configurations (Figure 7.4d). They suggest that where sediments are concentrated in the centre of lakes they will have little effect on capture zone geometry.

7.1.4 Predicted Flow Regimes at Perry Lakes

The models of Townley, Nield and others provide an easy to visualise theoretical framework. The models are steady state and rely on a large number of assumptions[2] and simplifications while the real world is highly complex and constantly changing. They rely on recharge values which represent spatial and temporal averages, and therefore simulate net surface water-groundwater interaction over some (unspecified)

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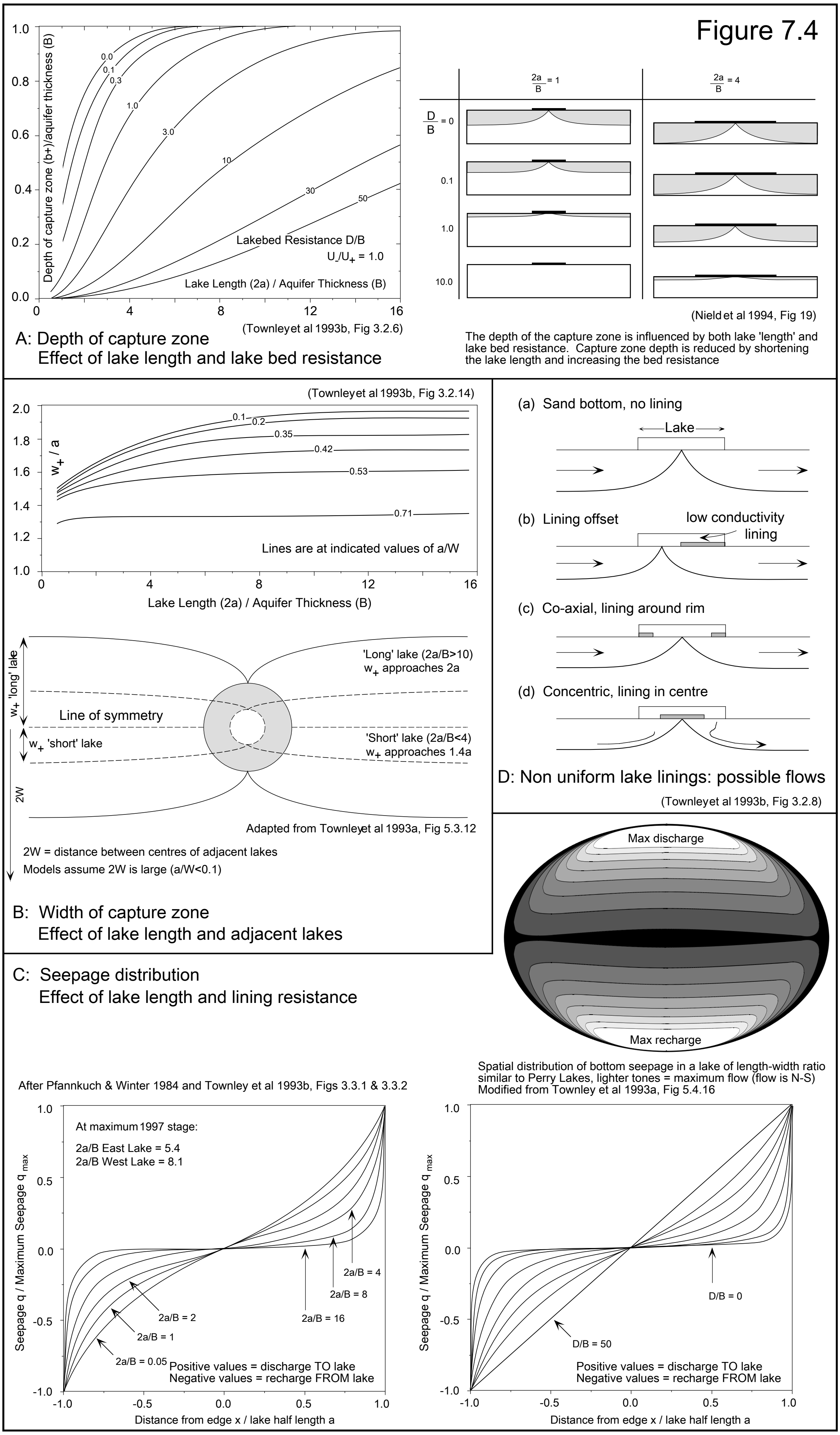
[2] Assumptions include: steady saturated groundwater flow, shallow water body relative to aquifer thickness, a 'long' water body (parallel to groundwater flow such that a 2D approach in vertical section is valid), homogeneous hydraulic conductivity, a horizontal phreatic surface within the model domain, distance L is always equal to $2B$, uniform horizontal fluxes across vertical boundaries, uniform sediment resistance, uniform recharge (a spatial and temporal average over some period of time), effect of U_+/K_x, (representing the slope of the phreatic surface) assumed to be negligible.



A: Depth of capture zone
Effect of lake length and lake bed resistance

B: Width of capture zone
Effect of lake length and adjacent lakes

C: Seepage distribution
Effect of lake length and lining resistance

D: Non uniform lake linings: possible flows time period (Nield *et al* 1994, p2464). But they also are based on measurable (or readily estimated) components of the lake water balance and physical characteristics of the lake and aquifer. Accurate short term water balances, such as the daily balances summarised in Chapter 6, allow realistic, detailed temporal analyses of East and West Lake as they respond to natural and artificial stimuli. The models provide not only a theoretical framework and classification scheme for describing lake-aquifer interaction but also easy to visualise 'snapshot' simplifications of a highly complex and dynamic system. Many of the regimes, while theoretically possible, have not been observed in nature. Many will probably not occur or at best occur as transient transition phases under Swan Coastal Plain hydraulic conditions.

Townley *et al* (1995) hypothesised flow regimes which might occur at Perry Lakes taking into account a regime of summer maintenance in East Lake (Figure 7.5). A seasonal oscillation between discharge and recharge regimes formed the principal theme of their predictions. In particular they suggested regular excursions to discharge in early summer (when evapotranspiration increases rapidly and the lake level falls more rapidly than the surrounding water table) and in West Lake in late summer (when the lake might become an evaporative sump). Many of their predictions have proven to be accurate as will be demonstrated later in this chapter. During early winter storm drain flow both lakes do become recharge lakes, frequently with a large single release zone encompassing both lakes. Over winter 1997 both lakes frequently exhibited separate capture and release zones while they were in flow-through status. The individual capture and release zones commonly coalesced as winter progressed (Figure 7.5 d, e & f) just as predicted by Townley *et al* (1995). What was not predicted was the persistence of flow-through regimes as lakes approached dryness and the very complex summer inter lake flows and reverse flows which result from heavy local groundwater extraction and persistent top up in East Lake. Discharge regimes proved to be extremely rare and at best transitory. These results are presented and discussed later in this chapter.

In the sections that follow we examine flow regimes observed over two years at Perry Lakes. It is worth emphasising again however that the models upon which they are based are gross simplifications of real world complexity. Aquifer anisotropy, complex lake shapes and lining distribution, surface topography, vegetation cover, land use (in particular groundwater extraction and use of wetlands as storm water depositories) all add layers of complexity which cannot be addressed in the models. The models (and flow regime designations) do however, provide a convenient framework which allows the reader to more easily visualise (in 2D steady state) what is actually happening (in 3D non steady state), under hydrologically complex conditions.

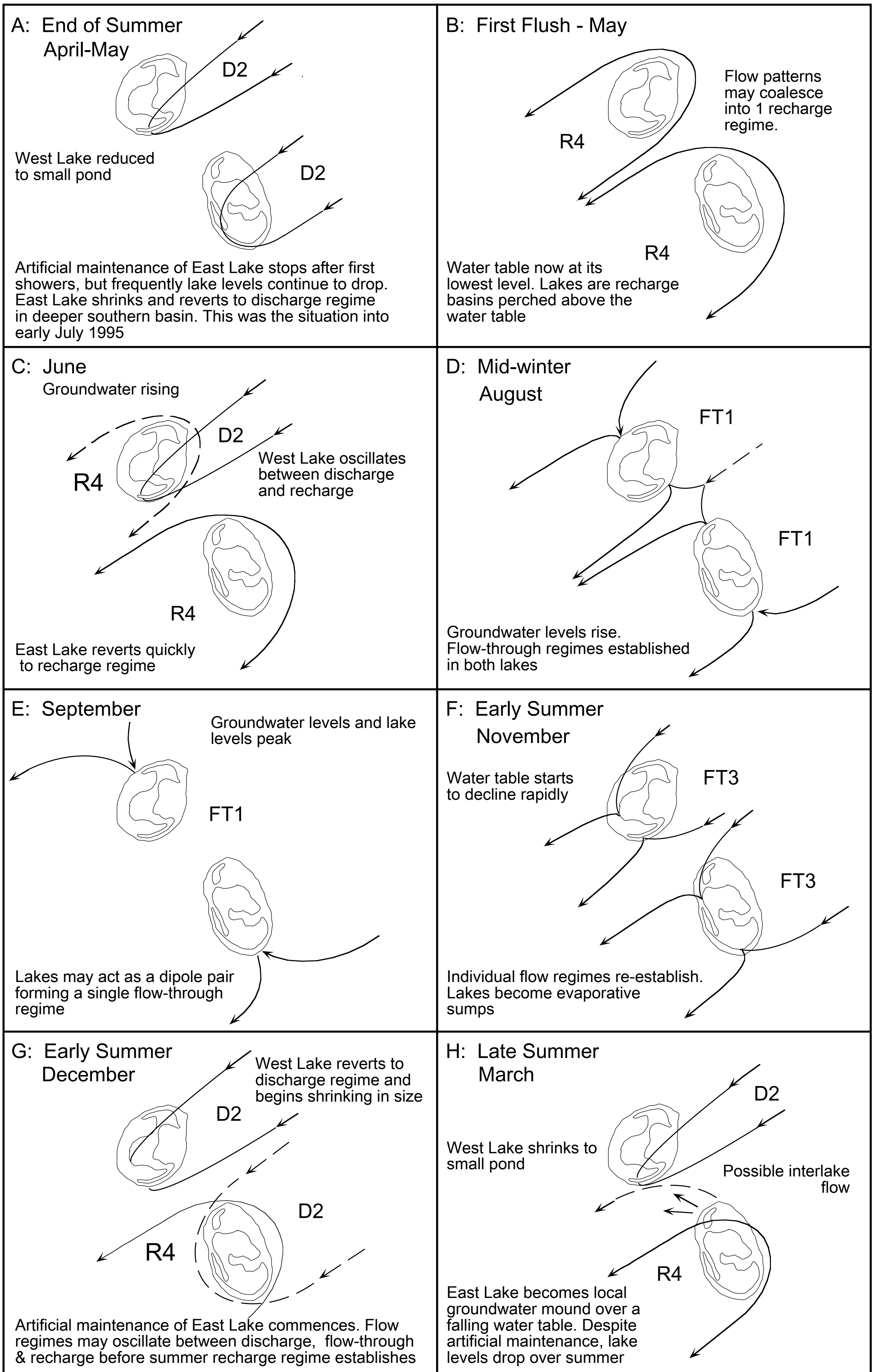


Figure 7.5

Flow Regimes Hypothesised by Townley et al 1995

7.2 FIELD IDENTIFICATION OF FLOW REGIMES

In their natural state wetlands such as Perry Lakes had no surface inputs or outflows except direct rainfall and evaporation. In normal years they were not subject to drying out. At normal water levels the sandy rim ensured good hydraulic coupling to the aquifer. This suggests that under normal climatic conditions $Q / U_+ B$ remained close to zero and flow-through regimes persisted year round. During periods of high rainfall, the lakes would tend towards a recharge state (FT3, FT9 etc) and similarly under extreme summer evapotranspirative stress would tend towards a discharge state (FT2, FT8 etc). It appears unlikely that true recharge and discharge regimes would have been achieved for any considerable period. Section 7.2.4 shows how extensive field experiments confirm that flow-through persists even as the lakes approach dryness.

Today artificial flow regimes are induced principally through large inputs either as top up or storm water. Both induce local mounding of one or both lakes. Persistent summer groundwater extraction induces additional artificial flows.

At Perry Lakes six field techniques were used to identify flow regimes.

- nested piezometers
- in-lake piezometers close to the FT1 dividing streamline
- near lake water table levels
- identification of transient reverse water table gradients
- dividing stream line mapping using lake edge 'mini piezometers'
- lake sediment thermal profiling
- water balances

7.2.1 Nested Piezometers

Nested piezometers were planned as the principal means of identifying seasonal and transient (rain and pumping) changes in flow regime. In summary the piezometers failed to operate as planned. Mini piezometers (Section 7.2.3) close to the lake edge displayed large differences in equipotential over depth. Head differences of 10^{+}cm were routinely recorded between the water table and 2.5m depth. In the nested piezometers however equipotential differences over half the vertical thickness of the aquifer (about 20m) were typically <10mm. More importantly these data often displayed no seasonal change and were often in direct contradiction of the flow regime determined by other means.

Nested piezometers are a primary tool in lake-aquifer interaction studies (Townley *et al* 1993 a&b). It was anticipated that they would perform a similar function at Perry Lakes providing a simple physical indication of lake-aquifer interaction. Simply put, a piezometer is a small diameter well, sealed along its length and either open at the bottom or screened over a short distance. When inserted into an aquifer to depth *d* water will rise within it in proportion to the hydraulic head at *d*. In lake-aquifer interaction studies it is the vertical hydraulic gradient which is of primary interest. Around a flow-through lake this gradient will be positive or upwards close to the shore on the up gradient side and negative or downwards on the down gradient side. It is these upward and downward flows which drive the groundwater discharge and recharge in flow-through lakes (Figure 7.4c). The water in a piezometer on the up gradient side of such a lake will rise above the level of the water table. This is because there is a greater hydraulic head at depth than at the water table. This vertical gradient drives the upward flow. Similarly on the down gradient side the vertical gradient and flow direction will be reversed and water in the piezometer will be below the level of the water table.

In Section 7.1.3 we examined partially and fully penetrating flow regimes. The 2D sections in Figures 2, 3 & 4 clearly demonstrate that capture and release zones do not always penetrate to the base of the aquifer. Constructing a nest of piezometers terminating at different depths allows the vertical distribution of hydraulic heads to be defined. It was our initial intention that extensive 2D modelling would be performed to augment the field studies completed by Townley *et al* (1993 a&b) and validate the models of Nield *et al* (1994). In particular it was proposed that calibrated 2D models might be capable of defining the groundwater flux by combining solute and isotopic data with the dimensionless ratios defined in Table 7.1. This method (Townley *et al* 1993a p287-294) relies on knowing (among other things) the release zone depth (b_-). The ratio of release zone depth to aquifer thickness (b_- / B) and (b_-) must be measured at a distance $L = 2B$ down gradient in an equivalent isotropic domain (*ibid* p298). In an anisotropic real world this distance is increased by the square root of the anisotropy ratio (*ibid* p171 & 298). This ratio was (and remains) unknown, but using the assumption $K_x / K_z = 50$, and where B is 35m then

$$L = 50^{0.5} 2(35) \qquad (7.1)$$

This suggested that N5 should be a minimum 400-500m down gradient of East Lake - where it was ultimately constructed[3]. Piezometers N1-N4 were installed at the up and

[3] the only available data (Chapter 3, Table 3.4) suggests anisotrophy ratios of 100 to over 1000 for Swan Coastal Plain sediments. This resulted in N5 placements 700 to 2200m down gradient, an impractical distance.

down gradient basin margins along the regional groundwater flow lines where they bisected each lake (Figure 3.3 and insert Figure 7.6). Nest N5 was located 420m down gradient of East Lake. All five were of identical construction, comprising three wells designated a to c as summarised in Table 7.4. It was important that the deepest ('c') piezometers were screened at or below the maximum capture and release zone depths (b_{-}). Possible values were estimated from FlowThru (Townley *et al* 1992). Using known values of $2a$ and B, setting K_x / K_z equal to 10 to 100 and D equivalent to up to 2m of mud with hydraulic conductivity 1.0 to 0.1m d^{-1} suggested that b_{-} lay in the range 10 to 18m below the water table. Using an auger rig, all deeper holes were terminated in limestone with the target depth reached only with difficulty. All 15 piezometers were fitted with capacitive water level loggers calibrated with weekly manual readings.

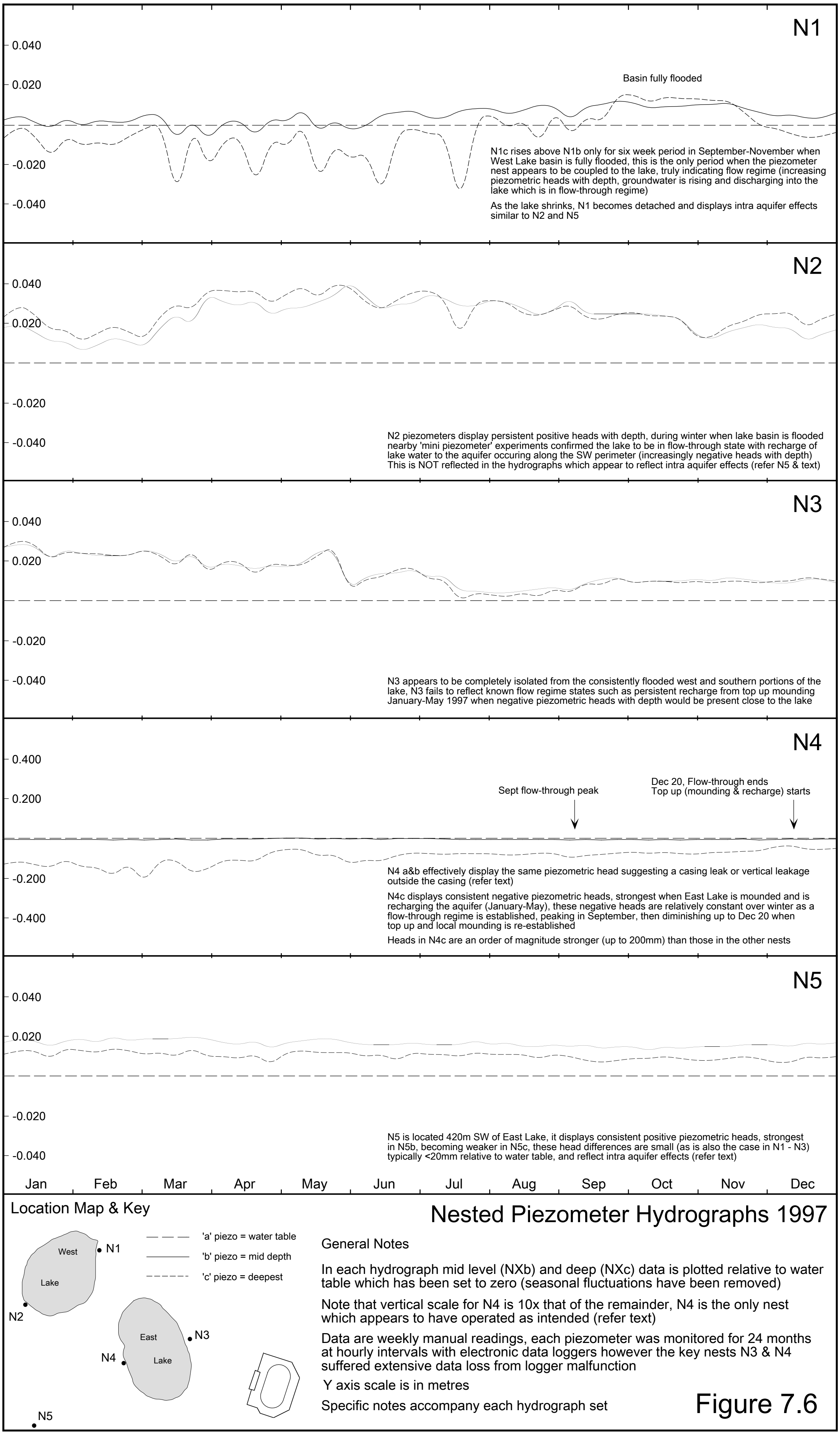
Table 7.4 Nested piezometer details N1-N5

Target	Well	Depth[1]	Screen
Water table	'a'	2.0	1.5-2.0
Mid level	'b'	10.0	9.5-10.0
Max b_{-}	'c'	18.0	17.5-18.0

1 depth below minimum winter water table
All piezometers constructed from 50mm PVC

The nested piezometers were to be the primary physical tool by which lake flow regimes would be identified and monitored. It was anticipated that their data would provide an unequivocal framework for guiding the integrated balances which would quantify water masses and in particular the groundwater flux. Considerable thought and discussion preceded the piezometer installation and it is therefore important to digress slightly and investigate why they failed to function as planned.

The study period 1996-97 coincided with the transition from permanent to seasonal lakes. When the piezometer nests were planned during 1994 West Lake had not (in recent years) completely dried out over summer and weekend top up was sufficient to maintain East Lake as a contiguous water body from the NW Arm to the South Basin. West Lake first dried out completely (apart from the basin around the staff gauge) in February 1995 and remained so as late as the first week of July 1995. East Lake on July 4, 1995 was at a stage of only 2.9m and confined to the South Basin. These extreme low water conditions were ascribed to several seasons of below average rainfall. In hindsight these levels were merely a continuation of a long term decline in regional groundwater levels (Chapter 2). Unfortunately the piezometer installation coincided with the critical point where the lakes became dry for portions of each annual groundwater cycle.


N1
0.040
0.020
-0.020
-0.040
Basin fully flooded
N1c rises above N1b only for six week period in September-November when West Lake basin is fully flooded, this is the only period when the piezometer nest appears to be coupled to the lake, truly indicating flow regime (increasing piezometric heads with depth, groundwater is rising and discharging into the lake which is in flow-through regime)
As the lake shrinks, N1 becomes detached and displays intra aquifer effects similar to N2 and N5
N2
0.040
0.020
-0.020
-0.040
N2 piezometers display persistent positive heads with depth, during winter when lake basin is flooded nearby 'mini piezometer' experiments confirmed the lake to be in flow-through state with recharge of lake water to the aquifer occuring along the SW perimeter (increasingly negative heads with depth) This is NOT reflected in the hydrographs which appear to reflect intra aquifer effects (refer N5 & text)
N3
0.040
0.020
-0.020
-0.040
N3 appears to be completely isolated from the consistently flooded west and southern portions of the lake, N3 fails to reflect known flow regime states such as persistent recharge from top up mounding January-May 1997 when negative piezometric heads with depth would be present close to the lake
N4
0.400
0.200
-0.200
-0.400
Sept flow-through peak
Dec 20, Flow-through ends
Top up (mounding & recharge) starts
N4 a&b effectively display the same piezometric head suggesting a casing leak or vertical leakage outside the casing (refer text)
N4c displays consistent negative piezometric heads, strongest when East Lake is mounded and is recharging the aquifer (January-May), these negative heads are relatively constant over winter as a flow-through regime is established, peaking in September, then diminishing up to Dec 20 when top up and local mounding is re-established
Heads in N4c are an order of magnitude stronger (up to 200mm) than those in the other nests
N5
0.040
0.020
-0.020
-0.040
N5 is located 420m SW of East Lake, it displays consistent positive piezometric heads, strongest in N5b, becoming weaker in N5c, these head differences are small (as is also the case in N1 - N3) typically <20mm relative to water table, and reflect intra aquifer effects (refer text)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Location Map & Key
West
Lake
East
Lake
N1
N2
N3
N4
N5
'a' piezo = water table
'b' piezo = mid depth
'c' piezo = deepest
Nested Piezometer Hydrographs 1997
General Notes
In each hydrograph mid level (NXb) and deep (NXc) data is plotted relative to water table which has been set to zero (seasonal fluctuations have been removed)
Note that vertical scale for N4 is 10x that of the remainder, N4 is the only nest which appears to have operated as intended (refer text)
Data are weekly manual readings, each piezometer was monitored for 24 months at hourly intervals with electronic data loggers however the key nests N3 & N4 suffered extensive data loss from logger malfunction
Y axis scale is in metres
Specific notes accompany each hydrograph set
Figure 7.6

Piezometers were installed in December 1995 in positions which assumed that the bulk of the lake basins would be covered by water for most of the year. Instead West Lake became dry for 6-7 months of every year and the wetland managers had increasing trouble maintaining water in East Lake for 6 months of every year (refer Chapter 7.6). Commencing in late summer 1995 only the South Basin had permanent water despite regular top up. Over the period of intense monitoring (1996-98), the permanently wetted area of East Lake continued to decline and became restricted to the South Basin, well offset from N3 and N4. Similarly, West Lake was dry for at least half of both 1996 and 1997.

Despite this, it was expected that the piezometer nests would function as planned during winter high water conditions when both lake basins were flooded. They didn't. What we found instead were seasonally persistent patterns of very weak positive or negative heads (relative to the water table) which often contradicted the lake-aquifer hydrology indicated using other methods (Figure 7.6). These are interpreted as piezometric effects within the aquifer resulting from its strongly layered stratigraphy, particularly the presence of limestone. For example the magnitude of these head differences in N5 (420m distant from East Lake) is similar to those observed in N1 and N2 when West Lake is dry. Importantly local pump tests (Table 3.4) confirm that the surficial aquifer is not unconfined. This is in agreement with pump tests elsewhere on the Swan Coastal Plain which indicate persistent semi-unconfined and locally semi-confined conditions consistent with strong vertical heterogeneity. Local vertical differences in piezometric head are probably widespread, but seldom documented. They have been reported west of the East Beeliar chain of wetlands, around Jackadder Lake and elsewhere (refer Chapter 7.7).

N4 was the only nest which appeared to consistently indicate lake-aquifer interaction. We can really only compare N4a and N4c as heads in a and b displayed negligible difference. There are two possible explanations:

1: the piezometer casing in N4b leaks close to the water table

2: vertical mixing is occurring outside the casing neutralising any head differences

Vertical mixing results from incorrect piezometer construction. The recommended way to construct piezometers in sand/rock layered aquifers is to insert the piezometer tube into a cased hole and then back grout to prevent vertical communication outside the casing (Wallis Drilling pers com). The grout is injected under pressure via the annulus between the casing and the piezometer tube, as the casing is withdrawn, completely sealing the drill hole void above the piezometer screen. This was not possible with the equipment used to construct these piezometers which were drilled open hole and backfilled by hand filling drill spoil from the top of the hole.

As we will see in subsequent sections of this chapter strong piezometric heads persisted in and close to the wetted sections of the lake basins. Apart from N4 (which was within 10m of water most of the time) the piezometers were simply outside the zone of lake-aquifer interaction. The data represent a graphic field demonstration of the extreme influence of anisotropy on lake-aquifer domain geometry.

7.2.2 In Lake Piezometer Close to the Dividing Stream Line, East Lake

Piezometric heads in nest N3 failed to provide any resolution of lake-aquifer flow regimes. Lack of funding precluded construction of a second piezometer nest closer to the South Basin. During July and August 1996, access tubes for thermistor strings were installed at ten locations within East Lake. These are shown in Figure 5.1a and described in detail in Chapter 9. These tubes were sludged[4] through the lake lining to a constant depth of 7m below the sediment-water interface. The tubes were open at the bottom and sealed to above the water surface, and therefore (unintentionally) functioned as in-lake piezometers. Observations prior to thermistor string installation showed consistent positive heads in tubes close to the east shore (TS 2, 6 and 9) and negative heads close to the west shore (TS 5, 8 and 10). TS 3 displayed weaker positive heads while TS 4 and 7 had levels close to that of the lake (but generally weakly positive). The access tube data showed quite clearly that the lake was in flow-through mode and that the position of the dividing streamline must lay close to and slightly west of TS 4 and TS 7. Head differences in TS 2, for example, were typically in the order of 300mm relative to the lake surface. This effect became progressively less intense in TS 3 and TS 4. These observations are entirely consistent with model simulations of bottom seepage (Townley *et al* 1993b p28). Moore & Turner (1989) used similar techniques to confirm and sample discharge across the bed of Lake Clifton. In Wisconsin, Cherkauer & Zager (1989) used in-lake piezometers to identify reverse flow from adjacent transient mounds.

These quite accidental observations suggested that a shallow piezometer located close to the winter position of the dividing streamline could show subtle changes in flow regime. During rain, storm drain inputs would raise the lake surface, the lake would immediately tend towards recharge (say from FT1 to FT3 or R). Regardless, the dividing stream line would also migrate up gradient and the level within the piezometer would fall as the piezometer would now be on the down gradient side of the dividing streamline. At Shenton Park Lake Sim (1995) showed that small lakes with large storm water inputs can oscillate rapidly between flow-through and recharge status.

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[4] using a sludge pump (a miniature version of the familiar cable tool drill rig bailer) consisting of a section of steel pipe with a ball valve at the base.

A single in-lake permanent mini-piezometer W28 (Figures 5.1a & 7.7b) was sludged through the lake lining clays close to the anticipated winter position of the dividing stream line. Subsequent mini-piezometer experiments November-December 1997 showed that the dividing stream line orientation becomes more east-west as the lake shrinks however this was not known when W28 was installed. The W28 location was therefore a compromise. As the lake shrinks and approaches dryness, the dividing stream line migrates southwest, however for lake stage >3m W28 lies on or very close to the dividing stream line. The piezometer was fitted with a standard Dataflow logger and 2m capacitive water level sensor. Data (Figure 7.7a) was collected from April 15 to October 18, 1997 (at which time the logger failed).

Interpretation of the W28 data assumes that:

- the piezometer always lies on or close to the dividing stream line, therefore under stable flow-through conditions, piezometric head will be very close to lake surface level
- during storm events drain inputs will push the lake towards recharge status, the lake surface will then exceed the piezometric head

Interpreted flow status is summarised in Figure 7.7a. During April and May East Lake was being periodically maintained through top up and was clearly mounded (recharge status). This situation continued into July, becoming more extreme during rain events in late June. Between early July and lake stage peak (3.575m September 10) the lake oscillated between recharge and flow-through status. This oscillation between flow states is a direct consequence of storm drain inputs which can double the lake volume and substantially increase lake stage within a few minutes. The patterns are similar to those observed at Shenton Park Lake (Sim 1995). Following September peak stage, flow through status persisted as the lake shrank until artificial maintenance commenced December 20.

