CHAPTER

4

WATER BALANCE CONCEPTS

4.1 INTRODUCTION

A water balance is an accounting of all inputs and losses of water from a hydrologic system, balanced against the change in water stored within that system. It must account for all inputs, losses and interactions between atmospheric, surface, subsoil and aquifer water. A water balance may be calculated at any spatial scale from global such as the worlds oceans to regional such as an aquifer system to local such as a small pond. A water balance can be calculated at any temporal scale; a day, week, month, year or longer. A balance may comprise water mass or other components including dissolved chemical species such as salts or nutrients, isotopes or heat. In the case of wetlands such as Perry Lakes a simple water balance may be thought of as:

$$\text{Water In} - \text{Water Out} = \text{Change in Water Storage} \qquad (4.1)$$

Water balances are extremely important in that they form the underlying basis of wetland hydrological modelling (Townley *et al* 1993a).

4.2 REGIONAL BALANCE ON THE SWAN COASTAL PLAIN

The Swan Coastal Plain may be thought of as a hydrological system. Most shallow lakes within it occur where the regional unconfined aquifer (hosted by predominantly sandy sediments) intersects the undulating land surface. Exceptions occur (particularly along the Darling Scarp) where clay soils (or clay lenses within sands) may trap precipitation and surface run-off (Hill *et al* 1996). The elevation of the water table in a general sense follows regional surface topography. In the case of Perry Lakes, groundwater flow originates 30-40km to the north east on the Gnangara Mound (Figure 1.2) and terminates at the Darling Fault, Swan River or Indian Ocean which collectively form the system boundaries (Figure 4.1a). Over this distance the elevation of the water table drops by only about 50m so that for practical purposes the water table and groundwater flow gradient may be thought of as being essentially horizontal. Rainfall recharges the aquifer over its entire area although the amount of recharge varies greatly from area to area depending on surface land use. Natural bush intercepts large amounts of precipitation in the canopy and that which enters the soil may be subsequently re-evaporated or transpired via deep rooted vegetation. Whereas natural bush may recharge anywhere from nil to around 13% of rainfall, cleared farmland and urban areas may recharge much more. Much rainfall is lost in evaporation from the soil and transpiration from plants. Close to wetlands water may be evaporated directly from the water table via capillary rise and transpired by phreatic vegetation. Most water leaves the aquifer system by discharging directly into rivers and the ocean however large amounts are also extracted from bores. This may be treated as potable water and then exported to elsewhere in the system where it may be recharged as lawn and garden irrigation or in the case of irrigation bores, applied in situ. The aquitard forming the base of the unconfined aquifer is seldom completely impermeable. Water may be lost to or received from deeper confined aquifers.

Before urbanisation the unconfined aquifer would have been in a state of dynamic equilibrium or balance. The water table would move up and down seasonally in response to winter recharge and summer evapotranspiration. Urbanisation creates a new set of conditions. The clearing of deep rooted native vegetation reduces canopy interception and evapotranspiration from the vadose zone. Recharge to the aquifer increases markedly. Shallow rooted vegetation such as lawns recharge an increased amount of rain. Impervious shedding surfaces such as roofs and roads shed rainfall either directly to the aquifer via soak wells or via storm drains to infiltration basins and wetlands. Bores and drainage ditches extract water directly from the aquifer. The original natural 'dynamic balance' is upset. Given enough time a new balance is established which may result in a water table higher or lower than that which prevailed under natural conditions.

The final factor which affects the water balance under both natural and urban conditions is the climate. Long term climate change, both temperature and rainfall, affect recharge and evapotranspiration. As the climate slowly changes so too the regional water balance slowly adjusts.

4.3 URBAN BALANCE CONCEPTS

Urbanisation has significant impacts on the local water balance. In central business districts impervious shedding surfaces comprise almost 100% of the land surface. Most of the rain which falls is intercepted. In the Perth CBD this is channelled by drains directly into the Swan River. Recharge below the CBD is minimal. Figure 4.1b illustrates the principal components of the local urban water balance in suburban areas which make up the vast bulk of the Perth metropolitan area.

