CHAPTER

6

WATER BALANCE INTEGRATION

6.0 INTRODUCTION

The theory of integrating measured mass components of the water balance with solute and stable isotope balances is introduced. The methodology by which this was achieved at Perry Lakes is discussed and integrated balance data presented. Groundwater recharge and discharge (which are the only components of the water balance not directly measured) are estimated.

6.1 SIMULTANEOUS MULTIPLE BALANCES

6.1.1 Theory

Chapter 4 discussed the uncertainties in measuring the mass components of any water balance. At Perry Lakes groundwater recharge and discharge are the only mass components which were not easily directly measured. Perry Lakes are not alone in this deficiency. As Winter (1981, p82) points out 'the interaction of lakes and ground water is the most elusive factor of all'. Table 6.1 summarises the water balance components and their associated solute and stable isotopic values measured at Perry Lakes.

Table 6.1 Water balance components measured

Component	Mass	Cl	^{2}H	Heat	Comments
Lake volume	X	X	X	X	Data logger (20 minutes), daily manual lake stage
Rainfall	X	X	X	X	Daily manual (4 in-lake) gauges
Storm drains	X	X	X	X	Continuous data logger (1 & 2 minute data)
Summer top up	X	X	X	X	Flow meters, read daily
Groundwater discharge		X	X	X	Estimated by integrated mass-solute-isotope balance
Groundwater recharge		X	X	X	Mass bal (R regimes) integrated bal (FT regimes)
Evaporation	X		X		Daily, floating Class A pan
Transpiration	X				Estimated by water table techniques, logger data

It is clear that while groundwater recharge and discharge mass could not be measured, their associated solute and stable isotope signatures were easily measured. This points out the advantage in simultaneous multiple balances. Stable solutes such as chloride are conserved during evaporation and transpiration, becoming concentrated in the lake waters. Stable isotopes on the other hand, fractionate during evaporation. Both impart different, but predictable signatures on the residual lake water.

Solutes and isotopes therefore provide complementary information on mass balance components (Townley *et al* 1993b, p30). In so doing they allow difficult to measure components (such as groundwater) to be better estimated.

6.1.2 Simultaneous Multiple Balances

The mass balance for East Lake may be written:

$$\Delta S = S_i + P + GW_i - S_o - E - E_t - GW_o \qquad (6.1)$$

where

ΔS = change in surface water storage

S_i = all surface water inflows (storm drains, surface run-off)

P = precipitation

GW_i = groundwater discharge from the aquifer through the lake lining

S_o = all surface water outflows (there are none at Perry Lakes)

E = evaporation

E_t = evapotranspiration from emergent vegetation

GW_o = groundwater recharge from the wetland directly to the aquifer

Each mass balance comprised a time interval of 'one Perry Lakes day' which commenced and ended at 08:00 hr. Area and storage volume were calculated from the lake stage at the end of each balance period. Water volume (with units of m^3) was used as a proxy for mass. This was for computational convenience and was considered acceptable since over the annual observed water temperature range of 15˚C to 35˚C thermal expansion results in a stage increase of about 0.5mm at lake stage 3.0m. This lies within the reading error of manual stage measurement. It should always be remembered however that it is mass NOT volume which is actually conserved. In all formulae which follow 'mass' was measured as volume (ignoring temperature and density). Thermal expansion and water density effects are further explored in Chapters 7 & 10.

Under flow-through regimes all mass components except groundwater discharge and recharge were measured directly. When the lakes were in recharge, this component (recharge) was estimated as the residual in the mass balance.

Rearranging (6.1) and ignoring E_t the mass balance becomes:

$$\Delta S - [S_i + P] + E = GW_i - GW_o \qquad (6.2)$$

Expanded and expressed in words this becomes:

$$\left[\left(Vol_{final}\right) - \left(Vol_{initial}\right)\right] - \left[(drains) + (top\,up) + (rain)\right] + (evap) = \left(Gw_{in} - Gw_{out}\right) \qquad (6.3)$$

No groundwater discharge mass was measured directly. The term $-Gw_{out}$ is designated the 'apparent groundwater flux' in Appendices 6.2 and 6.3. It represents the residual in the mass balance. Under recharge flow regimes it represents an estimate of lake water recharged to the aquifer. Under flow-through conditions it is the difference between recharge and discharge. A mass balance alone, cannot differentiate groundwater flux components. Only by integrating complementary solute and isotope data can all components be estimated.

The chloride balance may be expressed as: (6.4)

$$\left[\left(Vol_{final}\right)*\left(Cl_{final}\right) - \left(Vol_{initial}\right)*\left(Cl_{initial}\right)\right] - \left[(drains)*\left(Cl_{drains}\right) + (top\,up)*\left(Cl_{outlet\,A}\right) + (top\,up)*\left(Cl_{outlet\,B}\right) + (rain)*\left(Cl_{rain}\right)\right] = \left[\left(Gw_{in}\right)*\left(Cl_{in}\right) - \left(Gw_{out}\right)*\left(Cl_{lake\,av}\right)\right]$$

Note that top up outlets have separate chloride values and that the recharge term $\left(Gw_{out}\right)$ has a chloride value equal to the lake average for the period. Each term has the form $mass\left(m^3\right)*Cl\left(mg\,L^{-1}\right)$ yielding units of grams of chloride. Values for all terms, including $\left(Cl_{in}\right)$ and $\left(Cl_{lake\,av}\right)$ are known. The only unknowns are the mass terms $\left(Gw_{in}\right)$ and $\left(Gw_{out}\right)$. Rearranging yields:

$$\left(Gw_{out}\right) = \left(Gw_{in}\right)*\left(Cl_{in}\right) - \frac{\left[\left(Vol_{final}\right)*\left(Cl_{final}\right) - \left(Vol_{initial}\right)*\left(Cl_{initial}\right)\right] - \left[\left(drains\right)*\left(Cl_{drains}\right) + \left(top\,up\right)*\left(Cl_{outlet\,A}\right) + \left(top\,up\right)*\left(Cl_{outlet\,B}\right) + \left(rain\right)*\left(Cl_{rain}\right)\right]}{Cl_{lake\,av}} \qquad (6.5)$$

For any given balance period, (6.5) defines a family of chloride balance solutions where for any value of $\left(Gw_{in}\right)$, a value of $\left(Gw_{out}\right)$ can be defined.

Chloride is a conservative solute. It is essentially non reactive and not influenced significantly by biological or chemical proccess (in particular evaporation) within a watershed or water body (Schwartz & Gallup 1978). Therefore (6.5) requires no evaporation term. On the other hand deuterium and other isotopes such as oxygen 18 are non conservative. Various physiochemical processes including changes of state, and chemical and biochemical transformations can result in isotopic fractionation (Clark & Fritz 1997). In water balance studies evaporation is the principal fractionation process of interest (Townley et al 1993b) so an evaporation term must be included in the balance equation. Again $\left(Gw_{out}\right)$ has a deuterium value equal to the lake average for the period. Each deuterium term takes the form $mass\left(m^3\right)*\left(1+\delta\right)$ and the deuterium balance becomes:

$$\left[\left(Vol_{final}\right)*\left(1+\delta_{final}\right) - \left(Vol_{initial}\right)*\left(1+\delta_{initial}\right)\right] - \left[\left(drains\right)*\left(1+\delta_{drains}\right) + \left(top\,up\right)*\left(1+\delta_{outlet\,A}\right) + \left(top\,up\right)*\left(1+\delta_{outlet\,B}\right) + \left(rain\right)*\left(1+\delta_{rain}\right)\right] \qquad (6.6)$$
$$+\left[\left(evaporation\right)*\left(1+\delta_{E}\right)\right] = \left[\left(Gw_{in}\right)*\left(1+\delta_{Gw\,in}\right) - \left(Gw_{out}\right)*\left(1+\delta_{lake\,av}\right)\right]$$

Rearranging:

$$\left(Gw_{out}\right) = \left(Gw_{in}\right)*\left(1-\delta_{in}\right) - \qquad (6.7)$$
$$\frac{\left[\left(Vol_{final}\right)*\left(1+\delta_{final}\right) - \left(Vol_{initial}\right)*\left(1+\delta_{initial}\right)\right] - \left[\left(drains\right)*\left(1+\delta_{drains}\right) + \left(top\,up\right)*\left(1+\delta_{outlet\,A}\right) + \left(top\,up\right)*\left(1+\delta_{outlet\,B}\right) + \left(rain\right)*\left(1+\delta_{rain}\right)\right] + \left[\left(evap\right)*\left(1+\delta_{E}\right)\right]}{\left(1+\delta_{lake\,av}\right)}$$

