CHAPTER
13

CLIMATE, URBANIZATION & WETLANDS

13.1 INTRODUCTION

When viewed within the broader time frame of geological time (even just Holocene time), it becomes evident that wetlands are far from being permanent features. Perry Lakes, like many other Swan Coastal Plain wetlands are merely shallow deflation hollows whose base lies below the present groundwater table. As we examined in Chapter 2, Perry Lakes as known since colonisation, have existed within an unconfined aquifer whose level fluctuated between approximately 3 to 4m AHD. In recent summers the groundwater level has fallen below this range. Leaving aside for a moment the reasons why this might be happening, what we are observing is a process which occurs naturally in water table wetlands everywhere. As the water table declines the area of open water diminishes and a well documented sequence of vegetational changes follow. The distribution of emergent wetland plants adjusts quickly to the altered hydrologic regime, occupying areas which were formerly open water. Trees and other non aquatic vegetation quickly become established in areas which were formerly seasonally inundated. In East Lake mature stands of flooded gums (*E. rudis*) now occupy areas which 40 years ago were permanent open water. While wetland managers and conservationists may mourn their disappearance, they must accept that such wetlands on a geological time scale are at best ephemeral, existing only under very specific groundwater conditions.

Pre colonisation, the unconfined aquifer below the Swan Coastal Plain was in a state of approximate dynamic equilibrium, controlled by recharge (ultimately reflecting rainfall) and discharge (ultimately into the Indian Ocean and Swan River) plus water drawn by phreatophytes. Over time frames of a few years the mean water table level at any point fluctuated seasonally around an average level which probably varied little from year to year, and which reflected the prevailing average rainfall. Within the longer time frame of decades and centuries rainfall and the water table changed.

Variations in rainfall or the more inclusive term 'climate change' are viewed with fear and misunderstanding by many. Understanding of this largely natural phenomenon is not aided by poorly substantiated speculation and scare mongering in the popular press. Human beings do not like change and uncertainty, preferring instead constants and predictability. In part, this may be why the notion of 'average rainfall' arose in the first place, yet the concept is arguably flawed because rainfall, like all natural processes is constantly changing. When viewed over the shorter context of decades, (and even the period over which Australia has maintained meteorological records) rainfall may appear to be more or less constant, but over centuries and longer, the notion of average rainfall becomes less and less viable. Table 13.1 shows average decade rainfall for Perth over 12 decades. The current average (1875 - 2002) is 861.3mm, while the 'official' average quoted by the Bureau of Meteorology remains 869mm. The average 2000 to 2002 was only 741mm.

Table 13.1 Perth average decade rainfall

Decade	1880-89	1890-99	1900-09	1910-19	1920-29	1930-39
Average (mm)	844	833	881	868	992	927
Range	630-1016	602-1188	688-1008	514-1161	799-1251	753-1161
Decade	1940-49	1950-59	1960-69	1970-79	1980-89	1990-99
Average (mm)	895	876	860	772	820	816
Range	509-1339	617-1182	574-1042	560-974	691-930	648-960

Possibly water engineers and hydrologists in Perth should cease quoting an average rainfall and deal with the reality that the last decade average is only 816mm. Wetland managers must face the same reality. Perth is now into its fourth decade of declining rainfall. The overall trend since records commenced in 1875 is one of decreasing rainfall. This trend is substantially greater in the period 1955-2002 (Figure 13.1). The water table is declining and wetlands are shrinking or disappearing altogether. This is largely a natural process, modified by urban effects. Under the prevailing climatic regime, wetlands can only be maintained in their former configurations through non natural intervention. This then becomes a decision influenced by cost, and the cultural, recreational and conservation value placed on the wetland.

The Town of Cambridge are the wetland managers for Perry Lakes. The key and over riding management issue is declining groundwater levels. Perry Lakes are disappearing. The original four wetlands (Camel Lake, South or 'Hidden Lake', East Lake and West Lake) present in the 1950's are now reduced to just East and West Lake (Chapter 2). West Lake dried out completely (apart from the small artificially deepened sump around the staff gauge) in 1995, and has done so every summer since. East Lake is now (2002) reduced to the South Basin (Figure 2.15), and must be artificially maintained by pumping groundwater for approximately half the year. Without this pumping, East Lake would also completely dry out every summer.

There is no single cause for the present hydrologic situation at Perry Lakes. Rather it is the end result of a number of natural and anthropologic factors which in combination have resulted in a large decline in the local groundwater level. These include:

- natural short term climatic cyclicity
- natural long term climatic change
- anthropologic effects on climate (global warming and greenhouse gas increase)
- urbanization and effects from changing land use patterns
- public and private groundwater extraction from the unconfined aquifer
- aquifer hydrogeology

This chapter will examine each of these factors. Chapter 14 provides some possible management options.

13.2 NATURAL CLIMATIC VARIABILITY

When viewed from the long perspective of geological time, it becomes abundantly evident that the only aspect of climate which is constant is change. Discussion of climatic change is meaningless without examining the concept of climatic cycles. Many of the phenomena which in sum total combine to form the earth's climate, if taken as a time series, show cyclicity (Burroughs 1992). The problem is that regardless of the chosen time frame, cyclicity is usually present. Quite simply, cyclicity is an inherent feature of climate. On a very large time scale such as the 3 billion or so years represented in the geological record, major ice ages occur roughly in cycles of several hundred million years. At the opposite extreme, are much shorter cycles. Between 1880 and 1980, 23 warm cycles associated with the El Niño Southern Oscillation (ENSO) have been recorded (Jones and Kelly 1988), on average one every 4 years.

The sun is the ultimate energy source driving the earth's weather systems. Frohlich (1988) discusses the 'solar constant', the level of energy output from the sun. Between 1980 and 1985 solar output decreased 0.019%, a decrease which must ultimately be reflected in our climate. In the shorter term, Frohlich has identified prominent cyclicity in the sun's output with periods of 51.4 to 4.8 days. These variations must also affect the heat balance of the earth and in time contribute to climatic change. He notes that within a larger time frame, variations in the solar constant appear to modulate the climate on a period of 11 and 22 years corresponding to the waxing and waning of sun spots on the solar surface. Mitchell (1990) has tied the rhythm of drought in the mid west USA to this 22 year solar cycle.

Three separate cyclic changes in the earth's movements through space can also combine to produce overall changes in the amount of solar radiation received by the earth. These have come to be known as the Milankovich Model after the Yugoslav Milutin Milankovich who first suggested that these astronomical variations could be linked to the ice ages (Gribbin 1979). The longest cycle is 90 to 100,000 years corresponding to variations in the shape of the earth's orbit around the sun from almost circular to elliptical. In an elliptical orbit, there is variation in the distance from earth to sun, the net result being a greater contrast in the seasons. The second cycle has a period of about 40,000 years corresponding to changes in the tilt of the spinning earth. When the tilt is pronounced, seasonal differences also increase. The third cycle known as the precession of the equinoxes has a period of 20,000 to 25,000 years and is effectively a wobble in the earth's rotation resulting from variations in the gravitational pull of the sun and the moon. Each cycle alone would result in variations in the amount of solar radiation received at different latitudes during the year. The sum total of the additive effect of the cycles is constantly changing. Imbrie (1985 & 1987) has suggested that the very abrupt changes in climate or 'terminations' which mark the ends of several of the late Pleistocene ice ages occurred when the sum or additive effects of these orbital variations was very large. Kerr (1986) suggests that Milankovich cycles account for 80% of the climatic variability on time scales of 20,000 to 100,000 years.

Climatic records for the Holocene have long shown that the 10,000 years since the end of the last ice age was far from being climatically tranquil. These records, based on dendrochronology, palynology, glacial ice and sediment cores, corals and other 'proxy data' show a highly dynamic world climate in which temperature and rainfall distribution displayed pronounced variability on all time scales from year on year to century on century (Pearce 1996, Crowley 2000). In Australia, such independent evidence also suggests that similar variability is likely to persist in the future regardless of any human influences (De Deckker *et al* 1988). More recently there has been growing acceptance of evidence indicating that the earth is prone to sudden and drastic changes in climate. Rather than the gradual change often predicted by climate models, the proxy data indicate that the global climate operates on a number of stable states, and that the change from one to another can be very rapid. The Sahara is possibly the best known example. It was covered in forest around 6000 years ago, the change to desert occurred within a few decades (Pearce 2001).