Depending on housing density impervious shedding surfaces may comprise typically 20% to 40% of the land surface. Roofs may direct rain either directly to the vadose zone via soak wells (where most is recharged) or into storm drains. These in turn direct water (including water from roads and car parks) either into infiltration basins (where most is recharged to the unconfined aquifer) or into wetlands. In some areas domestic septic tanks channel sewage and grey water into leach drains which also add recharge to the aquifer. Shallow rooted lawns and ornamental gardens are key features of the suburban landscape. Natural rain quickly infiltrates past the shallow root zone so that a much greater proportion is recharged compared to natural bushland. In summer excess lawn irrigation may exceed usage and also be recharged. This may be either local groundwater extracted from a domestic bore and effectively 'recycled' or scheme water imported from elsewhere. Trees are frequently shallow rooted ornamental species which intercept water only from the shallowest portion of the vadose zone. Compared to native bushland, canopy interception by lawns and shrubs is much less.

4.4 WETLAND WATER BALANCES

Wetlands on the Swan Coastal plain outside the urban area have very simple water balances. Most wetlands are simply deflation hollows which lie below the level of the local water table. Rainfall recharges the water surface directly and is recharged through the sandy soils surrounding the lake. These wetlands typically have no riparian inputs or losses and nil surface run off. Water is lost from the system via direct evaporation from the water surface and evapotranspiration from emergent and phreatic fringing vegetation. The lakes both receive groundwater on the up gradient side as discharge and return water on the down gradient side as recharge. As such they are termed 'flow through' lakes (Nield *et al* 1994).

Wetlands in urban areas have a more complex suite of balance components (Figure 4.1c). Additional water inputs may include storm water channelled directly into the wetland via storm drains or open ditches, run off from adjacent impervious shedding surfaces such as car parks, and 'top up' water to maintain levels over summer. This may be local water from the unconfined aquifer pumped into the lake from nearby bores or imported water from a confined aquifer. Additional losses may include water extracted directly from the lake for lawn irrigation, or water pumped out to prevent winter flooding. The local water table may be affected by heavy local groundwater extraction for ornamental lawns. These water bodies also function as flow through lakes; however, during periods of heavy rain (and subsequent storm drain flow) discharge from the aquifer may cease. Under these conditions the lakes recharge water back to the aquifer until equilibrium levels are re-established.