An isotope (deuterium or ^{18}O) balance is simply a variation of the chloride balance but has a particular quirk with the use of the delta ('δ') notation, defined as the relative difference in the ratio (R)of deuterium (or ^{18}O) to the more abundant light isotope, measured relative to the reference ocean water VSMOW (Clark & Fritz 1997):

$$R = ratio\left[\frac{^{2}H}{^{1}H}\right] \qquad \text{or} \qquad R = ratio\left[\frac{^{18}O}{^{16}O}\right] \tag{6.8}$$

In the case of deuterium (^{2}H) is 155.76‰ VSMOW. This notation may be thought of as being the gram atoms of deuterium per litre. Using delta notation:

$$\delta_{sample} = \left[\frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}}\right] \tag{6.9}$$

or, written per mille (‰) becomes:

$$\delta_{sample} = \left[\frac{R_{sample}}{R_{VSMOW}} - 1\right] * 1000‰$$

(6.10)

This means that

$$1 + \delta_{sample} = \frac{^{2}H_{sample}}{^{1}H_{VSMOW} + ^{2}H_{VSMOW}}$$

(6.11)

which is the grams of deuterium per grams of hydrogen (protons and deuterons) in the water. The process may be visualised by converting delta notation to ppm deuterium. The R value of VSMOW is equivalent to 155.76 ppm deuterium ($\delta = 0‰$). Therefore when water has a delta value of 0.00‰, we are simply describing water with an isotopic ratio equal to VSMOW. Substituting into (6.10):

$$\delta = \left[\frac{155.76}{155.76} - 1\right] * 1000‰ \qquad = 0‰$$

(6.12)

What should be clear however is that the $(mass) * (1 + \delta)$ notation is describing water with deuterium greater or less than 155.76 ppm, the range of natural waters being approximately 90-165 ppm (Clark & Fritz 1997). For any given balance period, (6.7) defines a family of deuterium balance solutions where for any value of discharge (Gw_{in}), a value of recharge (Gw_{out}) can be defined.

6.2 METHOD

All balances were completed within a strict framework of balance 'periods' (refer Appendices Chapter 6). Each period was 12, 16 or 20 days long and consisted of 3, 4 or 5 sub-balance periods of exactly four days. A balance 'day' started and ended at exactly 08:00 hours. The division between balance periods was dictated by rainfall and storm drain flow. Each period starts and ends in a dry period.

Mass balances were computed daily. Water from both lakes was sampled daily but deuterium and chloride analyses were completed only every four days. Mass, chloride and deuterium were integrated for each of these four day 'sub-balance' periods. The chloride and deuterium were therefore known at the start and end of each four day period, allowing an 'average' figure to be calculated for recharge. They appear in the denominators of Equations (6.5) and (6.7).

In East Lake four day integrated mass-solute and isotope balances were completed from balance periods 4 to 50 (146 sub-balances). East Lake was in a recharge condition for balance periods 1 to 3 which were computed by mass balance only. West Lake chloride was analysed from August 1996 to March 1997 only, covering the transition from lake (winter maximum) to residual sump (summer minimum). Integrated balances cover periods 11-19A only. In West Lake chloride was analysed every 12 days (start and end of each balance period) while deuterium was analysed every four days. Four day sub-balances (using interpolated Cl estimates) and twelve day balances are included in Appendix 6.3. The two methods result in only small differences in estimated groundwater flux. Figure 6.1 shows the 50 balance periods and the distribution of mass, deuterium and chloride measurements.

Equations (6.5) and (6.7) were applied to each four day sub-balance period (Appendices 6.2 and 6.3). For each equation a range or 'family' of estimates of groundwater recharge was used to calculate a corresponding range of values for groundwater discharge. These estimates of recharge and corresponding discharge plot as straight lines. The deuterium solutions comprised two solution 'sub-families', computed using δ_E derived experimentally specifically for Perry Lakes from pan experiments (Chapter 12), and δ_E calculated empirically using experimentally determined values of δ_A (refer also to Chapter 12) and Equation 23 of Craig & Gordon (1965). The groundwater flux estimates presented in Table 6.2 and Appendices 6.2 and 6.3 all utilise the experimentally derived values of δ_E . Final balance integration was done both graphically and algebraically by solving for the intersection of the two linear equations (6.5) and (6.7). The intersection of the chloride and isotope curves indicates a unique solution for discharge and recharge. Solutions calculated using empirically and experimentally determined δ_E typically varied by less than 2%. In the examples shown in Figure 6.2, the differences range from 0.07% (recharge sub-balance 33B) to 1.8% (discharge sub-balance 33E). At transition to flow-through (Figure 6.2b) calculated groundwater discharge figures are sometimes very small, in sub-balance 33D for example, being 22 and 25m^3. Here the apparent differences can become larger however when compared to the other inputs (in this case rain and storm water totalling 3440m^3) such differences become insignificant.

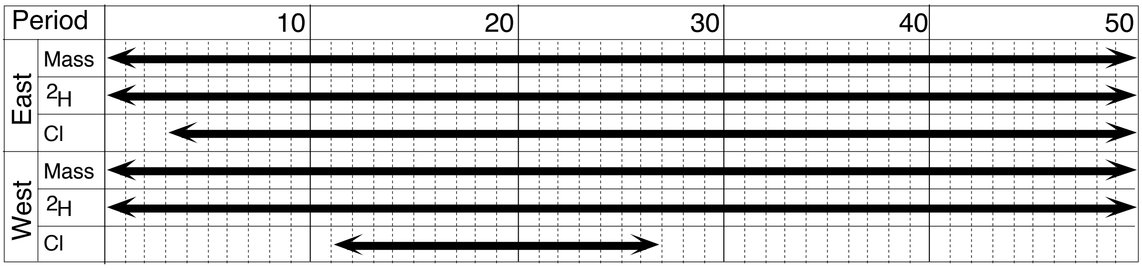


Figure 6.1 Distribution of mass, deuterium and chloride balances over 50 balance periods (vertical lines). Integrated mass - solute - isotopic balances were completed for all balance periods where all three components were measured.

Three basic flow regime states were identified.

Recharge Regimes (Figure 6.2a)

Lake water is recharged to the aquifer. No groundwater is discharged into the lake. The mass balance therefore contains only one unknown (recharge) which is solved as the residual of the mass balance. Similarly chloride and deuterium are solved for zero discharge. The chloride and deuterium solutions plot as parallel (or near parallel) lines, their y intercepts being recharge. Here mass, solute and isotope balances provide three independent estimates of recharge, allowing an average 'best estimate'.

Transition to Flow-through (Figure 6.2b)

The transition between regimes is marked by oscillation between weak flow-through and recharge. These are common over winter when heavy rain and storm drain inputs push the lake into or close to recharge. The temporal resolution of our integrated balances was four days. At this scale it was not possible to resolve short term detail.

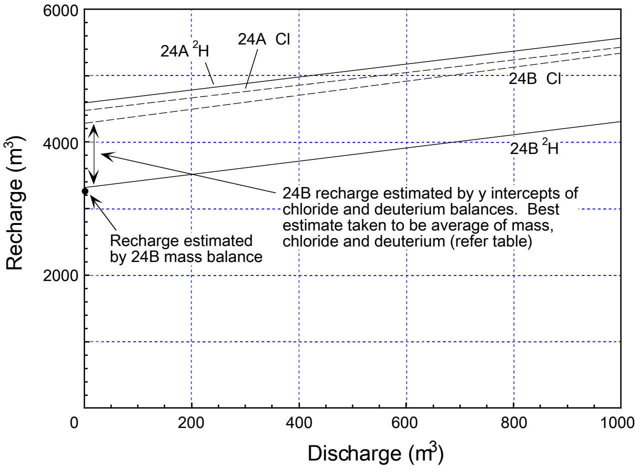
Flow-through Regimes (Figure 6.2c)

Groundwater is discharged into the lake and lake water is recharged to the aquifer. The mass balance therefore contains two unknowns and cannot be solved. Chloride and deuterium balance solutions plot as intersecting lines. The intersection (representing the solution to two linear equations) describes a unique solution satisfying the conservation of both chloride and deuterium.