As a single fixed piezometer W28 was of limited usefulness because its position relative to the dividing stream line was never certain. Along with the thermistor tubes however it provided valuable 'proof of concept' data. This lead directly to experiments with numerous 'mini piezometers' to track dividing streamline migration, described later in this chapter.

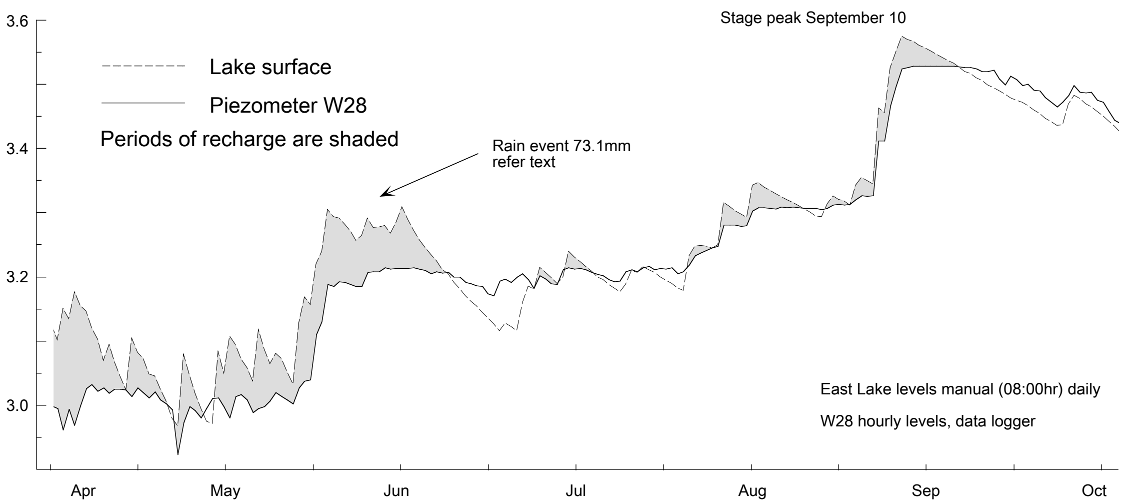
7.2.3 Near Lake Water Table Levels

Comparison of lake and monitoring well levels

Where lakes intersect the unconfined aquifer there is nil horizontal gradient. The lake surface is horizontal and piezometric head at the sediment-water interface is everywhere

In Lake Piezometer W28 Hydrograph, Winter 1997

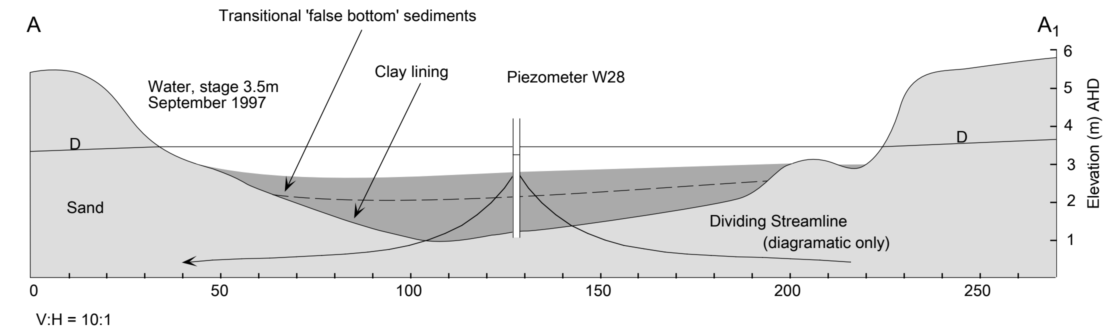
Figure 7.7a

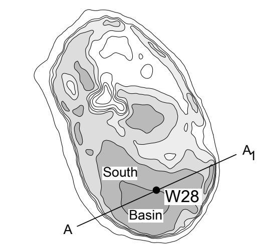


East Lake flow regimes winter 1997 as indicated by piezometer located on the approximate position of the dividing streamline, data spans April 15 - October 18, a well defined constant recharge regime in late summer oscillates between recharge and flow-through as lake and local water table levels rise over winter with constant flow-through established by late winter peak levels

In Lake Piezometer on the Dividing Stream Line

Figure 7.7b





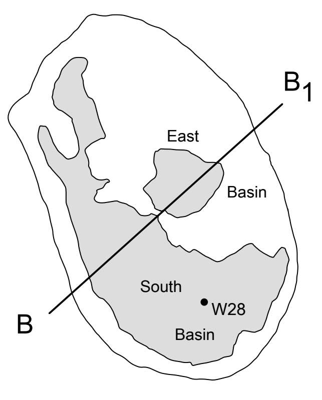
Shaded areas are water surface at 3.5m stage

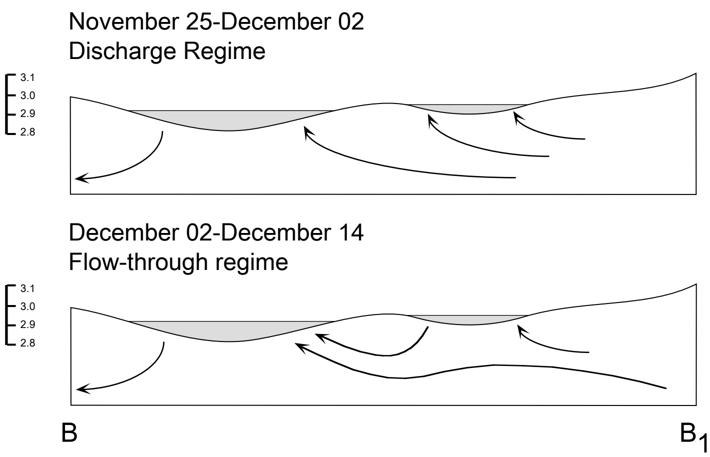
Piezometer W28 is shown located directly on the position of the dividing streamline. Initial experiments over winter 1996 during thermistor access tube construction suggested that once a winter flow-through regime was established in East Lake the position of the dividing streamline did not vary much. This lead directly to the W28 experiment (installed April 1997) and later mini piezometer experiments as East Lake approached dryness Nov & Dec 1997

W28 was fitted with a standard Dataflow logger and capacitive water level probe, readings hourly

Flow Regime Detail, East Basin

Figure 7.7c

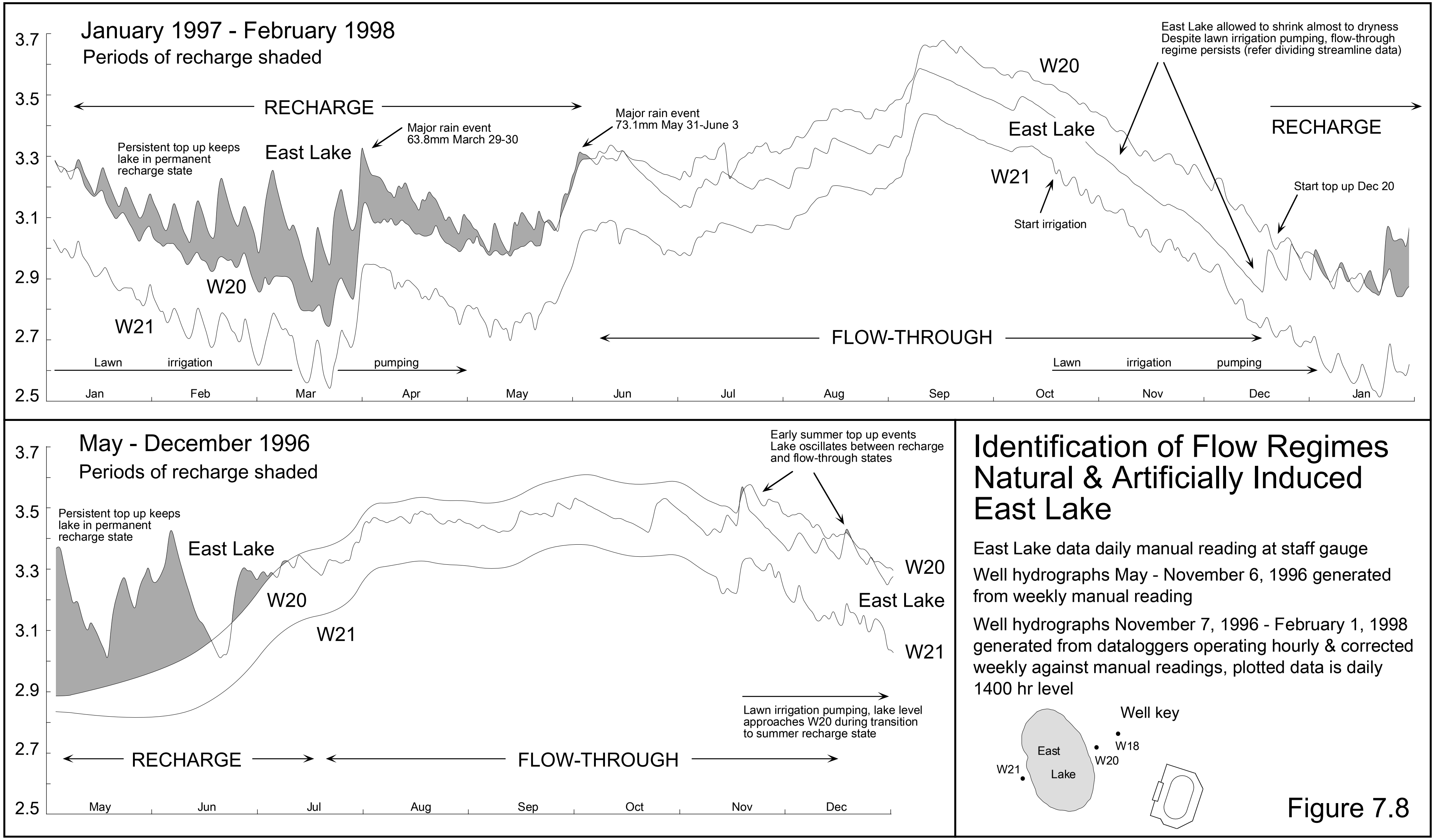




equal to the elevation of the water surface (Townley *et al* 1995 p28). Therefore subtle differences in water table close to a flow-through lake can assist in providing clues about its flow state. Consider a roughly circular lake within which a flow-through regime is established. Along a line bisecting the lake and parallel to the regional gradient groundwater levels will increase up gradient and decrease down gradient. A line bisecting the lake normal to the regional gradient will exhibit no change in slope as the lake is approached. Such a line is parallel to the regional water table contours at a water table elevation equal to the lake surface. Keeping this in mind, changes in the relationship between lake level and nearby groundwater level can provide additional clues regarding lake-aquifer flow status.

Detailed analysis of electronic logger data from wells W20 and W21 immediately up and down gradient provide gross patterns of annual flow status in East Lake. With reference to Figure 7.8 summer (1996 and 1997) top up maintained a local groundwater mound with the lake level always above W20 (defined by shading in Figure 7.8). This pattern was maintained up to the major early winter frontal passage May 31-June 3 when 73.1mm rain fell over four days. Shortly thereafter a winter flow-through regime was established with W20 SWL>East Lake>W21 SWL. Comparing Figure 7.7a (the in-lake piezometer W28) with Figure 7.8 it is evident that in such highly permeable sands such mounds decay quickly. The mound was present at W20 only for several days whereas in and immediately adjacent to East Lake recharge status persisted for about three weeks. This large storm induced mound will be further discussed in Section 7.3.

The relationship between a flow-through lake and wells equidistant up and down gradient is clearly illustrated in the hydrographs October-December 1997 where the East Lake level lies between but is synchronous with W20 and W21. Approximately two weeks after top up commenced lake level was higher than W20 (shaded) for each top up session (defined by peaks in the hydrographs). Remember that W20 was 50 to 100m up gradient of the closest flooded section of the lake. The shaded portions of the hydrograph records represent mounding peaks. East Lake was often locally mounded but with a stage less than the SWL in W20. As an experiment plots showing the level of W20 were adjusted down by an amount equal to the average watertable difference between W20 and East Lake during stable winter flow-through conditions (about 120mm). Experimentally setting W20 120mm lower essentially duplicated the patterns observed using the in-lake piezometer W28.



Identification of Flow Regimes Natural & Artificially Induced East Lake

East Lake data daily manual reading at staff gauge

Well hydrographs May - November 6, 1996 generated from weekly manual reading

Well hydrographs November 7, 1996 - February 1, 1998 generated from dataloggers operating hourly & corrected weekly against manual readings, plotted data is daily 1400 hr level

Figure 7.8

Identification of Reverse Groundwater Gradients

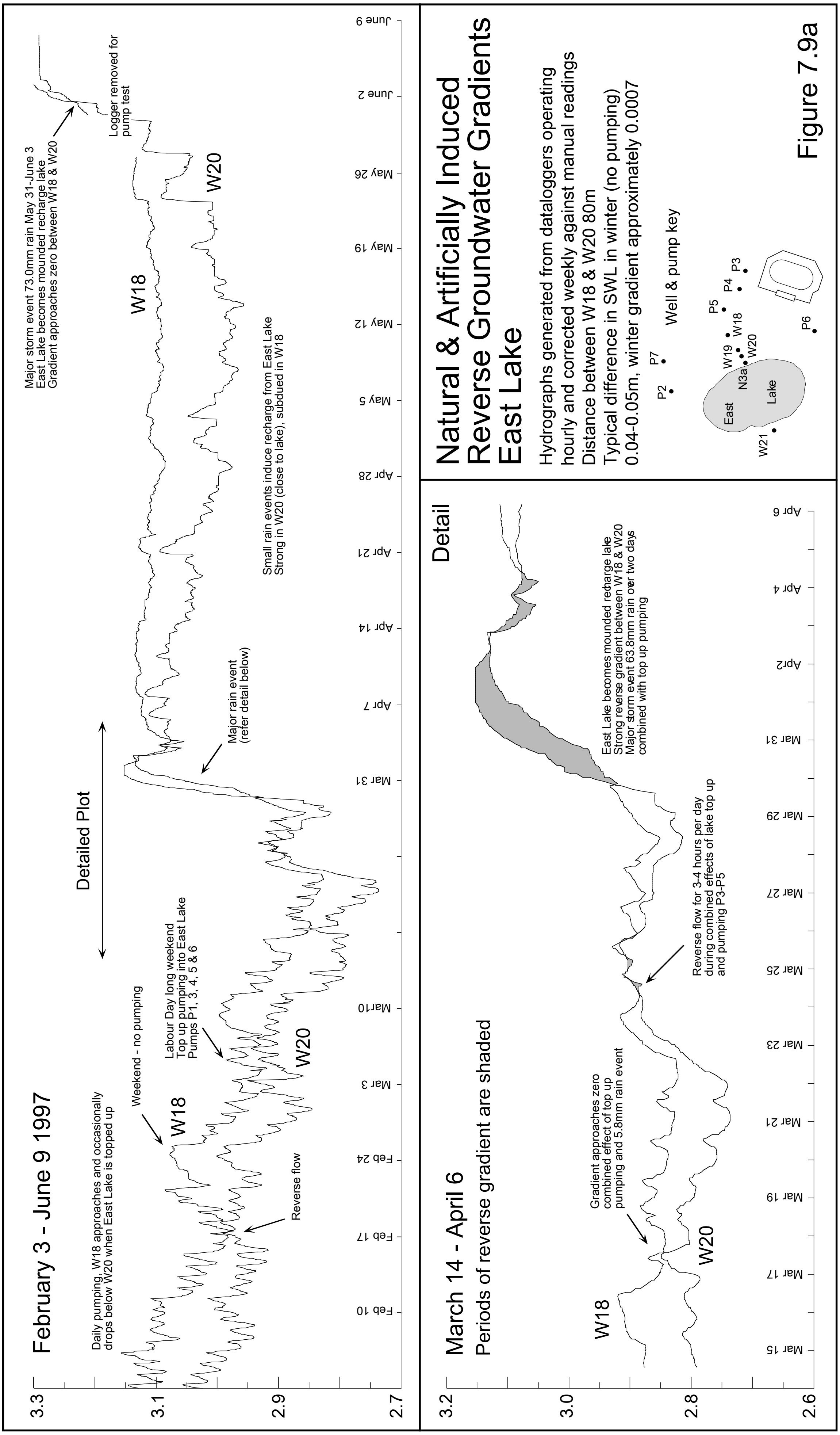
Mounding, whether from lake top up or storm water, induces negative groundwater gradients northeast of East and West Lake. Such gradients can also be enhanced by, or result directly from irrigation pumping. Wharton (1981a) identified reverse gradients east of Lake Jandabup from heavy pumping for the production of potable water. At Perry Lakes the effects are frequently transient, occurring daily during irrigation. The gradient then reverses during overnight or weekend recovery. Reverse gradients were observed in hydrograph data from W18, W19, W20 and N3a at East Lake and W1, W2, W3 and N1a at West Lake. The combination of artificial lake level maintenance and persistent pumping combine to create a very dynamic groundwater system over summer. This is illustrated in data logger hydrographs from W1, W3, W18 and W20 (Figures 7.9 a&b). Well and irrigation pump locations are included in the insert maps with each figure.

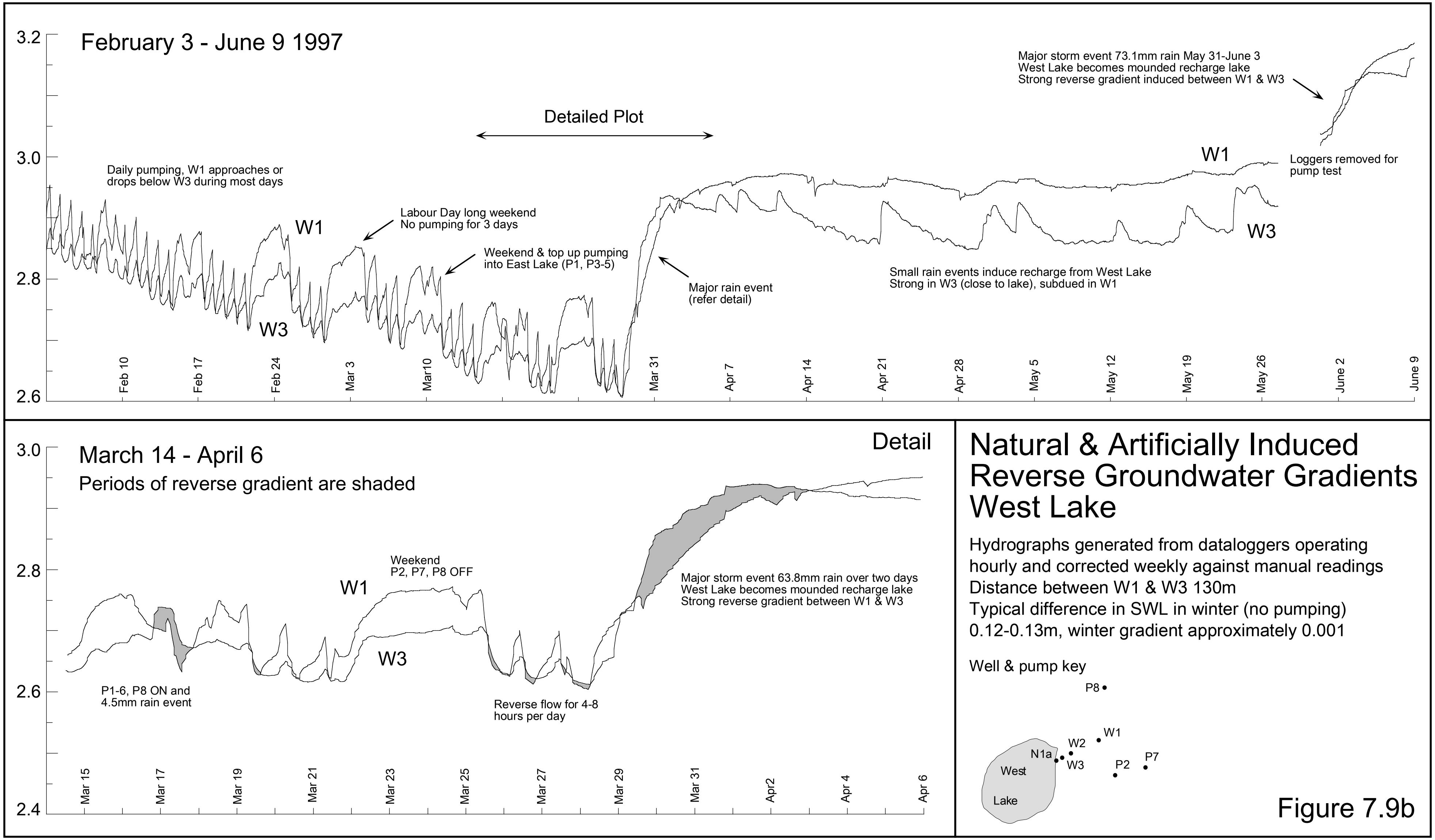
East Lake Figure 7.9a

- bores P3-P5 were used daily over summer for lawn irrigation and frequently for weekend top up to East Lake
- during daily pumping, W18 frequently approaches and occasionally drops below W20 indicating a local pump induced reverse gradient
- this usually occurs immediately following lake top up when the local mound around the lake combines with the local depression of the water table around P3-P5 (detail Figure 7.9a)
- the effect intensifies in late summer because W18 continues to decline in step with the regional water table while East Lake is maintained at the equivalent of early summer levels
- these pump induced effects are small compared to lake top up and mounding from large late summer storm events such as that of late March 1997 which mounded East Lake creating reverse gradients which persisted for a week (detail Figure 7.9a)

West Lake Figure 7.9b

- over summer 1997 the West Lake basin remained dry, reverse gradients in W1 and W3 resulted directly from irrigation pumping from P2, P7 and P8
- difference in level between W1 and W3 diminishes in late summer, but unlike East Lake this is a direct consequence of pumping which maintains a very shallow groundwater gradient below the Alderbury Flats over summer
- the gradient recovers when pumps are off for several days such as March 22-24 (detail Figure 7.9b)
- as in East Lake, the pump induced effects are small in comparison with the storm induced lake mounding in late March (detail Figure 7.9b)


February 3 - June 9 1997
Detailed Plot
Daily pumping, W18 approaches and occasionally drops below W20 when East Lake is topped up
Weekend - no pumping
Labour Day long weekend Top up pumping into East Lake Pumps P1, 3, 4, 5 & 6
Reverse flow
Major rain event (refer detail below)
Small rain events induce recharge from East Lake Strong in W20 (close to lake), subdued in W18
Major storm event 73.0mm rain May 31-June 3 East Lake becomes mounded recharge lake Gradient approaches zero between W18 & W20
Logger removed for pump test
W18
W20
3.3
3.1
2.9
2.7
Feb 10
Feb 17
Feb 24
Mar 3
Mar10
Mar 31
Apr 7
Apr 14
Apr 21
Apr 28
May 5
May 12
May 19
May 26
June 2
June 9
March 14 - April 6
Periods of reverse gradient are shaded
Detail
Gradient approaches zero combined effect of top up pumping and 5.8mm rain event
Reverse flow for 3-4 hours per day during combined effects of lake top up and pumping P3-P5
East Lake becomes mounded recharge lake Strong reverse gradient between W18 & W20 Major storm event 63.8mm rain over two days combined with top up pumping
W18
W20
3.2
3.0
2.8
2.6
Mar 15
Mar 17
Mar 19
Mar 21
Mar 23
Mar 25
Mar 27
Mar 29
Mar 31
Apr2
Apr 4
Apr 6
Natural & Artificially Induced Reverse Groundwater Gradients East Lake
Hydrographs generated from dataloggers operating hourly and corrected weekly against manual readings
Distance between W18 & W20 80m
Typical difference in SWL in winter (no pumping) 0.04-0.05m, winter gradient approximately 0.0007
Well & pump key
P2
P7
W19
W18
W20
N3a
P5
P4
P3
P6
W21
East
Lake
Figure 7.9a



February 3 - June 9 1997
Detailed Plot
Daily pumping, W1 approaches or drops below W3 during most days
Labour Day long weekend No pumping for 3 days
Weekend & top up pumping into East Lake (P1, P3-5)
Major rain event (refer detail)
Small rain events induce recharge from West Lake Strong in W3 (close to lake), subdued in W1
Major storm event 73.1mm rain May 31-June 3 West Lake becomes mounded recharge lake Strong reverse gradient induced between W1 & W3
Loggers removed for pump test
W1
W3
3.2
3.0
2.8
2.6
Feb 10
Feb 17
Feb 24
Mar 3
Mar10
Mar 31
Apr 7
Apr 14
Apr 21
Apr 28
May 5
May 12
May 19
May 26
June 2
June 9
March 14 - April 6
Periods of reverse gradient are shaded
Detail
Weekend P2, P7, P8 OFF
P1-6, P8 ON and 4.5mm rain event
Reverse flow for 4-8 hours per day
Major storm event 63.8mm rain over two days West Lake becomes mounded recharge lake Strong reverse gradient between W1 & W3
3.0
2.8
2.6
2.4
Mar 15
Mar 17
Mar 19
Mar 21
Mar 23
Mar 25
Mar 27
Mar 29
Mar 31
Apr2
Apr 4
Apr 6
Natural & Artificially Induced Reverse Groundwater Gradients West Lake
Hydrographs generated from dataloggers operating hourly and corrected weekly against manual readings
Distance between W1 & W3 130m
Typical difference in SWL in winter (no pumping)
0.12-0.13m, winter gradient approximately 0.001
Well & pump key
P8
W1
W2
N1a
W3
P2
P7
West
Lake

Figure 7.9b

7.2.4 Dividing Stream Line Mapping using Lake Edge 'Mini Piezometers'

The method was adapted from earlier field experiments used to define the distribution of seepage into lakes (Lee & Cherry 1978, Woessner & Sullivan 1984) and pore water sampling (Krabbenhoft & Webster 1995) who used small tubes around groundwater discharge/recharge points to determine the vertical direction of the hydraulic gradient at the sediment-water interface. Previous experiments with the in-lake piezometer W28 and thermistor access tubes clearly indicated that piezometric head differences could be readily measured close to the edge of the lake. Cherkauer & Zager (1989) used similar in-lake piezometers to plot stagnation zone migration.

Initial experiments using 'short' (relative to aquifer thickness) piezometer tubes confirmed that head differences could easily be resolved using tubes as short as 1m when installed close to the lake margin, using the level of the lake as a datum. A tube 2.5m long (Figure 7.11c) was chosen as a 'standard' (it is the longest practical length which can be installed with a manual sludge pump without having to glue sections). Mini piezometers are easiest to use when the piezometer lip is about 10cm proud of the lake surface. Head differences can be rapidly observed and measured. Once the approximate position of the dividing stream line has been established, additional piezometers can be installed to provide greater resolution. Figure 7.10 demonstrates how mini piezometers installed around a flow-through lake can be used to resolve the position of the dividing streamline. Piezometers located on the dividing streamline will show piezometric heads equal to the lake surface. Maximum and minimum piezometric heads occur at the centre-line of the capture and release zones respectively. Mini piezometer studies permit rapid identification of gross flow state (D-FT-R) and allow the position of the dividing streamline to be mapped as the lake responds to differing hydrological conditions.

During the period November 11-December 20 1997, East Lake was allowed to recede almost to dryness without artificial top up. Migration of the dividing stream line was observed by daily (early morning) observation of the mini piezometers. As levels declined additional piezometers were installed and existing ones removed and re-installed. The process was labour intensive, but provided a detailed picture of the dividing stream line migration over a two month period.

The results are displayed graphically in Figures 7.11a-c, and summarised below.

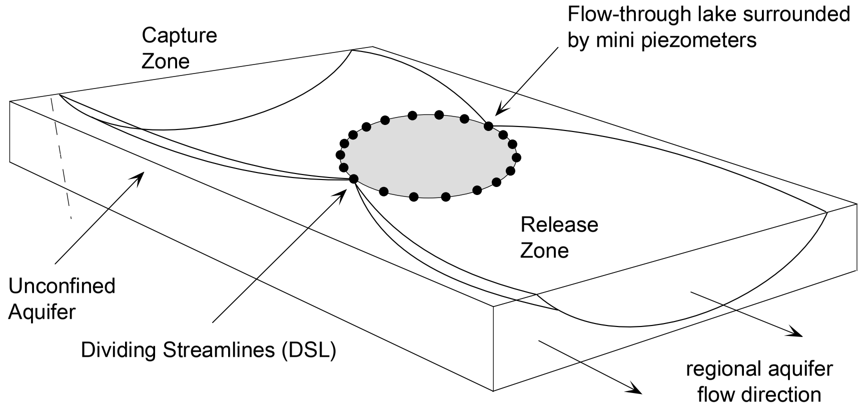
- During the period November 17-20 the dividing streamline position was observed to oscillate between mini piezometers MP 9 & 10. The reason for these small shifts is not known but is probably related to nearby pumping.
- Between November 20 & 29 the southwest section of West Lake detaches from the main lake. The dividing streamline immediately shifts position.