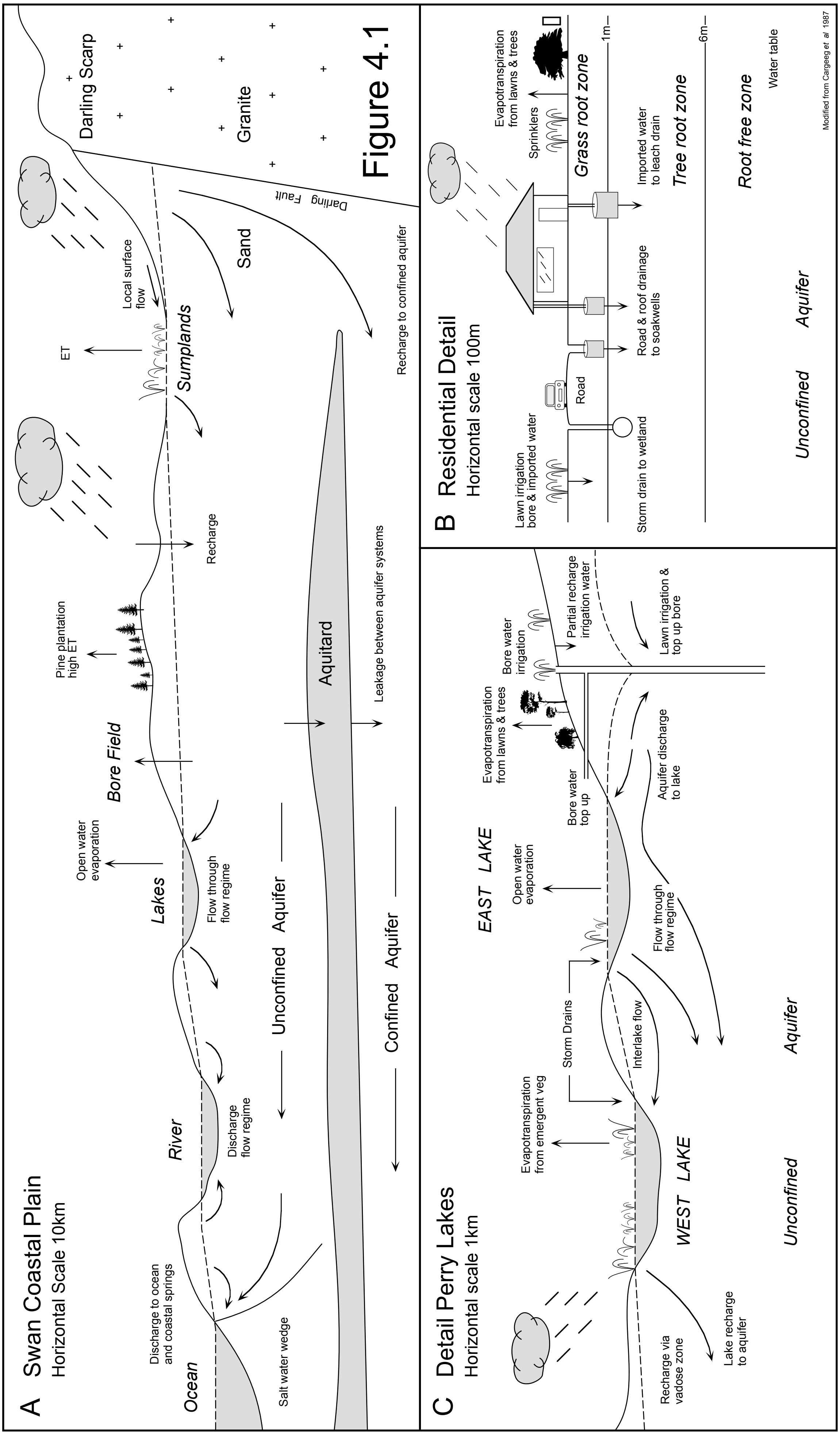
A Swan Coastal Plain
Horizontal Scale 10km
Darling Scarp
Granite
Darling Fault
Sand
Local surface flow
ET
Sumplands
Recharge to confined aquifer
Recharge
Pine plantation high ET
Bore Field
Aquitard
Leakage between aquifer systems
Open water evaporation
Lakes
Flow through flow regime
Unconfined Aquifer
Confined Aquifer
River
Discharge flow regime
Discharge to ocean and coastal springs
Ocean
Salt water wedge
B Residential Detail
Horizontal scale 100m
Evapotranspiration from lawns & trees
Sprinklers
Grass root zone
1m
Imported water to leach drain
Tree root zone
6m
Root free zone
Water table
Modified from Cargeeg et al 1987
Road & roof drainage to soakwells
Road
Lawn irrigation bore & imported water
Storm drain to wetland
Unconfined Aquifer
C Detail Perry Lakes
Horizontal scale 1km
Partial recharge irrigation water
Bore water irrigation
Lawn irrigation & top up bore
Evapotranspiration from lawns & trees
Bore water top up
Aquifer discharge to lake
EAST LAKE
Open water evaporation
Flow through flow regime
Storm Drains
Interlake flow
Evapotranspiration from emergent veg
WEST LAKE
Unconfined Aquifer
Recharge via vadose zone
Lake recharge to aquifer

Figure 4.1

At first glance, calculation of a water balance appears deceptively simple. In fact all of the components of the balance are difficult to measure accurately with the result that all components plus the resulting balance are subject to considerable error. Groundwater components are arguably one of the most difficult balance components to quantify (Hunt *et al* 1996). As a result groundwater is frequently simply estimated as the residual in the balance (Winter 1981, Carter 1986) or is simply ignored. Alternatively, only net groundwater contribution to the lake is estimated or either groundwater inflow or outflow is arbitrarily set to zero, allowing the other to be estimated (Rinaldo-Lee & Anderson 1980, Crowe 1993). Winter (1981) provides an overview of these difficulties and demonstrates how errors in the measurement of each component can be compounded, resulting in a very large uncertainty in the residual. Over time many of these errors cancel, therefore the longer a water balance survey is, the more accurate it is likely to be. Rigorous measurement of each component in the balance eliminates some of the gross errors associated with calculating one component as a residual. Even so, because some components of the balance are disproportionately large compared to others, small errors in their calculation become significant. In Perth, for example, evaporation is the largest single factor contributing to water loss from wetlands. In dry years evaporation may exceed by three times the precipitation, yet evaporation remains very difficult to measure accurately. Even using energy budget techniques, annual errors may exceed 10% (Winter 1981). Such discrepancies can represent very large volumes of water and significant proportions of the water balance.