Mass, Solute & Isotope Data Graphical Integration

Figure 6.2

A Recharge Regime



24B recharge estimated by y intercepts of chloride and deuterium balances. Best estimate taken to be average of mass, chloride and deuterium (refer table)

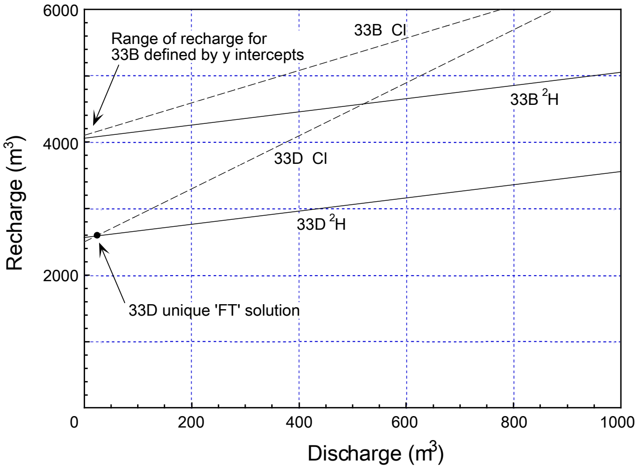
Recharge estimated by 24B mass balance

Under recharge ('R') regimes only groundwater recharge occurs. Discharge = 0. Each line represents solutions for groundwater recharge & discharge however we only consider the 'y' intercept which provides independent chloride and deuterium balance solutions for discharge. The mass balance provides a third solution.

Discharge (Gw IN) & Recharge (Lw OUT), m^3

Sub-balance	24A (Feb 97) Gw IN	Lw OUT	24B (Feb 97) Gw IN	Lw OUT
Mass	0	4647	0	3293
Chloride	0	4490	0	4274
Deuterium	0	4602	0	3339
Deuterium*	0	4632	0	3362
Average		4579		3635

B Transition to Flow-through



Range of recharge for 33B defined by y intercepts

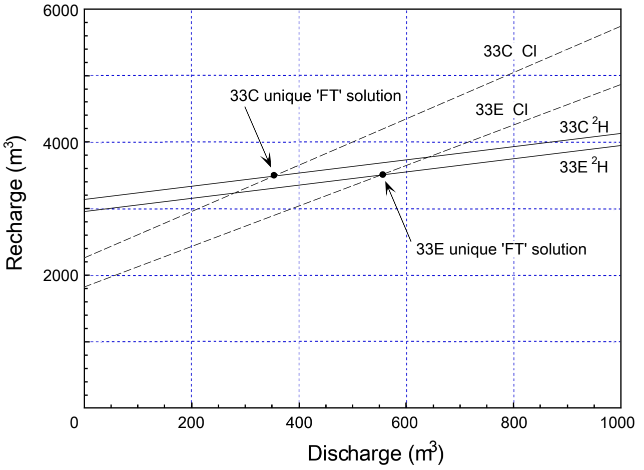
33D unique 'FT' solution

Transition between regimes is frequently marked by oscillation between weak flow-through ('FT') and recharge ('R'). Sub-bal 33 is 'R' but with 'FT' about to commence (Sub-bal 33C below). This in turn oscillates around the transition in 33D, which is very weakly FT.

Discharge (Gw IN) & Recharge (Lw OUT), m^3

Sub-balance	33B (Jun 97) Gw IN	Lw OUT	33D (Jun 97) Gw IN	Lw OUT
Mass	0	4049	0	2568
Chloride	0	4102		
Deuterium	0	4057	22	2607
Deuterium*	0	4060	25	2621
Average		4069		

C Flow-through Regime



33C unique 'FT' solution

33E unique 'FT' solution

Each Cl & deuterium line represents an infinite family of possible solutions. Their intersection is a unique solution satisfying both balances.

Balance 33 marked the 1997 transition from summer recharge regimes to winter flow-through regimes.

These data represent typical FT results

Discharge (Gw IN) & Recharge (Lw OUT), m^3

Sub-balance	33C (Jun 97) Gw IN	Lw OUT	33E (Jun 97) Gw IN	Lw OUT
Mass	0	3194	0	2970
Chloride				
Deuterium	355	3502	554	3513
Deuterium*	357	3511	564	3543

Key to graphs

- - - - - - - - - - - - - -
Chloride

Deuterium & Deuterium*

'Deuterium' solutions calculated using $\delta_{E(lake)}$ calculated from pan experiments at Perry Lakes

'Deuterium*' solutions calculated using Equation 23 of Craig & Gordon (1965)

6.3 RESULTS

Results are summarised by balance period in Table 6.2 and graphically in Figures 6.3 to 6.5. Appendices 6.2 and 6.3 contain daily mass balance and four day integrated balance calculations. They include all of the information required to complete each balance including solute and isotopic data.

Water balance studies generally are subject to incomplete data sets (Winter 1981). Most are mass only or mass and solute or mass and isotope balances. The single factor which makes the Perry Lakes study unique is the degree to which individual mass, solute and isotopic components have been independently measured. At Perry Lakes ALL mass components and their associated solute and isotopic signatures have been individually measured or experimentally derived including δ_A and δ_E (refer Chapter 12) Under flow-through regimes ONLY the mass of groundwater discharge and recharge are unknown. Under recharge regimes lake water recharged to the aquifer is the residual of the mass balance. This combined with independent solute and isotopic balances provides a highly accurate 'best estimate' average. In other words under recharge conditions there are really no unknowns although the recharge component is not directly measured. The integrated balances were not applied 'blindly'. Much additional information provided independent clues to likely lake-aquifer relationships. These include detailed lake stage and water table measurements, nested piezometers, in lake 'mini piezometers', irrigation pumping records and storm water and top up records. These are explored in detail in Chapter 7.

The single most significant result of the integrated balances is the non symmetrical nature of East Lake under flow-through conditions. It was assumed that groundwater discharge and recharge would be similar, more or less balancing each other. The data (Figure 6.3) shows that recharge always exceeded discharge. This pattern was established early in the winter and prevailed over both 1996 and 1997. The pattern was more pronounced in 1996 (when heavy lake maintenance top up commenced early in the summer) as compared to 1997 (when the lake was allowed to approach dryness naturally). Data for West Lake in 1996 (Figure 6.5) is similar to East Lake.

The ratio of recharge to discharge $Gw_{out}:Gw_{in}$ is one of a number of dimensionless ratios useful in describing flow regimes. Mathematical models (Nield *et al* 1994) have been restricted to $Gw_{out}:Gw_{in}$ in the range -2.0 to +2.0 (Nield *et al* use the notation U-:U+). These are more fully explored in Chapter 7. Table 6.3 shows that East and West Lake largely operated outside that range. This indicates that for most of each winter the lakes were always close to or approaching recharge status. The dividing stream line lay close to the up gradient shore in each lake, an observation confirmed experimentally using mini piezometers (Chapter 7).

Table 6.2 Integrated Balance Summary

East Lake

Bal	Start Date	Days	Med Area	Med Vol	Evap	Rain	Drains	Top Up	Gw IN	GW Out	Total Flux
1996											
1	April 22	12	43650	11072	1358	35	27	23265	0	26963	51648
2	May 04	12	40397	9025	930	923	3165	12175	0	14483	31676
3	May 16	12	42855	10459	996	128	222	25850	0	23198	50394
4	May 28	12	39690	8748	965	1496	2344	14075	0	22722	41602
5	June 09	16	40108	9040	820	5414	11718	0	600	10738	29290
6	June 25	12	46115	12514	968	3396	5994	0	421	8030	18809
7	July 07	12	47747	13620	1145	2923	4951	0	1146	7059	17224
8	July 19	20	52517	17852	2149	6495	10623	0	835	8552	28654
9	August 08	12	55973	20963	1395	2086	2859	0	216	5194	11750
10	August 20	12	55415	20238	1335	1759	2311	0	499	4083	9987
11	September 01	12	56191	21224	1679	2681	4103	0	396	3029	11888
12	September 13	12	57565	22949	2317	2357	3379	0	532	3689	12275
13	September 25	12	57430	22778	2216	1164	1702	0	1148	3176	9406
14	October 07	12	55577	20506	2397	435	419	60	787	2470	6568
15	October 19	12	55257	20110	2952	2081	2730	4714	55	4269	16801
16	October 31	12	56293	21382	3140	748	1005	5129	1069	4685	15776
17	November 12	12	55276	20139	3142	2250	3592	538	722	7110	17354
18	November 24	16	53162	18015	2788	267	265	12931	867	13277	30395
19	December 10	12	49732	15271	4062	327	390	8905	0	9206	22890
1997											
20	December 22	12	44775	11672	3728	0	0	8477	0	8156	20361
21	January 03	12	40989	9336	3356	0	0	13038	0	11285	27679
22	January 15	12	38921	8175	2840	12	0	11957	0	10479	25288
23	January 27	12	28627	4978	2092	0	0	5728	0	9170	16990
24	February 08	12	25887	3702	2060	10	0	17267	0	12668	32005
25	February 20	12	38300	8093	1489	41	45	21923	0	14466	37964
26	March 04	12	26336	5826	1548	7	0	2017	0	10911	14483
27	March 16	12	17723	2028	1292	174	570	17420	0	13563	33019
28	March 28	12	31420	5034	1468	3291	7235	10251	0	15136	37381
29	April 09	12	36197	6666	1209	542	947	21079	0	14413	38190
30	April 21	12	31634	5120	801	427	864	4896	0	8473	15461
31	May 03	12	27173	3555	645	62	247	7489	0	6940	15383
32	May 15	12	26389	3385	658	845	2004	7650	0	9872	21029
33	May 27	20	35832	7906	1361	6264	12389	9558	931	18103	48606
34	June 16	12	41610	9841	726	338	303	95	230	5975	7666
35	June 28	12	38650	8037	769	1957	4229	0	265	3773	10993
36	July 10	12	39593	8566	772	876	1806	0	176	3037	6667
37	July 22	12	38661	8014	941	1079	1778	0	315	2402	6515
38	August 03	16	43803	11248	1615	4088	7763	77	1582	5154	20279
39	August 19	12	48688	14266	1381	758	1226	0	1455	2602	7422
40	August 31	12	54920	20856	1645	6665	11965	0	1489	4757	26521
41	September 12	12	60060	25909	2198	47	31	0	790	2334	5400
42	September 24	12	57074	22255	2644	154	138	0	1510	2767	7213
43	October 06	12	55180	19962	2948	1523	2298	0	1716	3609	12094
44	October 18	12	51547	16734	3180	75	73	0	1158	3865	8351
45	October 30	12	44418	11548	2837	0	0	0	70	2193	5100
46	November 11	12	37620	7557	2206	190	451	0	272	1850	4969
47	November 23	12	29286	4441	1951	43	36	0	0	1337	3367
48	December 05	12	16476	1754	1336	0	0	0	0	1059	2395
49	December 17	8	10419	812	645	0	0	2220	0	1145	4010
1998											
50	December 25	9	10593	831	686	0	0	2352	0	1953	4991