Climate researchers have long believed that underlying these seemingly chaotic climatic records there may be a more fundamental order (Burroughs 1992). The search for predictable cyclicity has been given added impetus by the spectre of anthropologically induced (or at least) exacerbated global warming. Proving that human activity has contributed to climate change implies an ability to differentiate between natural and non natural climatic patterns. If natural variations can be identified then the ability to recognise and quantify non natural changes are enhanced. Cycles with frequencies of decades to centuries are believed to be paced by the oceans and polar ice where ponderously slow currents and massive reservoirs of heat provide the timing mechanism (Kerr 2000). For example one such oscillation first identified in the Atlantic Ocean appears to affect global climates. It has a frequency of approximately 70 years (Delworth & Mann 2000). Simulations using a coupled ocean-atmosphere model predict the oscillation and simulate observed warming patterns from instrument records (Delworth & Knutson 2000). The combination of instrument data, proxy climate records and climate models all point to a 50 to 70 year oscillation. The data and models predict that much of the current global warming is therefore part of a natural cycle which will persist for the next few decades (Kerr 2000).

Evidence for shorter cycles linked to solar variability and in particular the sunspot cycle have predominated in the search for global climatic patterns (Burroughs 1992). Sunspot density fluctuates with a mean period of approximately 11.2 years. The total solar radiance varies with sunspot number by about ± 0.04%. In climatic studies generally however 20 to 22 year cycles are prevalent. These roughly correspond to the Hale magnetic cycle[1] (or 'double solar cycle') of 22.4 years.

13.3 ANALYSIS OF PERTH RAINFALL

Historic rainfall data for Perth are reviewed in Chapter 2. The data show an apparent cyclicity and over the past forty years there has been an obvious decline in average rainfall (Table 13.1). Perth monthly rainfall data 1876 to 1998 was analysed by discrete Fourier transform. The power spectrum (Figure 13.1) displays distinct peaks centred around 10.3 and 20.1 years. There is also a weak peak at 30.1 years. McFarlane (1984) using auto correlation techniques noted an 11 year assumed sunspot cycle. Allison & Davis (1993) applying geostatistical techniques to a 100 year rainfall data set found a 22 year 'double solar' signal (Figure 13.1). Examination of the power spectrum using Fourier analysis (Pittock & Lean cited Allison & Davis 1993) suggested only an 11.2 year signal. The current analysis based on a longer data set of 123 years suggests a similar signal. This analysis approximates the 11 year solar cycle of Allison & Davis (1993) for Perth data. The 8.0, 5.6, 4.0, 3.0 and 2.2 year signals of Gentilli (1971 p196) could not be substantiated by Fourier analysis. The 30 year signal is of a similar period to the Inter-

[1] In one 11.2 year sunspot cycle leading spots in the sun's northern hemisphere will have positive polarity while trailing spots will be negative. The polarities are reversed in the sun's southern hemisphere. The pattern reverses in successive 11.2 year cycles.

decadal Pacific Oscillation (Luntz 1999), which may control El Niño and La Nina events in the Pacific.

The Perth rainfall data of 123 years covers far too short a time span to be a useful long term predictive tool. When plotted together, the sunspot and averaged rainfall data do not particularly display an obvious correlation (Figure 13.1). Because of the slightly different period they are out of synchronisation. The International Sunspot Number time series records go back to 1700 (SIDC 2002), with the periodicity determined from 26 complete cycles. The Perth rainfall data comprises only six 20 year cycles, probably too short to determine an accurate period. This lack of absolute correlation between observed cycles and the solar cycle is not unique to the Perth data and is commonly reported in many climate studies. Over longer time series such as the 2556 year tree ring data of Nordemann *et al* (2001) an 11 year signal is commonly reported. The presence of such solar related cycles corresponding to sunspot, solar irradiance and the solar magnetic cycles (Lean 1991, Webb *et al* 1984) is common in meteorological time series (Burroughs 1992).

Just how changes in irradiance translate into changes in rainfall is problematic. Goode *et al* (2001) have suggested that during sun spot minima (when the sun's magnetic field is also weaker), more galactic cosmic rays enter the sun-earth system. These may, in part act to seed clouds resulting in increased rainfall. Most of the irradiance variations associated with sunspot activity are in the UV range. UV is absorbed by stratospheric ozone and oxygen and then warms the lower stratosphere (Gribbin 1996). Small changes in irradiance are therefore amplified in the Earth's atmosphere. Evidence from the UK (Lawrence 1996) suggests that rainfall peaks about two years before each sunspot maxima. While astronomers and meteorologists have long suspected a link between solar activity and weather the specific mechanisms are not understood and the link with rainfall appears to vary from area to area. Certainly Perth rainfall exhibits an approximate 20 to 21 year cycle which may be linked to solar activity.

The data suggest that the next rainfall peak will occur about 2013. In absolute terms however it is doubtful that rainfall in the next few decades will be anything like the historic average of approximately 860mm. The present decrease in Perth rainfall is part of a regional phenomena. Since the 1950's there has been a major reduction in rainfall throughout the south west of Western Australia (Wright 1992). Research in progress (Nicholls 1998) suggests that neither ENSO events nor variations in Indian and Southern Ocean sea surface temperatures display a strong correlation with this change. Allan & Haylock cited Wright (1992) note that long term rainfall variation may have multiple