Dividing Streamlines Defined using Mini Piezometers Figure 7.10

Notes:

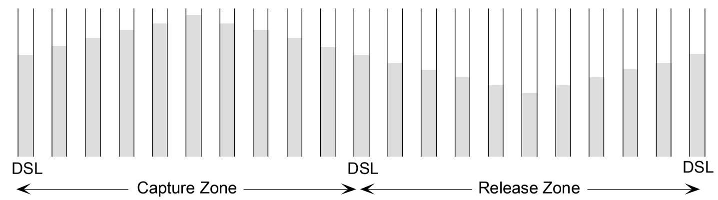
Model assumes a homogeneous aquifer and distribution of lake lining with all piezometers installed to same depth and position relative to shore

In a flow-through lake, the dividing streamlines occur where the piezometric head is equal to the lake surface



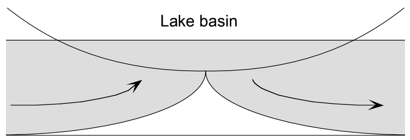
3-D sketch adapted from Townley et al (1993b) p39

Piezometer Response



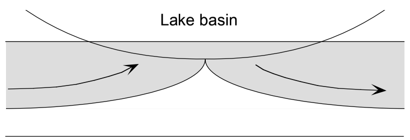
Transition in Flow Patterns as Flow-Through Lake Dries Out

A



Lake basin completely flooded, influence of positive and negative piezometric pressure extends well beyond the lake basin

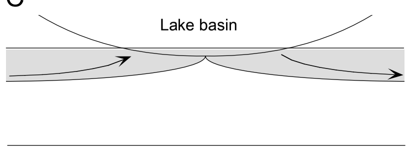
B



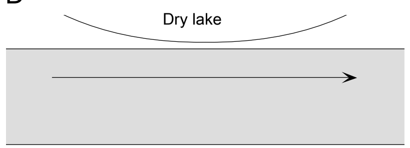
As the lake shrinks, areal influence of the locally induced positive and negative heads becomes smaller and smaller.

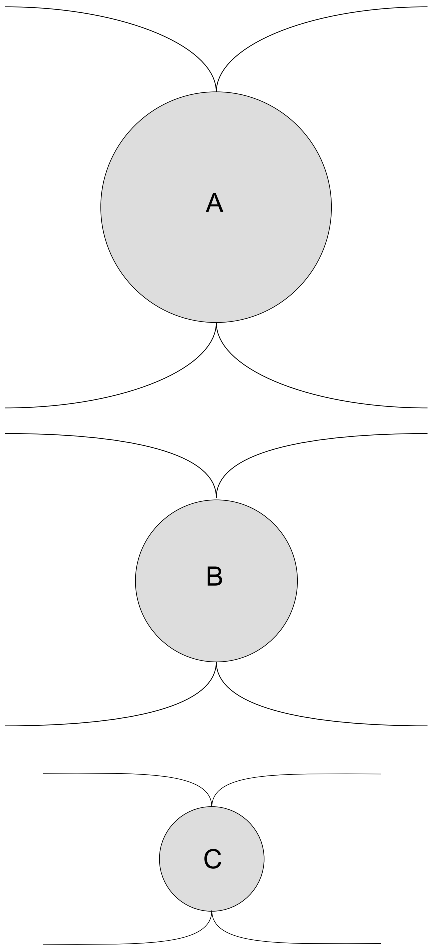
As dryness is achieved, horizontal flow is re-established in aquifer

C



D



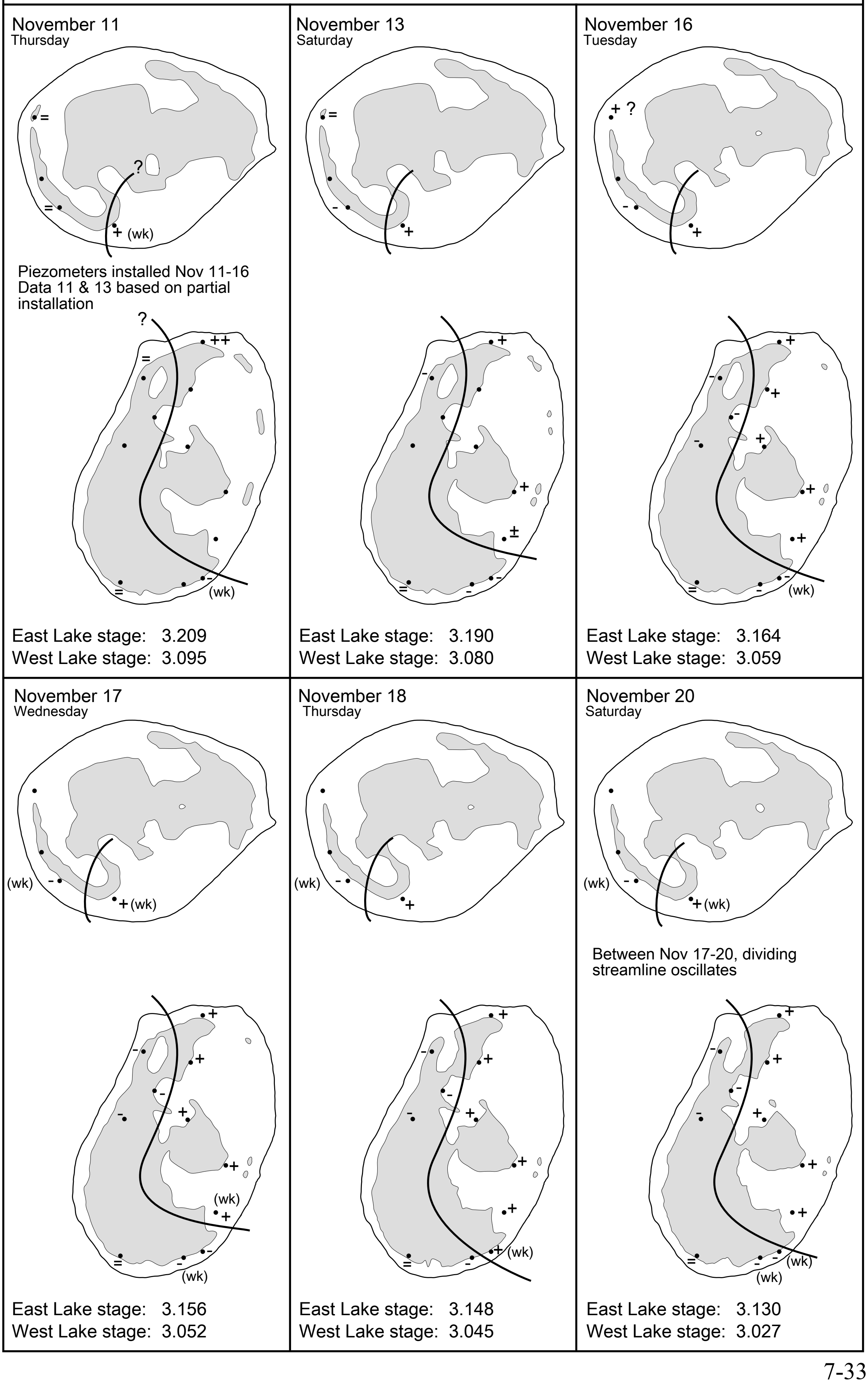


These patterns help explain why piezometer nests adjacent to the lake basins did not respond to flow regimes in the lakes whereas much shallower mini piezometers within or at the lake shore displayed large differences in piezometric head

Sketches adapted from Townley et al (1993b) p71

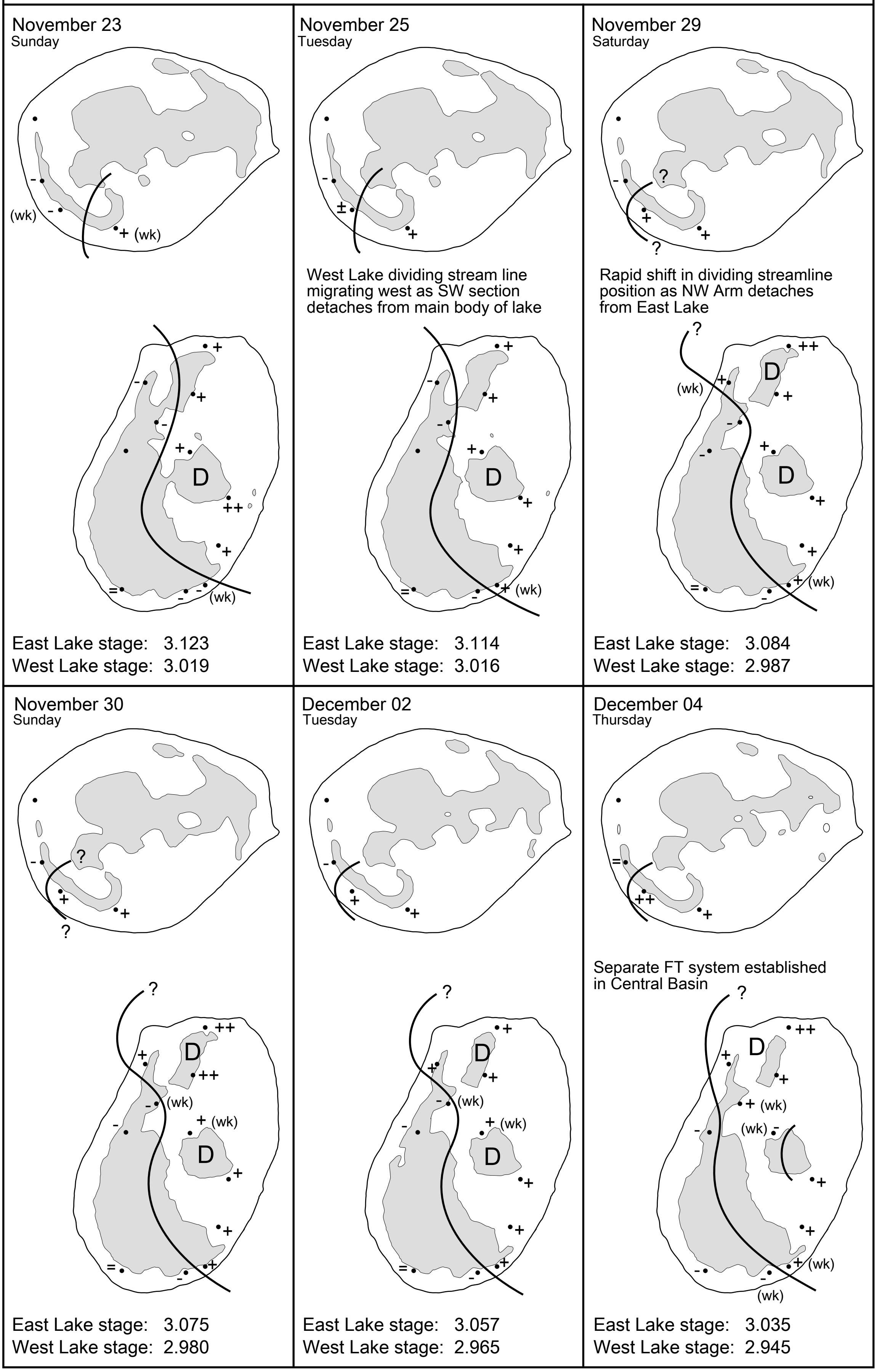
Dividing Stream Line Migration

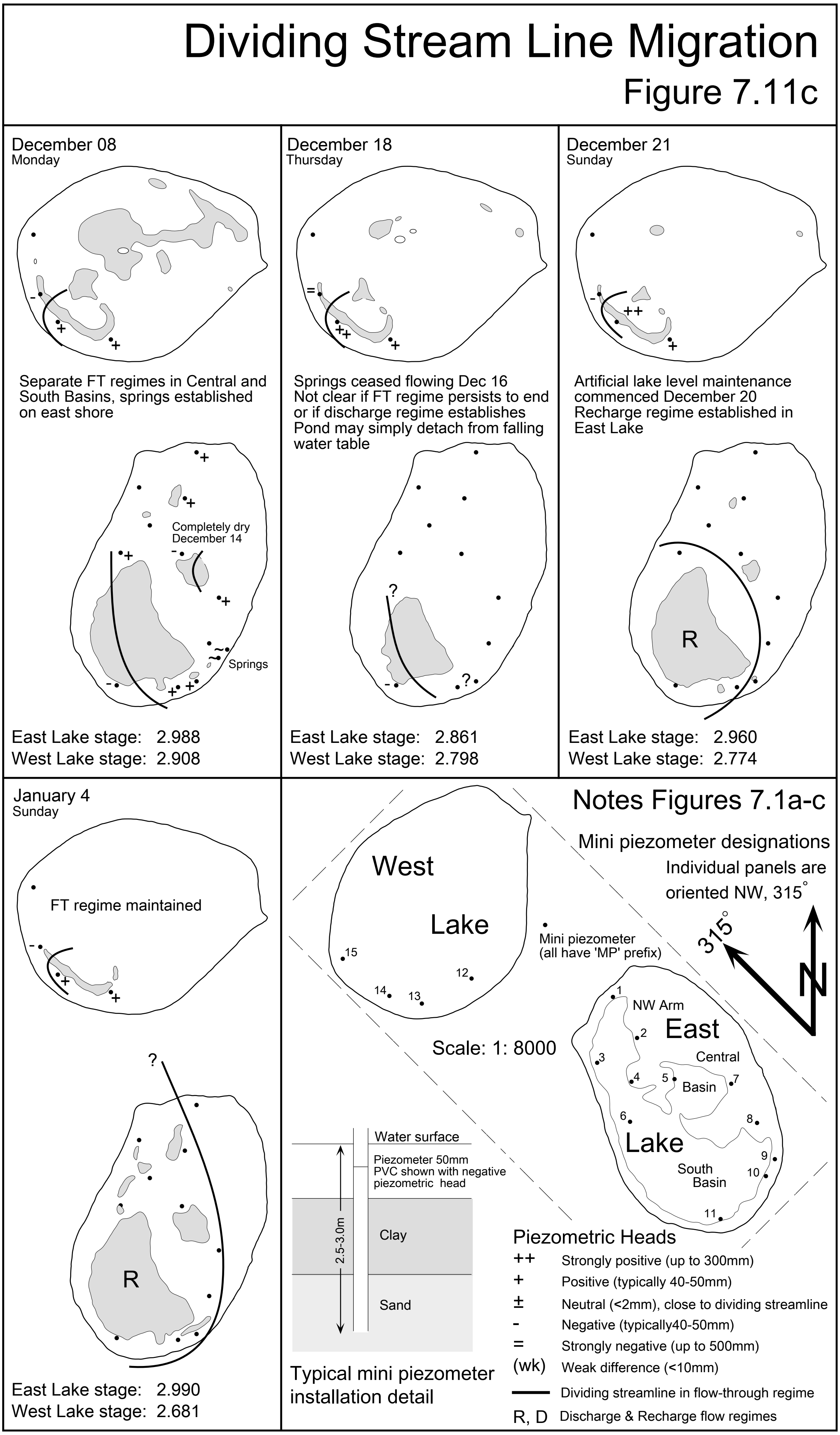
Figure 7.11a



Dividing Stream Line Migration

Figure 7.11b





Dividing Stream Line Migration
Figure 7.11c
December 08
Monday
Separate FT regimes in Central and South Basins, springs established on east shore
Completely dry December 14
Springs
East Lake stage: 2.988
West Lake stage: 2.908
December 18
Thursday
Springs ceased flowing Dec 16
Not clear if FT regime persists to end or if discharge regime establishes
Pond may simply detach from falling water table
East Lake stage: 2.861
West Lake stage: 2.798
December 21
Sunday
Artificial lake level maintenance commenced December 20
Recharge regime established in East Lake
R
East Lake stage: 2.960
West Lake stage: 2.774
January 4
Sunday
FT regime maintained
R
East Lake stage: 2.990
West Lake stage: 2.681
Notes Figures 7.1a-c
Mini piezometer designations
Individual panels are oriented NW, 315°
315°
N
West Lake
Mini piezometer (all have 'MP' prefix)
Scale: 1: 8000
NW Arm
East
Central Basin
Lake
South Basin
Water surface
Piezometer 50mm PVC shown with negative piezometric head
2.5-3.0m
Clay
Sand
Typical mini piezometer installation detail
Piezometric Heads
++ Strongly positive (up to 300mm)
+ Positive (typically 40-50mm)
± Neutral (<2mm), close to dividing streamline
- Negative (typically40-50mm)
= Strongly negative (up to 500mm)
(wk) Weak difference (<10mm)
Dividing streamline in flow-through regime
R, D Discharge & Recharge flow regimes

- Between November 23 & 29 the Central Basin separates from East Lake. This separate pond then functions as a discharge ('D') lake for about 10 days until a separate flow-through ('FT') regime establishes. This separate FT regime does not appear to form until the principal dividing streamline has shifted west in response to detachment of the northwest arm about November 29. The detached section of the northwest arm also becomes a discharge lake.
- Between December 2 and December 8, the principal dividing streamline in East Lake continues to shift west as the lake shrinks and mini piezometers 4 & 6 develop positive heads. By December 8 the position of the dividing streamline suggests the lake may approach the FT 3 or FT 5 flow regimes of Nield *et al* (1994). A similar FT regime persists in West Lake.
- Once artificial level maintenance commenced December 20, a permanent recharge regime was established in East Lake. In West Lake a flow-through regime (possibly FT 3 or FT 5) was maintained into January 1998 when observations ceased.

As the East Basin detached separate water samples were collected daily and analysed for deuterium. This data plotted along with the routine South Basin sampling is plotted in Figure 7.12. The initial three samples were enriched relative to the South Basin. Rainfall November 22 disrupted the experiment. It was expected that under discharge conditions an influx of isotopically depleted groundwater might be observed. This would have an isotopic signature similar to that observed in the upper portions of the aquifer in N3 (Table 6.7), typically about -11‰. Isotopic enrichment of the water through evaporation however appears to predominate over any discharge which is probably minimal given that the lake lining here is 1.0 to 1.4m thick.

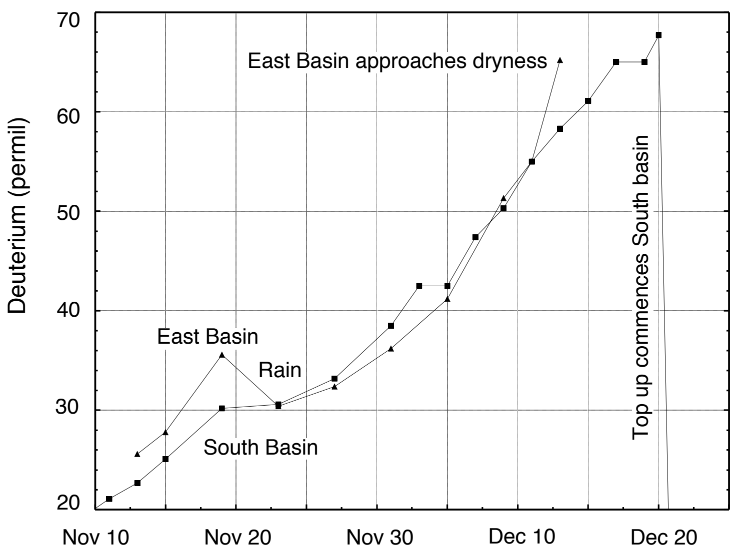


Figure 7.12 Deuterium enrichment East and South Basin. Transition from discharge to flow-through (December 4) is not evident in the data. When last sampled on December 13 the East Basin was a small pool 5x5m and 20 to 30mm deep. By December 14 it was dry

The vertical piezometric head differences observed in the mini piezometers are much greater than those observed in the large piezometer nests. Around the southern end of East Lake groundwater head differences of up to 0.7m were observed in mini piezometers only 100m apart, separated by the dividing stream line. The results indicate that when a small lake approaches dryness, the piezometric effects of lake-aquifer interaction become extremely localised. These observations agree with theoretical modelling (Townley *et al* 1993b, p28) which showed that maximum seepage in flow-through lakes occurs at the lake edge, and that this effect is enhanced by a resistive lake lining.

Townley *et al* (1995) hypothesised that as levels dropped in spring, East Lake might under go a transition from flow-through to discharge regime (Figure 7.5) prior to the commencement of summer artificial recharge. No such transition was observed. Rather flow-through regimes were maintained virtually to lake extinction. The only exceptions were the detached sections of the lake isolated up gradient which did become small discharge ponds. In the East Basin this persisted for about 12 days before a small local flow-through regime was established (Figure 7.11b). Once such a separate flow-through regime is established the two pools represent a miniature example of cascading flow through lakes where enriched waters in the release zone of one lake are captured by the adjacent down gradient lake and further enriched. Townley *et al* (1993b) illustrate a larger scale example from Lakes Pinjar and Nowergup. Figure 7.7c illustrates schematically the probable flow regime detail over the period November 25 to December 14 1997. Lakes on the Swan Coastal Plain which continue to hold water during January and February when evapotranspiration is greatest may undergo transition to discharge regimes, but such changes were not observed in the main body of East Lake as it approached dryness.

Springs and Seeps

Springs and seeps are commonly observed close to the up gradient shores of flow-through lakes on the Swan Coastal Plain (Allen 1979, Hall 1985). As levels declined in East Lake, two small springs developed along the east shore and persisted for about 10 days (December 08 panel, Figure 7.11c). The spring water is isotopically enriched (Table 7.5) suggesting that it is derived from the top of the aquifer where lawn irrigation and high evaporation off the adjacent playing fields probably produce strongly fractionated recharge.

Table 7.5 Deuterium analyses, East Lake Seeps

Date	Sample	Deuterium ‰
Dec 9	SP 1	48.7
Dec 11	SP 2	54.1
Dec 15	SP 3	56.5

7.2.5 Lake Sediment Thermal Profiling

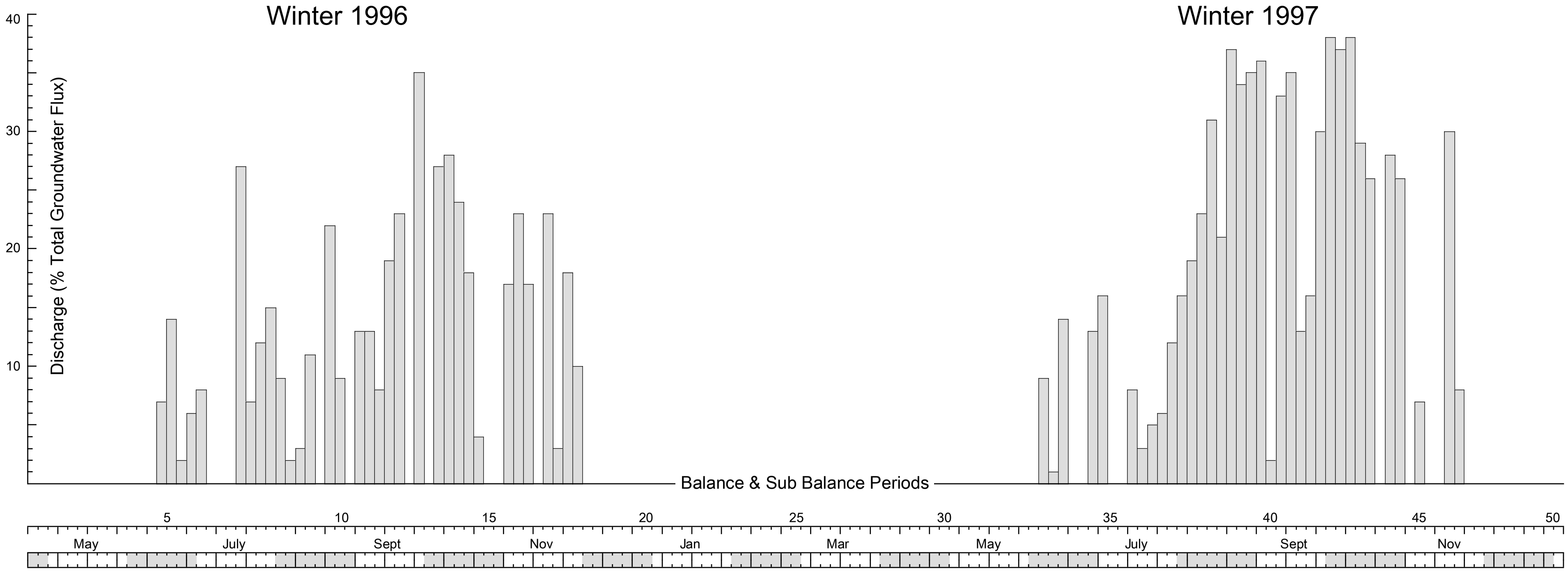
Groundwater maintains an almost constant temperature throughout the year. Lake water on the other hand displays large temperature variations over a year. Changes in flow regime therefore induce distinctive patterns in the thermal gradients below lakes. These are the subject of Chapter 9.

7.2.6 Water Balances

It is clear from the hydrograph and in-lake piezometer data that storm water, top up and intense groundwater extraction combine to make Perry Lakes a very dynamic lake-aquifer system. Reverse flow zones induced from heavy pumping may last just a few hours. In the lakes, oscillation between flow-through and recharge regimes, as a result of storm water inputs, may similarly last a few hours or several days. The integrated water balances, however, provide the best overview of lake-aquifer flow status. Balance results for December 1997 show that while piezometric data may indicate flow-through status (or at least piezometric heads conducive to flow-through) once the water is retained in the deeper clay lined portions of the lake basin the amount of water discharged becomes so small as to be non quantifiable using the integrated balances. Despite the presence of positive and negative piezometric heads, a lake is really only in a flow-through state if water is actually being discharged and recharged, in other words if there is a measurable groundwater flux through the lake.

In Chapter 6 balance results were presented (along with all other components of the balance) as 12 to 20 day 'balance period' data. If we consider only the groundwater flux components and use the more detailed four day sub balances we can obtain considerably greater detail about gross lake-aquifer status. In Figure 7.13 four day balance discharge and recharge data is presented. This is basically an integrated overview of lake-aquifer interaction over two winters and one summer. The histograms plot East Lake discharge as a percentage of groundwater flux (discharge from the aquifer and recharge to the aquifer) for all 155 four day sub balances. Where a histogram is absent, the lake was in recharge flow status (discharge equal to zero). The presence of a histogram indicates a four day sub balance in which there was measurable groundwater discharge using integrated mass-solute-isotope balances.

It is important to remember that in summer the regional water table declines naturally. As the water table declines so too do the levels in any associated water table lakes. Any mass balance must take into account all water lost and that includes water which leaves the lake due to surrounding water table decline. Therefore in summer a lake may be in



Notes

Histograms plot discharge as a percentage of total groundwater flux. Percentage flux (rather than absolute discharge water mass) is plotted because of the huge seasonal changes in lake volume (and hence discharge volume). Discharge is plotted for all 155 four day sub balances. Where vertical bars are absent East Lake was in recharge flow status (discharge equals zero). The presence of a bar indicates a four day sub balance in which there was a measurable groundwater discharge using integrated mass-solute-isotope balances. In other words periods in which East Lake was in flow-through status with measurable discharge.

The mini piezometers indicated flow-through status for some periods not indicated with vertical bars. This is because a lake is really only in flow-through status if water is actually being discharged and recharged, ie there is a measurable groundwater flux through the lake.

Refer Appendix 6.2 for sub balance details.

Flow Regime Summary East Lake 1996 - 1998

Figure 7.13

flow-through status but with constantly falling lake levels. In this case the recharge component of the groundwater flux will generally be far greater than the discharge component because it must include all water lost as the surrounding water table declines.

7.3 FLOW REGIMES AT PERRY LAKES

7.3.1 Development of Flow Regime Contour Plots

In addition to the nested piezometers only a few of the monitoring wells in Perry Lakes Reserve were equipped with data loggers. With reference to Figure 7.15a and Appendix 2.1 these were PL1, W1, W3, W5, PL2, W15, W17, W18, W20, W21 and W25 (Camel Lake). Hydrograph data from these wells was augmented with manual readings from an additional 19 wells within Perry Lakes Reserve and 11 regional wells within a 2km radius of East Lake. These included a monitoring well within the grounds of the CSIRO complex, two wells within the UWA Field Station, GE1 in Bold Park, an abandoned production well at City Beach High School, a disused government monitoring well on Lemnos Street, two wells in McLean Park, a well adjacent to the Floreat tennis courts, one well in McGillivray playing fields and one well in Henderson Park. SWL in all wells was read manually weekly. These data comprise Appendix 7.1. The data from the regional wells were important as they imposed accurate boundary conditions for detailed water table contouring within the area of interest. Contours were generated in SURFER using a kriging routine on 10x10m grids. East and West Lake were set as constant head boundaries at the 0800hr stage. The local effect of irrigation wells was known to be large as evidenced by the persistent pumping induced reverse flow zones identified in the hydrograph data (Figure 7.9 a&b). The effects of pumping wells were imposed on the contours by estimating the form and boundary heads of the depression cones.

On a sloping water table the cone of depression of a pumping well will approximate an eccentric ellipse (Bear 1972, p323) with water table contours distorted around the well (Figure 7.14). Using pump test drawdown data for P1 and similar data logger hydrograph records for P5 from wells W18 and W20, drawdown curves (drawdown vs distance from pumped well) were developed for pumping times up to 10 hours. These two wells are representative of the two principal well types at Perry Lakes , which have different irrigation and open pipe outputs as summarised in Table 7.6.

Table 7.6 Irrigation well characteristics, Perry Lakes

Bore	Wells	Irrigation Rate	Top Up (measured)
Submersible	P1	$55m^3/hr$	$110.5m^3/hr$ - $120.7m^3/hr$
Turbine	P2-P8	$38m^3/hr$	$74m^3/hr$-$79.5m^3/hr$

Irrigation rate is manufacturer's rated output into typical pressurised distribution system
Top up rate is output measured with flow metres into non pressurised pipe during lake top-up, bores P1 & P6

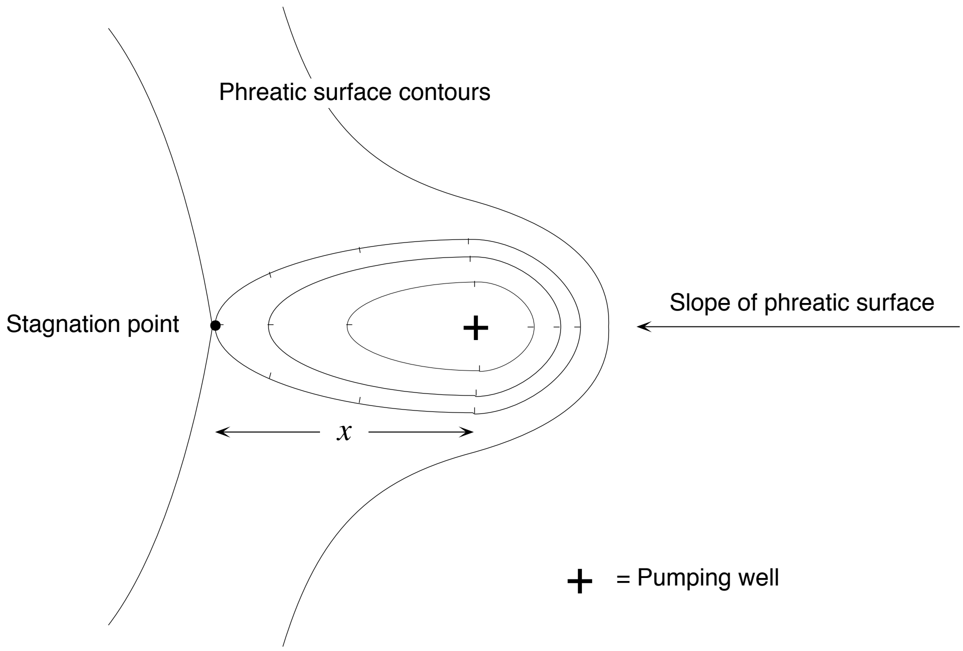


Figure 7.14 General form of the cone of depression from a pumping well superimposed on a sloping phreatic surface (after Bear 1972 Figure 7.8.10).