West Lake

Bal	Start Date	Days	Med Area	Med Vol	Evap	Rain	Drains	Top Up	Gw IN	GW Out	Total Flux
11	September 01	12	50648	14975	1499	2517	6423	0	544	4630	15613
12	September 13	12	52824	17045	2133	2221	6080	0	411	5665	16510
13	September 25	12	52358	16600	2041	1185	3714	0	691	5707	13338
14	October 07	12	49815	14266	2153	372	1243	0	55	2617	6440
15	October 19	12	48730	13210	2572	1734	4497	0	573	3387	12763
16	October 31	12	47408	12436	2703	653	2306	0	410	3101	9173
17	November 12	12	46686	12400	2750	1976	6262	0	2744	6668	20400
18	November 24	16	42318	9770	3417	341	870	0	2923	6243	13794
19A	December 10	4	36128	6694	727	231	709	0	965	1707	4339

Notes

All area in m^2, all volumes m^3
All balance periods commence and end at 08:00 hr on date shown
Total flux is the total of all in coming and out going fluxes
West Lake data based on 12 day Cl data prorated into 4 day sub balances (refer text)

It only required a small additional input of storm water to push the lake from flow-through into recharge status.

Table 6.3 Groundwater recharge:discharge $Gw_{out}:Gw_{in}$

Balance	East '96 $Gw_{out}:Gw_{in}$	West '96 $Gw_{out}:Gw_{in}$	Balance	East '97 $Gw_{out}:Gw_{in}$
5	17.9	-	33	19.5
6	19.0	-	34	26.0
7	6.2	-	35	14.2
8	10.3	-	36	17.3
9	24.1	-	37	7.6
10	8.2	-	38	3.3
11	7.7	8.5	39	1.8
12	6.9	13.8	40	3.2
13	2.8	8.3	41	3.0
14	3.1	47.5	42	1.8
15	77.3	5.9	43	2.1
16	4.4	7.6	44	3.3
17	9.8	2.4	45	31.3
18	15.3	2.1	46	6.8
19A	-	1.8	-	-

These data provide insights illustrating how urban wetlands have been hydrologically modified. Under natural conditions such wetlands had no riparian inputs. They were maintained solely by direct rainfall and groundwater discharge. Table 6.4 summarises East Lake balance hydrology for calendar year 1997. It must be remembered that 1997 was atypical because top up was withheld for about 8-10 weeks compared to 'normal' years. Despite this, 'non natural' drain and top up inputs comprise 41.7% of the total water budget and 83.6% of total inputs. Virtually all wetlands on the Swan Coastal Plain now operate as storm water infiltration basins. Introducing storm water fundamentally modifies the way a water table lake operates. Groundwater discharge is reduced and replaced by 'non natural' surface inputs. This also affects the lake chemistry since rain and groundwater usually have substantially different cation and isotope signatures.

Table 6.4 Total balance components East Lake 1997

	Rain	Drains	Top Up	Evap	GW Discharge	GW Recharge	Total 1997
Mass (m^3)	29,468	56,398	155,017	49,299	11,957	205,289	507,428
Percent	5.81	11.11	30.55	9.72	2.36	40.46	100.0
No av lake vol	3.2	6.1	16.7	5.3	1.3	22.1	54.6

Average lake volume is at mean annual stage: 3.215m, mean volume 9300m^3, mean area 40990m^2

Covers January 3, 1997 (start sub-balance 21a) to 4 January, 1998 (end sub-bal 50b).

In permanent Swan Coastal Plain wetlands under natural conditions it appears likely that flow-through regimes were maintained all year. During heavy rain events such lakes would move towards or possibly into recharge, but these excursions from flow-through regimes would be transient. The annual trace of lake stage would approximate a smooth