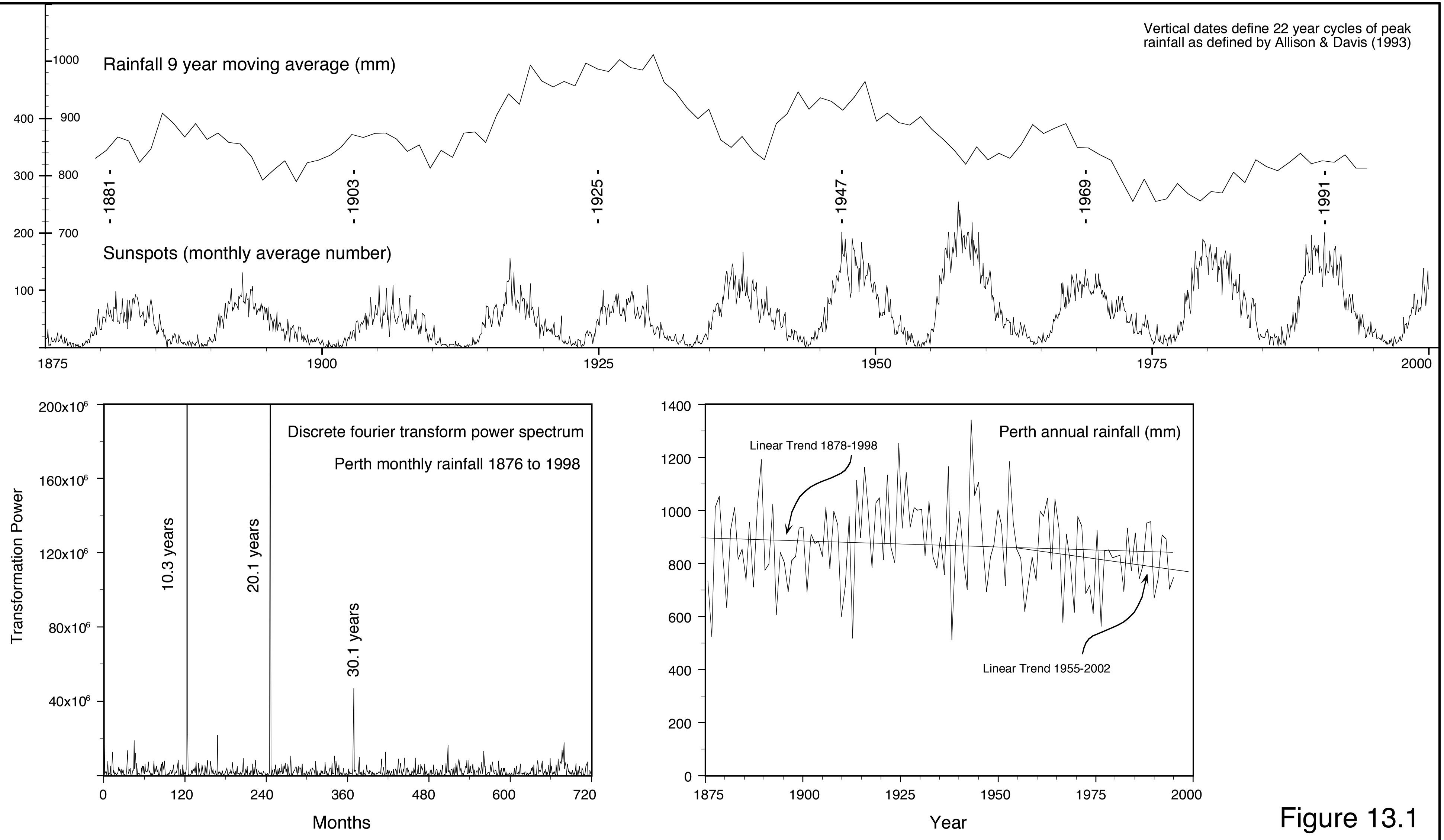
Vertical dates define 22 year cycles of peak rainfall as defined by Allison & Davis (1993)
Rainfall 9 year moving average (mm)
Sunspots (monthly average number)
1000
900
800
700
400
300
200
100
- 1881 -
- 1903 -
- 1925 -
- 1947 -
- 1969 -
- 1991 -
1875
1900
1925
1950
1975
2000
Transformation Power
200x10^6
160x10^6
120x10^6
80x10^6
40x10^6
Discrete fourier transform power spectrum
Perth monthly rainfall 1876 to 1998
10.3 years
20.1 years
30.1 years
0
120
240
360
480
600
720
Months
Perth annual rainfall (mm)
Linear Trend 1878-1998
Linear Trend 1955-2002
1400
1200
1000
800
600
400
200
0
Year

Figure 13.1

causes including natural long term variations, random fluctuations in rainfall pattern and natural or anthropologically induced climate change, acting alone or in combination.

Much of Australia has been getting wetter since about 1910. The south west of Western Australia however (which includes the Perth metropolitan area) has been getting drier with a 19% total reduction and 25% winter rainfall reduction over the period 1910-1995 (Hennessy *et al* 1999). This drying is in agreement with some models of greenhouse warming. However the issue of greenhouse versus natural variability is difficult to resolve. Models show that long dry periods spanning decades occur naturally without any input from the greenhouse effect. The problem for wetland managers is that no one really has any firm idea what the climate and in particular rainfall over the next few decades is likely to do. Depending on the global climate model used, regional climate change scenarios (CSIRO 1996) predict both a continuation of this drying trend and a reversion to wetter conditions. The general trend over the past 125 years as expressed by a simple linear regression is decreasing rainfall (Figure 13.1).

The Indian Ocean Climate Initiative (IOCI) is currently examining the current decline in rainfall in the south west of Western Australia. In particular the initiative hopes to investigate the effects of the Indian and Southern Oceans on inter-seasonal and inter-decadal climate variability in the region (Bates 1999). Preliminary conclusions suggest that the pronounced drying over the past 30 years is unusual both at a regional and global scale. Within an historical context the recent dry years are very unusual. Drying has resulted from both a reduction in the number of rain days and rainfall amounts in extreme events including extreme intensity and extreme frequency (Nicholls *et al* 1999). Linkage has been demonstrated between atmospheric pressure over the continent represented by Perth mean sea level pressure (MSLP) and regional rainfall. When pressure increases mid-latitude depressions pass further to the south of Australia (Wright 1992, Allan & Haylock 1993). Nicholls *et al* (1999) believe that about half the observed rainfall decline can be attributed to changes in regional circulation as represented by Perth MSLP. When viewed at decadal and longer scales however, little of the observed rainfall decline can be attributed to the El Niño - Southern Oscillation or to changes in Indian Ocean sea surface temperatures (Nicholls *et al* 1999).

Climate model simulations for the south west of Western Australia run over 1000 years suggest that natural variability alone can explain decadal and longer dry spells and that these can occur without any obvious external factors (Hunt *et al* 1999). The simulations suggest that the present drying trend is not unique but neither are such trends a particularly common occurrence. The return period of a 10 year rainfall trend is about 1000 years with annual rainfall losses of 20-30%.

13.4 GREENHOUSE WARMING

The greenhouse effect is an anticipated global climate change associated with increased atmospheric concentrations of CO_2 and other gases. These allow sunlight through to the earth's surface but impede the passage of infra-red radiation back into space resulting in a net warming (Pittock 1988). There is general agreement that global warming in excess of that which would be expected from natural climatic variation is already occurring (IPCC 2001, NRC 2002) although the amount which can be attributed to human activity and the anticipated effects on future global climate remain controversial (Calamai 2001). It will not be until there is widespread agreement that the actual climate changes observed exceed natural climatic variability that we will be able to ascribe these changes to the greenhouse effect (Pittock 1988). Regardless of the causes, such warming results in gross changes in global climate patterns including rainfall.

Climate model simulations of global warming from increased greenhouse gas for south west Western Australia include average temperature increases of 1.5° to 5.2° between 2030 and 2070 (Pyper 2001) and reduced rainfall. Model simulations suggest that greenhouse effects will become more pronounced later in the twenty first century. Using the CSIRO Mark 2 coupled climate model Hunt *et al* (1999) allowed carbon dioxide to triple over the period 1881 to 2083. The model predicts declining rainfall through to at least 2100 (Figure 13.2) however the constant decline predicted from 1881 to 2120 is contrary to observed rainfall and suggests that while greenhouse effects may influence climate they are not the sole cause of the declines noted since the 1960's.

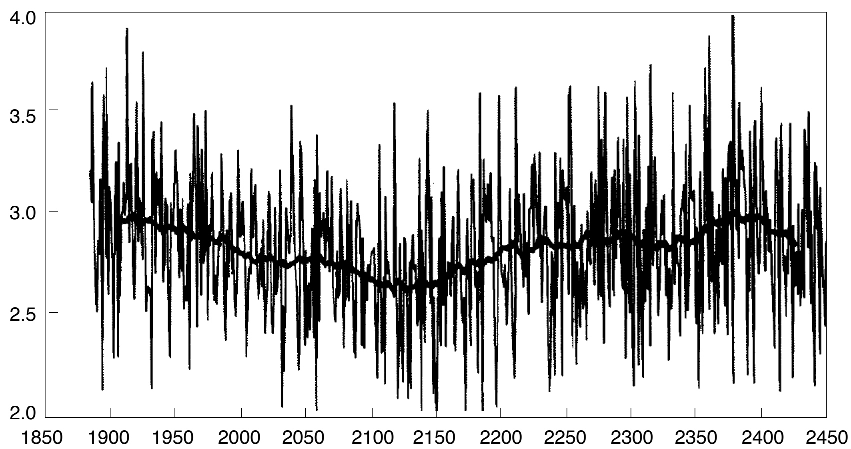

Figure 13.2 Simulated annual mean winter rainfall changes over south west WA under greenhouse conditions. Effective atmospheric CO_2 content tripled between 1881 and 2083 and held constant thereafter. Thin lines are annual mean values for each year, thick line is smoothed trend, y axis is rain mm d^{-1} (Figure 35 of Hunt *et al* 1999)

Where does all this uncertainty leave wetland managers? The most prudent approach must be to assume that the present trends (reduced average rain and general lack of summer rain) will continue. Perth rainfall has declined by more than a third over three decades. None of the drought simulated by Hunt *et al* (1999) lasted more than 30 years (Adler 1999). An optimistic approach would be to assume imminent change. The uncertainties of differentiating between natural variability and greenhouse effects however preclude this as a responsible option. Predicting long term rainfall trends anywhere remains difficult.