Theoretical distance x to the stagnation point is given by Todd (1959) as

$$x = -\frac{Q}{2\pi Kbi} \tag{7.2}$$

where Q is discharge rate ($m^3\ d^{-1}$), K is hydraulic conductivity ($m\ d^{-1}$), b is average saturated aquifer thickness (m) and i is natural water table slope. Table 7.7 shows theoretical equilibrium values for x at typical lawn irrigation and top up rates.

Table 7.7 Distance to stagnation point x

Hydraulic Cond K ($m\ d^{-1}$)		15	20	25	30
Discharge (hour)	Discharge (day)	x (m)	x (m)	x (m)	x (m)
$38m^3\ h^{-1}$	912	262	196	157	131
$55m^3\ h^{-1}$	1320	379	284	227	189
$75m^3\ h^{-1}$	1800	516	387	310	258
$120m^3\ h^{-1}$	2880	826	619	496	413

Slope set to 0.001 which is average phreatic surface slope around Perry Lakes, b set to 37m

For each contour period a stagnation point elevation was estimated and an ellipse of x = 100m (P2-P8) and 200m (P1) set as a constant head boundary in SURFER. Where P3-P4-P5 were pumping simultaneously, the outline of superimposed ellipses was used. In many cases the position of the stagnation point can be closely estimated from monitoring wells. This, when compared to Table 7.7 suggests that the effective hydraulic conductivity for wells pumped in the basal sands and monitored at the phreatic surface approaches 30m d^{-1}. This is very close to the 27m d^{-1} estimated in Chapter 3 from steady state pump test data.

Data for 17 February to 5 May 1997 were collected on Mondays while irrigation bores were operating to maximise the combined 'artificial' effects of weekend top up and weekday lawn irrigation. There was no lawn irrigation over the period 2 June to 12 October during which data was generally collected on Sundays. 'Unnatural' flows during this period were induced solely by storm drain input.

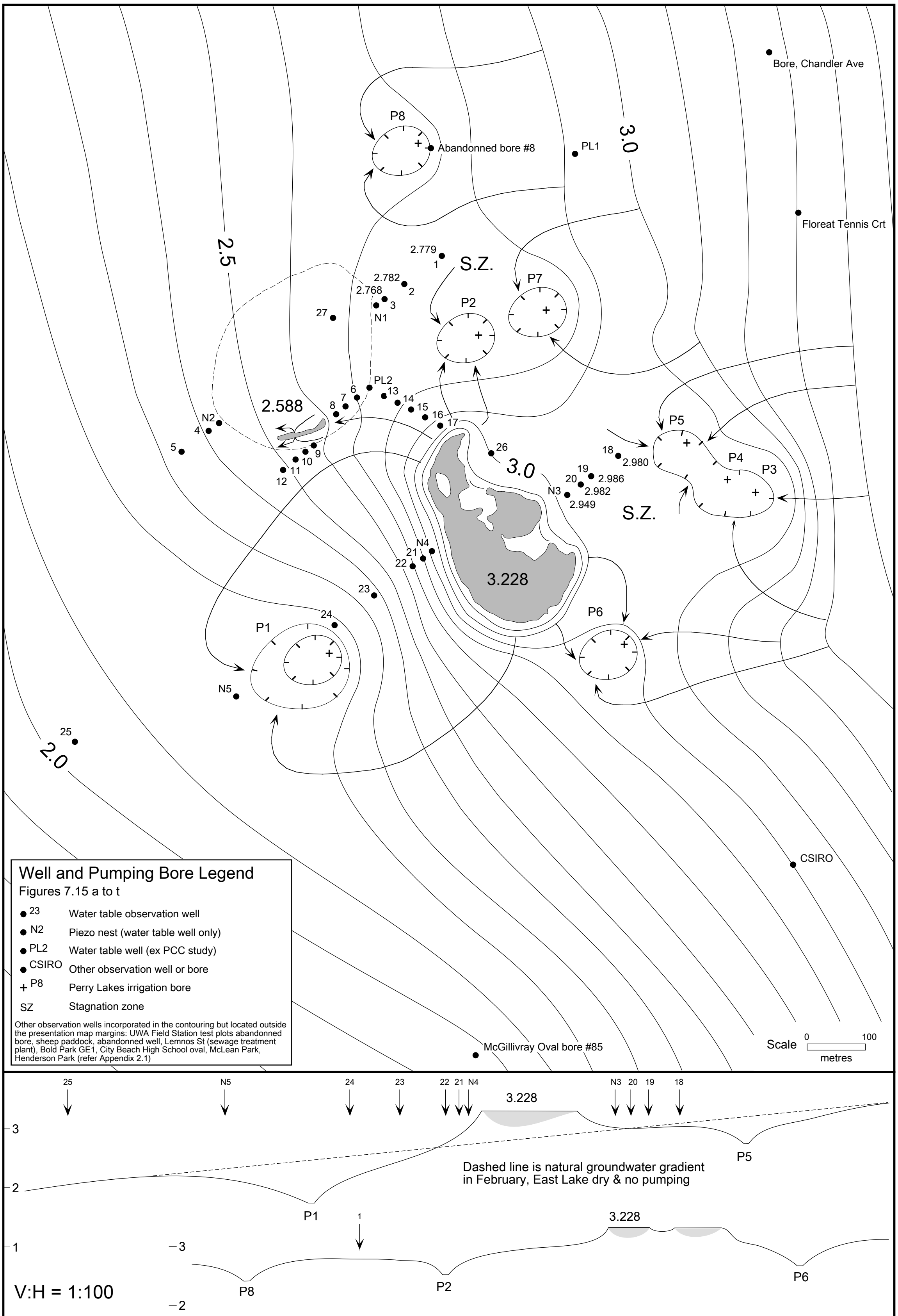
Weekly water table contour plots with flow nets were generated of which 20 are presented here. These are 'snapshots' of a continuum of both natural and artificially induced flow patterns reflecting wetland response to natural and artificial stimuli over a period of one year. Each plot represents average conditions over about 6 hours (the average time taken for one person to measure all monitoring wells). They are therefore not truly steady state and contain unavoidable time effects. These effects were minimised by always reading bores in the same order and starting about six hours after irrigation pumping commenced.

7.3.2 Results

Late summer top up and irrigation pumping

Figure 7.15a illustrates a typical mid summer Monday morning pattern. Wells P1-P7 have all been operating since the previous Friday evening topping up East Lake and now (in addition to P8) are being used for lawn irrigation. East Lake is a local water table mound. It is elevated 0.3 to 0.5m above the natural position of the groundwater surface (section through P1 & P5). The local mounding is enhanced by cones of depression around the pumping bores. These cones of depression surround East Lake on all four sides (refer sections). The plan and cross sections illustrate the long standing difficulty which has plagued managers attempting to maintain Perry Lakes as viable wetlands by topping up from local bores. The harder the pumping the greater the head difference between the lake and the natural water table. When these same bores are used for lawn irrigation during the week, the cones of depression create an even greater head difference relative to East Lake which drains away even faster.

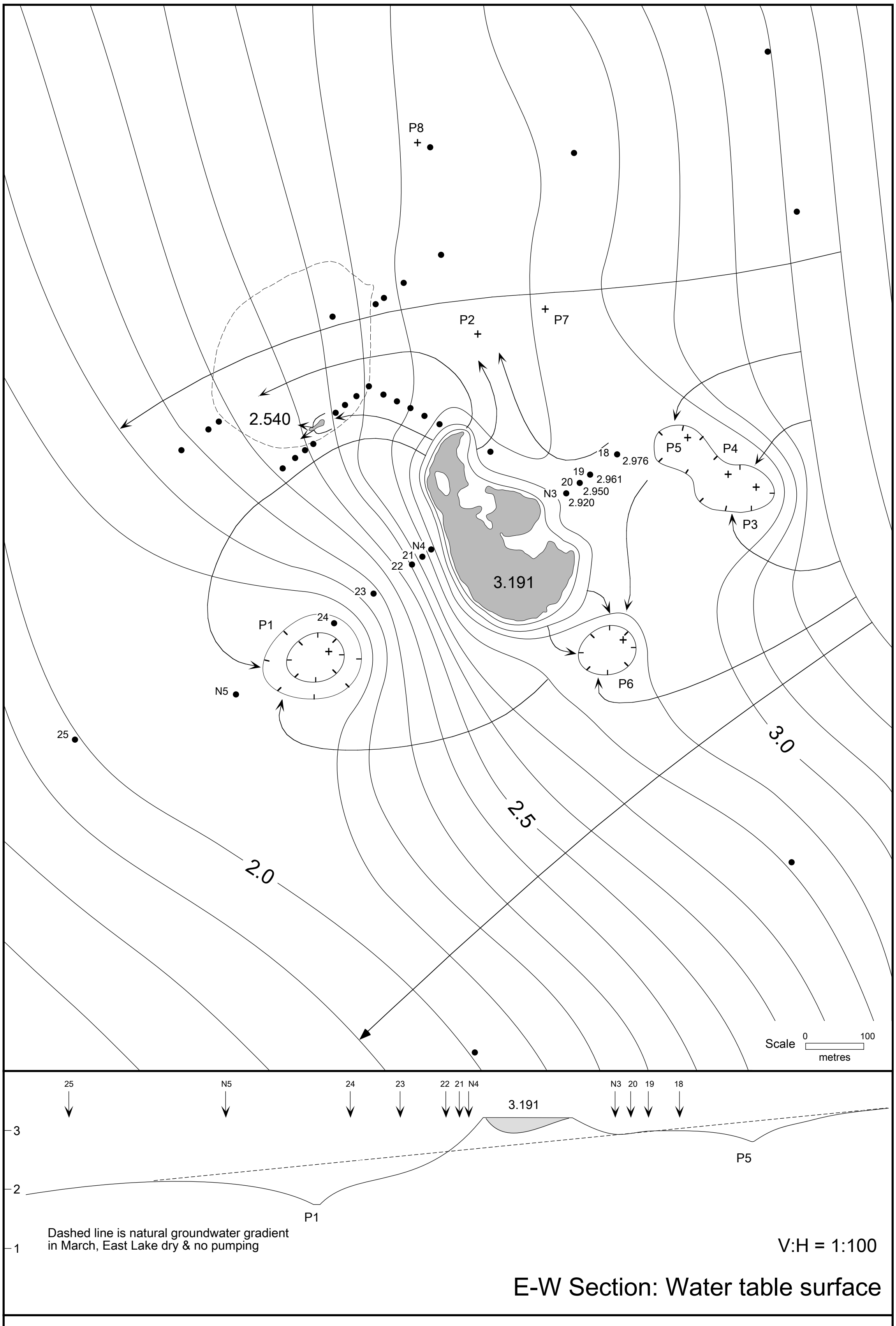
In this example the water table between East Lake and P3-P5 becomes almost flat with a stagnation zone close to W19. Recharge from East Lake is drawn towards P2 and P6 along with inter-lake flow into West Lake. This example is typical of extreme summer conditions in which East Lake has only recently been topped up and every irrigation bore is operating.



February 17, 1997 Flow Regimes: East Lake = R West Lake = F-T Figure 7.15a

Monday, all irrigation pumps operating following weekend top up pumping into East Lake. The natural water table lies about 0.3m below the deepest portion of East Lake which would normally have been dry by late December. East Lake is not only locally mounded by about 0.5m but also surrounded by cones of depression around the bores. The plan and cross sections illustrate the long standing difficulty which has plagued the wetland managers attempting to ensure some water in East Lake over summer by pumping from local bores. Water can only be maintained by persistent pumping. The harder the pumping, the greater the local head and groundwater gradient between the lake and bores and the faster water drains from the lake.

When P2 & P7 are turned off, flow lines from the NE sector of East Lake pass through vicinity of piezo next N1. This in part may explain the isotopic enrichment east of West Lake.



March 3, 1997 Flow Regimes: East Lake = R West Lake = F-T Figure 7.15b

Monday, the irrigation pumps operating are the same pumps used over the weekend to top up East Lake. This pattern is identical to that occurring during top up. SWL from wells 18-20 & N3 confirm there is a shallow divide between well 18 and the zone of depression around bores 3-5. The situation is similar to February 17, with operating bores increasing the effective head in East Lake.

West Lake has shrunk to almost the seasonal lowest point (absolute low was 2.511 on March 16 when top up was initiated in West Lake). A flow-through regime persists with ratio of recharge:discharge fluctuating as head between East & West Lake varies.

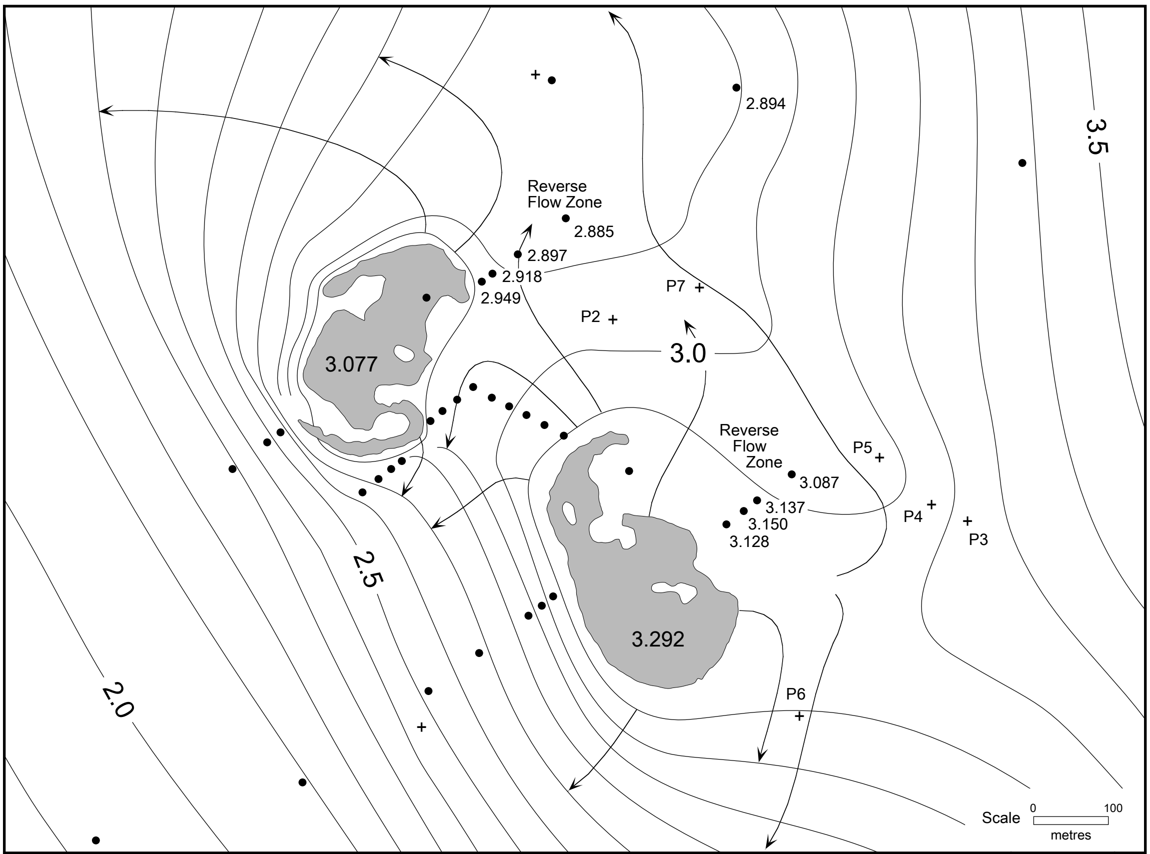
Figure 7.15b shows a similar Monday morning situation where the bores used to top up East Lake over the weekend have been left running and switched to lawn irrigation. P2, P7 and P8 have yet to be switched on.

Extreme summer storm events

Extreme summer thunderstorms can introduce more water in an hour than an entire weekend of top up. The example in Figure 7.15c is the Monday morning situation after a weekend of heavy rain and top up pumping. The wetland managers set the top up pumps to operate automatically over the weekend. Early Saturday morning heavy rain commenced which continued into Sunday. Early Monday morning the pumps have shut off but there remains remnant depressions around P2-P5. P6 and P7 were not operating. Both East and West Lake have filled and are mounded from storm water inputs. East Lake has also received top up water resulting in a head difference between the two lakes of 0.215m. Under normal winter conditions the two lakes have a natural head difference of about 0.1m. East and West Lake are in recharge, with a large release zone which extends beyond the boundaries of the map. The extreme head in East Lake results in flow lines which envelop West Lake. This was the largest example of a mutual release zone identified over 20 months of detailed monitoring.

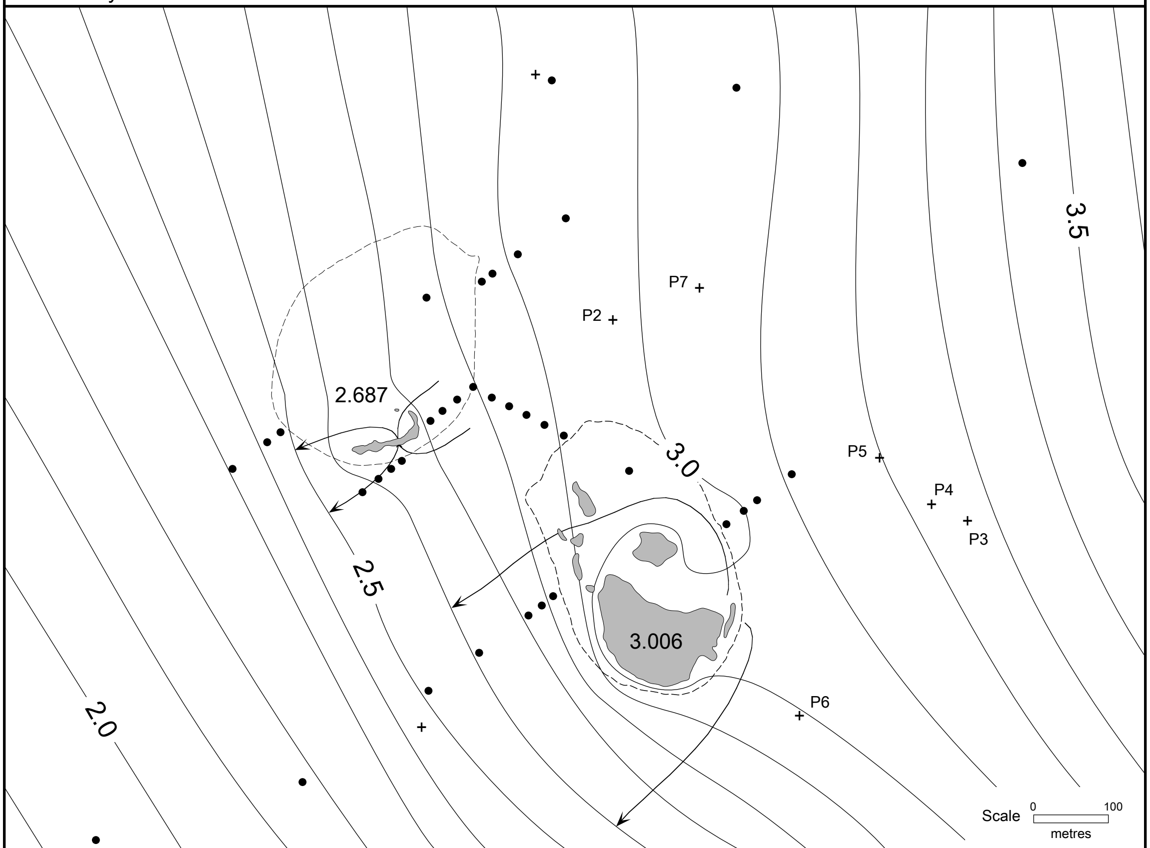
A similar situation occurred June 02 (Figure 7.15e). Here East Lake had received top up the previous week during the pump test May 27-29. This was followed by three days of heavy rain May 30 to June 1 totalling 73mm in the East Lake gauge. Despite the pump testing, head difference between East and West Lake was only 0.118m. Pumps P2-P8 had not been run for several weeks, so there were no pump induced depressions of the water table up gradient of either lake. This combined with the lower head difference between the lakes resulted in a smaller and less irregularly shaped mutual release zone than that mapped on March 31. A mutual release zone was predicted by Townley *et al* (1995) and appears to be a common early winter phenomenon which occurs in response to high stormwater flows into dry or nearly dry lake basins. Prior to the introduction of storm drains it is doubtful such flow patterns would ever have occurred.

Figure 7.15d shows the current 'normal' late summer and early winter flow pattern. East Lake is periodically maintained with top up and is in recharge flow state. This was generally restricted to just enough water to keep the South Basin flooded. The release zone is small and confined to the immediate vicinity of the lake. West Lake is confined to a small residual pond and is in flow-through status. There is no inter-lake flow despite the large inter-lake head difference of 0.319m.



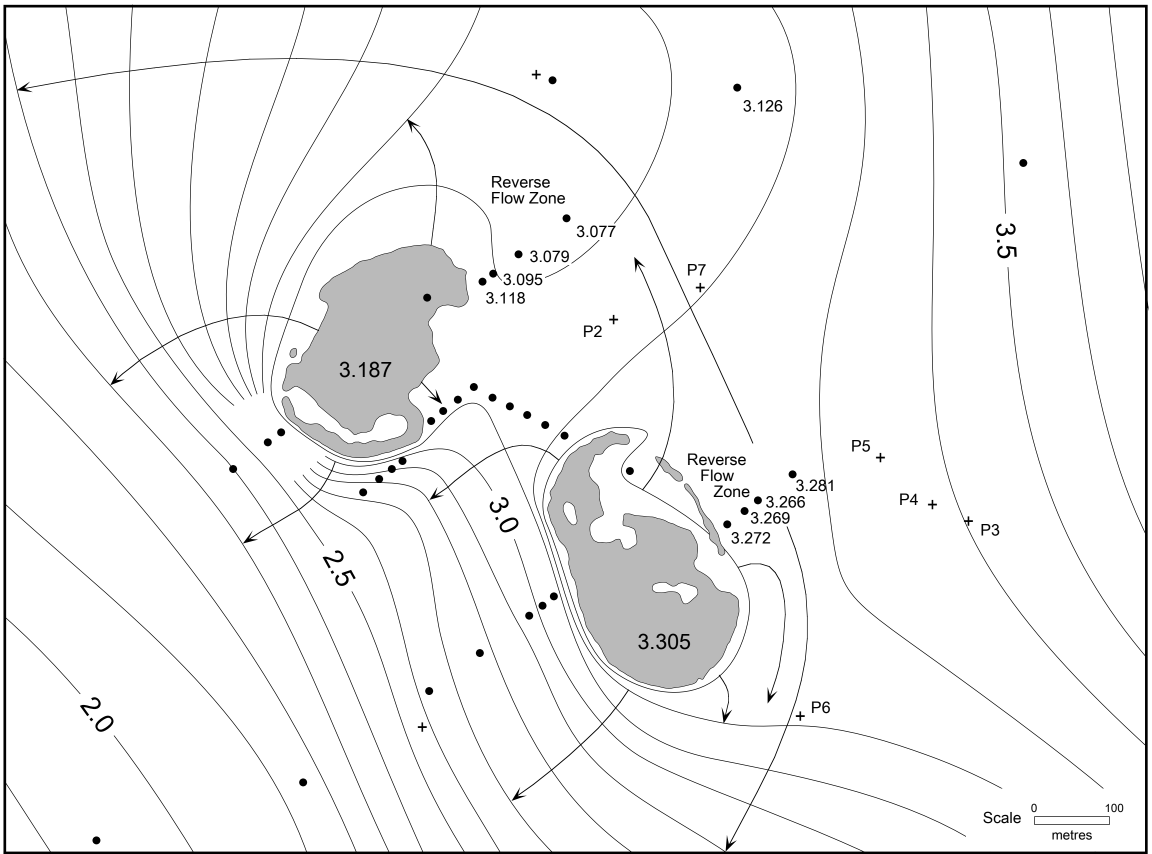
March 31, 1997 Flow Regimes: East Lake = R West Lake = R Figure 7.15c

Major rain event March 29-30 (63.8mm) coincided with top up to East & West Lakes. Contours reflect remnant pump induced groundwater depression with reverse flow from N1 to PL1 and N3 to 18. Low gradient zone beneath the Alderbury Flats has formed in response to mounding in West Lake, recent pumping in P2, P7 & P8 and direct recharge from heavy rain



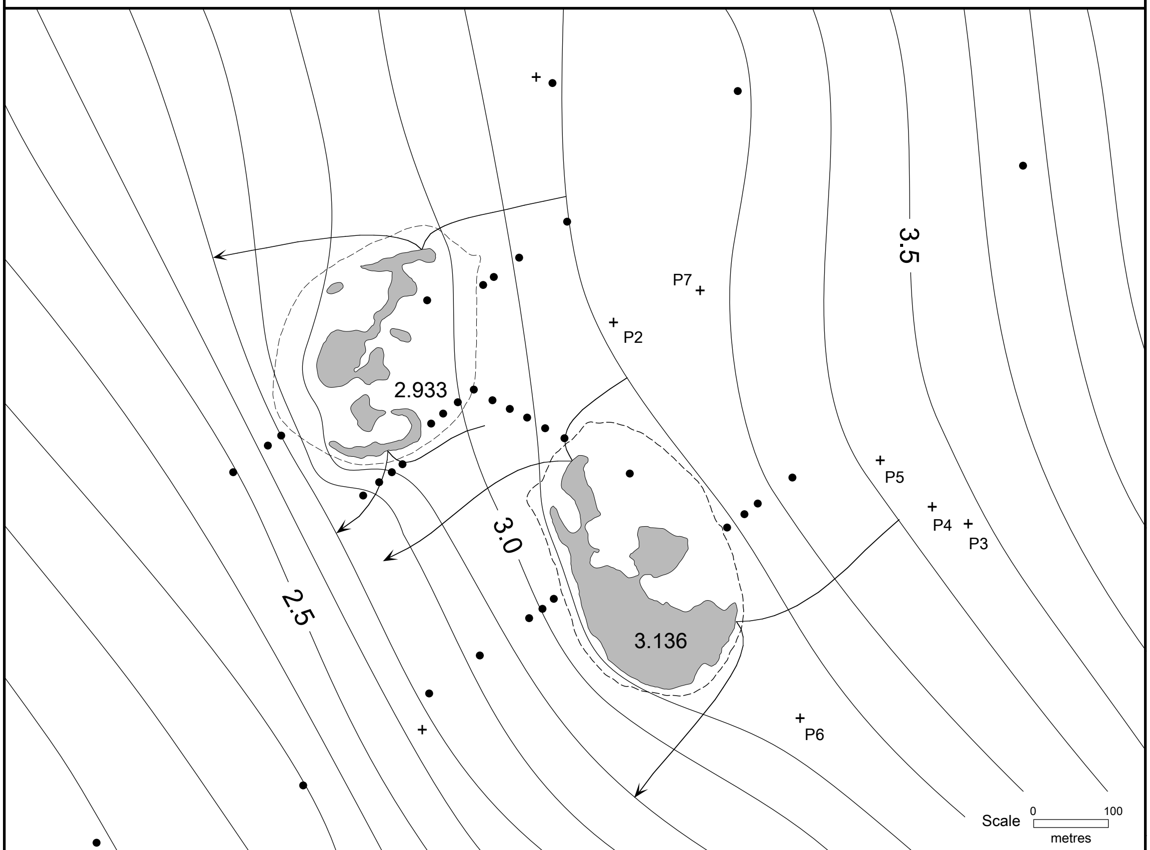
May 05, 1997 Flow Regimes: East Lake = R West Lake = FT Figure 7.15d

Following top up April 29 and rain May 1 & 3 (12.0mm) East Lake reverts to weak recharge status. West Lake remains a small flow-through pond. Storm drain inputs to West Lake seep into the NE section of the dry lake basin and do not reach the open water. Situation is almost identical to early summer (December 21b).



June 02, 1997 Flow Regimes: East Lake = R West Lake = R Figure 7.15e

Heavy rain totalling 73.0mm May 30-June 2 were preceeded by top up to East Lake (water discharged from 48hr pump test) May 27-29. Both Lakes are mounded, West Lake from storm water inputs only. This is an extreme case where the lakes share a common release zone. Extensive reverse groundwater gradients occur NE of both lakes.



June 30, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15f

Insignificant rain fell since June 11. Last top up to East Lake was June 15. Regional water table has risen sufficiently to recapture lakes. Weak flow-through regime established in both lakes. West Lake probably comprises a number of separate FT regimes in disjointed smaller ponds.