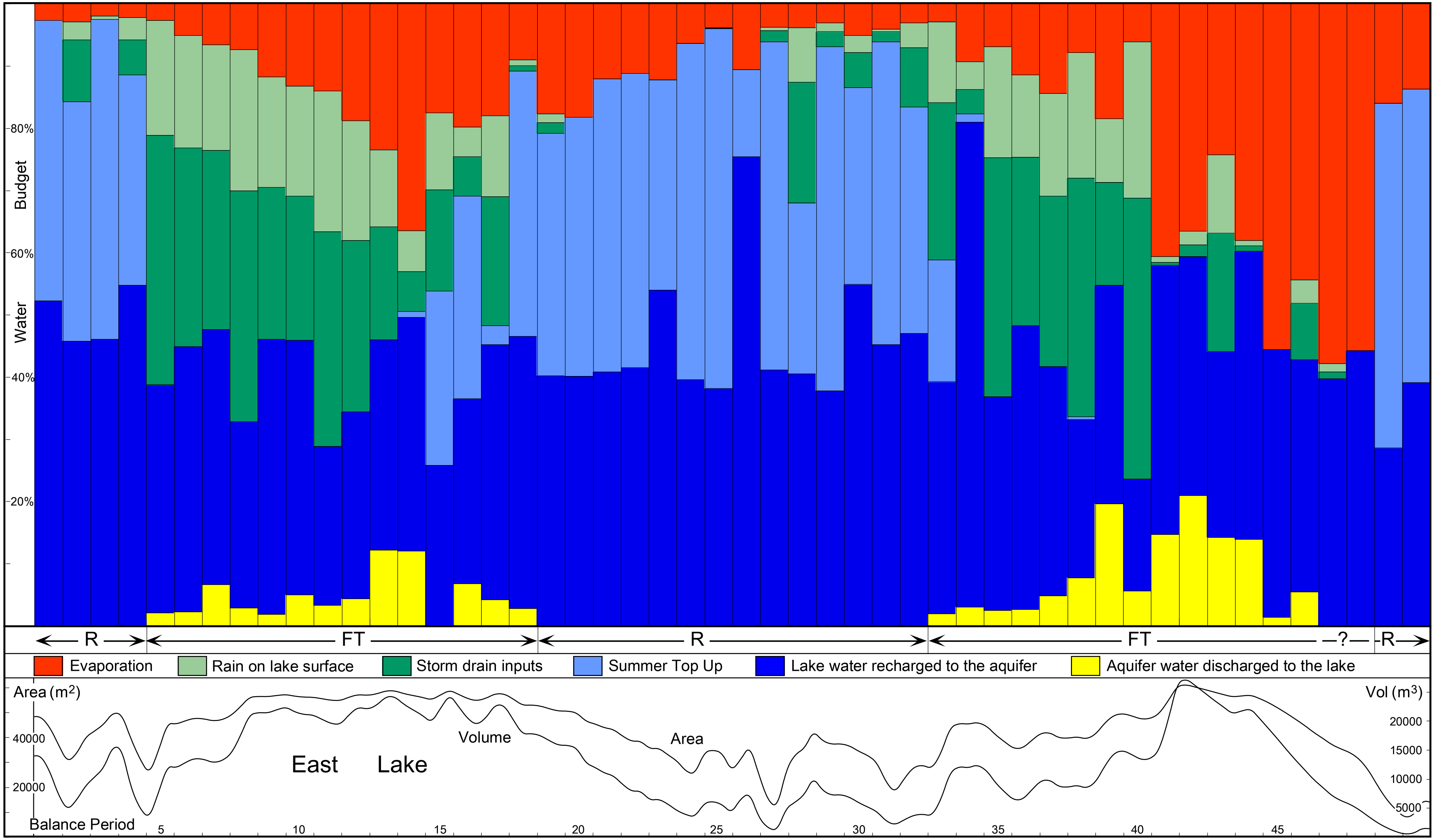
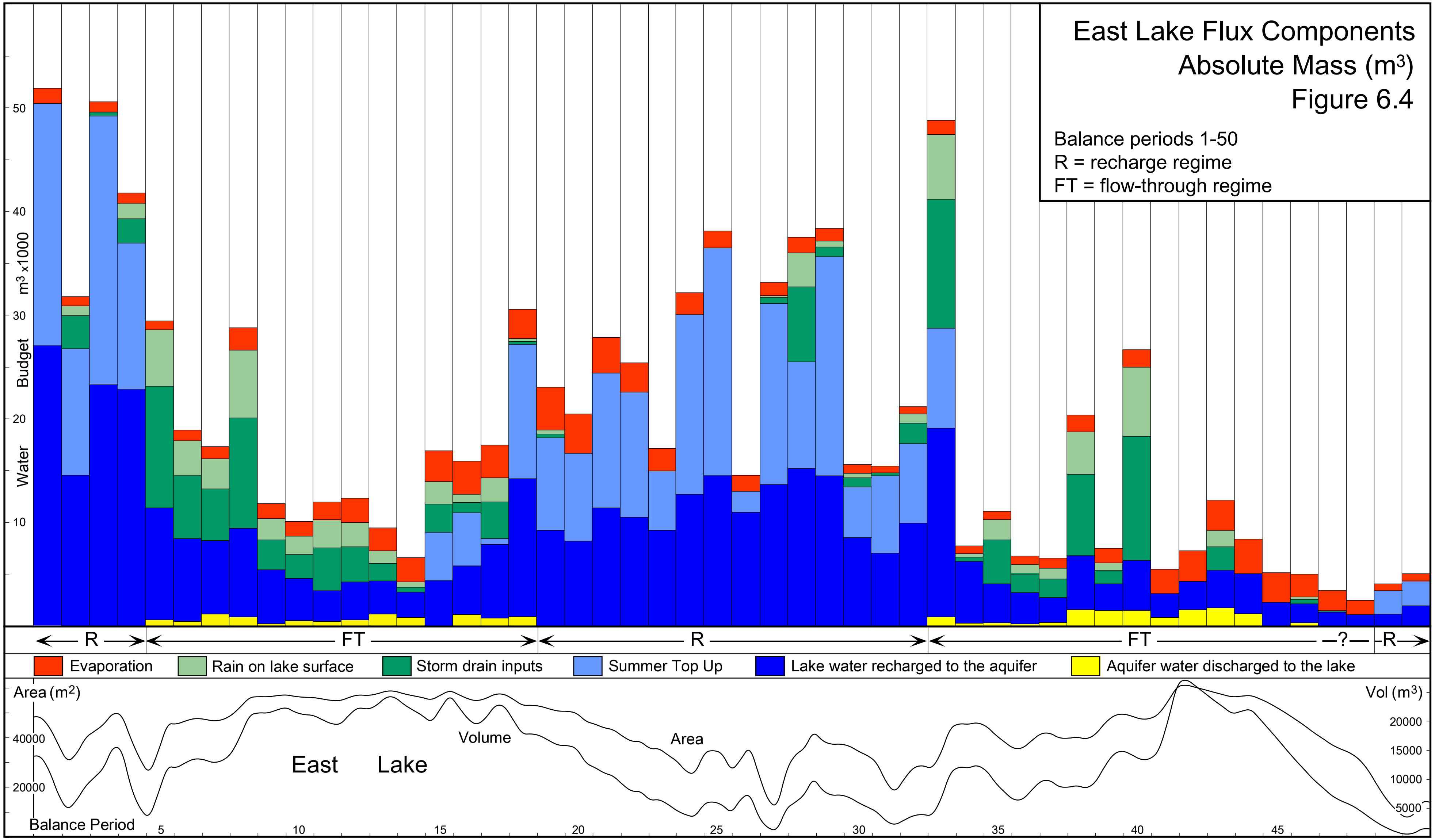

80%
60%
40%
20%
Water Budget
R
FT
R
FT
?
R
🟥 Evaporation
🟩 Rain on lake surface
🟩 Storm drain inputs
🟦 Summer Top Up
🟦 Lake water recharged to the aquifer
🟨 Aquifer water discharged to the lake
Area (m2)
40000
20000
Vol (m3)
20000
15000
10000
5000
Volume
Area
East Lake
Balance Period
5
10
15
20
25
30
35
40
45

Figure 6.3



East Lake Flux Components
Absolute Mass (m^3)
Figure 6.4

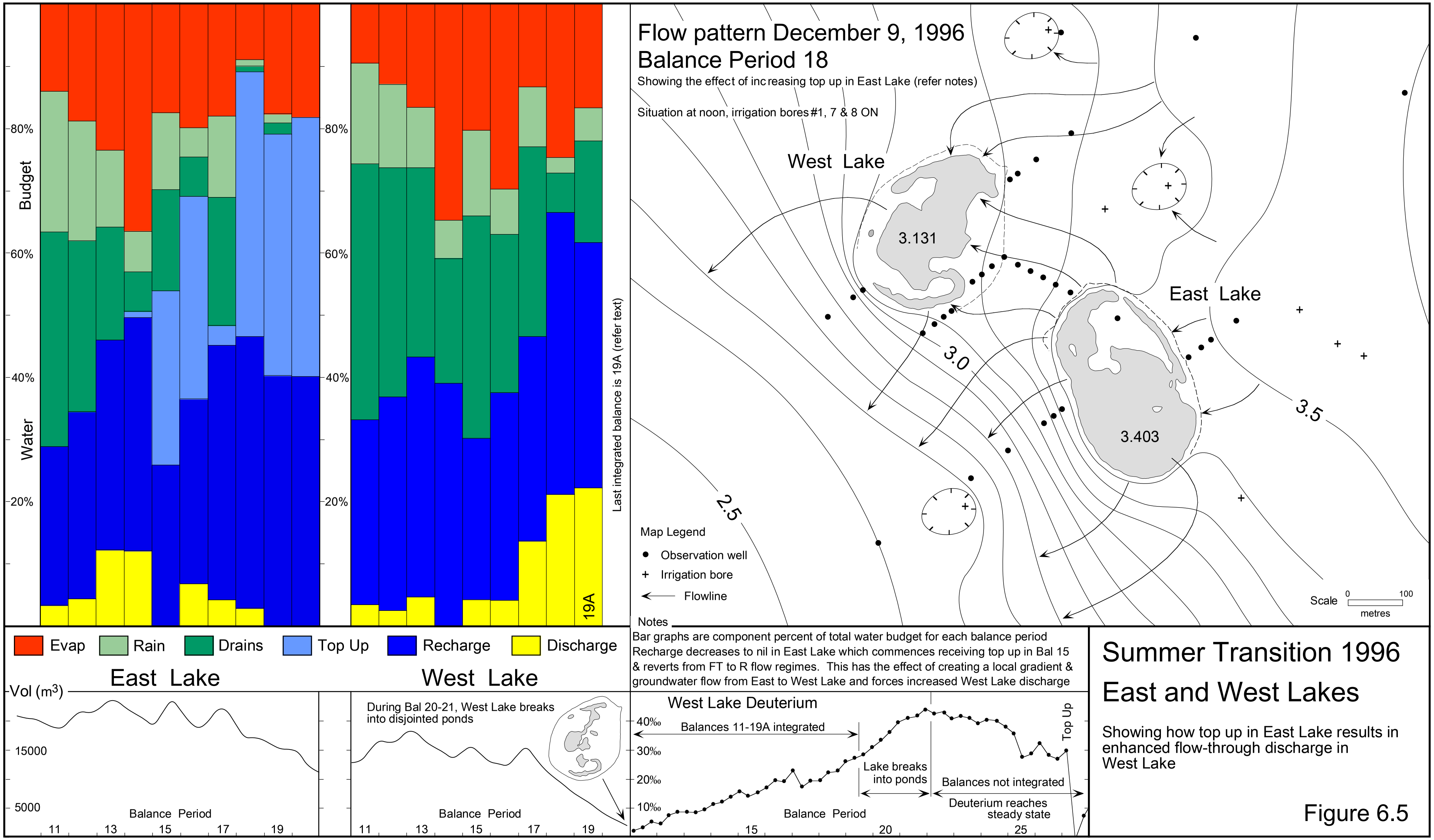
Balance periods 1-50
R = recharge regime
FT = flow-through regime

sinusoid, similar to seasonal fluctuations in the surrounding water table. Storm drains vastly increase the amount of rain water entering a wetland. These inputs are almost instantaneous and force the lake on numerous excursions towards or into recharge. The net result over winter is vastly reduced groundwater discharge compared to that which would have occurred under natural conditions.