Neville Nicholls[2] (pers com) has put the difficulties in predicting Perth rainfall into perspective. Nicholls believes the only predictions which have any real credibility are those based on the enhanced greenhouse effect and these are strongly scale dependent. Predictions for a small area such as Perth are doubtful. Just a small change in the prevailing winds, for example, could produce a large (and unforeseen) change in rainfall. The decline in rainfall is a true research problem which is unlikely to be understood quickly (if at all). Nicholls believes that the likelihood of developing credible means for predicting Perth rainfall 20 to 30 years ahead are 'vanishingly small'.

This places wetland managers in the difficult position of either attempting to minimise the impact of climate change by acting on the basis of theory or waiting and potentially risking situations which are irredeemable. Wetland managers therefore need to approach the future management of Perry Lakes using trends over the past 30 years and current predictions of likely ongoing rainfall decline. Decisions will have to be approached on the basis of risk assessment, probabilities and inadequate records. These are routine problems in engineering and business (Pittock 1988) and form the basis for exploring long range management options. They include:

- do nothing
- increased groundwater top up
- dredging
- importing water
- reducing regional bore extraction thereby raising the regional water table

These options are examined more closely in Chapter 14.

[2] meteorologist, Bureau of Meteorology Research Centre, Melbourne.

13.5 URBAN EFFECTS

Urbanisation over unconfined aquifers has long been recognised to disturb their long term dynamic equilibrium. In general urbanisation leads to an increase in recharge and a rise in the water table. In Perth four separate factors act in combination (McFarlane 1981) once native vegetation is removed:

- reduction in interception losses from native vegetation
- reduction of transpiration losses
- additional recharge from imported water (lawn irrigation and septic systems)
- increased recharge from impervious shedding surfaces (roofs and roads)

Impervious shedding surfaces make up 30 to 40% of urban areas. They collect most of the rain which falls on them and redirect it back to the water table. In Perth, roofs and roads drain either to soak wells or storm water drains which terminate in wetlands. These shedding surfaces effectively circumvent the high interception, evaporative and transpirative losses associated with native vegetation. Urban areas are also dominated by lawns. Their extremely shallow root systems lead to significant recharge both from heavy rainfall and lawn irrigation (McFarlane 1984). In Perth, groundwater recharge below individual residential blocks may be many times that of natural recharge. Williamson & Cole (1976) estimated that where natural recharge below native bushland was 250 mm, recharge (rain and imported water) from residential blocks was as high as 940 mm yr^{-1}.

The increase in recharge is moderated by other urban factors. These include:

- extraction from bores
- flood mitigation drains (eg Herdsman Lake)
- sewering of areas serviced by septic tanks

The competing gains and losses are seldom in equilibrium so in the short term at least the effect of urbanisation is for the water table to rise or fall. In Perth recharge generally exceeds extraction and levels rise. However elsewhere, such as the Perry Lakes area, losses now appear to exceed recharge and the water table is falling. The reasons for this are examined in the following sections. Ultimately the aquifer will achieve a new state of dynamic equilibrium however in a rapidly expanding urban area such as Perth this is unlikely to be achieved in the short term.

13.6 GROUNDWATER EXTRACTION

The whole issue of groundwater extraction is a contentious one (not just at Perry Lakes but world wide) centred around the key concept of sustainability. Bredehoeft *et al* (1982) argue that 'sustainable' groundwater extraction is a myth. Their key argument hinges on the concept that under natural conditions (before human interference) aquifers are in a state of approximate dynamic equilibrium. Theis (1940) argued that extraction represents an additional discharge superimposed upon a previously stable system. Under such conditions the water table will remain unchanged only if there is an increase in recharge, or decrease of the natural discharge. Bredehoeft *et al* (1982) believe that there exists a widespread misconception among hydrologists and water managers that the water budget determines the magnitude of possible (*i.e.* sustainable) groundwater development. They argue that truly sustainable extraction (that which will cause no long term decline in the water table) depends on how much the rate of natural recharge or discharge can be changed. Increase rainfall, say, or capture through pumping water naturally lost from the system would satisfy these requirements for truly sustainable human groundwater extraction. In practice capture of natural discharge is largely impossible and increasing recharge (as rain) cannot be controlled. At Perry Lakes urbanization has already increased natural recharge however this occurred 60-70 years ago and is not now likely to change much.

In many situations, extraction is simply groundwater mining. Water managers 'get away with it' because of the generally slow response times of aquifers (Bredehoeft *et al* 1982). These depend on aquifer parameters transmissivity, and storage co-efficient (confined aquifers) or specific yield (unconfined aquifers) and boundary conditions. In Perth, water managers have maintained an illusion of sustainability because of the partial counterbalancing effect of increased urban recharge. Even here however overall extraction now exceeds recharge and despite the effect of changing land use overall declining water levels will continue unless absolute recharge is increased or high volume extraction is moved to the discharge margins of the Gnangara Mound (Salama *et al* 2003).

As early as 1915 the idea that significant quantities of water could be extracted 'regularly and permanently without dangerous depletion of the storage reserve' was a concept widely accepted by hydrogeologists (Lee 1915 cited Fetter 1994). Lohman (1972) reviewed the definitions of safe (or 'sustainable') yield. He concurred with Thomas (1951 cited Lohman 1972) that the concept is an illusion, describing it as an 'Alice in Wonderland' term which means whatever its user chooses. Todd (1959) took a more practical approach suggesting that safe yield was the amount which could be abstracted 'without producing an undesirable result'. Fetter (1994) suggests that taking into account the important concept of environmental degradation, a composite definition as currently used might be 'the amount of naturally occurring groundwater that can be withdrawn from an aquifer on a sustained basis, economically and legally, without impairing the native groundwater quality or creating an undesirable effect such as environmental damage'. Applying this more pragmatic approach to Perry Lakes it can be argued that at least within the Perry Lakes sector of the Gnangara Mound, abstraction is having an undesirable effect on wetlands and is therefore unsafe. This concept is not new. Almost half a century ago Kazmann (1956) argued that the term safe yield be abandoned because it failed to address the intimate link between groundwater and surface water. Sophocleous (2000) and Glennon (2002) provide current examples from the United States. Critical examination of sustainable yield has lead many to the conclusion that it is largely a myth. Fetter (1994) describes safe yield as a paradox while Bredehoeft *et al* (1982) conclude that in most cases 'sustainable' groundwater extraction is simply an acceptance that such extraction will inevitably result in a new state of dynamic equilibrium and that such changes (usually a lowered water table) are deemed 'sustainable' simply because they are environmentally (or just politically) tolerable.

In the Perry Lakes Sector discharge to the ocean or Swan River cannot be captured (although pumping from the downstream end of the aquifer system could reduce discharge). Recharge from rain has decreased, recharge from elsewhere in the aquifer (boundary input) is either constant or declining slowly as more water is used for domestic supply. On the basis of rainfall alone, a decline would have occurred anyway. If rainfall increased markedly (as it did around 1920) we could factor in some truly sustainable extraction. The situation now is that pumping is not sustainable (neither in its true hydrologic sense nor in its 'acceptable decline of water table' sense) and is probably seriously contributing in a 'death by a thousand cuts' sense to the declining wetland water levels. Sadler *et al* (1988) predicted that for the Perth metropolitan area, a 20% reduction in mean annual rainfall would necessitate a 40% reduction in groundwater draw from bores supplying potable water. Arnold (1988) suggested that on the Swan Coastal Plain the combined effect of reduced rainfall and increased demand for groundwater extraction by both public and private users would inevitably result in many wetlands disappearing. These predictions are now coming to fruition.