Also evident when examining flow-through lakes are the reasons why a rigorous determination of the groundwater component is essential. Large volumes of water may enter and leave a lake through its bottom sediments over the period of a year. If however the lake level does not change, this groundwater flux will remain unaccounted for in simple balances because the lake volume shows no apparent change. Clearly where we are dealing with water quality and nutrient balance issues, such uncertainties are unacceptable. We know that the proportions of water discharged to the lake may be markedly different to that being recharged back to the aquifer and that these proportions will vary seasonally, annually and between wetlands.

All balances attempted so far for Swan Coastal Plain wetlands have been non-rigorous. This is inevitable because groundwater inflow and outflow are extremely difficult to measure. At Lake Jandabup, groundwater components were estimated as the residual in a combined mass-solute (chloride) balance (Congdon 1985). Such residuals are highly prone to error since they include the sum of all other errors in the balance (Winter 1981). In most studies balances were determined annually between identical lake stages so that the change in storage ΔS did not have to be determined. Lake storage involves knowing accurately the stage-area-volume relationships of the lake. It represents a significant field work undertaking. Table 4.1 summarises balance results for other Swan Coastal Plain lakes.

Table 4.1 Simple Annual Mass Balances Swan Coastal Plain Lakes

Lake and Reference	Years	±GW	±ΔS	+P	$+S_i$	-E
Bibra Lake (Megirian 1982)	1972-1981	+0.71	+0.01	+0.65	+0.02	-1.37
Jandabup (Allen 1979)	1977-1978	+3.43	+0.12	+2.04	+0.00	-5.87
North Lake (Megirian 1982)	1977-1981	+0.32	0.00	+0.32	+0.12	-0.76
Joondalup (Congdon 1985)	1979-1980	+0.77	0.00	+3.37	+0.90	-5.04
Mariginiup (Hall 1985)	1979-1980	+1.00	0.00	+1.10	+0.10	-2.20

All quantities $x10^6m^3$, GW groundwater, ΔS change in storage, P precipitation, Si Surface inputs, E evaporation,

4.5 MULTIPLE SIMULTANEOUS BALANCES

On the basis of a mass balance alone, groundwater can only be differentiated as a net input or loss. There is no way to differentiate or quantify groundwater discharge to the lake or lake recharge to the aquifer. All earlier workers were aware of groundwater flows. Nested piezometers (Allen 1979, Hall 1985) and seepage meters (Congdon 1985) clearly showed water to be entering and leaving. Allen (1979) attempted to estimate the groundwater components for Lake Jandabup using the Darcy equation and (vertically exaggerated) equipotentials. These suggested that only the upper portion of the aquifer was interacting with the lake. Subsequently it was shown that the entire aquifer section was interacting with the lake (Townley *et al* 1993a). While the detail of Allen's interpretation was incorrect, he was able to confirm the earlier observation of Balleau (1973) that groundwater chloride concentrations increase to the west of lakes on the Swan Coastal Plain. A similar result (with a similar misrepresentation of equipotentials) was obtained for Lake Mariginiup by Hall (1985). All of these simplified balances indicate that there is a net surplus of groundwater entering these lakes. They are over the longer term evaporative sumps. What the balances cannot do is accurately quantify groundwater discharge and lake recharge. Lakes highly modified by urban drainage may show the opposite effect. McFarlane (1984) found that in Mason Gardens and Shenton Park Lake, recharge of storm water back to the aquifer was the largest component of the annual balance.