Storm drains were introduced to Perry Lakes in the late 1950's (Chapter 2). We therefore have no lake stage records of either lake operating under natural conditions. The Camel Lake monitoring well W25 can be used to approximate natural lake stage patterns. The water table in W25 lies approximately 1m below surface and therefore responds quickly to precipitation. In Figure 6.6 (insert) continuous 5 year data logger data shows a sinusoid annual water table pattern. The water table responds to large rain events just as an adjacent lake would. A water table lake inserted into such an aquifer would function in a similar way. East Lake and W25 data logger records for calendar 1997 are superimposed. The W25 curve approximates the pre-urbanisation natural stage curve for East Lake. The most significant single feature in the East Lake data are the huge winter excursions above the 'natural' curve induced by storm drain inputs. Remember a 50mm rain event will only raise the lake surface of a natural wetland by 50mm, while a wetland acting as a retention basin is raised many times that amount. The 63.8mm event flagged in Figure 6.6 (combined with top up) raised the lake stage by over 300mm.

Figures 6.3 and 6.4 illustrate clearly the effects of early top up. In 1996 groundwater discharge into the lake is suppressed by the combined forces of early top up and lawn irrigation (commenced October 19, Balance Period 15). Extraction for lawn irrigation lowers the groundwater gradient to the east and increases it to the west, further suppressing discharge and enhancing recharge. By comparison, withholding top up in November and December 1997 significantly increased discharge, both as a percentage of the mass budget (Figure 6.3) and absolutely (Figure 6.4). If lawn irrigation extraction could also have been delayed the effect would have been even larger.

As East Lake approached dryness in December 1997, integrated balances show no discharge beyond lake stage 3.126m on November 23, sub-balance 46C (Appendix 6.2). Below this level the lake sits almost entirely within a clay lining. This, and the increasing influence of pump extraction probably combined to reduce discharge to negligible amounts. Mini piezometer surveys (Chapter 7) confirmed that positive piezometric heads were maintained on the east side of the lake until at least December 8 and negative piezometric heads persisted on the west side until top up commenced December 20. East Lake at no time became a discharge lake.

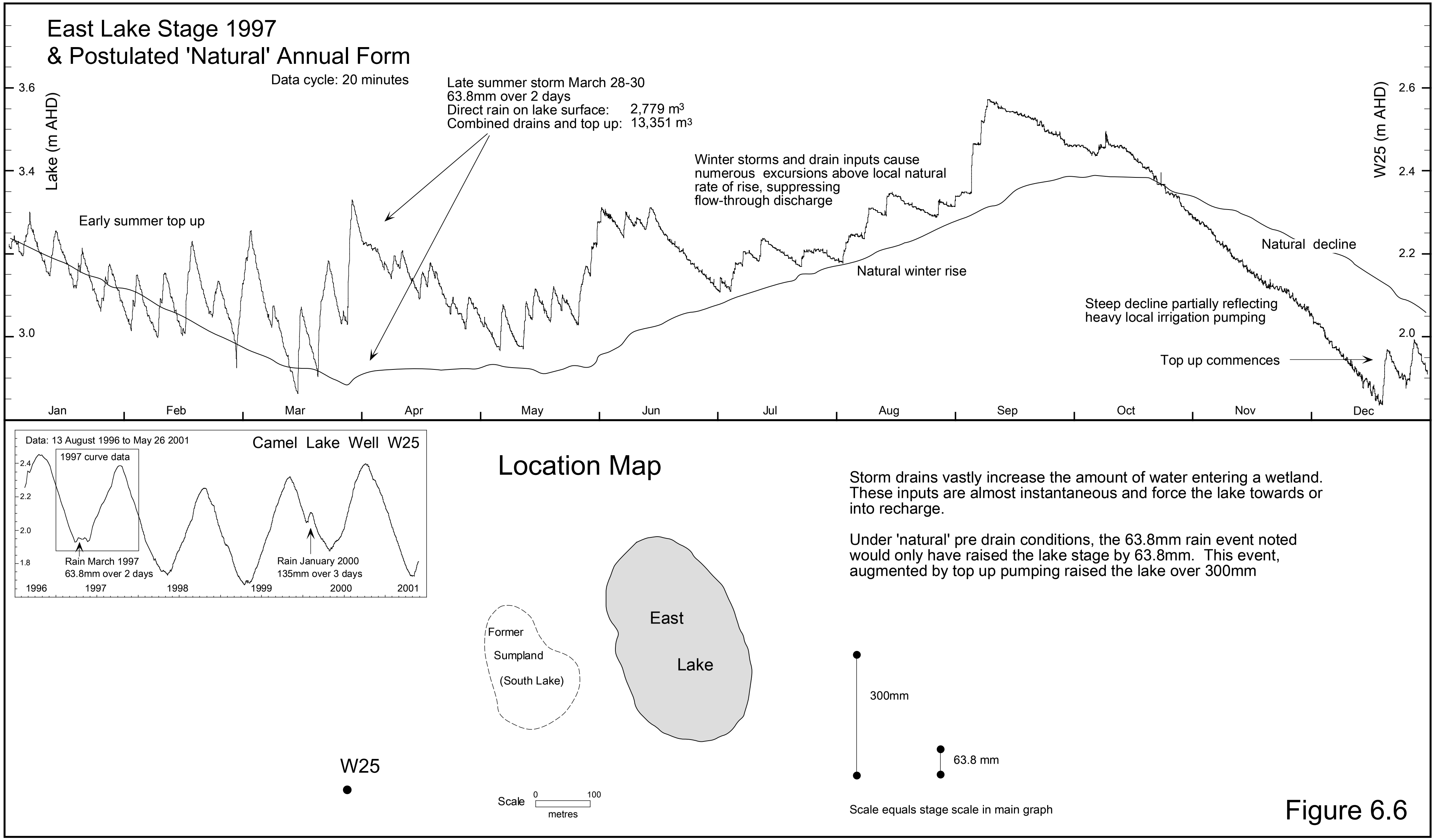


Notes
Bar graphs are component percent of total water budget for each balance period
Recharge decreases to nil in East Lake which commences receiving top up in Bal 15 & reverts from FT to R flow regimes. This has the effect of creating a local gradient & groundwater flow from East to West Lake and forces increased West Lake discharge

Summer Transition 1996
East and West Lakes

Showing how top up in East Lake results in enhanced flow-through discharge in West Lake

Figure 6.5



East Lake Stage 1997
& Postulated 'Natural' Annual Form

Data cycle: 20 minutes

Storm drains vastly increase the amount of water entering a wetland. These inputs are almost instantaneous and force the lake towards or into recharge.

Under 'natural' pre drain conditions, the 63.8mm rain event noted would only have raised the lake stage by 63.8mm. This event, augmented by top up pumping raised the lake over 300mm

Figure 6.6

Figure 6.5 shows comparative water budgets for East and West Lake for September 01 to January 03 1996-97 (balance periods 11-20). As discharge diminished and then ceased in East Lake, it increased in West Lake. In East Lake, early top up suppressed and then halted discharge. East Lake became locally mounded, setting up a local inter-lake flow pattern. This local groundwater gradient was steeper than the regional gradient (already depressed by lawn irrigation pumping). The result was increased discharge into West Lake.

Chloride and deuterium data was available for West Lake to March 16, 1997 (Balance 27). Despite being a small residual 'sump', West Lake continues to function as a flow through lake over summer with discharge strongly influenced by top up events in East Lake and the constantly changing local water table gradient between the two lakes.