13.7 DOMESTIC BORE MAPPING

In order to quantify what effect bores might be having in the Perry Lakes area a comprehensive program of bore mapping was initiated. Bores are unlicensed in Perth and hence there are absolutely no records of bore locations or density. Perth residents have laboured for many years under the illusion that there is an abundance of groundwater. This impression has not been helped by the fact that domestic bores for garden watering require no licence and are actively encouraged by the authorities as a means of reducing the pressure on treated reticulated water. In the wake of the 2002 drought Water Corporation were offering a $500 rebate on new domestic bores. Maps indicating areas considered hydrologically suitable for bores continues to include the Perry Lakes/Floreat area.

13.7.1 Mapping of Public and Private Bores

Domestic 'back yard' bores were mapped on the ground in an area of about 6x3 km around Perry Lakes (Figure 13.3). This involved walking all streets within the survey area during summer (January-March) and looking for well irrigated lawn and gardens and the ubiquitous iron staining. Groundwater contains dissolved iron which is stable under reducing conditions (Davidson 1995, p89). Upon exposure to air this is oxidised to ferric iron which imparts distinctive yellow-brown stains on walls and pavement. Iron concentrations in the superficial aquifer vary from 1 to greater than 50mg/l. This mapping program was a slow and tedious task which took two summers (1996-97 and 1997-98) to complete.

Depth to the water table is probably the single biggest factor in bore density within any area. Most domestic bores use simple centrifugal pumps which have a net maximum suction lift of less than one atmosphere or about 10m (Bouwer 1978, p186). In many older installations centrifugal pumps are frequently installed at the bottom of dry wells 10-15m deep thereby allowing access to water 20-25m below surface level. Beyond this depth small submersible pumps are employed. Shallow installations where limestone is absent frequently use spear points installed by jetting or sludge pump. Deeper bores or bores in limestone must be drilled, substantially increasing costs. Block size and general affluence are also factors. Many new houses in established suburbs are on small subdivided blocks where the cost of a bore cannot be justified. More affluent home owners also frequently opt to use scheme water to avoid iron staining on pavement. Some developments specifically ban the use of bore water for this reason. In general however, depth to water is the single greatest factor determining domestic bore density (Table 13.2). Where bores are very expensive to construct, a single, larger capacity bore is frequently shared between 2 to 4 homes. These have been mapped as single bores.

Based on average residential block density of 1000-1200 blocks per km^2 bore density ranges from 100 - 125 per km^2 in elevated limestone areas such as City Beach to 650 - 775 per km^2 in low areas such as those immediately adjacent to Perry Lakes.

Table 13.2 Topographic Influence on Domestic Bore Density

Depth[1]	Area	Blocks	Bores	Percent	Comments
5-10	Floreat	136	88	64.7	adjacent to Perry Lakes, no limestone
5-10	Churchlands	279	159	57.0	adjacent Herdsman Lake, no limestone
10-20	City Beach	374	71	19.0	limestone (?)
10-20	Wembley	311	138	44.4	mostly sand
10-20	Floreat	168	88	52.4	adjacent to Perry Lakes, no limestone
20-25	Floreat	419	210	50.1	mostly sand
25-30	Floreat	170	57	33.5	sand and limestone
25-30	Floreat	275	72	26.2	sand and limestone
30-40	Floreat	194	35	18.0	sand and limestone
over 40	City Beach	353	36	10.2	limestone, depth to water >60m in places

1: approximate depth to water table (m)

Bores used to irrigate public open space and large private lawns employ either 'turbine pumps' (impellor pumps which operate below the water surface, driven from the surface by a rotating shaft), and submersible pumps. Bore location, pump type and capacity were obtained from the Town of Cambridge and City of Nedlands. Where capacity was not known, it was estimated based on pump type and outlet pipe diameter. Pump data are included in Figure 13.3.

13.7.2 Estimates of Extraction and Recharge in Parks and Reserves

Water usage in parks and reserves is difficult to estimate. Groundwater extraction is not monitored nor are records kept by any of the local councils on bore usage. These general comments apply equally to Perry Lakes Reserve.

At Perry Lakes there are 9 production bores (Figure 3.3). These have differing pumping capacities and usage (Table 13.3). Bores 1-8 are connected to a ring main system which allows irrigation water to be distributed from any bore or combination of bores to various parts of the reserve. Top up maintenance water to East Lake is drawn from the ring main via two outlets (Figure 5.1a). The ring main between these two outlets can be isolated via a gate valve such that the south outlet can be fed by bores 1 and 6 only and the north by bores 2-5 and 7. Bore 8 irrigates Alderbury Flats and the median strip within Oceanic Drive between Perry Lakes and Brookdale Street. Bore 9 irrigates the verge and median strip only, west from Perry Lakes Drive.

The irrigation rates are manufacturer's recommended rates feeding a pressurised system. When bores 1, 3 or 6 were operated alone for lake top up, the ring main operated at very low pressure resulting in substantially increased pump output. Top up was typically performed using bores 1,2,3 and 6 or occasionally in combination with bores 4, 5 and 7. Generally no more than five bores were operated at one time. Top up flow meter