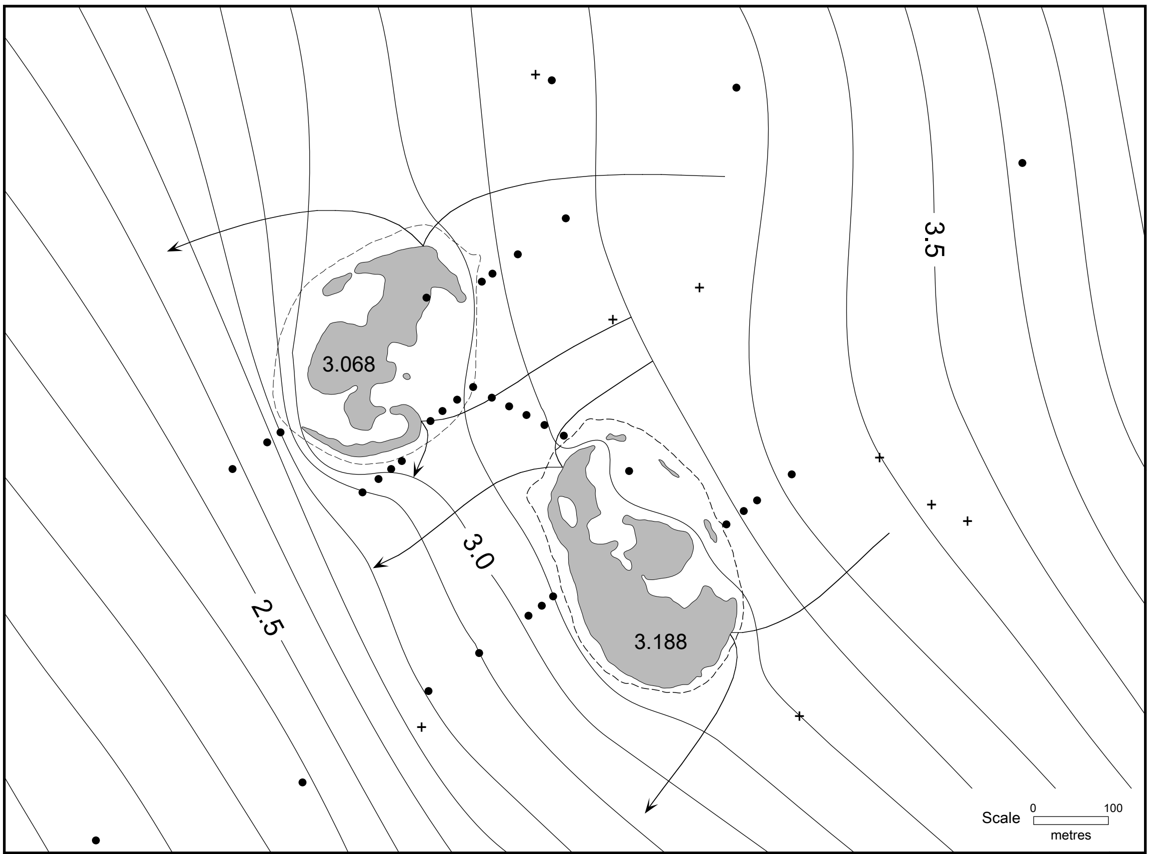
Establishment of natural winter patterns

Following further early winter rain a typical winter flow regime pattern is established in both lakes by late June (Figure 7.15f). The integrated balances (Figure 7.13) indicate that East Lake oscillated between recharge and flow-through status during June before settling into a permanent winter flow-through regime. Rainfall over winter 1997 was below average. Separate capture and release zones appear to have persisted until early August (Figures 7.15 g, h&i) although there is really insufficient monitoring well density to confirm this beyond doubt. Certainly by early September (Figure 7.15j) capture and release zones had coalesced This occurred before the lakes and local water table reached their peak winter elevation on September 10. Periodic storm water inputs shift both lakes towards (but never into) recharge status. Notice how the position of the dividing stream line at the north end of East Lake (constrained by the SWL in W17) shifts relative to the August 25 (Figure 7.15i) and September 15 (Figure 7.15k) positions. A similar shift occurs in West Lake. The up gradient excursion of the dividing stream line towards recharge status was in direct response to rain and storm water inputs several days earlier.

This pattern of common capture and release zones persisted into late October (Figures 7.15 l, m&n) and beyond the start of pumping for lawn irrigation October 20.

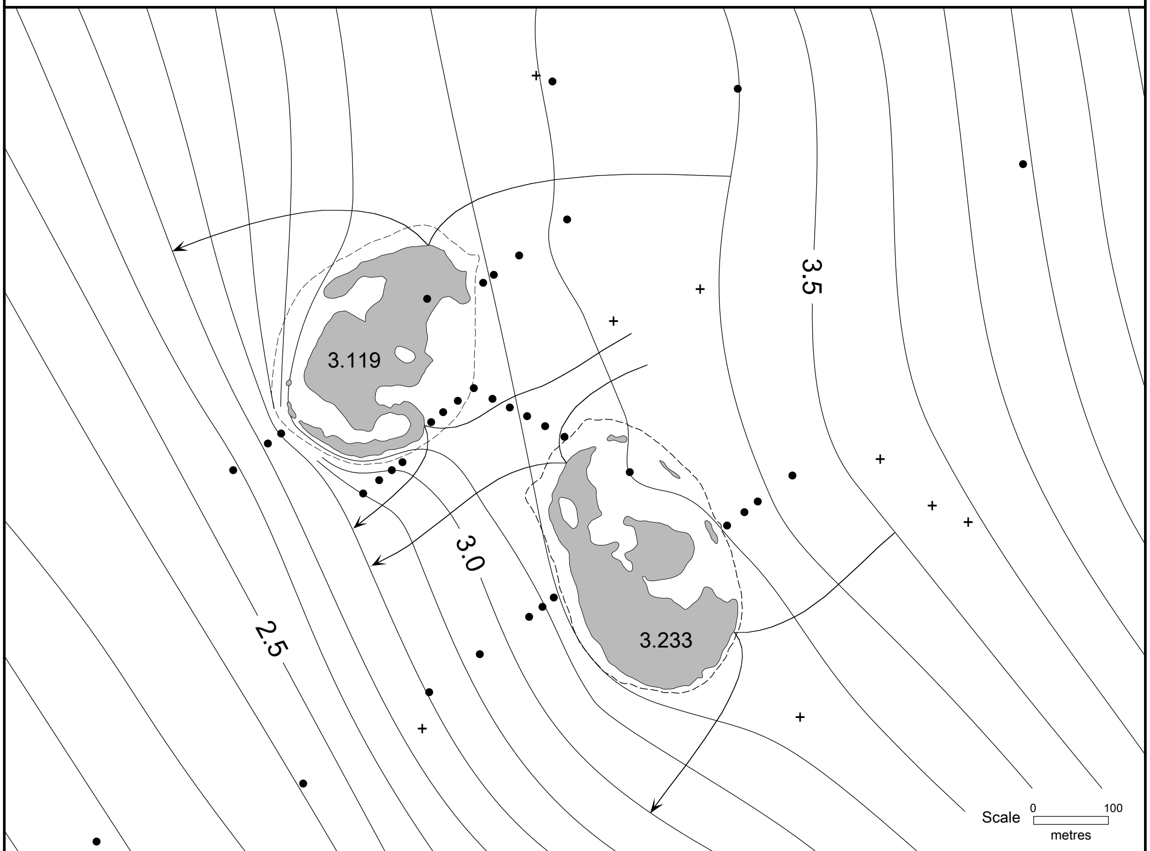
Shrinking lakes and the approach to dryness

In early November separate capture and release zones are re-established (Figure 7.15o). Monitoring well data was augmented from November 11 onwards by the detailed mini piezometer data (Figures 7.11 a-c). On November 23 (Figure 7.15p) West lake detached into two ponds and the Central Basin became hydrologically detached from East Lake with a local discharge regime becoming established. Three days later the NW Arm also detached and became (along with the Central Basin) local discharge basins sitting within the East Lake capture zone. By December 8 (Figure 7.15q), the East Lake capture zone had shrunk, and was now controlled only by the South Basin. A separate flow-through regime has established in the former Central Basin and the remnant pond which was formerly part of the NW Arm has become a discharge pond. West Lake is slowly approaching dryness and in so doing is breaking into a number of separate ponds, still encompassed by common capture and release zones. As these ponds approach dryness transient discharge regimes are established for a few days similar to those observed in East Lake (Figure 7.15r).



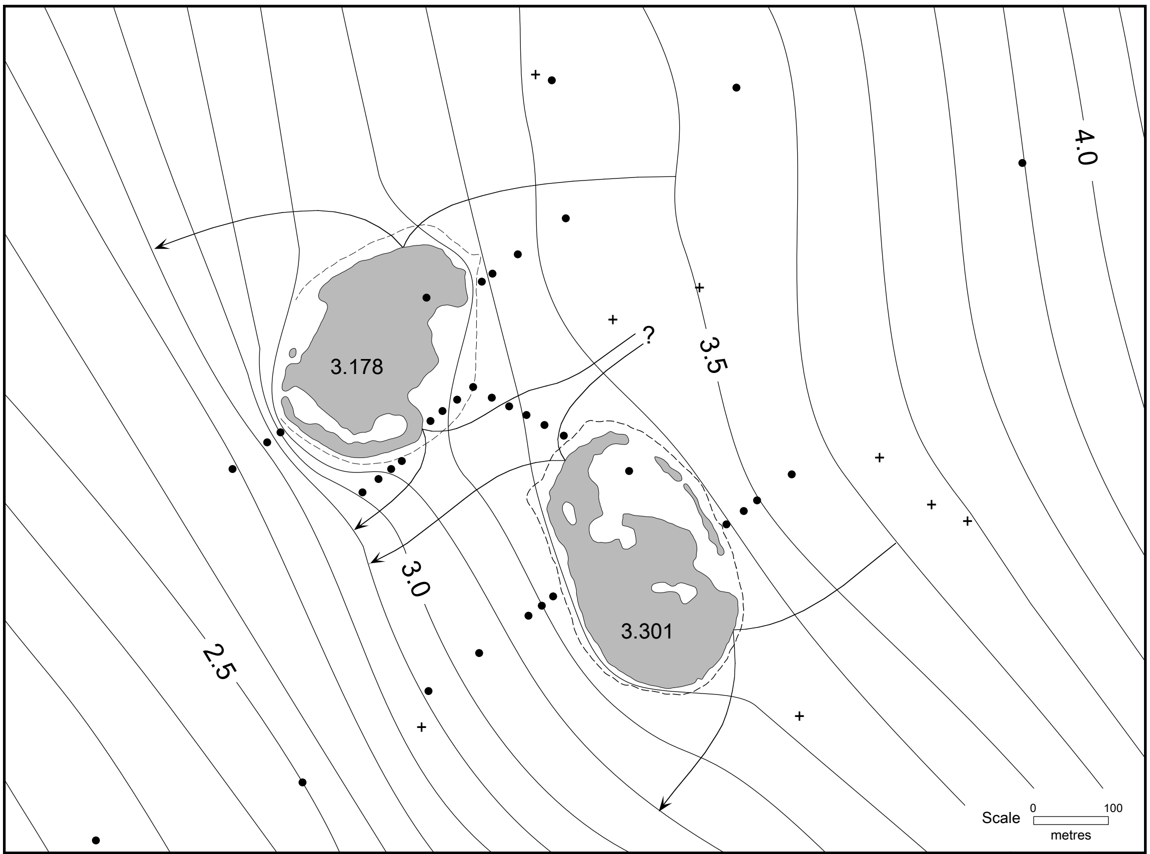
July 21, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15g

Dry conditions since July 13 when a 20.9mm rain event pushed lake levels to 3.157 & 3.240m. During this event FT flow status was maintained however the position of the dividing stream line shifted NE indicating an increased proportion of recharge to discharge. West Lake is on the verge of becoming a single, sinuous water body.



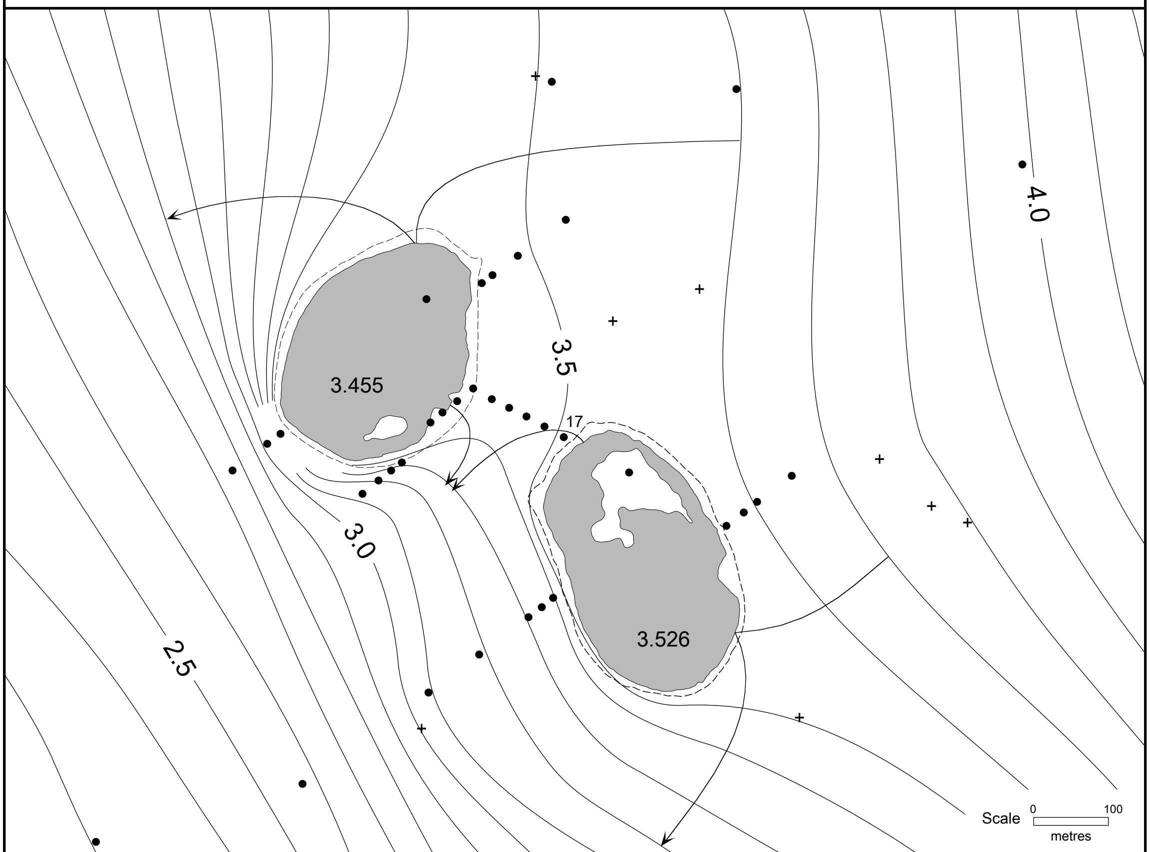
August 04, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15h

Lake levels rising slowly in response to regional groundwater rise. Stable winter flow-through regimes with separate capture and release zones established in both lakes.



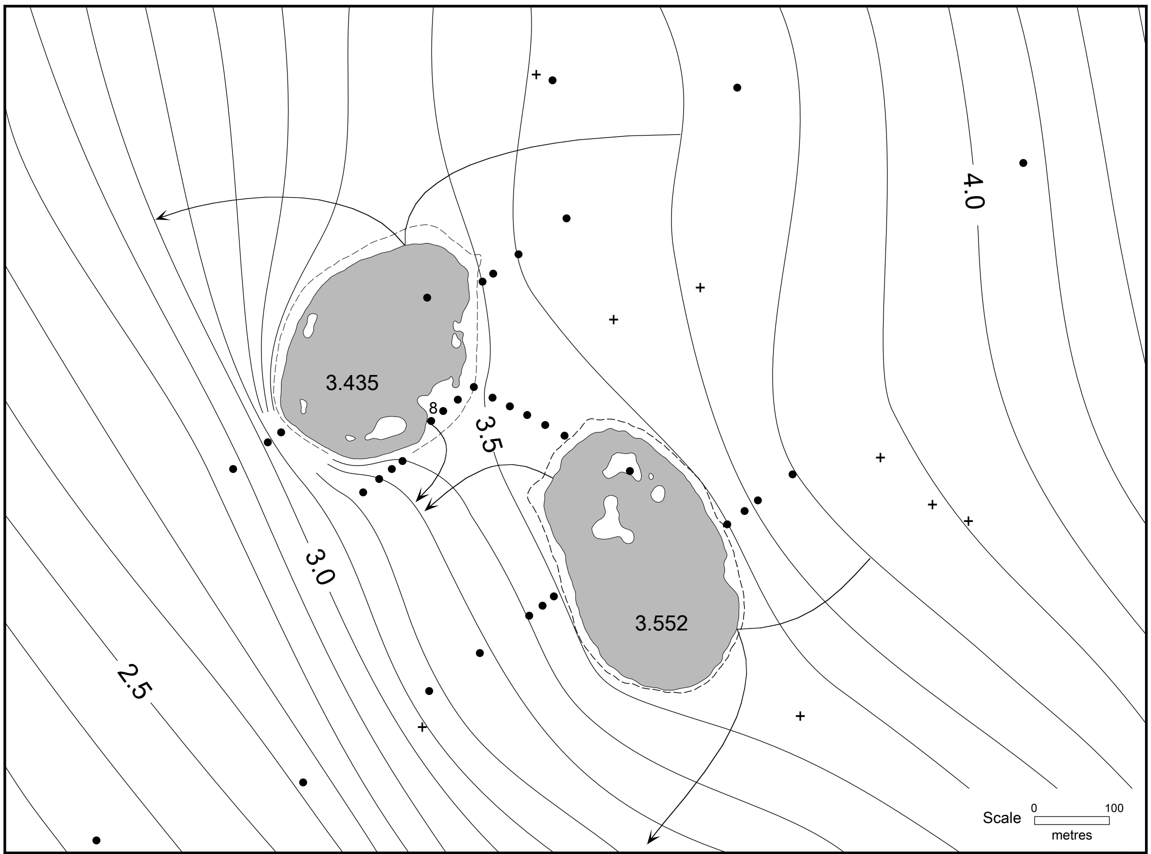
August 25, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15i

Levels rising in response to regional groundwater rise. No significant rain since August 14. Lakes exhibit stable winter flow-through regimes.



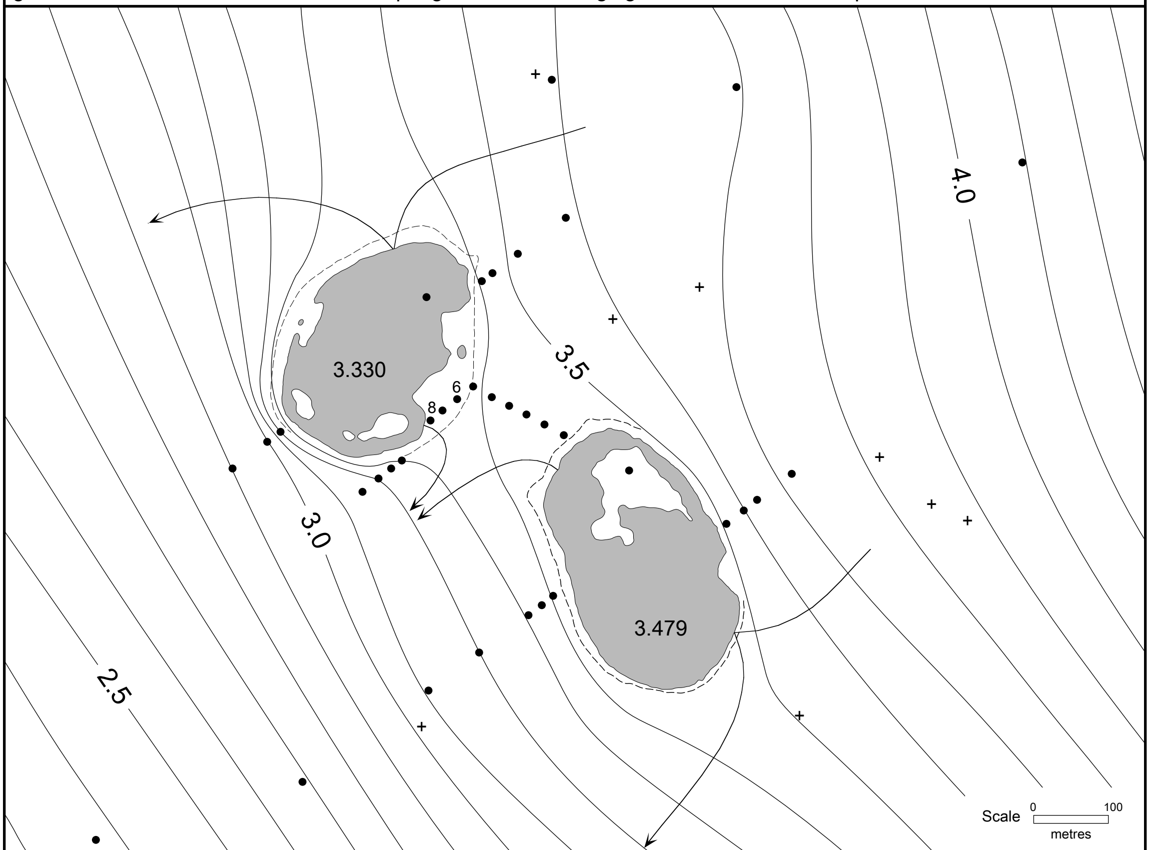
September 08, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15j

Both lakes rising towards annual peak stage on September 10. Capture and release zones merge. Notice how the position of the dividing stream line at the N end of East Lake (constrained by the level in W17) shifts relative to the Aug 25 & Sept 15 positions. A similar shift occurs in West Lake. These shifts are in direct response to storm water inputs (rain 20.3mm Sept 1-2 & 66.6mm Sept 5-8) which shift the lakes towards recharge flow regimes.



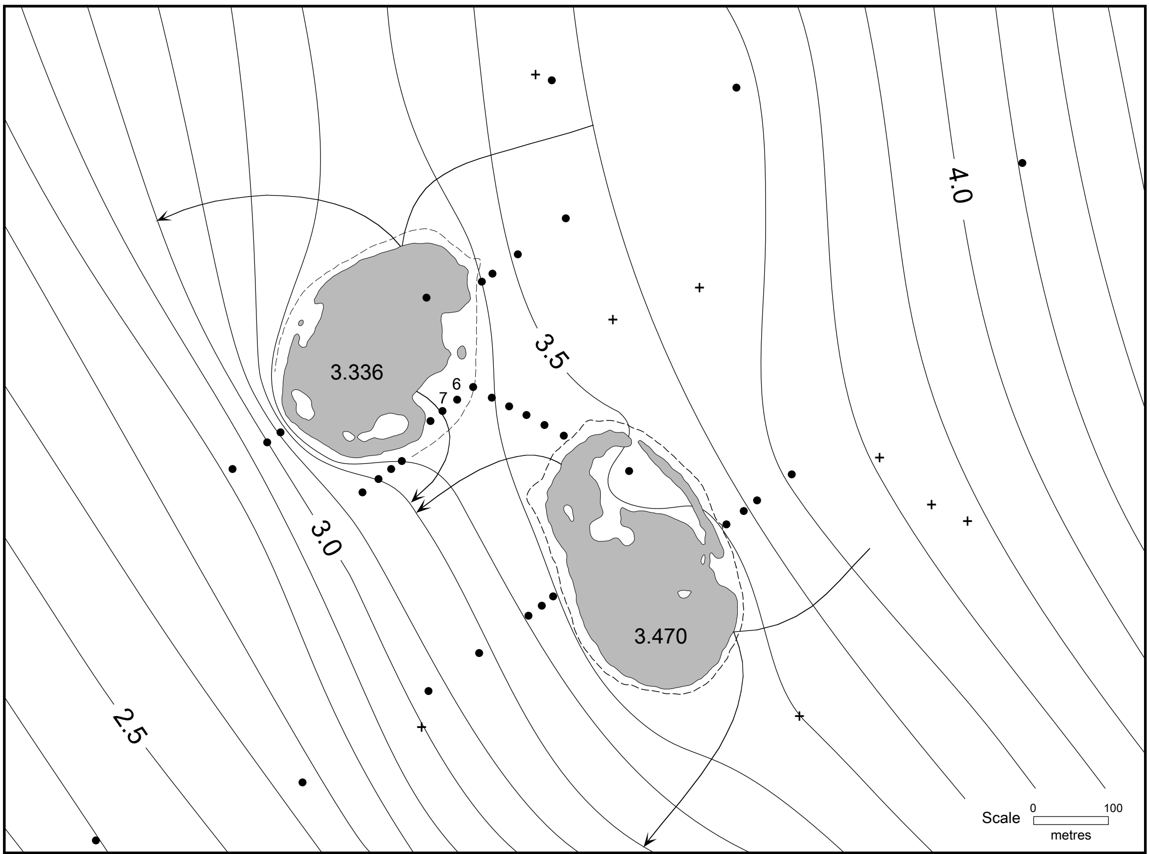
September 15, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15k

West Lake and East Lake commence summer decline following winter peak stages of 3.492 & 3.575 on Sept 10 in response to final major winter frontal passage (114mm rain over 9 days). Both lakes probably reverted to recharge flow regimes briefly before reverting to flow-through regimes with common capture and release zones. The summer groundwater decline is co-incident with spring leaf burst of fringing deciduous trees on Sept 8. SWL in W8 3.436 = DSL.



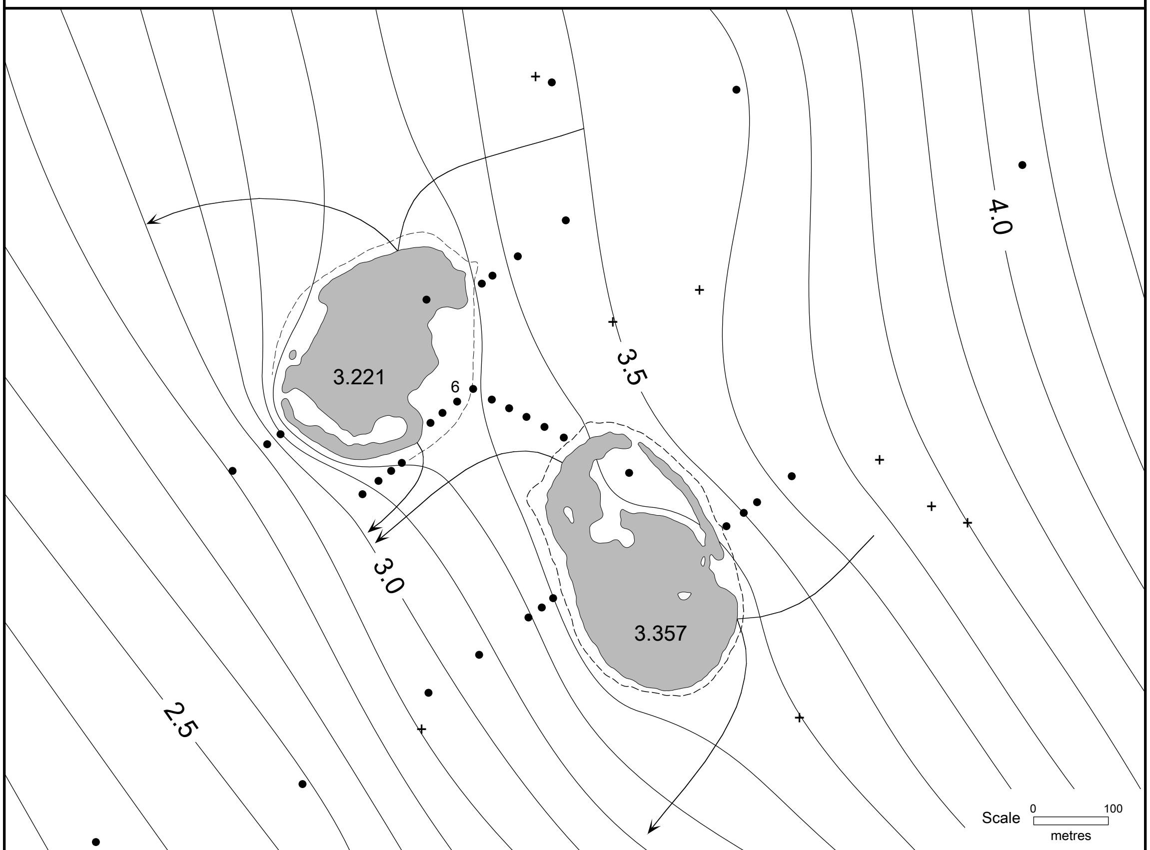
September 29, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15l

Summer water table decline commences. Flow-through regimes with common capture and release zones. Positive piezometric heads in W6 and SWL in W8 of 3.338 constrains position of dividing stream line (refer text).