Figure 6.5 includes water table contours and flow patterns for December 9, 1996 within Balance 18. In East Lake excessive top up has suppressed the flow through regime and pushed the lake towards total recharge status. The East Lake stage is about 300mm above West Lake. This creates a pronounced groundwater gradient between the two lakes. Water recharged from East Lake flows towards West Lake augmenting natural discharge. In other words the effect of top up in East Lake temporarily increases the flow-through effect in West Lake. Unfortunately immediately after this (Balance 19A) West Lake broke up into a number of small disjointed ponds (refer insert map Figure 6.5). Balance computations were disrupted while the lake dried shrinking to just one residual pool in the southwest corner (Balance 21). From January 15 (Balance 22) onwards West Lake was one contiguous small pond, however isotopic balances could not be integrated with the mass and solute data because the deuterium in West Lake had reached a steady state value of about 40‰. (refer deuterium plot Figure 6.5). The lake was analogous to a constant feed evaporation pan with a small leak. Isotopic steady state is a common phenomenon in restricted water bodies such as evaporation pans and saline lakes (Gonfiantini 1986). We did not expect to see it in a freshwater lake. Extremely high deuterium enrichment has been reported in similar lakes (Fontes & Gonfiantini 1967) without steady state being achieved. These concepts are explored further in Chapter 12 where seasonal variations in isotopic steady state are used to determine isotopic exchange parameters.

6.4 MEASUREMENT OF CRITICAL BALANCE COMPONENTS

6.4.1 Groundwater Discharge (GW_{in})

Integrated balances require knowledge of the deuterium and chloride values of groundwater discharged to the lake. Two options were considered:

- periodic sampling of pore water in the lake sediments close to the up gradient shore
- periodic sampling of the aquifer up gradient of the lake

Krabbenhoft & Webster (1995) used average pore water samples. They point out however that lake bed pore water and samples from near shore piezometers may be quite different. This is probably due to flow reversal where former lake water enters the aquifer during a recharge regime and is subsequently discharged again to the lake when flow-through conditions are re-established. In Perry East pore water sampling was considered logistically impractical due to the constantly varying position of the 'shore'.

The 15 nested piezometer wells N1a-c to N5a-c were analysed for deuterium and chloride on 17 occasions (approximately monthly) between March 1996 and December 1997. An equivalent of three well volumes was bailed prior to sampling. Samples were collected from the screened sections using a position sampler. In addition irrigation bores within and in vicinity of Perry Lakes Reserve were also sampled. This was to provide data on the highly variable isotopic values noted in top up water (refer Section 6.4.2) and determine if Perry Lakes lay within the recharge plume from Herdsman Lake. Irrigation bores and piezometer samples for March 1996 were analysed for ^{2}H, ^{18}O and Cl. Remaining monthly piezometer samples (September 1996-December 1997) were analysed for ^{2}H, and Cl only. It was anticipated that wells in nests down gradient such as N4 might exhibit distinct seasonal changes in water chemistry reflecting summer solute and isotope enrichment. No obvious seasonal patterns were evident. Mean values appear in Tables 6.5 and 6.6. Note that there is a distinct isotopic enrichment in piezometers and bores down gradient from the lakes. These include N2, N4, N5 and P1.

Table 6.5 Mean deuterium and chloride, nested piezometers

Well	N1a	N1b	N1c	N2a	N2b	N2c	N3a	N3b	N3c	N4a	N4b	N4c	N5a	N5b	N5c
^{2}H	-10.7	-8.9	0.8	0.2	-2.5	-4.9	-12.5	-8.7	-13.3	-1.4	-2.2	0.3	-9.3	15.2	14.6
Cl	377	228	323	145	188	198	298	253	199	179	181	199	350	397	383

Deuterium permil (‰), Cl (mg/l)

Table 6.6 Deuterium and chloride, irrigation bores

Well	P1	P2	P4	P5	P6	P8	Ag Stn N	CSIRO
^{2}H	-2.0	-12.6	-16.9	-16.5	-13.3	-4.3	-14.9	-13.6
Cl	217	211	143	146	161	324	n/a	211

Plotting ^{2}H, ^{18}O relative to the Perth meteoric water line and considering Cl allows some conclusions to be drawn on the history of groundwater surrounding Perry Lakes. With reference to Figure 6.7 isotopically enriched water occurs down gradient from West Lake (N2) and East Lake (N4, N5 & P1). These wells lie within the lake discharge plumes.

There is a distinct chloride gradient reflecting the long term change in lake chloride chemistry discussed in Chapter 2. Waters in piezometer N5 contain chloride levels seldom encountered in East Lake today but which were common before the recent initiation of constant summer maintenance. Figure 2.14 shows that in the 1970's minimum winter chloride levels were about 200mg l^{-1} rising to 500 to 700mg l^{-1} over summer. Similar values probably persisted into the early 1990's. Now summer levels largely reflect local groundwater. Most top up water comes from P1 and P2. This is reflected in the mean summer chloride concentrations of around 180 to 200mg l^{-1}. Winter storm water dilutes this to about 30mg l^{-1}.

The isotopic data presents a similar pattern where the most isotopically enriched water occurs in N5. Up gradient of East Lake, N3 and all sampled bores (P4, P5 & P6) plot close to the Perth meteoric water line (MWL) and are considered to represent unevaporated groundwater (Figure 6.7). N1 displays increasing isotopic enrichment with depth, P8 is also enriched and both display elevated Cl. In contrast P2 displays little isotopic or solute enrichment. N1 and P8 may penetrate water evaporated from the former adjacent sumplands (now Alderbury Flats, refer Figure 6.7). Setting hydraulic conductivity at 10 to 30 m day^{-1} and assuming an effective porosity of 0.3 and gradients of 1 to 2m km^{-1} yields a seepage velocity range of approximately 12 to 72m y^{-1}. Considering that the swamps were filled in 1960-61 (refer Chapter 2), it could be argued that this evaporated groundwater must have another source such as the recharge plume from Herdsman Lake; however this, for the time being is speculation. Flow net analysis (Chapter 13) suggests that this may well be the case.

For the purpose of completing the isotopic balances it was essential that a truly representative value for groundwater discharge into both lakes be determined. Samples from N1 and N3 were considered to best represent up gradient groundwater. Average values (Table 6.7) were computed from all data from all levels in each piezometer. The raw data is included as Appendix 6.4.

Table 6.7 Average discharge water chemistry

	^2H	Cl	Derivation
East Lake	-11.5‰	250mg l^{-1}	Average of all data from nested piezometers N3a-N3c
West Lake	-6.3‰	309mg l^{-1}	Average of all data from nested piezometers N1a-N1c

This data is considered reasonable for East Lake. West Lake however shrinks over summer to a small residual pool. When East Lake is topped up, a local groundwater mound is formed with a strong local groundwater gradient towards West Lake. In hindsight a piezometer between East and West Lake would have been valuable in providing better definition of summer discharge chemistry to West Lake.

6.4.2 Summer Lake Level Maintenance

Summer lake level maintenance represented one of the most difficult problems in terms of estimating solute and isotope levels in the absence of direct sampling. The irrigation ring main system allowed water from all bores to be mixed in varying proportions and discharged through 100mm (south) and 80mm (north) flow meter equipped outlets (Figure 5.1a). Despite attempts to encourage the gardening staff to standardise the top up procedure (use the same bores and valve settings) the process remained largely *ad hoc*. Depending on whether isolation valves in the system are open or closed, water from any bore may exit through either outlet. A total of 69 samples were collected during top up events and analysed for deuterium and chloride. As a rule we attempted to sample all top up events which generally commenced either Friday evening or Saturday morning. In general water from the south outlet is dominated by P1 and to a lesser extent P6 while the north outlet is dominated by P2 and to a lesser extent P3, P4, P5 and P7. This is reflected in the average top up water chemistry (Table 6.8). Detailed top up isotopic data is included within Appendices 6.2 and 6.3.