382000
383000
6467000
6466000
6465000
6464000
Indian
Ocean
City
Beach
Ovals
School
Bowls
Club
Retirement
Village
Water
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High
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PARK
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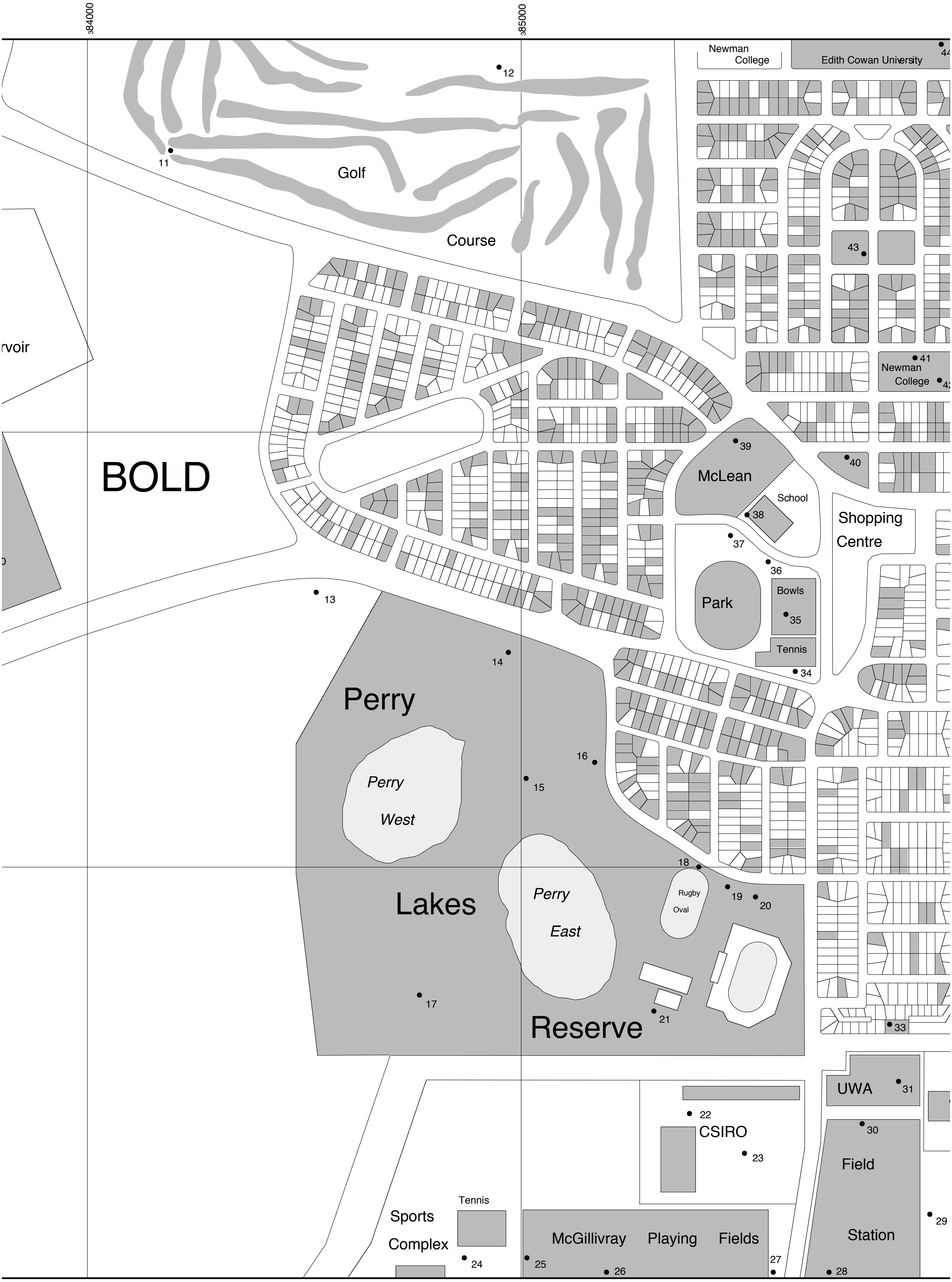
384000
385000
Newman College
Edith Cowan University
44
12
11
Golf
Course
rvoir
BOLD
43
41
Newman College
42
39
40
McLean
School
38
Shopping Centre
37
36
Park
Bowls
35
Tennis
34
13
14
Perry
Perry West
16
15
Lakes
Perry East
18
Rugby Oval
19
20
17
21
Reserve
33
UWA
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CSIRO
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Field Station
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Tennis
Sports Complex
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McGillivray Playing Fields
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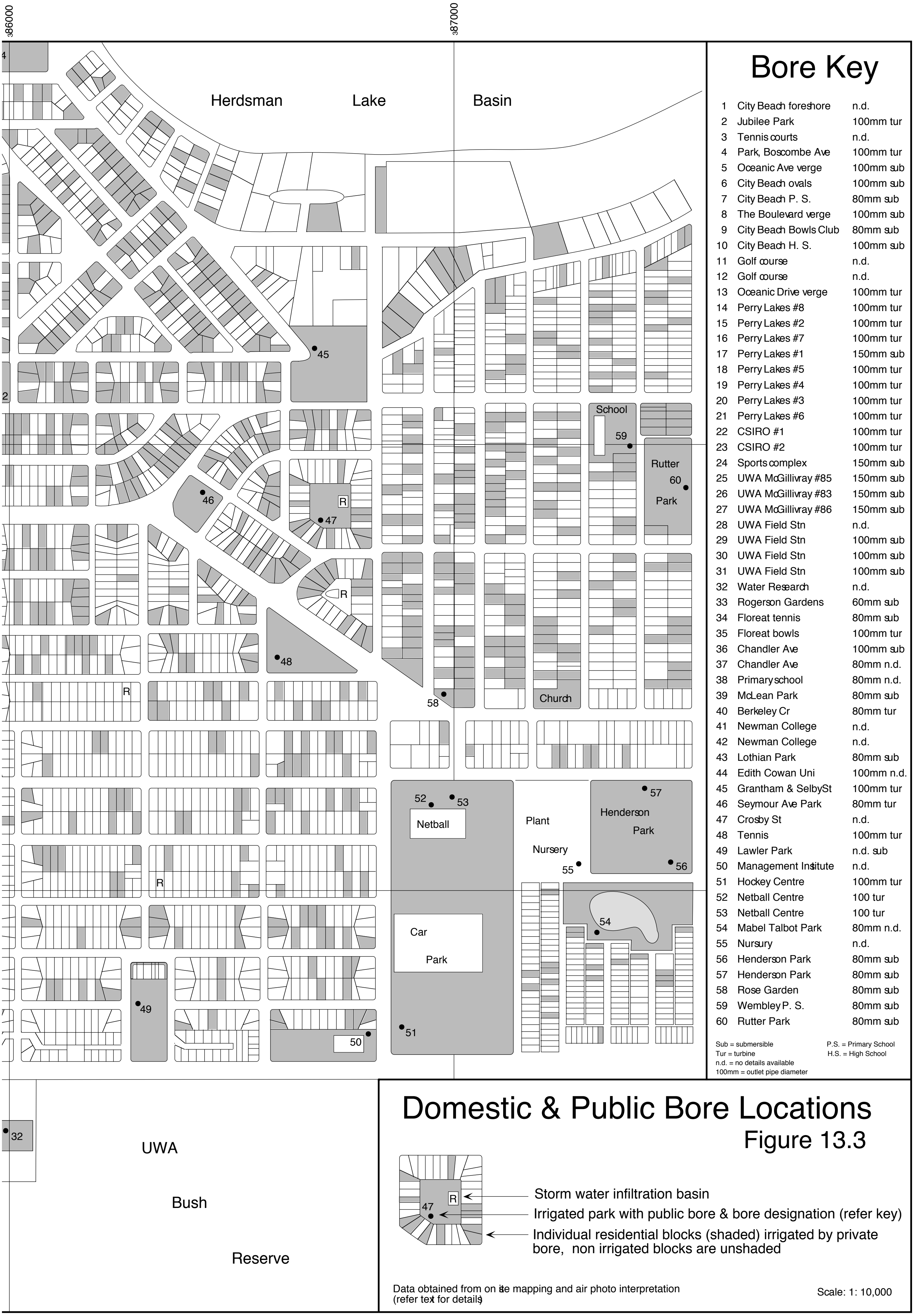

Bore Key

1	City Beach foreshore	n.d.
2	Jubilee Park	100mm tur
3	Tennis courts	n.d.
4	Park, Boscombe Ave	100mm tur
5	Oceanic Ave verge	100mm sub
6	City Beach ovals	100mm sub
7	City Beach P. S.	80mm sub
8	The Boulevard verge	100mm sub
9	City Beach Bowls Club	80mm sub
10	City Beach H. S.	100mm sub
11	Golf course	n.d.
12	Golf course	n.d.
13	Oceanic Drive verge	100mm tur
14	Perry Lakes #8	100mm tur
15	Perry Lakes #2	100mm tur
16	Perry Lakes #7	100mm tur
17	Perry Lakes #1	150mm sub
18	Perry Lakes #5	100mm tur
19	Perry Lakes #4	100mm tur
20	Perry Lakes #3	100mm tur
21	Perry Lakes #6	100mm tur
22	CSIRO #1	100mm tur
23	CSIRO #2	100mm tur
24	Sports complex	150mm sub
25	UWA McGillivray #85	150mm sub
26	UWA McGillivray #83	150mm sub
27	UWA McGillivray #86	150mm sub
28	UWA Field Stn	n.d.
29	UWA Field Stn	100mm sub
30	UWA Field Stn	100mm sub
31	UWA Field Stn	100mm sub
32	Water Research	n.d.
33	Rogerson Gardens	60mm sub
34	Floreat tennis	80mm sub
35	Floreat bowls	100mm tur
36	Chandler Ave	100mm sub
37	Chandler Ave	80mm n.d.
38	Primary school	80mm n.d.
39	McLean Park	80mm sub
40	Berkeley Cr	80mm tur
41	Newman College	n.d.
42	Newman College	n.d.
43	Lothian Park	80mm sub
44	Edith Cowan Uni	100mm n.d.
45	Grantham & Selby St	100mm tur
46	Seymour Ave Park	80mm tur
47	Crosby St	n.d.
48	Tennis	100mm tur
49	Lawler Park	n.d. sub
50	Management Institute	n.d.
51	Hockey Centre	100mm tur
52	Netball Centre	100 tur
53	Netball Centre	100 tur
54	Mabel Talbot Park	80mm n.d.
55	Nursury	n.d.
56	Henderson Park	80mm sub
57	Henderson Park	80mm sub
58	Rose Garden	80mm sub
59	Wembley P. S.	80mm sub
60	Rutter Park	80mm sub

Sub = submersible
Tur = turbine
n.d. = no details available
100mm = outlet pipe diameter
P.S. = Primary School
H.S. = High School

Domestic & Public Bore Locations

Figure 13.3

Storm water infiltration basin
Irrigated park with public bore & bore designation (refer key)
Individual residential blocks (shaded) irrigated by private bore, non irrigated blocks are unshaded

Data obtained from on site mapping and air photo interpretation (refer text for details)

Scale: 1: 10,000

records show that regardless of the number of bores operated, maximum top up output is about 235m^3/hr. This limiting value (described in detail in Chapter 7) reflects increased pressure in the ring main with all water forced to exit through the 100mm (south) and 75mm (north) top up outlets.