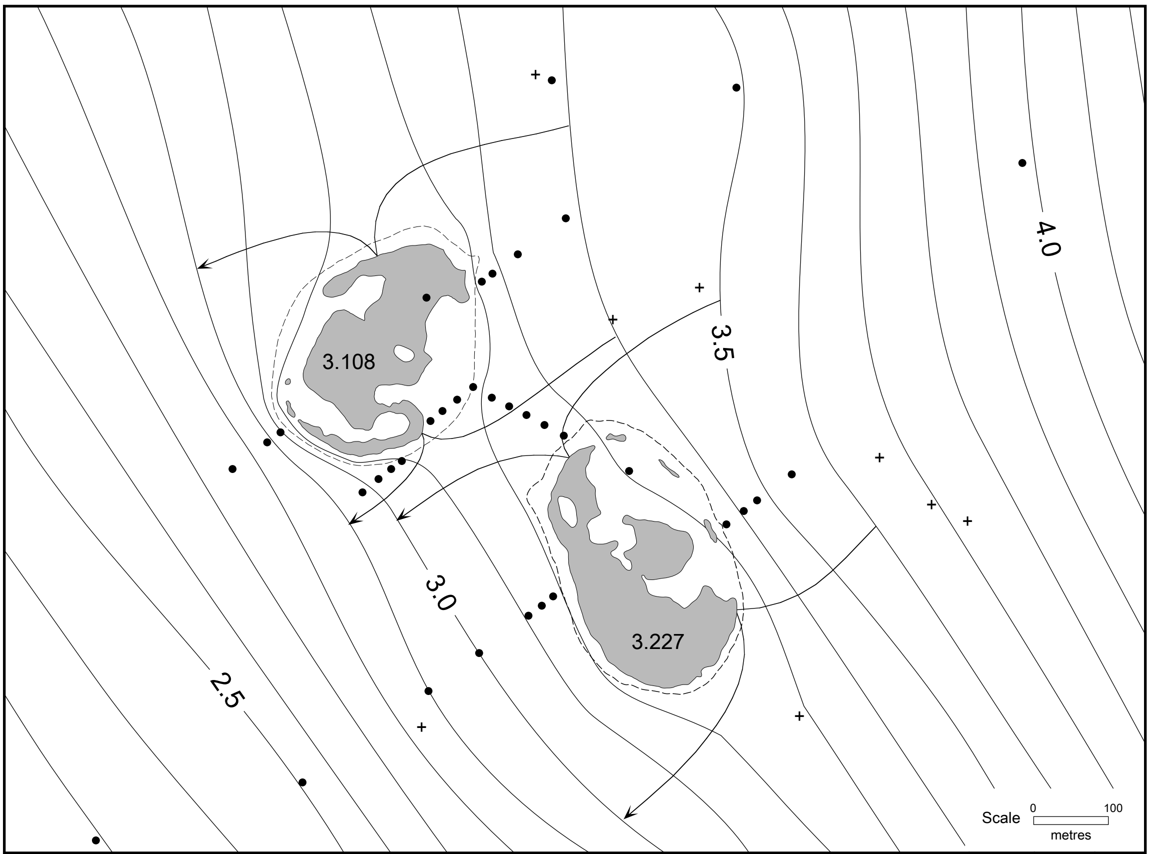
October 12, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15m

Flow-through regimes with common capture and release zones. Positive piezometric head in W6 & level in W7 of 3.336m (same as West Lake) constrains & defines position of dividing stream line.



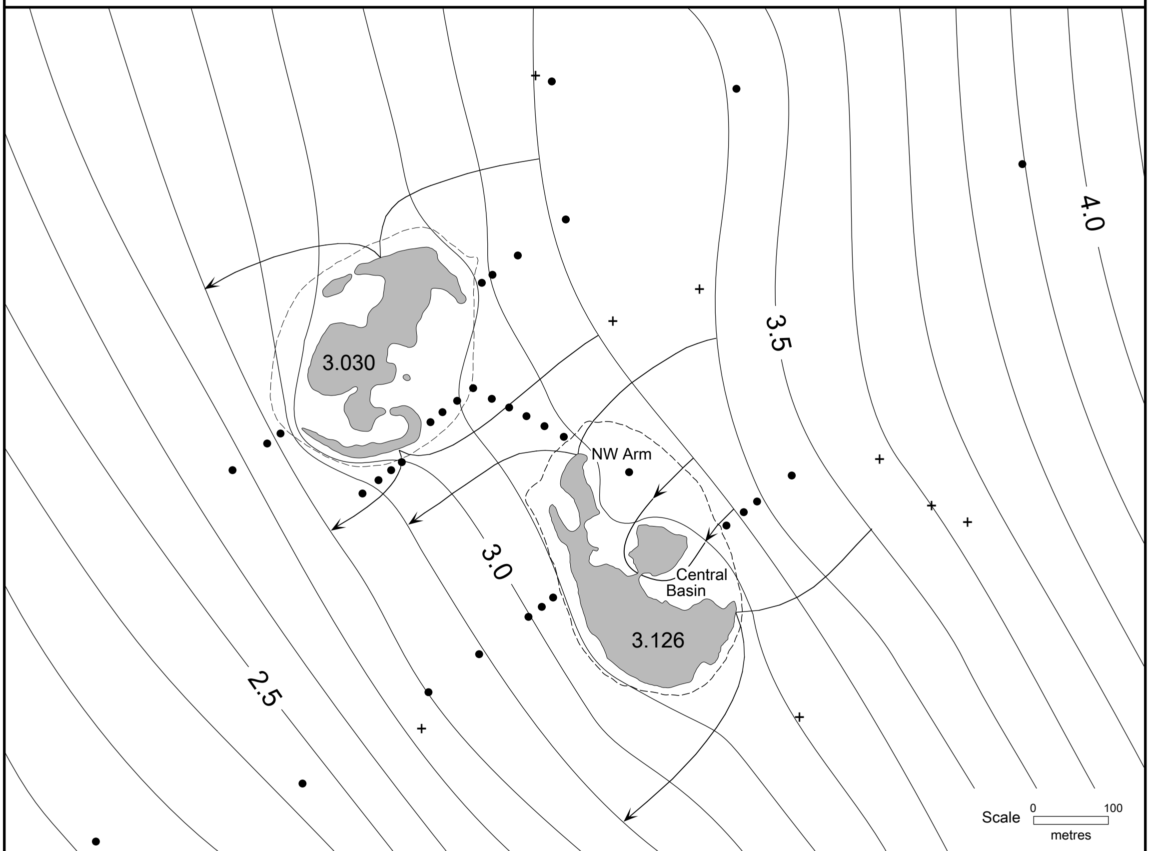
October 26, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15n

Levels in both lakes start to decrease rapidly as rainfall decreases and evaporation increases. Groundwater extraction for lawn irrigation commenced October 20. Positive piezometric heads in W6 constrains position of dividing stream line in West Lake.



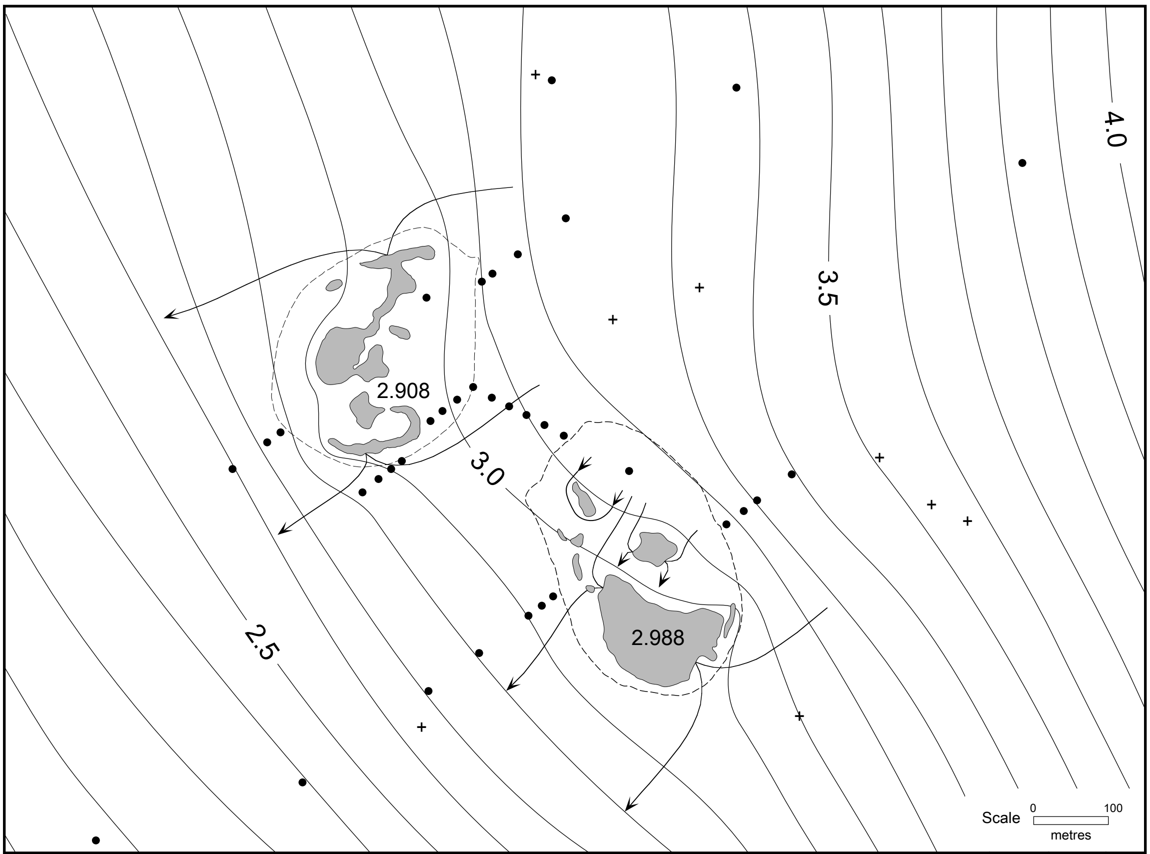
November 09, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15o

Separate capture and release zones re-established.



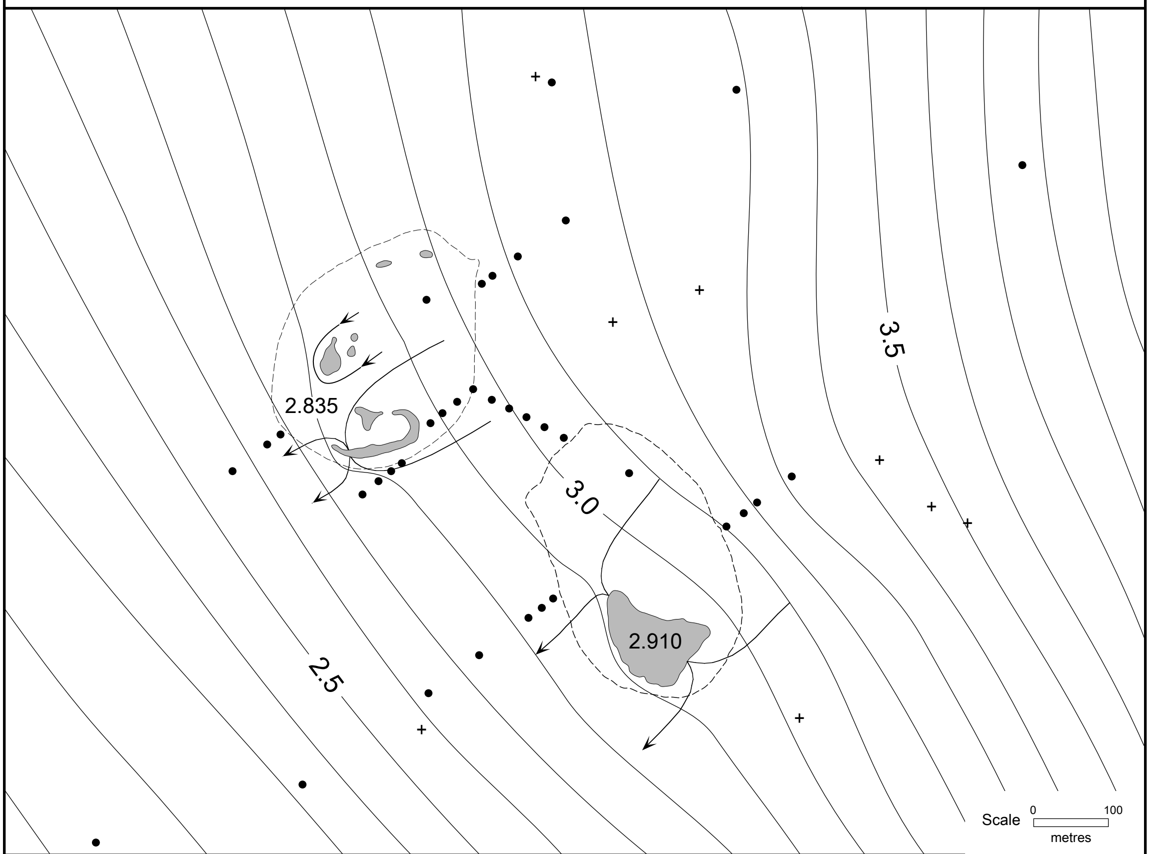
November 23, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15p

West Lake detaches into two separate ponds with common capture and release zones. In East Lake, Central Basin is hydrologically separated and becomes pond with discharge flow regime, refer Dividing Stream Line (DSL) Study. NW Arm separates Nov 26.



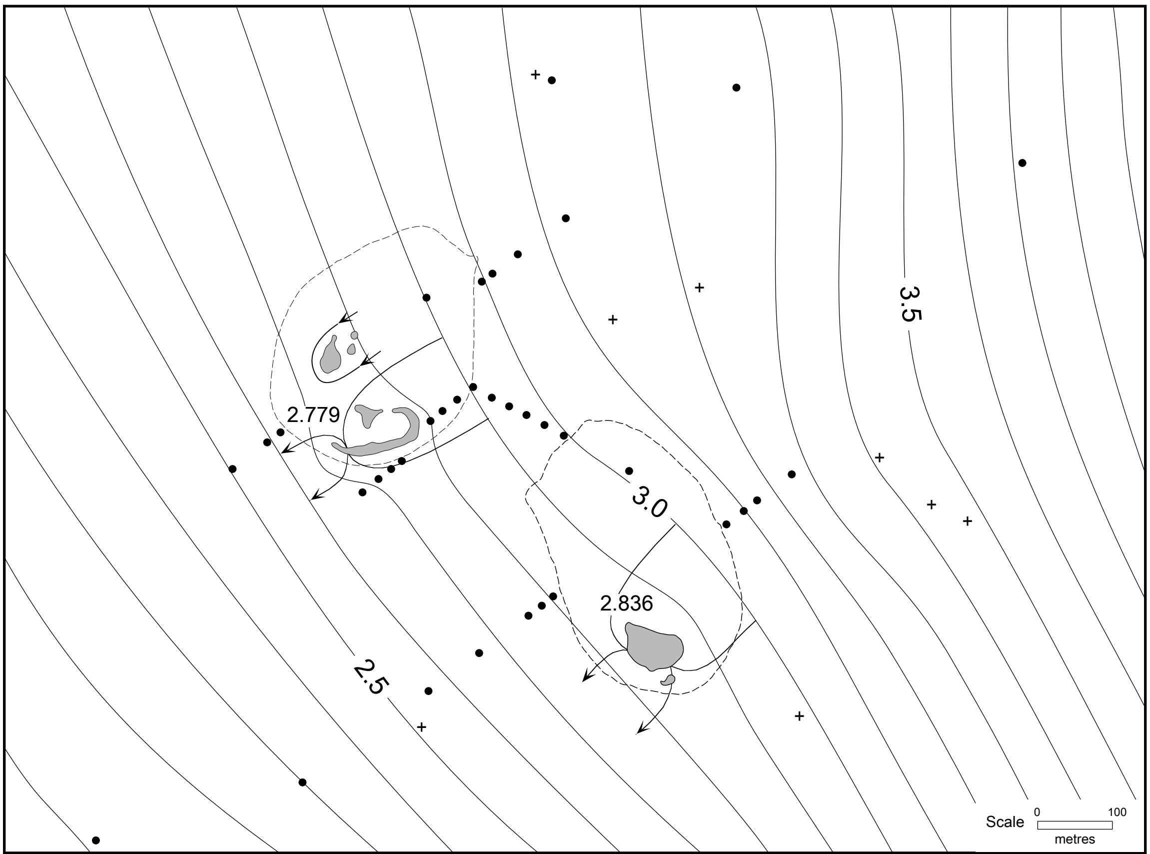
December 08, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15q

West Lake breaks into three separate ponds. Flow-through regime is confirmed in the most southerly (refer DSL study). East Lake also breaks into three major ponds. Discharge regime persists in northerly pond (ex NW Arm), Flow-through regime in Central Basin is nested within capture zone to South Basin.



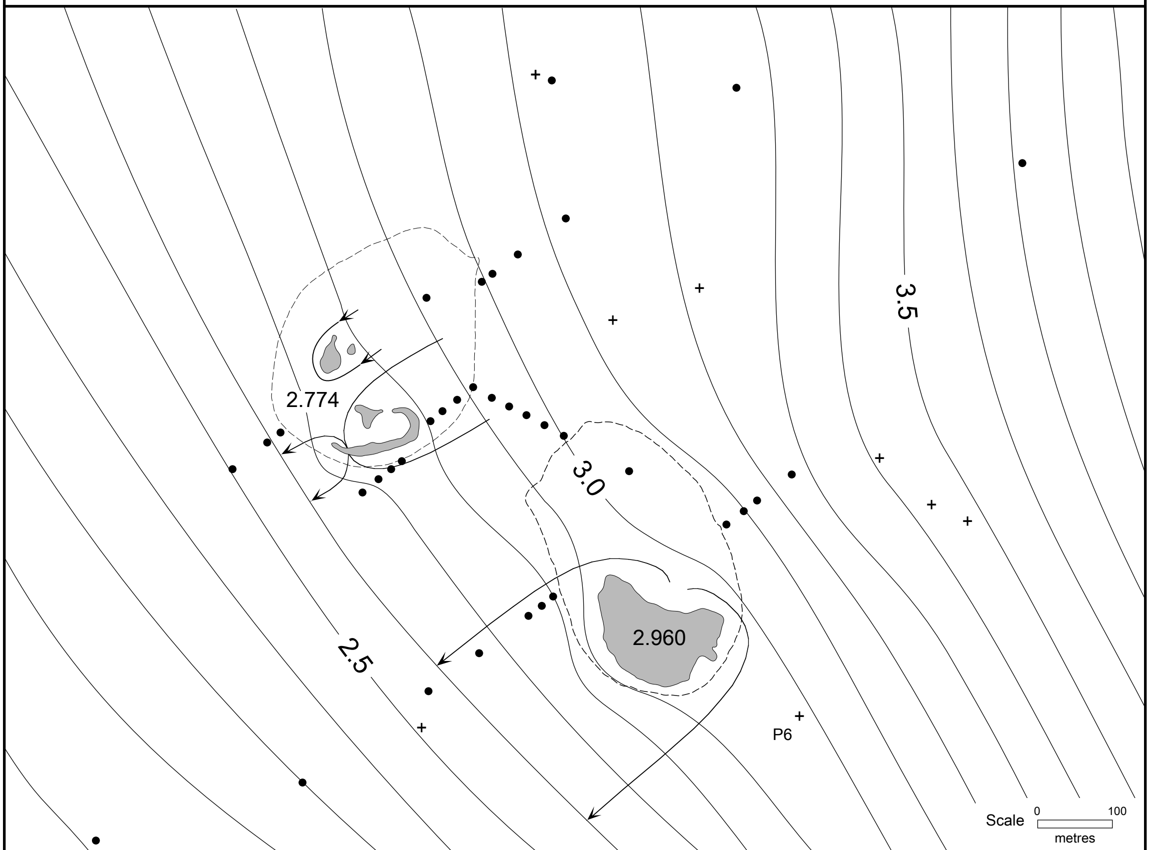
December 14, 1997 Flow Regimes: East Lake = FT West Lake = FT Figure 7.15r

West Lake ponds shrinking, discharge regime postulated in remnant SW Basin as dryness is approached. Remnant SW pond in West Lake operates as flow-through pond. East Lake is now confined to South Basin which continues to operate as a flow-through pond.



December 21a, 1997 08:00hr Flow Regimes: East Lake = FT West Lake = FT Figure 7.15s

East Lake stage reaches lowest recorded minimum of 2.836 (area 6160m^2, volume 357m^3, av depth 58mm). DSL has migrated as flow regime moves towards discharge status. East Lake is now becoming hydrologically isolated from the aquifer, sitting completely within low K lake lining clays. It is likely that if allowed to proceed to dryness, a discharge regime would be established for a few days. Dryness would have been achieved approximately December 25.



December 21b, 1997 16:00hr Flow Regimes: East Lake = R West Lake = FT Figure 7.15t

Summer lake level maintenance commenced 09:00hr, bore 6 only, input 72m^3/hr. East Lake becomes recharge lake. West Lake remains as a small flow-through pond. Remnant ponds perched on low conductivity clays postulated as discharge regimes.

Return of artificial lake maintenance

Throughout December both East and West Lakes continued to shrink and approach dryness. Flow-through regimes (or at least the potential for flow-through regimes) were maintained as evidenced by mini piezometer data. Our agreement with the Town of Cambridge stipulated that top up into East Lake would commence when the long necked tortoises (*Chelodina oblonga*) appeared to be endangered. Top up commenced December 21 (Figures 7.15 s&t). A recharge regime was immediately re-established. Had East Lake been allowed to proceed to dryness it is likely that a transient discharge regime might have been established similar to those observed in other remnant ponds.

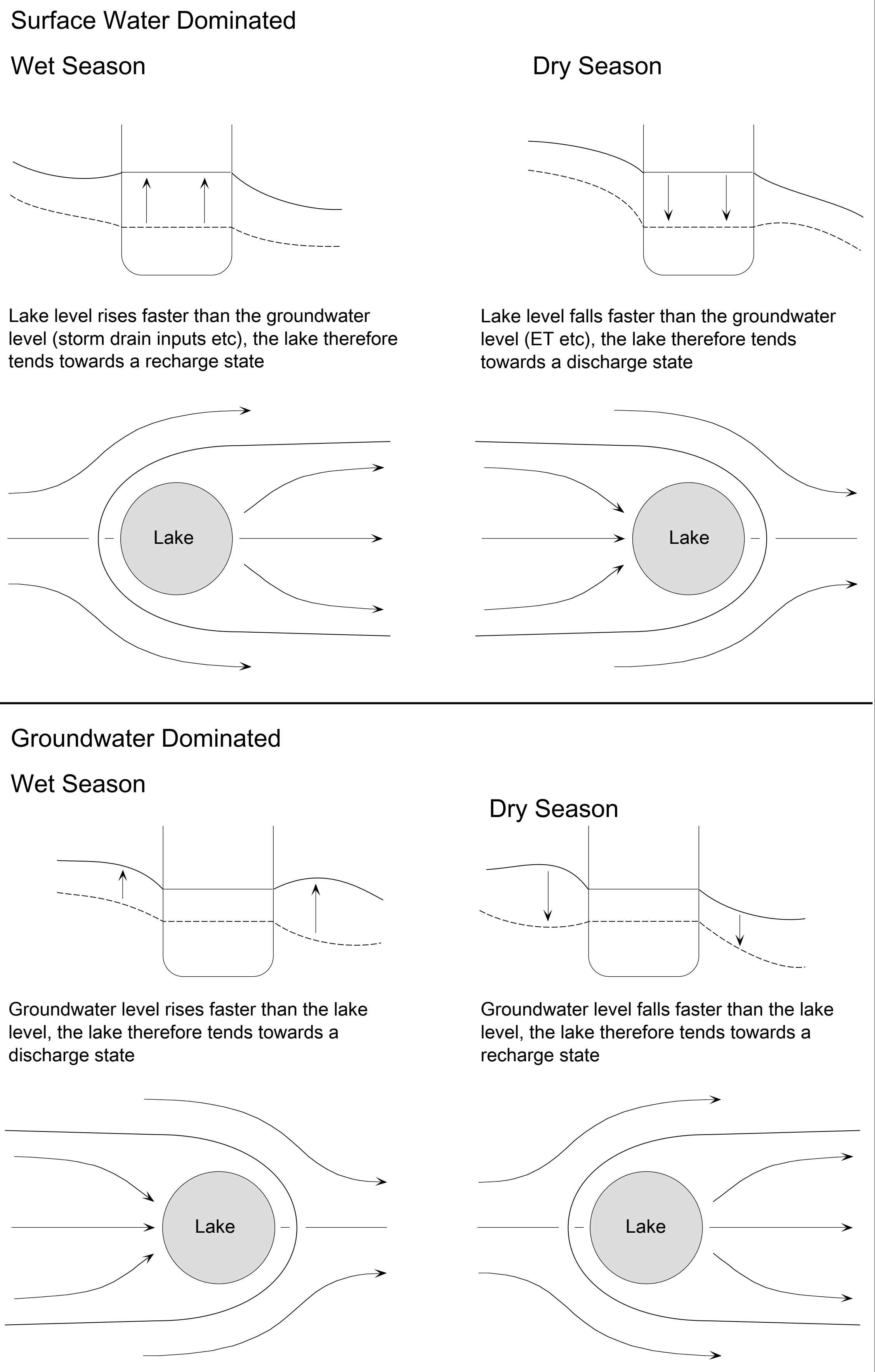
7.4 LAKE-AQUIFER COUPLING

7.4.1 Concepts of Surface and Groundwater Dominated Wetlands

Townley *et al* (1993b) suggested that lakes may be either groundwater or surface water dominated (Figure 7.16). The water level in a groundwater dominated lake reflects the surrounding water table. Therefore depending on lake-aquifer coupling the lake levels will lag to a greater or lesser degree behind the nearby groundwater levels. In the winter a groundwater dominated lake will lag behind rises in the surrounding water table. As a result the lake may tend towards discharge flow regimes. In summer groundwater levels fall faster than the lake and the lake then tends towards recharge regimes. This classification should not be confused with regime dominance concepts such as Born *et al* (1979) where a 'groundwater dominated lake' is one where groundwater simply dominates in the lake water budget.

Surface water dominated lakes are characterised by large lake volume changes in response to surface water inputs. In urban areas this is almost exclusively from storm drains. In winter surface water dominated lake levels rise ahead of and drive level changes in the surrounding aquifer. The lake therefore tends towards recharge regimes. In summer the lake may become an evaporative sump, falling more quickly than the surrounding water table and therefore tending towards discharge regimes.

In their natural state most lakes on the Swan Coastal Plain had no riparian inputs and therefore probably tended towards being groundwater dominated. The advent of storm drains (and at Perry Lakes summer top up) means most lakes are now surface water dominated, at least over winter.



Seasonally different behaviour of surface water dominated and groundwater dominated lake-aquifer systems

Sketches adapted from Townley et al (1993b) p70

Figure 7.16

7.4.2 Coupling Signals in East Lake

The way in which lakes react to pumping and evapotranspiration (ET) provides a direct measure of the degree of coupling between the lake and the aquifer. It can also provide some measure of aquifer homogeneity or heterogeneity. Lake stage hydrographs are difficult to interpret in detail. They tend to be extremely noisy, a combined result of wave action, seiche effects, pump start up spikes and evapotranspiration, all superimposed on a longer scale trend of rise or decline. East and West Lake hydrograph records were compared to data from nearby monitoring wells. There is an almost instantaneous correlation between pump start up spikes in observation wells and Perry Lakes (Figures 7.18 a&b). These hydrographs suggest (but do not quantify) a strong hydrological coupling between the lakes and the aquifer. We would expect this because both lakes have a sandy rim created by stripping the original clay lining and re-contouring during the 1960's (refer Chapter 2). Examining the East Lake hydrographs in detail (see Figure 7.20) confirms that these spikes persist into March and April when East Lake is strongly mounded. This suggests that despite weekly excursions towards dryness followed by weekend top up and extreme local mounding, East Lake never detaches from the aquifer but rather, always remains in hydraulic connection with it. Rosenberry (2000) reported that lakes can be partially perched along their margins. He described a small pond that grew rapidly in response to heavy rain, expanding to cover sediment of greater permeability than the lake lining (a situation analogous to East Lake). The pond water rapidly infiltrated the more permeable sediments, trapping adjacent partially saturated 'wedges' located beneath the lower permeability lake lining. A similar situation may occur in East Lake.

Similarly data from September 1997 to February 1998 was examined to compare the strong evapotranspiration signal in W26 to any similar signal in East Lake. This monitoring well was equipped with a high resolution capacitive probe specifically for monitoring evapotranspiration in the non flooded portion of the East Lake basin. This is examined in detail in Chapter 11. The ET signal in W26 had a consistent almost sinusoidal wave form. Levels commence dropping just after sunrise. On a typical sunny warm day this drawdown continued until just before sunset. Days with no pumping and little wind provided the best data. Most of the time the ET signal is swamped by the larger effects of wave noise. The data indicates that response in the lake is roughly synchronous with that in the surrounding water table again indicating strong lake-aquifer coupling. In the November example portions of the sandy high conductivity basin rim were still flooded. By December 16 the lake was approaching dryness and was reduced to a small pond within the clay lined South Basin. Despite this there is still a near synchronous ET signal. Strong ET signals are also evident in West Lake in late

December and in hydrograph records for W3, 15, 18, 20 and 21 over weekends in November and December 1997 including two four day non irrigation periods over Christmas and New Years (Figures 7.18 a&b).