Table 6.8 Average outlet water chemistry

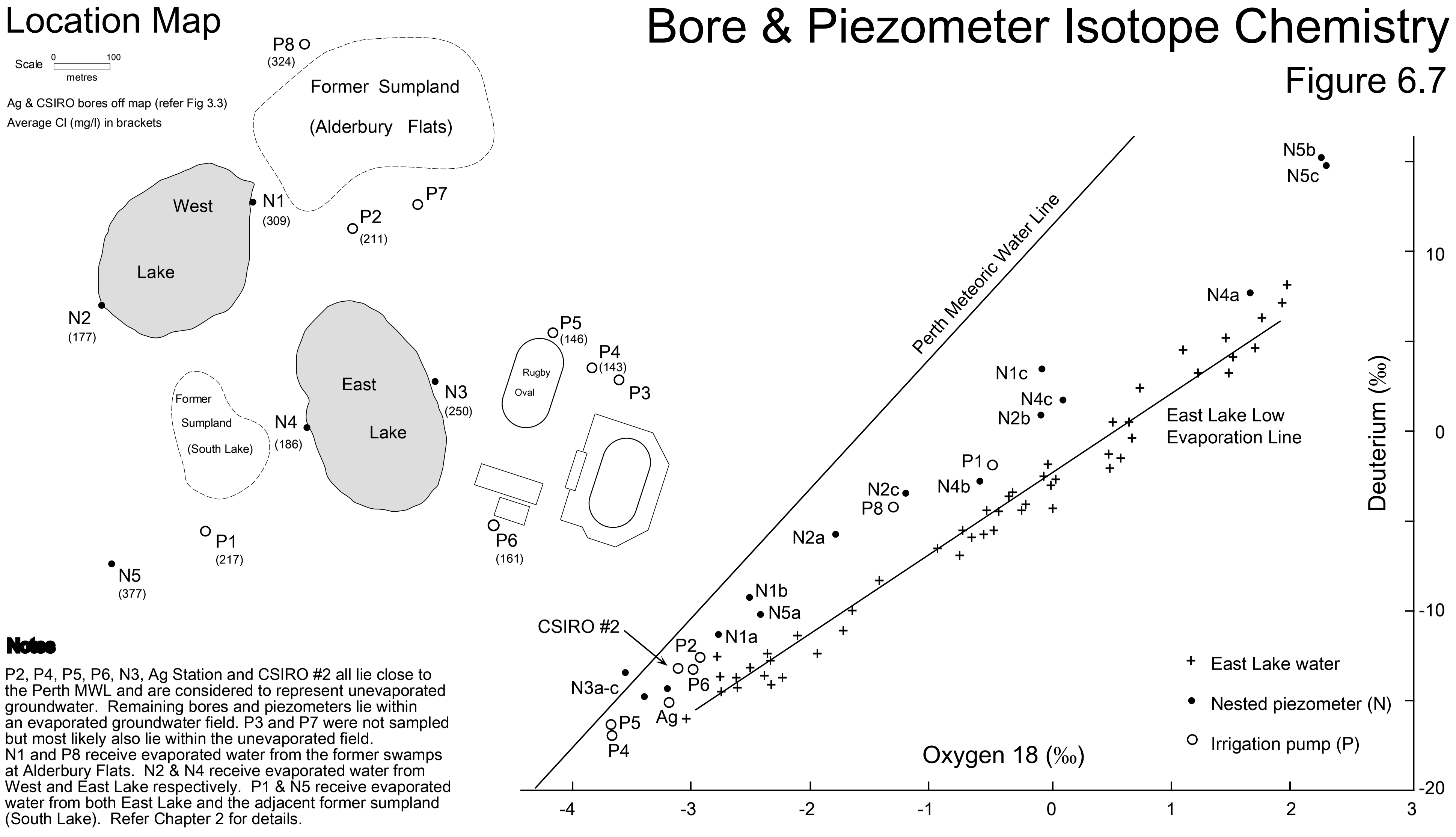
	Deuterium (‰)	Chloride (mg L^{-1})
South Outlet 'A'	-2.5	208
North Outlet 'B'	-13.5	169

Outlet 'A' is dominated by P1 which lies within the East Lake evaporated groundwater field. Bores feeding outlet 'B' all lie within the unevaporated groundwater field and have similar chloride and deuterium levels. These average values were applied to non sampled top up recorded on the flow meters.

Prior to flow metre installation (October 11, 1996), top up volume was estimated from pumping records kept by Town of Cambridge staff and rated irrigation capacity of each bore (Townley *et al* 1995). Estimated gross input chemistry utilised the outlet averages weighted against average relative outlet volume (average volume from B being 0.35 that from A). This 'average total chemistry' for water entering the lake from any top up event was -5.3‰ deuterium and 198mg l^{-1} chloride.

Bore & Piezometer Isotope Chemistry

Figure 6.7



Location Map

Notes

P2, P4, P5, P6, N3, Ag Station and CSIRO #2 all lie close to the Perth MWL and are considered to represent unevaporated groundwater. Remaining bores and piezometers lie within an evaporated groundwater field. P3 and P7 were not sampled but most likely also lie within the unevaporated field.
N1 and P8 receive evaporated water from the former swamps at Alderbury Flats. N2 & N4 receive evaporated water from West and East Lake respectively. P1 & N5 receive evaporated water from both East Lake and the adjacent former sumpland (South Lake). Refer Chapter 2 for details.

6.4.3 Direct Rainfall

Rainfall was measured manually every 24 hours using 100mm diameter gauges. Rain samples for deuterium analysis were collected beneath silicon oil. This process is further described in Chapter 12 and Figure 12.4. The deuterium sampler was drained after each frontal passage or isolated rain event. Between May 5, 1996 and January 17, 1998, 112 samples were collected for individual analysis. These are included in Appendix 6.5.

Chloride in individual rain events was not measured. Chloride concentration is a function of the intensity of westerly winds (Teakle 1937) and distance from the coast (Hingston 1958). Average values for Perth rainfall are summarised in Table 6.9. A value of 12.0 mg l^{-1} was used. This is the average for samples collected adjacent to Perry Lakes at CSIRO Floreat (Hingston & Gailitis 1976).

Table 6.9 Chloride in Perth Rainfall

Location	Year	Ocean* (km)	Av Cl (mg L^{-1})	Reference
Perth Observatory	1926	8.0	16.5	Teakle (1937)
University of WA	1952-56	6.0	11.5	Hingston (1958)
Floreat (Perry Lakes)	1973-74	3.2	10.7-13.0	Hingston & Gailitis (1976)

* distance to the coast

6.4.4 Storm Water

Deuterium and chloride for any given rain event were applied directly to storm water. Early winter 'first flush' storm water however is known to carry elevated chloride. In Floreat, annual dry fallout of salt is about 12.4 kg ha^{-1} (Hingston & Gailitis 1976). Analysis of early winter 'first flush' storm water (Table 6.10) confirmed that chloride quickly diminishes to values approaching that of average rain.

Table 6.10 Deuterium and chloride in 'first flush' storm water

Drain	Date	Time	Rain (mm)	^{2}H in Rain	^{2}H in Drain	Cl in Drain
East Lake main drain	9 May 1995	2045	n/m	n/m	n/m	12.84*
East Lake CSIRO drain	"	2030	"	"	"	3.55*
West Lake main drain	"	2050	"	"	"	6.72*
East Lake main drain	22 March 1996	1630	1.4	"	"	51.6
East Lake CSIRO drain	"	"	"	"	"	46.3
East Lake basketball drain	"	"	"	"	"	47.8
West Lake main drain	"	1045	"	"	"	40.4
East Lake main drain	8 May 1996	0920	13.4	-6.2‰	-10.9‰	13.7
East Lake CSIRO drain	"	0900	13.4	"	-12.3‰	12.4
West Lake main drain	"	0940	14.0	"	-13.0‰	14.5

Deuterium in permil, Cl in mg l^{-1}

* average of three consecutive samples, n/m = not measured

The rain events on 9 May, 1995 and 8 May, 1996 were true 'break of season' events. Drains had flowed for at least an hour before sampling. The data show that already, summer salt build up had been flushed and confirm the validity of the average 12 mg l^{-1}. The small summer rain event 22 March 1996 probably approximates what happens when drains first flow. It is evident however that these elevated values do not persist. The 8 May drain deuterium values are 'point' samples whereas the rain value of -6.2‰ is the mean for the entire rain event.

6.5 COMMENTS ON WATER SAMPLING WEST LAKE

In East Lake, chloride and deuterium determinations were available every four days. Samples were collected from the centre of the south basin with all storm water and much top up water entering nearby. When East Lake was in recharge, estimates for recharge (lake water returned to the aquifer) were always similar with mass, chloride and solute balances often within 5% of each other suggesting that a single sample from the centre of this small, well mixed lake was representative. By comparison, West Lake presented a number of practical and hydrologic problems.

Sampling was at the extreme southwest corner while all storm drain inputs are in the extreme northeast corner. The lake experiences poor mixing. The sampling site is the deepest point and the only area which does not dry out in summer, however in hindsight it was probably not always adequately representative. There is almost certainly a chloride and deuterium gradient within the lake over winter. Congdon (1985) for example found significant chloride gradients within Lake Joondalup of up to 140 mg l^{-1} over distances of about 1000m. At times West Lake is really two or more lake systems comprising a southwest permanent 'sump' and remnant disjointed ponds elsewhere in the basin which receive varying amounts of storm drain water. This occurs during dry up in early summer and during early winter storm events when some storm water never reaches the southwest pond where all sampling was conducted. The extent of errors in the West Lake balances as a result of these problems remains unknown.

This study concentrated on the period September 1, 1996 to March 1997 (winter maximum to summer minimum). Financial restrictions precluded full chloride analyses.

6.6 CONCLUDING COMMENT

The integrated balances demonstrate that Perry Lakes oscillate between flow-through and recharge states and that the two lakes have a strong influence on each other's hydrology. In Chapter 7 the integrated balance information is combined with other data to examine in detail how Perry Lakes interact with the surrounding unconfined aquifer.