Table 13.3 Pump specifications, Perry Lakes Reserve

Pump	Type	Rating (hp)	Irrigation Rate (m^3/hr)	Top Up Rate (m^3/hr)	Watt-hour meter	Hour meter	Amp meter
1	submersible	30	37.4	120	X	X	X
2	turbine	40	55.1		X		X
3	'	20	34.9	72			X
4	'	25	37.4				
5	'	25	37.4				
6	'	25	37.4	72			
7	'	25	37.4		X		
8	'	25	37.4		X		
9	'	25	37.4				

Total groundwater extraction is irrigation plus top up. Top up water was metered, irrigation water was not. Townley *et al* (1995) estimated lawn irrigation and lake maintenance over summer 1992-93 from grounds staff records of bore usage and irrigation application rates. Over 1996-97 irrigation usage was estimated from a combination of watt-hour meter, amp meter and hour meter data[3] from bores 1, 2, 7 and 8. Bores 3, 4, 5 and 6 are not metered separately (power is drawn via the stadium complex), bore 9 was ignored. In general rated horsepower (hp) where 1hp = 746 watts was used to estimate hours of pump operation, checked by amp meter data (where current x voltage = watts) and direct hour meter data. Data was corrected for other power use (principally flood lighting) by measuring daily lighting usage over winter when pumps were off. Hours used for top up were back calculated from the flow meter data assuming average input of 235m^3/hr. Bores 3, 4, 5 and 6 were assumed to run similar hours to bore 2 (but always with one bore off). Total groundwater extraction estimates appear as Table 13.4.

Table 13.4 Groundwater extraction, Perry Lakes Reserve

Period	Top Up (m^3)	Irrigation (m^3)	Sub Total	Seasonal Total
Dec 26 1992-May 16 1993	42875			
Dec 4 1993-May 28 1994	60226			
March 2-May 2 1993		100578		
Sept 15-Dec 31 1996	34783	123958	158741	Summer 1996-97
Jan 1-June 15 1997	145968	266569	412537	571278
Oct 21-Dec 21 1997	NIL	163628		

3 Detailed irrigation and top up records were also kept by grounds staff for this study. These records were lost when the maintenance vehicle (along with irrigation log book) was stolen.

Therefore over summer 1996-97 approximately 571,000m^3 of groundwater was extracted within Perry Lakes Reserve. Lawn irrigation totalled about 390,000m^3. Lake maintenance totalled about 180,700m^3 and about 210,000m^3 was returned to the aquifer as measured recharge in water balance calculations (combined recharge plus rainfall and storm drain inputs). During the period December 10, 1996 to May 15, 1997 (Balance periods 19-32) when there was nil groundwater discharge to East Lake (*i.e.* constant recharge conditions with nil flow-through), 154,700m^3 were added as top up of which 136,700m^3 were recharged to the aquifer. Intense lawn irrigation occurs for about 180 days each summer. The 1996-97 irrigation therefore averaged about 2160m^3/day. The total irrigated area is about 400,000m^2 suggesting an application average of about 5mm/day. Agriculture WA recommends 4mm/day to maintain an adequate lawn (Cargeeg *et al* 1987 p39) and CSIRO (1979) 16mm/week (average 2.3mm/day). This suggests that the lawns are over watered.

Recharge is difficult to measure. In Perth recharge estimates over natural vegetation vary from 5.5 to 13% of annual rainfall (refer Chapter 11). Recharge over lawns and playing fields is considerably greater (nil canopy effect and shallow root systems). McFarlane (1984) monitored soil water profiles under an urban lawn in Dalkeith (5km southeast of Perry Lakes) where summer irrigation was 40-50% of potential evapotranspiration (PET). These data estimate percent total input (rain + irrigation) becoming recharge at differing depths. McFarlane's field results confirm the suggestion made by Carbon (1975) that deep drainage becomes significant in Perth soils only when water input exceeds 60% PET. In Perry Lakes Reserve, depth to water table varies from about 2.5m over most of the reserve, rising to about 8m at piezometer nest N5. These data, summarised in Figure 13.4, allow recharge to be estimated.

The PET of lawn was considered never to exceed open water evaporation as measured at adjacent East Lake. Table 13.5 provides estimates of monthly irrigation, distributed over 180 days, with the most intensive irrigation occurring between December -February. These daily average irrigation rates are approximately equal to PET and suggest that significant recharge occurs from summer irrigation.

Table 13.5 Recharge Estimates to 3m water table, Perry Lakes Reserve 1997

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rain (mm)	<1	2	70	31	86	109	98	104	118	30	7	0	653
Irrigation (mm)	213	138	143	56						57	158	209	975
Total	214	140	212	87	86	109	98	104	118	87	164	209	1628
PET (mm)	209	135	139	82	65	42	53	70	87	145	154	205	1385
Inputs:PET (%)	102	104	152	105	132	261	184	149	135	60	107	102	
Recharge (%)	35	37	85	38	75	85	85	85	80	0	42	35	
Recharge (mm)	73	50	118	31	49	35	45	59	70	65	72	93	667

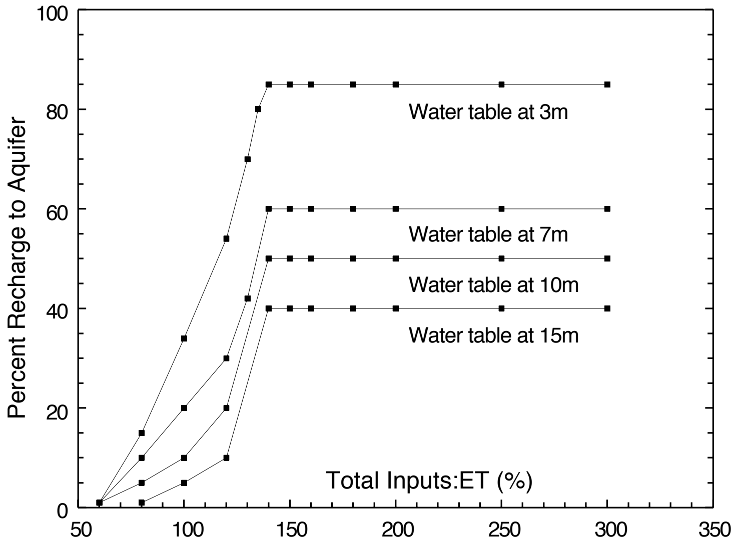

Figure 13.4 Recharge from lawns in Perth, data adapted from McFarlane (1984, p195)

Total annual input to irrigated lawns is estimated at 1628mm of which 667mm is recharged to groundwater. This is significantly greater that the 80 or so mm recharged below native coastal vegetation. It approximates the annual amplitude of the local water table cycle.

13.7.3 Regional Water Balance Estimates

A simple mass balance model was computed for an area of 9 km^2 comprising all areas east of AMG 384 500 in Figure 13.3. This is a square 3x3 km comprising approximately 2 km^2 of parks, reserves and native bush and 7 km^2 of low density residential housing. Table 13.6 shows estimates of bore extraction (low to high) within this area.