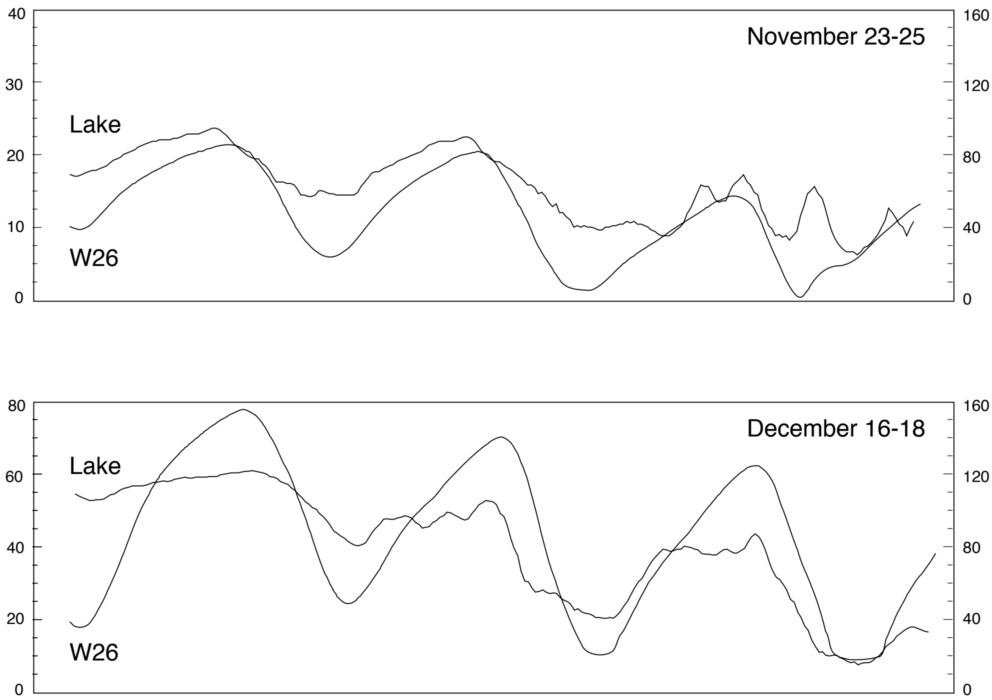


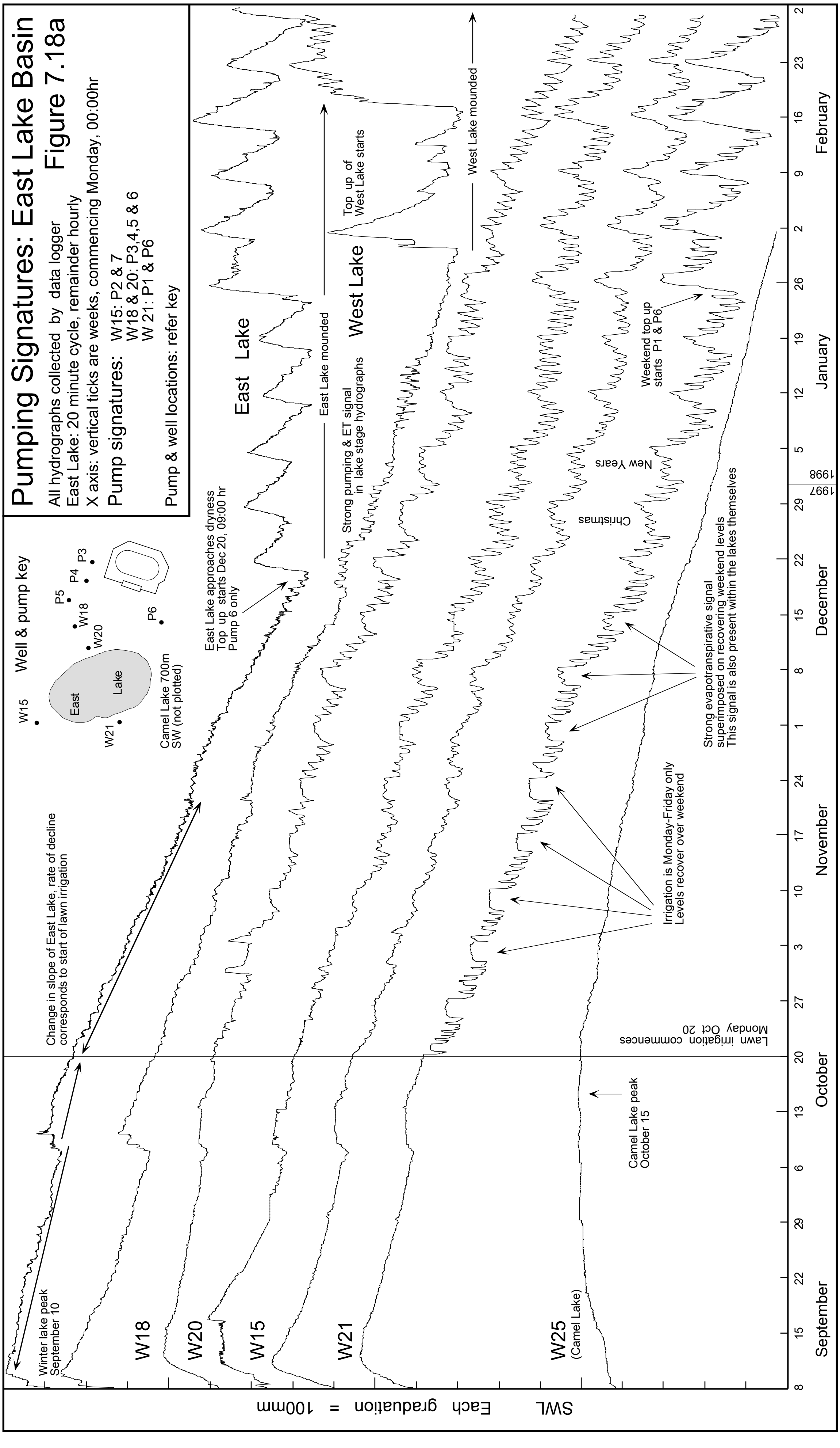
Figure 7.17 Hydrograph records of East Lake and monitoring well W26 located in the *Typha* dominated sumplands in the northeast East Lake basin (Figure 7.15a). Note that left hand y axis is lake stage which has been exaggerated vertically 4x and 2x relative to W26 (right side y axis). Peaks are sunrise (end of overnight recovery), low points are late afternoon. November data spans Sunday-Tuesday. Lake signal is disrupted Tuesday by superimposed noise. Pumping signals are superimposed on the December data.

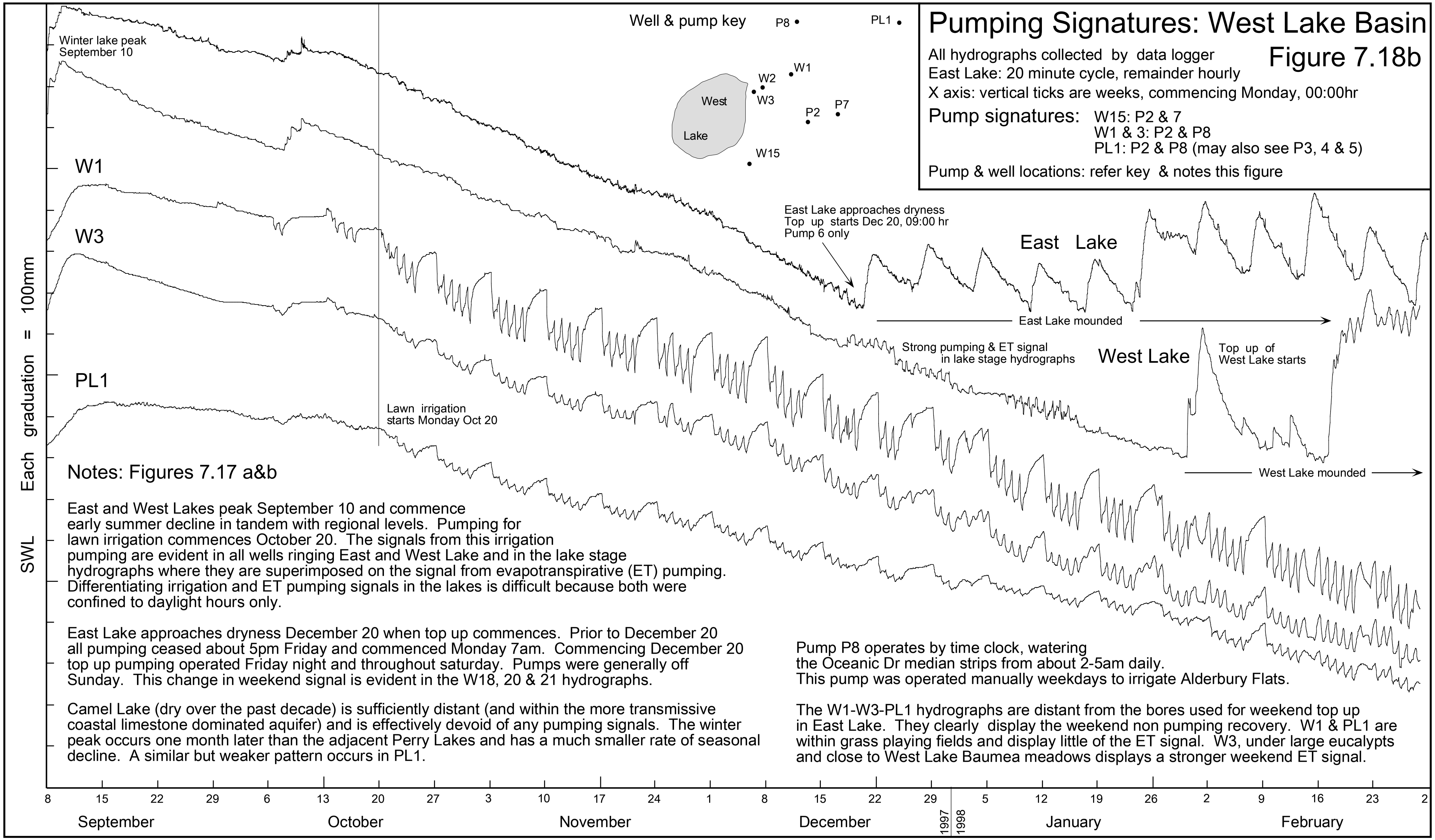
7.5 GROUNDWATER EXTRACTION AND WETLANDS

In September 1997 the Town of Cambridge was asked and agreed to delay East Lake level maintenance (normally commenced in October). This allowed a number of additional experiments to be conducted as summarised below.

- comparison of the natural rate of lake level decline with the summer seepage rate under artificial maintenance regimes
- investigate the effects of lawn irrigation pumping on lake decline (*i.e.* is there a measurable lake level recovery on weekends?)
- allow the groundwater flux to be more accurately measured in the water balance calculations without the complicating effects of artificial maintenance
- provide some baseline data for studies of lake-aquifer coupling

All of these pertain to the question 'does pumping affect Perry Lakes and if so to what extent?' This was the key issue posed by the Perth City Council when they approached CSIRO in 1992. It remains the central management issue at Perry Lakes.


Pumping Signatures: East Lake Basin
Figure 7.18a
All hydrographs collected by data logger
East Lake: 20 minute cycle, remainder hourly
X axis: vertical ticks are weeks, commencing Monday, 00:00hr
Pump signatures: W15: P2 & 7
W18 & 20: P3,4,5 & 6
W 21: P1 & P6
Pump & well locations: refer key
Well & pump key
W15
W21
W20
W18
P5
P4
P3
P6
East
Lake
Camel Lake 700m
SW (not plotted)
Winter lake peak
September 10
Change in slope of East Lake, rate of decline
corresponds to start of lawn irrigation
East Lake approaches dryness
Top up starts Dec 20, 09:00 hr
Pump 6 only
East Lake
East Lake mounded
Strong pumping & ET signal
in lake stage hydrographs
West Lake
Top up of
West Lake starts
West Lake mounded
W18
W20
W15
W21
W25
(Camel Lake)
Camel Lake peak
October 15
Lawn irrigation commences
Monday Oct 20
Irrigation is Monday-Friday only
Levels recover over weekend
Strong evapotranspirative signal
superimposed on recovering weekend levels
This signal is also present within the lakes themselves
Christmas
New Years
Weekend top up
starts P1 & P6
SWL Each graduation = 100mm
8
15
22
29
6
13
20
27
3
10
17
24
1
8
15
22
29
5
12
19
26
2
9
16
23
2
September
October
November
December
January
February
1997
1998


Pumping Signatures: West Lake Basin
Figure 7.18b
All hydrographs collected by data logger
East Lake: 20 minute cycle, remainder hourly
X axis: vertical ticks are weeks, commencing Monday, 00:00hr
Pump signatures: W15: P2 & 7
W1 & 3: P2 & P8
PL1: P2 & P8 (may also see P3, 4 & 5)
Pump & well locations: refer key & notes this figure
Well & pump key
P8
PL1
W1
W2
W3
West
Lake
P2
P7
W15
Winter lake peak
September 10
W1
W3
PL1
SWL Each graduation = 100mm
Lawn irrigation
starts Monday Oct 20
East Lake approaches dryness
Top up starts Dec 20, 09:00 hr
Pump 6 only
East Lake
East Lake mounded
Strong pumping & ET signal
in lake stage hydrographs
West Lake
Top up of
West Lake starts
West Lake mounded
Notes: Figures 7.17 a&b
East and West Lakes peak September 10 and commence early summer decline in tandem with regional levels. Pumping for lawn irrigation commences October 20. The signals from this irrigation pumping are evident in all wells ringing East and West Lake and in the lake stage hydrographs where they are superimposed on the signal from evapotranspirative (ET) pumping. Differentiating irrigation and ET pumping signals in the lakes is difficult because both were confined to daylight hours only.
East Lake approaches dryness December 20 when top up commences. Prior to December 20 all pumping ceased about 5pm Friday and commenced Monday 7am. Commencing December 20 top up pumping operated Friday night and throughout saturday. Pumps were generally off Sunday. This change in weekend signal is evident in the W18, 20 & 21 hydrographs.
Camel Lake (dry over the past decade) is sufficiently distant (and within the more transmissive coastal limestone dominated aquifer) and is effectively devoid of any pumping signals. The winter peak occurs one month later than the adjacent Perry Lakes and has a much smaller rate of seasonal decline. A similar but weaker pattern occurs in PL1.
Pump P8 operates by time clock, watering the Oceanic Dr median strips from about 2-5am daily.
This pump was operated manually weekdays to irrigate Alderbury Flats.
The W1-W3-PL1 hydrographs are distant from the bores used for weekend top up in East Lake. They clearly display the weekend non pumping recovery. W1 & PL1 are within grass playing fields and display little of the ET signal. W3, under large eucalypts and close to West Lake Baumea meadows displays a stronger weekend ET signal.
8 15 22 29 6 13 20 27 3 10 17 24 1 8 15 22 29 5 12 19 26 2 9 16 23 2
September October November December 1997 1998 January February

7.5.1 The 'Natural Seasonal Decline' Experiment

As monitoring proceeded over winter 1997 it was evident (based on summer 1995 and 1996 data) that both lakes would be dry by about late December. Allowing lake levels to decline naturally had three objectives. Firstly, we wanted to observe the subtle changes in flow regime as East Lake approached dryness. It was unknown for example if a flow-through regime would be maintained or if a discharge regime might establish as ET increased. Secondly, we wanted to monitor the subtle changes in the position of the dividing streamline and lastly we wanted to measure the current early summer rate of lake decline under typical conditions of lawn irrigation pumping. These objectives were unachievable using the normal Town of Cambridge management prescription under which limited top up commences in early November, increasing as lake levels fall. Our studies required wetland conditions approaching those of an unmanaged wetland. The wetland managers agreed to withhold top up until East Lake had almost reached dryness. Lawn irrigation would proceed weekdays as usual. Weekly manual measurements of all wells was done Sunday afternoon (from October 12, 1997 onwards), thereby giving levels about 36 hours to recover from irrigation pumping.

Artificial top up commenced December 20 after East Lake reached a stage of 2.829m (area 5650m^2, volume 315m^3, average depth 5.5cm).

7.5.2 Current Groundwater Extraction at Perry Lakes

Pumping signals are evident in most monitoring wells within Perry Lakes Reserve (Table 7.8). Figure 7.19 shows the approximate extent of depression cones around the irrigation bores.

Table 7.8 Pumping Signals in Monitoring Wells

Monitoring Well	Pumping Signals
W1, W2, W3, Pl2, W13-17	P2 (minor signal from P7)
W1	P8
W18, W19, W20	P3, P4, P5
W21-24	P1

The pumping clearly shows the pattern of weekday irrigation and weekend recovery (Figures 7.18 a&b). Pumping does draw the lakes down on a daily basis. More importantly however, the general rate of groundwater decline within Perry Lakes Reserve clearly increases once irrigation commences, and this rate is much greater than any other rate which was observed regionally (Figure 7.19a). The almost instantaneous correlation between pump spikes in observation bores and adjacent East and West Lake confirms the strong lake-aquifer coupling.

Figure 7.15a demonstrates how summer pumping depresses the water table around the lakes. Hydraulic head is the sum of the elevation head and pressure head. Pumping increases both the head in East Lake and the hydraulic gradient (remembering that the lakes appear to be closely coupled and apparently do not detach). Darcy's law states that specific discharge υ is directly proportional to hydraulic head (Freeze & Cherry 1979 p16):

$$\upsilon = -K\frac{dh}{dl} \tag{7.3}$$

where h is hydraulic head, and dh/dl is the hydraulic gradient. Darcy's law shows that the rate of outflow (recharge to groundwater) of a mounded lake must increase if the head increases. Therefore when pumping lowers the water table around a lake it must theoretically also affect the level within the lake by increasing outflow.

We have no long term records of extraction apart from those estimated for 1993-94 (Townley *et al* 1995) and 1996-97 (this study). When bores were first drilled in 1961-62 it is likely that relatively small amounts of water were extracted. There are two reasons for this. Firstly groundwater levels were much higher so the water table was within about 1m of the surface below much of the lawn areas. Grass may have been maintained over summer largely through capillary rise. Secondly anecdotal evidence from early PCC grounds staff suggests there was not the same 'culture' of lush green lawn in a Mediterranean climate that prevails today. Lawn irrigation was more concerned with simply maintaining grass over summer. Over summer 1993-94 irrigation and top up were estimated to be 250,000m^3 and 60,200m^3 (Townley *et al* 1995). In 1996-97 this had increased to 390,530m^3 and 180,750m^3 respectively, an increase of 84%.

The regional water table on the Swan Coastal Plain displays a characteristic annual cycle. The water table rises during the winter from direct recharge and storm drain inputs to wetlands and storm water recharge basins. Over summer the water table declines in response to evapotranspiration and extraction from bores. This annual cycle can be approximated by a sin function, whose amplitude varies from area to area depending on the local recharge-discharge balance.

Where the vertical depth to the water table is great, such as beneath thick limestone ridges, the annual amplitude is low, reflecting low (or nil) winter recharge (McFarlane 1984) and nil evapotranspiration. Where the water table lies at shallow depth, both recharge and discharge increase as does the amplitude of the annual cycle. Wetlands represent an extreme case. They not only receive recharge directly as rain, but frequently have large additional inputs from storm drains. In summer they loose water directly from open water evaporation and evapotranspiration from fringing and nearby phreatophytes and soil. In summer such wetlands may act as evaporative sinks. In such cases the rate at which water is lost exceeds the rate at which it can be replaced from elsewhere in the aquifer.

Another way of visualising this is to consider a flow-through lake. As summer approaches the lake will receive more and more water from the aquifer to compensate for evaporative losses and recharge less and less back. The dividing streamlines will migrate towards the down gradient side. Flow regimes might shift from FT1 to FT3 and the lake is described as 'tending towards a discharge state'. The wetland and its surrounding basin (sumplands and damplands of Semeniuk 1987) does the same thing. If pumping is occurring close to a lake, the effects of this pumping must be additive to the natural evaporative pumping. Even in wetlands well removed from any extraction, evapotranspiration imposes a distinct signal on the open water surface and adjacent water table (Meyboom 1967).

The magnitude of daily open water evaporation and transpiration were estimated for Perry Lakes and their associated lake basins (Table 7.9) and compared to extraction from bores P1-P8 (Figure 7.19). Irrigation and top up clearly exceed natural evaporative losses. In the Perry Lakes basins extraction exceeds natural evapotranspiration by up to 19 times on a monthly basis. Intuitively this suggests that pumping should have an impact on local wetland water levels.

Table 7.9 Natural and artificial pumping (m^3), Perry Lakes Basin

Month (1997)	Evaporation	ET	Irrigation	Top Up	Ratio
January	9340	5380	49680	27210	5.2
February	4170	3310	51580	28240	10.7
March	4050	3420	77820	42610	16.1
April	3740	1550	42980	23530	12.6
May	1900	1150	38260	20950	19.4
June	3260	650	7010	3840	2.8

The figures include East and West Lakes and their associated basins. Evaporation is from open water, calculated from floating Class A pan, evapotranspiration from sumpland vegetation is estimated by hydrograph separation (Chapter 11) for East Lake and doubled to incorporate West Lake, lawn irrigation estimated from electric power consumption (Chapter 13), and lake maintenance 'top up' pumping measured from flow metres.

Area of strongly transpiring *Typha*/*Baumea*/*E. spp* sumpland taken to be 60,000m^2 split equally between each lake.

'Ratio' (Column 5) is the ratio of extraction (irrigation + top up) compared to natural loss (E + ET).

Evapotranspiration from the parkland outside the lake basins was not estimated as these areas are well irrigated and most vegetation presumably draw considerably from irrigation water in the vadose zone over summer.

7.5.3 Historic Regional and Wetland Rates of Summer Decline

Superimposed on seasonal water table cycles are longer term variations reflecting changes in climate and land use (Chapter 2). The key question is: does the intensive pumping for lawn irrigation close to Perry Lakes significantly affect summer water levels? The question must be divided into two parts:

- pre early 1990's when (most years) the local water table remained above the lake beds and top up was not required
- more recently when the lakes would have been completely dry for months every summer

We have already examined the second question. It is clear that East Lake, when locally mounded, remains strongly coupled, and that the rate of decay of this local mound is strongly influenced by enhanced local heads associated with pumping. What remains unanswered is:

- historically, have Perry Lakes suffered summer water levels lower than would otherwise have been the case?
- in years when the lakes dry up, is the date of complete dryness hastened by pumping?

One approach to answering this is to examine historic hydrograph records for Perry Lakes and compare them to nearby local monitoring well records. It can be argued that the early summer rate of daily water table decline at any location is a combination of aquifer wide decline superimposed upon local effects (phreatophytes, extraction, aquifer heterogeneity). If these local effects change over time, we should observe a modified rate of summer decline in comparison to nearby monitoring wells. Such changes might include extensive clearing of natural bush for housing, sealing of roads, conversion from septic to reticulated sewerage and installation of bores.

We also know that evaporation from wetlands imposes a strong local signal on the aquifer. This signal should change where formerly permanent wetlands become seasonally dry. This is because transpiration cannot exceed (and seldom equals) potential evapotranspiration (Fleming 1997). Often, plants and soils cannot meet the atmospheric demand on their evaporating surfaces. Therefore losses from open water will generally exceed any evapotranspiration from the surrounding basin. At Perry Lakes, for example, summer evapotranspiration from *Typha-E. rudis* sumpland is only 30-50% of evaporation from adjacent open water (Chapter 11). In a natural wetland the transition from permanent to seasonal lakes should, therefore, be accompanied by a reduction in open water losses and an attenuation in the rate of summer decline in historic records.

Historic Rates of Summer Decline 1963-1998

The rate of water table decline for West Lake[5] (mm d^{-1}) was calculated for the 60 day period covering December and January from 1963 to 1998. Complete records are not available spanning the same period for any nearby monitoring well. We wanted a well with similar aquifer hydrology. This precluded wells down gradient such as GE-1 in Bold Park (Appendix 2.1) where the aquifer transmissivity is significantly greater (Davidson 1995, p56).

All historic Water Authority, now Water and Rivers Commission (WRC) bore hydrographs were examined. None provide a complete record 1963-1998 and most are close to known pumping wells. Data from two wells was examined. The Floreat Bowls Club monitor, located 850m northeast of East Lake, data covers 1963-1969 and the Lemnos St. monitor, located 1300m southeast of East Lake, data covers 1970-1986 (WRC) and 1996-1998 (this study).

West Lake displayed an average early summer rate of decline of 4.9mm d^{-1} for the period 1969-1989. Earlier data 1965-1968 are only 2.0m d^{-1}. This was ignored as it corresponds to the period of maximum flood remediation pump station operation (Figure 2.13), which reduced the winter peak levels. There is an obvious increase in the rate of decline in 1977 to 6.3mm d^{-1} when the Perth City Council (PCC) first trialed summer maintenance pumping (Chapter 2), rising to 9.0mm d^{-1} by 1996. Bowls Club figures 1963-1969 averaged 4.2mm d^{-1} but the well monitored is believed to have been adjacent to a newer production bore (Floreat Bowls Club staff pers com) and this figure is therefore possibly misleading. The Lemnos St. monitor remained as the most likely 'best indicator' of annual aquifer characteristics close to Perry Lakes. This well is removed from any significant pumping and is surrounded by open bushland comprising an army storage depot, Subiaco waste water treatment plant, old Water Authority workshops, dog cemetery and native bushland reserve. SWL (1997) averaged about 5m below ground level. The early summer decline rate averaged 2.6mm d^{-1} for the years 1970-1986. By 1997-98 this had risen to 4mm d^{-1}. Figure 7.19b shows the West Lake and Lemnos St. data with best fit ($R = 0.69$ & 0.68) polynomial curves. Comparing these two data sets is problematic due to the gap in data for Lemnos St. 1987-1996. The West Lake data also display much greater variance (2.24, $n = 27$) compared to Lemnos St. (0.49, $n = 16$).

Two clear trends are evident:

1: the rate of decline has increased over time at both locations

2: the rate at Lemnos St. has been near linear while at Perry Lakes it has been non linear and is now increasing rapidly

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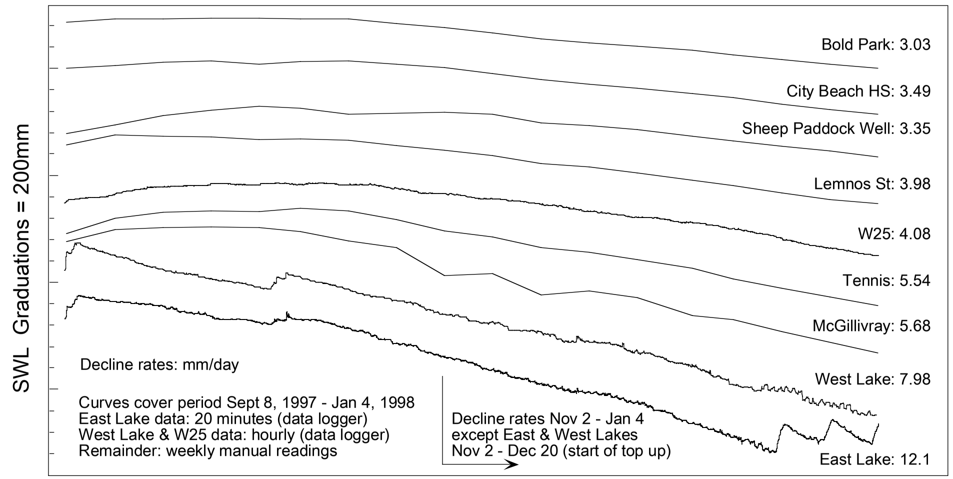
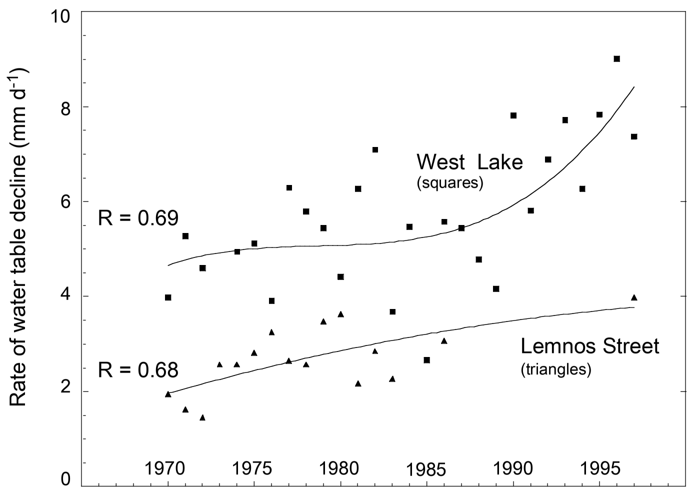
[5] the records for West Lake are more extensive (refer Chapter 2).

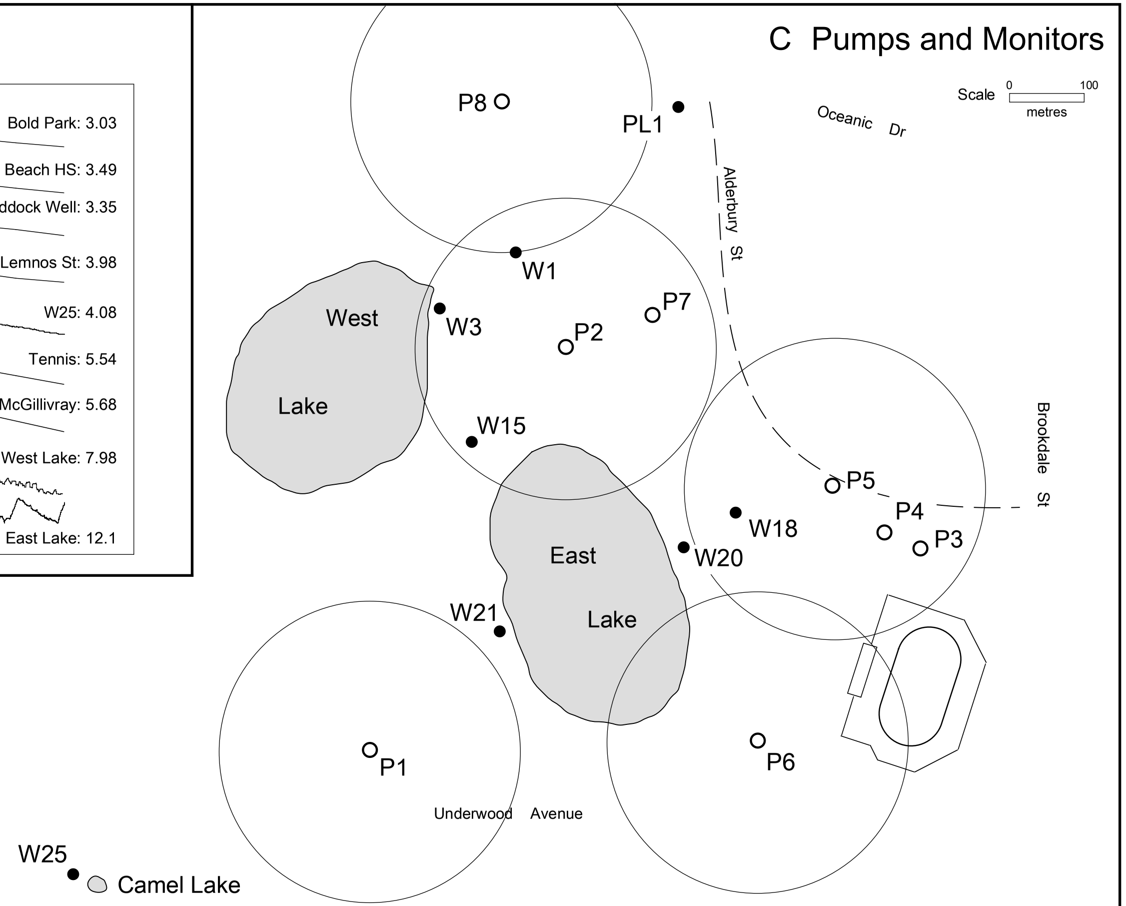
A Comparitive Water Table Decline Summer 1997-98



B Historic Rates of Dec - Jan Water Table Decline



C Pumps and Monitors



Notes

A: Location of bores and wells outside Perry Lakes Reserve refer Appendix 2.1

B: Historic West Lake early summer rate of decline defined by 3rd degree polynomial, Lemnos St rate defined by second degree polynomial, West Lake used instead of East Lake due to more complete historic data

C: Irrigation wells surrounded by zones of influence (r=200m), zones around P3, P4 & P7 omitted. W18 & 20 display strong influence from P3,P4 & P5 but are also probably influenced by P2, P6 & P7. PL1 appears to display signals from P2, P7 & P8.