This leads directly to the importance of simultaneous multiple rigorous balances. These are rigorous in the sense that (within practical limitations) every effort is made to measure *every* component of *each* balance. They are simultaneous in the sense that solute and isotope balances are calculated along with simple water mass. Integrating the balances allows the elusive groundwater flux components to be teased out. The detail on just how this is accomplished forms a large portion of Chapter 6. At Lake Joondalup for example, Congdon (1985) was able to demonstrate that where mass balances indicated a net monthly input (discharge) of groundwater, chloride balances simultaneously showed a net loss of chloride, *i.e.* a flow-through lake with recharge exceeding discharge.

Biologically conservative solutes have been widely used as water flow tracers (Allison & Hughes 1978, Allison & Leaney 1980). Chloride (as a solute balance) has been widely employed in combination with mass balances of Swan Coastal Plain lakes (Allen 1979, Hall 1985) and the unconfined aquifer (Davidson 1981 & 1995). Chloride is described as a conservative solute because its behaviour is simple and predictable and it does not fractionate during evaporation. Evaporating a closed body to half the original volume simply doubles the Cl content. Diluting the body with water of known Cl concentration permits the final concentration to be accurately predicted. Isotopes such as deuterium and oxygen 18 on the other hand are non conservative in that evaporation removes some of the isotope of interest. In a lake-aquifer system, isotope ratios are stable everywhere except at a lake surface where fractionation and enrichment occurs during evaporation (Gat 1981 d&e). This behaviour or 'isotope effect' (Gat 1981 a&b) is governed by well defined rules (Chapters 6 & 12) which when applied allow these isotopes to be used in a similar fashion to conservative solutes. Knowing the isotopic ratio within the system components, mass balance equations can be solved to estimate the groundwater component in lake water balances (Dinçer 1968, Turner *et al* 1983, Krabbenhoft *et al* 1990, Turner *et al* 2000). Krabbenhoft & Webster (1995), demonstrated the temporal variability of groundwater inflow-outflow including the transition from flow-through to recharge status using solute balances (calcium) and stable isotopes.

Other methods can be employed to provide independent clues about lake-aquifer coupling and interaction. These include nested piezometers, in-lake piezometers, water table contours and flow nets (Chapter 7) as well as thermal patterns in the lake sediments (Chapter 9).

4.6 PERRY LAKES

Townley *et al* (1993a) provide the theoretical framework for integrating mass, solute and isotopic balances to tease out the groundwater components of wetland water balances. This study represents a field validation of the theory. At Perry Lakes direct measurement of all components except groundwater flux has been combined with solute (chloride) and isotope (deuterium) techniques to allow all the groundwater components of the balance to be determined. These concepts are expanded in Chapter 6 while in Chapter 7 the balance data is combined with regional hydrologic data to elucidate lake-aquifer interaction under natural and artificially induced conditions.

The final execution and synthesis of any water balance is a compromise. Expense, available labour and the field site itself (availability of electric power, security, vandalism etc) all place restraints on what can and cannot be achieved. The Perry Lakes site had a number of distinct advantages which made it amenable to detailed water balance studies. In particular its location adjacent to CSIRO allowed highly labour intensive studies to be completed. Much of the data gathering was done manually on a daily basis. The provision of a secure compound immediately adjacent to East Lake with 240 volt power available was essential for the isotope experiments. The UWA Field Station immediately adjacent represented another secure area where evaporation pan experiments could be conducted.

Perry Lakes also had a number of distinct disadvantages. It is very heavily used by the public including school field days. Vandalism is a problem. Monitoring equipment must be either inaccessible or not visible. Hydrologically the reserve is subject to excessive groundwater extraction for at least half the year. Pumping from multiple bores occurs every week day for lawn irrigation. On weekends these same bores are used to top up East Lake. None of the bores are equipped with flow metres and many draw their power from the common stadium supply without separate hour or watt meters. Bore usage relied on written logs maintained by park staff. This was often difficult as staff were rotated through other reserves. Simple bad luck also plays a role. A complete seasons worth of bore usage records was lost when a park staff ute was stolen along with the bore log. The vehicle was recovered but not the log.

At the early planning stages (1994-95) West Lake retained some water over summer. By the time all equipment was constructed and in place (1997-98) West Lake was dry for half the year and East Lake was being artificially maintained for at least 6 months of the year. This represented a unique opportunity to study two closely coupled lakes, one of which was allowed to dry out naturally and one in which artificial intervention played a dominant role.