Figure 7.19

Simple linear regression leads to the same general conclusions. The West Lake and Lemnos St. trends diverge (slopes 0.11 & 0.07) but with poorer fit (R = 0.59 & 0.67).

The change in regional rate reflects long term changes in the water balance of this sector of the unconfined aquifer. Prior to urbanisation there should have been an approximate state of dynamic equilibrium and the difference in rates should have been constant over time. In any year the difference between the regional rate and the Perry Lakes rate would simply have reflected the added local stress on the aquifer from natural (E + ET) pumping. Urbanisation imposes a state of disequilibrium. The changes at Perry Lakes reflect these added stresses, of which pumping is the most obvious. The data suggests (but does not prove) that increased summer pumping has hastened the rate of summer lake level decline.

Rates of Decline, Summer 1997-1998

By way of comparison, Figure 7.19a shows hydrograph and daily rate of early summer decline for Perry Lakes and seven nearby monitoring wells, including Lemnos St. over summer 1997-1998. Bold Park and City Beach High School are located within the higher transmissivity coastal section of the aquifer. The Bold Park well is far removed from any bores, while the City Beach High School well is an abandoned bore 2m from the current production bore. Despite this the rates are low and almost identical to Bold Park suggesting that extracted water is more readily replaced from elsewhere in the aquifer in this area.

The sheep paddock well (UWA Field Station), Lemnos St. and W25 (at Camel Lake) are all considered 'typical' of aquifer conditions close to Perry Lakes. There is little or no extraction close by. In comparison 'Tennis' and 'McGillivray' (Figure 7.15a) are currently operating irrigation bores with aquifer hydrogeology similar to Perry Lakes. Despite the fact they were always monitored at least 12 hours after pumping ceased, their increased summer decline rate suggests that groundwater extraction occurs at a greater rate than replenishment.

The rate of decline in East Lake observed from 1997 winter peak stage (September 10) is far greater than that observed regionally. Accelerated rates close to wetlands are normal (Davidson 1995) and represent greater evaporative and transpirative losses which occur where the water table lies close to the surface. This results from capillary rise and evaporation from soil, direct surface evaporation and water use by phreatophytes. In East Lake however there is also a distinct steepening of the hydrograph slope coincident with the October 20 start of lawn irrigation (Figure 7.18a) suggesting that pumping does accelerate summer lake level decline.

Discussion

Clearly the greatest problem with interpretations of this sort is the paucity of long term data. We believe however that apart from climate, groundwater extraction and regional recharge appear to be the factors which have changed significantly over the past 40 years. Urbanisation through vegetation removal and increased impervious shedding surfaces promotes recharge to the unconfined aquifer (McFarlane 1984). Despite this the mean annual water table level in the Perry Lakes area has decreased steadily since the 1960's (Chapter 2). Climate change (reduced rainfall) and bores (increased groundwater extraction) are the only obvious causes. Climate change issues are explored in Chapter 13.

Exploitation of the unconfined aquifer for potable water commenced in 1979 and is therefore a very recent phenomenon, summarised in Table 7.10. Construction of bores for domestic garden irrigation and public open space also increased markedly from 1970 onwards. Restrictions on the use of mains water for gardens during 1977-79 led to an explosion in private bores from about 24,000 to 63,000 by 1980 (Cargeeg *et al* 1987). The latest estimate is 130 000 domestic bores within the Perth metropolitan area (Water and Rivers Commission 1998b). The first bores were drilled in Perry Lakes Reserve for lawn irrigation about 1962.

Table 7.10 Perth water supply summary history 1829-2000

Period	Perth Water Supply Sources
1829-1895	springs, dry wells and wetlands
1895-1940	artesian water 60%, supplemented from hills dams
1940-1970	steady rise in surface water from hills catchments and decrease in artesian to 10% by 1970
1979-2000	steady rise in use of unconfined groundwater which now supplies 70% of reticulated water

Source: Allen (1997)

Domestic bores are not licensed. Therefore we have no records of when bores were constructed in Floreat. McFarlane (1984) provides data from Nedlands-Dalkeith and Subiaco-Shenton Park showing that the majority of bores were constructed in the decade 1970-80, with most constructed 1978-80 (Table 7.11) in direct response to drought and water restrictions between 1977 and 1979. Anecdotal evidence from drilling contractors suggests that a similar pattern prevailed in Floreat.

Table 7.11 Domestic bore installation western suburbs

Date & Suburb	1940-50	1950-60	1960-70	1970-81	Unknown
Nedlands-Dalkeith	4	13	7	70	6
Subiaco-Shenton Park	12	0	13	63	12

The decade 1970 to 1980 corresponds to a very marked decline in groundwater levels at Perry Lakes (Figure 2.10). It was a period of significant drought (and therefore significantly increased lawn and garden irrigation), and initiation of the first summer top-up trials at Perry Lakes. Natural systems display an approximate dynamic equilibrium. This equilibrium is affected by any unnatural activity such as groundwater extraction (Bredehoeft *et al* 1982). The question of 'sustainable yield' in relation to Perry Lakes is a vexed one and is further examined in Chapter 13.

7.6 SUMMER WATER LEVEL MAINTENANCE ISSUES

Summer maintenance relies on maintaining a local groundwater mound. An 'ideal' lake might be considered as one in which there was an impermeable bottom allowing nil seepage back to the aquifer. Such lakes actually present wetland managers with great problems because water is only lost through evaporation, promoting the build up of salt and nutrients. In contrast there is a strong hydraulic connection between Perry Lakes and the unconfined aquifer such that the lake oscillates between flow-through and recharge flow regimes on a daily and seasonal basis.

7.6.1 Natural and Artificial Local Groundwater Mounds

At Perry Lakes groundwater mounds occur either from excess storm water or top up. Both are essentially 'artificial'. The storm water induced mounds are large, with radii of 3-4 lake diameters (Figures 7.15 c&e). Prior to urbanisation natural mounds would have been rare, induced only by direct rainfall and local surface runoff during sustained very heavy storms.

Hydrograph data suggest that as a mound becomes more localised its slope steepens. At Perry East, the top up induced mounding appears asymmetric (Figure 7.21e), becoming very steep on the east (up regional gradient) side. Such asymmetry would be expected when a mound is superimposed on a sloping water table. The asymmetric shape may also reflect the greater hydraulic conductivity of the upper sand unit west of Perry Lakes (Chapter 3).

Experiments on March 13, 1997 comprised digging holes to the local water table in mud along a line parallel to the regional gradient when the lake was very low (stage 2.960m). The observed gradient on the east side was 0.118m over 10m or approximately 0.012. This is an order of magnitude greater than the average regional gradient of about 0.001. The gradient on the western (down regional gradient) mound slope was 0.5-0.6m over 100m (about 0.005).

Figure 7.21e includes an estimated position of the water table on April 30, 1998 if no top up had occurred, based on data to December 20, 1997. At lake stage 3.0m the water surface was about 1.8m above its predicted natural position. It is important to remember that the cross section incorporates a 10x vertical exaggeration. The mound is in reality a very subtle feature on the regional phreatic surface, a small very slight bulge rather than a pimple!

7.6.2 Rates of Mound Decay

Storm water and top up induced mounds take very different forms. Storm water induced mounds occur whenever there is significant rain. Large volumes of water enter the lake in just a few minutes possibly doubling or tripling the lake volume. During extreme events such as March 31 and June 02 1997 (Figures 7.15 c&e) East and West Lake form a combined mound which extends up gradient several lake diameters and exhibits reverse gradients similar to those observed normally on the regional water table. In comparison to storm events, summer top up is an extremely slow process. The same lake stage change effected by storm water in under an hour may take 48 hours to achieve by top up pumping. The rate of mound decay very quickly approaches the rate of top up. The result is a mound which is extremely localised.

Rates of mound decay were expected to vary depending on the hydraulic head created by the mound, temperature (and hence water viscosity) and the proportion of clay and sand comprising the lake bed. Lake lining sediments particularly around the lake perimeters are highly disturbed. Perimeter clay lining was removed and the lakes deepened and expanded in the early 1960's (Chapter 2). The deeper portions however contain extensive recent and in situ palaeosediments up to 3.2m thick in East Lake and 2.2m thick in West Lake (Figures 3.6 a&b). Four situations were considered:

- Stable winter flow-through regimes
- Winter recharge regimes where a well defined local recharge mound persists following large storm water inputs
- Summer top up where the entire basin is filled
- Summer top up where the lake is wholly contained within the clay lining

The first three situations provide a 'basin averaged' figure since varying proportions of peripheral sandy rim and central clay lining are involved and a wide range of temperatures. Case four involves the thicker clay lining only and effects of warmer temperatures. Experimental estimates of K_Z for these two sediment types were determined by permeameter (Chapter 3) to be approximately 9.5 and 0.011 m d^{-1} respectively.

Rates of storm water induced winter mound decay were used as part of the storm drain calibration process (Figure 5.6). At lake stages of 3.3 to 3.4m decay rates were about 13mm d^{-1}. By comparison Table 7.12 shows rates of mound decay from summer top up.

Table 7.12 Average mound decay statistics at varying lake stages

Stage (m AHD)	Area (m^2)	Loss (mm d^{-1})	Hourly Loss (m^3)	Daily Loss (m^3)
2.8	3840	10	2.1	50
2.9	11220	17	8.0	191
3.0	20110	27	22.6	543
3.1	32580	35	47.5	1140
3.2	39920	38	63.2	1517
3.3	47000	47	92.0	2209
3.4	53440	51	113.6	2725
3.5	58220	54	131.0	3144

data compiled from 1996-1998 lake hydrograph data

The summer top up induces rates of mound decay which are three to four times those observed over winter from storm events.

7.6 3 Limits to Artificial Summer Maintenance

Pumping Capacity

As soon as top up pumping commences, the competing effect of mound decay (plus the ever present evapotranspiration) becomes operative. The extent to which artificial summer levels can be maintained is limited by pumping capacity. Perry Lakes Reserve bores P1-P8 have an estimated open pipe (non pressurised) combined capacity of about 620m^3 h^{-1}. Actual top up rates however are limited by the 6 inch (152mm) ring main and narrow (80 and 100mm) top up outlets (Figure 5.1a). The wetland managers frequently operated five bores simultaneously with a combined theoretical capacity of about 400m^3 h^{-1}, however the maximum measured top up rate was never observed to exceed 235m^3 h^{-1} (5640m^3 d^{-1}).

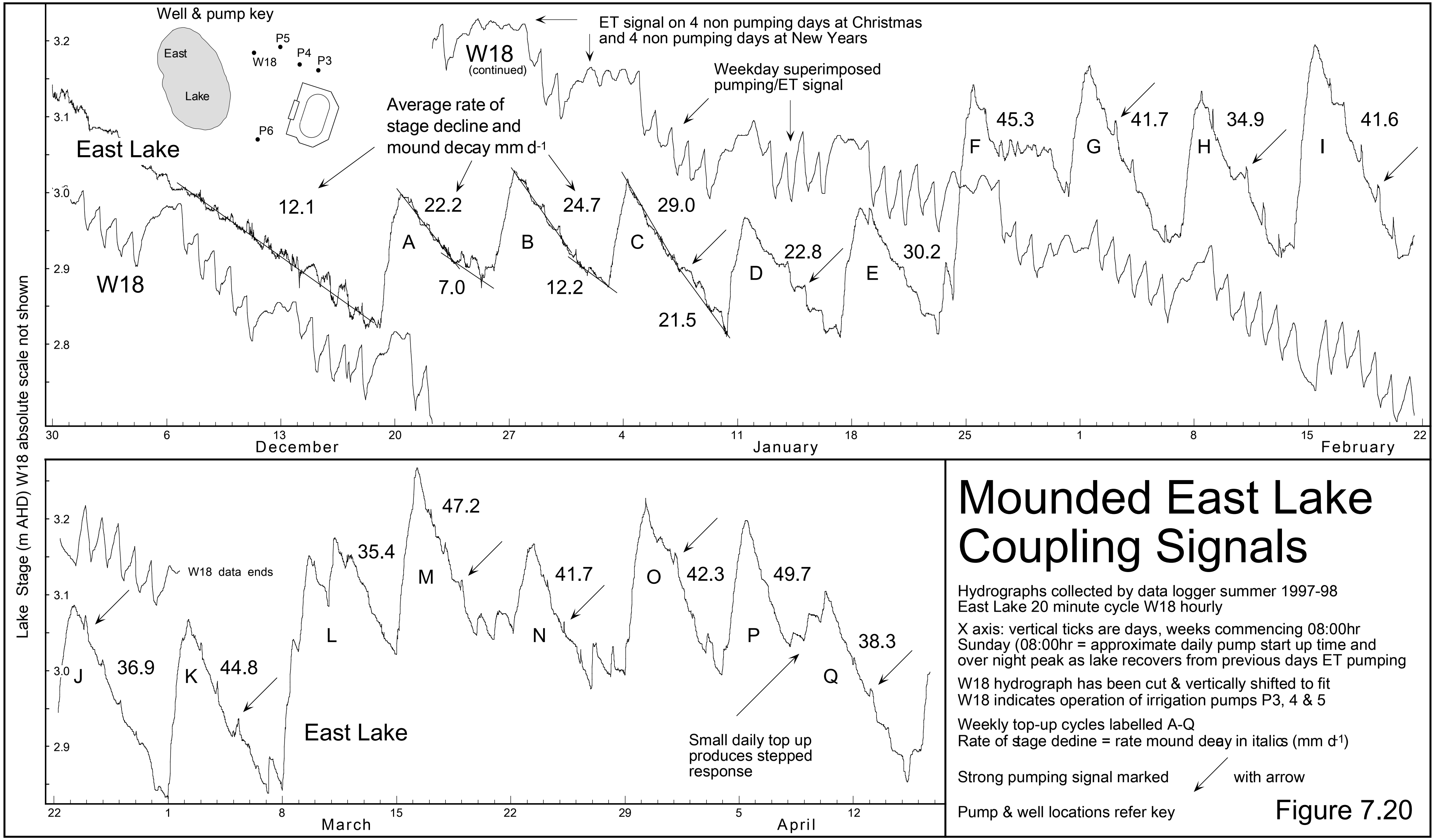
In summer the rate of mound decay increases as the head (effectively lake stage) increases (Table 7.12). Figure 7.20 also demonstrates how the rate of mound decay increases with stage height and effective head. Note how in top up cycle 'A' filling the lake to about 3.0m resulted in a decay rate of 22mm d^{-1}. Three months later a similar top up
(cycle 'K'), the rate had doubled to 45mm d^{-1}. This reflects the fact that in three months the natural position of the water table had fallen so that a top up to 3.0m in March creates a much higher mound than a similar top up in December.

The East Lake hydrograph for December 1997 (Figure 7.20) shows the natural rate of lake and local water table decline up to the commencement of top up pumping on December 20. The initial five top up cycles (A to E) all raised the lake level about 200mm. Average mound decay was 25.8mm d^{-1} or about double the natural rate of decline of 12.1mm d^{-1}. The initial three cycles all display a change in decay rate over time. At the top up peak stage of about 3.0m lake waters were in contact with the sandy basin rim. It is tempting to speculate that the change represents diminished seepage as the waters became completely constrained by the clay lining. This argument does not hold water however, as this effect was not evident during natural decline and disappears after top up cycle C. Reasons for this seemingly transient effect remain unclear. Decay rates clearly increase with higher lake stages. Small changes in rate between seemingly identical top up cycles such as J & K and those noted above reflect the effects of nearby pumping and differences in evaporation, water temperature and experimental error.

Models of lake maintenance performance were developed which predict lake stage in hourly time steps (Figure 7.21b). The models use observed seepage losses at summer water temperatures and evaporation rates (Figure 7.21d). Curves plot typical measured top up rates (maximum 235m^3 hr^{-1}). These models, in practice, are considered to be conservative. This is because seepage losses increase when top up commences at very low lake levels. Under such conditions approximately 25-40% of top up water enters the lake basin through the north outlet. Much of this seeps directly into the lake bed before eventually puddling and joining the expanding main body of the lake within the South Basin. Detailed observations of this on March 16, 1997 indicated that much of this water was returning to the aquifer via large mud cracks. Top up pumping commenced at a lake stage of 2.867m, at an average rate of 222m^3 hr^{-1} (139m^3 h^{-1} south outlet and 93m^3 hr^{-1} north outlet). It took 7 hours for the two expanding bodies of water to join. This occurs when the NE Arm fills and overflows into the South Basin. The model predicts a stage of 2.96m under such conditions, measured stage was 2.931m. The extra losses are those described above. The model curves agree well with observed top up hydrographs (Figure 7.21c). In practice top up seldom proceeds continuously for more than 48 hours (one weekend).

Temperature and Viscosity:

The hydraulic conductivity of any porous medium is affected by temperature which controls water viscosity. Viscosity decreases with temperature such that warmer water passes more easily through the sediment pore spaces. As the water temperature increases, so too does hydraulic conductivity. Temperature effects on hydraulic conductivity are



Mounded East Lake Coupling Signals

Hydrographs collected by data logger summer 1997-98
East Lake 20 minute cycle W18 hourly

X axis: vertical ticks are days, weeks commencing 08:00hr Sunday (08:00hr = approximate daily pump start up time and over night peak as lake recovers from previous days ET pumping

W18 hydrograph has been cut & vertically shifted to fit
W18 indicates operation of irrigation pumps P3, 4 & 5

Weekly top-up cycles labelled A-Q
Rate of stage decline = rate mound decay in italics (mm d^{-1})

Strong pumping signal marked with arrow

Pump & well locations refer key

Figure 7.20

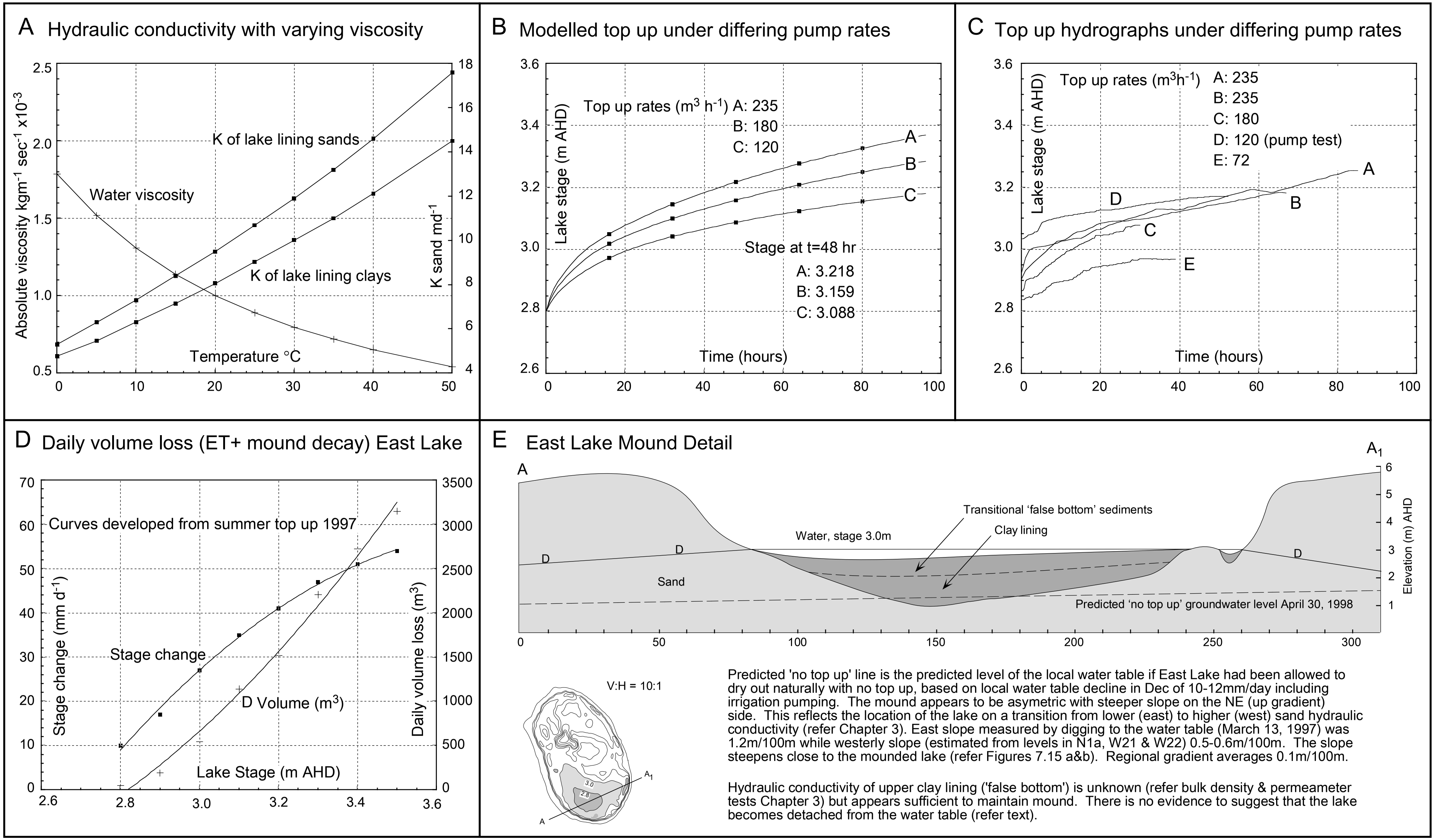

A Hydraulic conductivity with varying viscosity
Absolute viscosity kgm-1 sec-1 x10-3
K sand md-1
Water viscosity
K of lake lining sands
K of lake lining clays
Temperature °C
B Modelled top up under differing pump rates
Lake stage (m AHD)
Top up rates (m3 h-1) A: 235
B: 180
C: 120
Stage at t=48 hr
A: 3.218
B: 3.159
C: 3.088
Time (hours)
C Top up hydrographs under differing pump rates
Lake stage (m AHD)
Top up rates (m3h-1) A: 235
B: 235
C: 180
D: 120 (pump test)
E: 72
Time (hours)
D Daily volume loss (ET+ mound decay) East Lake
Curves developed from summer top up 1997
Stage change (mm d-1)
Daily volume loss (m3)
Stage change
D Volume (m3)
Lake Stage (m AHD)
E East Lake Mound Detail
Transitional 'false bottom' sediments
Clay lining
Water, stage 3.0m
Sand
Predicted 'no top up' groundwater level April 30, 1998
Elevation (m) AHD
V:H = 10:1
Predicted 'no top up' line is the predicted level of the local water table if East Lake had been allowed to dry out naturally with no top up, based on local water table decline in Dec of 10-12mm/day including irrigation pumping. The mound appears to be asymetric with steeper slope on the NE (up gradient) side. This reflects the location of the lake on a transition from lower (east) to higher (west) sand hydraulic conductivity (refer Chapter 3). East slope measured by digging to the water table (March 13, 1997) was 1.2m/100m while westerly slope (estimated from levels in N1a, W21 & W22) 0.5-0.6m/100m. The slope steepens close to the mounded lake (refer Figures 7.15 a&b). Regional gradient averages 0.1m/100m.
Hydraulic conductivity of upper clay lining ('false bottom') is unknown (refer bulk density & permeameter tests Chapter 3) but appears sufficient to maintain mound. There is no evidence to suggest that the lake becomes detached from the water table (refer text).

Figure 7.21

often ignored, however in shallow lakes with large seasonal changes in average daily temperature, the effect becomes significant. If hydraulic conductivity is determined at 20˚C, the change due to viscosity is given by Bouwer (1978) as:

$$K_t = \frac{K_{20}\mu_{20}}{\mu_t} \tag{7.4}$$

where K_t and μ_t are hydraulic conductivity and viscosity at temperature t. Vertical K_{20} for East Lake lining clays and sands was estimated by permeameter (Chapter 3) to be 0.0108 and 9.5m d^{-1} respectively. The range of water temperature within East Lake (1996-1998) was 9.2 to 40.9˚C. Over this temperature range the hydraulic conductivity of lining clays and sands varies between 0.008 to 0.017m d^{-1} and 7.1 to 14.8m d^{-1} respectively (Figure 7.21a). Therefore over the range of water temperatures occurring seasonally, lining hydraulic conductivity potentially doubles under extreme summer conditions. At depth, average temperature also increases within the clay lining (Chapter 9).

For wetland managers struggling to maintain water levels over summer, the cards are stacked against them. The lake is the visible top of a local groundwater mound which pumping attempts to maintain against a falling regional water table, locally depressed further by pumping, increased transpiration and open water evaporation. The rate of mound decay is further enhanced by reduced water viscosity and higher effective lining hydraulic conductivity.

7.7 WETLANDS ON THE SWAN COASTAL PLAIN - NEW INFORMATION

In Chapter 2 some anecdotal evidence was presented which implied that the position of wetlands within the landscape is not arbitrary. The most striking feature of regional maps is the well defined general north-south orientation of the major wetland systems. These include the Wanneroo chain of wetlands (Loch McNess to Lake Goollelal), including the more ill defined chain from the Carine Swamps to Herdsman Lake and south of the Swan River, the East Beeliar chain of wetlands from North Lake to The Spectacles. Many of the wetlands themselves display the same north-south elongation, in particular Lake Joondalup. It has long been recognised that these wetland chains decrease in age towards the coast (Allen 1981). It is also evident that some of the larger lakes lie on or close to the surface expression of geologic boundaries. Lakes Pinjar and Jandabup and the East Beeliar chain of lakes occupy the contact between Bassendean Sand and the leached sand facies of the Tamala Limestone. Lake Joondalup, the Carine Lakes including Lakes Karrinyup and Gwelup and Perry Lakes lie on the Tamala Limestone, on or close to the surface contact between calcarenite and basal sands (Figure 1.2).

Drillers in the City Beach-Ocean Reef area frequently comment that the upper 20m of the aquifer contains thin hard silcrete bands, but is also the most porous zone and often the only zone producing reasonable yields. Below this level it is often difficult to obtain useable flows (M. Davies, W. Brandt pers com). Davidson (1995) notes that the eastern margin of the Tamala Limestone is characterised by finer grained sand (and correspondingly lower hydraulic conductivity). Around Jackadder Lake which lies within this contact zone, drill contractors report poor yields in the near surface residual Tamala sands of 300-400m^3 d^{-1} (K. Wintergreen, pers com). Similarly Haselgrove (1981) notes a thin eastward dipping unit of clayey sand which occurs between Tamala Limestone and Bassendean Sand in the Kwinana area. He suggests that an abrupt change in aquifer hydraulic gradient in this area reflects lower aquifer transmissivity possibly due to this layer which is described as a 'barrier' to westward groundwater movement.

These hydraulic barriers produce a local steepening of the water table gradient. The detailed regional surveys show this effect west of Herdsman and Jackadder Lakes (Figures 2.5 & 2.6). At Perry Lakes a similar barrier effect (steepened gradient) occurs immediately southwest of both lakes. This is readily evident in many of the winter water table contour maps comprising Figure 7.15. This barrier zone is evident immediately adjacent to West Lake between wells N2 and W5 and about 200m southwest of East Lake between wells W24 and N5.

These effects are quite subtle and are not evident on regional scale maps. At Perry Lakes these data appear at first glance to be at variance with the pump test and grain size analyses which indicate an increase in hydraulic conductivity in this area. Regionally increased transmissivity in coastal limestone is well documented (Davidson 1995), and not disputed. This is an extremely localised zone and appears to define the boundary between Tamala Fm sand (to the east) and calcarenite ('limestone') to the west. Its position on a geologic contact, immediately west and down hydraulic gradient from Perry Lakes has obvious similarities to other areas. East of such barriers there is a local water table rise. This corresponds precisely to the position of the East Beeliar, Herdsman-Jackadder and Perry Lake systems. It suggests that hydrogeology plays a subtle but important role in defining the position of wetlands in the landscape.

7.8 CONCLUDING SUMMARY

Lake-aquifer interaction is an intrinsic characteristic of water table lakes. It can be described and modelled mathematically as a continuum of 'flow regimes'. This continuum is bounded by recharge lakes and discharge lakes which form end its members. The physical characteristics of both the lake and the aquifer and their respective water balances represent a plethora of factors which operate in combination to determine the flow regime prevailing at any time. These include (but are not limited to:

Characteristics of the lake and its water balance

- lake length and depth
- distribution and resistance of the lake lining
- horizontal flux ratio
- rainfall and evapotranspiration

Characteristics of the aquifer and its water balance

- wetted thickness
- anisotropy
- hydrogeology (sand, limestone, clay layers)
- slope of the phreatic surface
- recharge (function of climate and land use)

Landscape effects

- proximity to nearby lakes
- geologic boundary effects

Anthropologic effects

- effects of nearby pumping
- effects of artificial stimulation such as storm water drains and summer 'top up'

Perry Lakes are now characterised by recharge regimes for much of the time, either in response to storm water inputs and/or artificial summer 'top up'. Both have the effect of forcing the lakes to tend towards (or become) local groundwater mounds. Excessive local groundwater extraction further enhances this effect. In winter flow-through regimes occur but are highly non symmetric with recharge always exceeding discharge, again in response to large storm water inputs.