Table 13.6 Estimates of bore extraction in 9km^2 area (m^3x1000)

		Public	Bores		
Extraction (m^3 yr^{-1})	*10,000*	*20,000*	*30,000*	*40,000*	*50,000*
Domestic Bores					
750	1,352	1,842	2,332	2,022	3,312
1,000	1,640	2,130	2,620	2,310	3,600
1,250	1,927	2,417	2,907	2,597	3,887

Domestic bores were calculated using a range of 750 to 1250 m^3 per year based on an estimated mean annual extraction of 1000m^3 (Cargeeg *et al* 1987, p39) to 1100m^3 (Farrell 1981). Within the model area there were 1150 domestic bores and 49 public bores mapped. Average public bore extraction is more difficult to estimate. An annual rate of

10,000m³ to 50,000m³ per bore was used. This range is based on the average 1997 extraction for lawn irrigation at Perry Lakes of approximately 430,000m³ from eight bores (average 53,750m³). Perry Lakes is almost certainly at the high end of average public extraction. Within adjacent residential areas McFarlane (1984) found that impervious shedding surfaces (ISS) on private blocks (roofs, paths and driveways) comprised 21.7 to 28.8% of the surface area while public roads and car parks comprised 9.6 to 13.1%. Assuming roughly median values of 25.2% roofs and 11.3% roads yielded 36.5% impervious shedding surfaces within the 7 km² of residential land. These shedding surfaces were assumed to shed 75% of their intercepted rain back to the aquifer either via soak wells or storm drains into public infiltration basins or wetlands. This figure is based on roof and other estimates made by McFarlane (1984). All other areas (residential gardens, lawns, parks and native bush reserves), recharge was estimated to be 10% of rainfall. Table 13.7 shows the estimated total recharge for seven values of average rainfall.

Table 13.7 Total recharge for model area of 9km² area (m³x1000)

	Area (km)	850mm	800mm	750mm	700mm	650mm	600mm	550mm
ISS (R=75%)	2.5	1,594	1,500	1,406	1,312	1,219	1,125	1,031
Non ISS urban (R=10%)	4.5	382	360	337	315	292	270	247
Non urban (R=10%)	2.0	170	160	150	140	130	120	110
Total	9.0	2,146	2,020	1,894	1,767	1,641	1,515	1,389

Table 13.8 is the results of the simple regional water balance model. The data is an amalgamation of the extraction and recharge data, calculated as net annual change in the water table in mm. Boundary conditions assume flow in equal to flow out.

Table 13.8 Annual water table change (mm), typical recharge and extraction regimes

Rain (mm)	850mm	800mm	750mm	700mm	650mm	600mm	550mm
E&R* (m³x1000)	2,146	2,020	1,894	1,767	1,641	1,515	1,389
1,352	88	74	60	46	32	18	4
1,640	56	42	28	14	0	-14	-28
1,842	34	20	6	-8	-22	-36	-50
1,927	24	10	-4	-18	-32	-46	-60
2,022	14	0	-14	-28	-42	-56	-70
2,130	2	-12	-26	-40	-54	-68	-82
2,310	-18	-32	-46	-60	-74	-88	-102
2,332	-21	-35	-49	-63	-77	-91	-105
2,417	-30	-44	-58	-72	-86	-100	-114
2,597	-50	-64	-78	-92	-106	-120	-134
2,620	-53	-67	-81	-95	-109	-123	-137
2,907	-85	-99	-113	-127	-141	-155	-169
3,312	-130	-144	-158	-172	-186	-200	-214
3,600	-162	-176	-190	-204	-218	-232	-246
3,887	-193	-208	-222	-236	-250	-264	-278

* E&R is extraction and recharge from Tables 13.6 and 13.7

A study of this type is at best an estimate however it does provide valuable insights into the likely importance played by bore extraction in the regional water balance. It must be remembered that urbanisation has had two major (and partially counterbalancing) effects. Huge amounts of water are now extracted via bores while at the same time recharge has been enhanced through impermeable shedding surfaces. Such models should account for the average 40 to 50mm decline in the water table measured at Perry Lakes over the forty years (Chapter 2). A comprehensive regional water balance is well outside the scope of this study. The bore mapping has provided reasonable estimates of annual groundwater extraction. Most importantly extraction appears to be equal to or greater than the likely recharge, indicating that it is a significant factor in the local and regional water table decline. Many combinations of extraction and recharge (highlighted in Table 13.8) model the observed groundwater decline. The simple fact that bore extraction appears to approximately equal or exceed recharge suggests that hydrologically we are already operating at a net groundwater deficit.

13.8 AQUIFER GEOLOGY

Changes in aquifer hydrogeology within the Perry Lakes sector are also likely factors in long term water table decline.

Damming effects within the Superficial Aquifer

Regional water table contours (Figure 13.5) show a distinct steepening of the gradient west of Lake Monger. This corresponds roughly with the appearance of limestone within the aquifer section. Drillers in the Herdsman-Jackadder Lake area report a widespread clay layer at the sand-limestone contact. Bores screened within residual Tamala sands and limestone have low residual yields. Haselgrove (1981) describes similar hydrogeology on the Kwinana coastal strip where the aquifer comprises highly permeable Tamala Limestone, and displays a nearly horizontal water table. The eastern boundary of this zone is defined by a pronounced steepening of the water table gradient coincident with an eastward dipping clayey sand unit defining the contact between Bassendean sands and limestone. These widely reported 'damming' effects are co-incident with the chain of lakes running from Lake Joondalup to Thompsons Lake, including Herdsman Lake and Lake Monger. Positive piezometric heads have been reported by cable tool drillers in residual Tamala limestone sands around both Herdsman and Jackadder Lakes (K. Wintergreen[4] pers com) suggesting that some lakes may be in part maintained by discharge from upward flowing groundwater driven by both this damming effect and normal flow-through induced positive piezometric heads. This zone effectively acts as a barrier, impeding the westward flow of groundwater into coastal areas.

[4] cable tool drilling contractor, Perth

Variation in Aquifer Geology

Consider a transect from Herdsman Lake southwest through Perry Lakes to the coast at Swanbourne. The aquifer stratigraphy here undergoes a transition from 100% sand to mixed sand-limestone to predominantly Tamala limestone along the coast (Figure 13.6a). The coastal limestone generally has a high hydraulic conductivity (Davidson 1995). This is reflected in the generally lower slope of the water table (Figure 13.5). In the mixed sand-limestone zone however effective porosity of the limestone is highly variable (refer Appendix 3.4). At Perry Lakes bailing recovery in piezometers screened within the limestone was significantly less than those screened in the upper sand. Similarly around Jackadder and Herdsman Lake drillers frequently report low yields (about 300-400m^3 d^{-1}) from limestone and near surface residual sands derived from it. Where these sediments form a significant proportion of the aquifer, hydraulic conductivity and thus transmissivity is reduced. Therefore as a general rule, transmissivity increases close to the coast, decreasing eastward towards the 'barrier' described above.

Relationship to Constant Head Boundaries

The shape of the water table contours in Figure 13.5 reflects the constant head boundaries of the Indian Ocean and the Swan Estuary. Flow net analysis shows how water recharging the aquifer from Lake Monger rapidly becomes widely dispersed. An initial aquifer section of about 1000x30m or 30,000m^2 at Lake Monger expands to about 300,000m^2 along the constant head boundaries. The volume of groundwater entering this sector is initially impeded by the damming effect. Once past this low transmissivity bottle neck groundwater enters the Perry Lakes Sector of the Gnangara Mound. This is a much larger volume of aquifer sediment comprising predominantly highly transmissive coastal limestone. Much of it (such as Bold Park and the suburb of City Beach) are topographically elevated with low to nil annual recharge. Hydrologically the Perry Lakes Sector is partially isolated or detached from the Gnangara Mound. The water balance models confirm that current extraction exceeds recharge (which includes water entering through the eastern barrier sediments). The net effect is that extraction exceeds recharge resulting in a long term lowering of the water table.

The Cottesloe Peninsula (the northern portion of which is visible in Figure 13.5) is an extreme extension of the same phenomenon. It is almost completely surrounded by constant head boundaries and is almost hydrologically isolated from the Gnangara Mound. It is now completely underlain by salt water wedges with the maximum thickness of fresh water midway between the Indian Ocean and the Swan River being less than 15m. It represents a more extreme example of an area where extraction exceeds

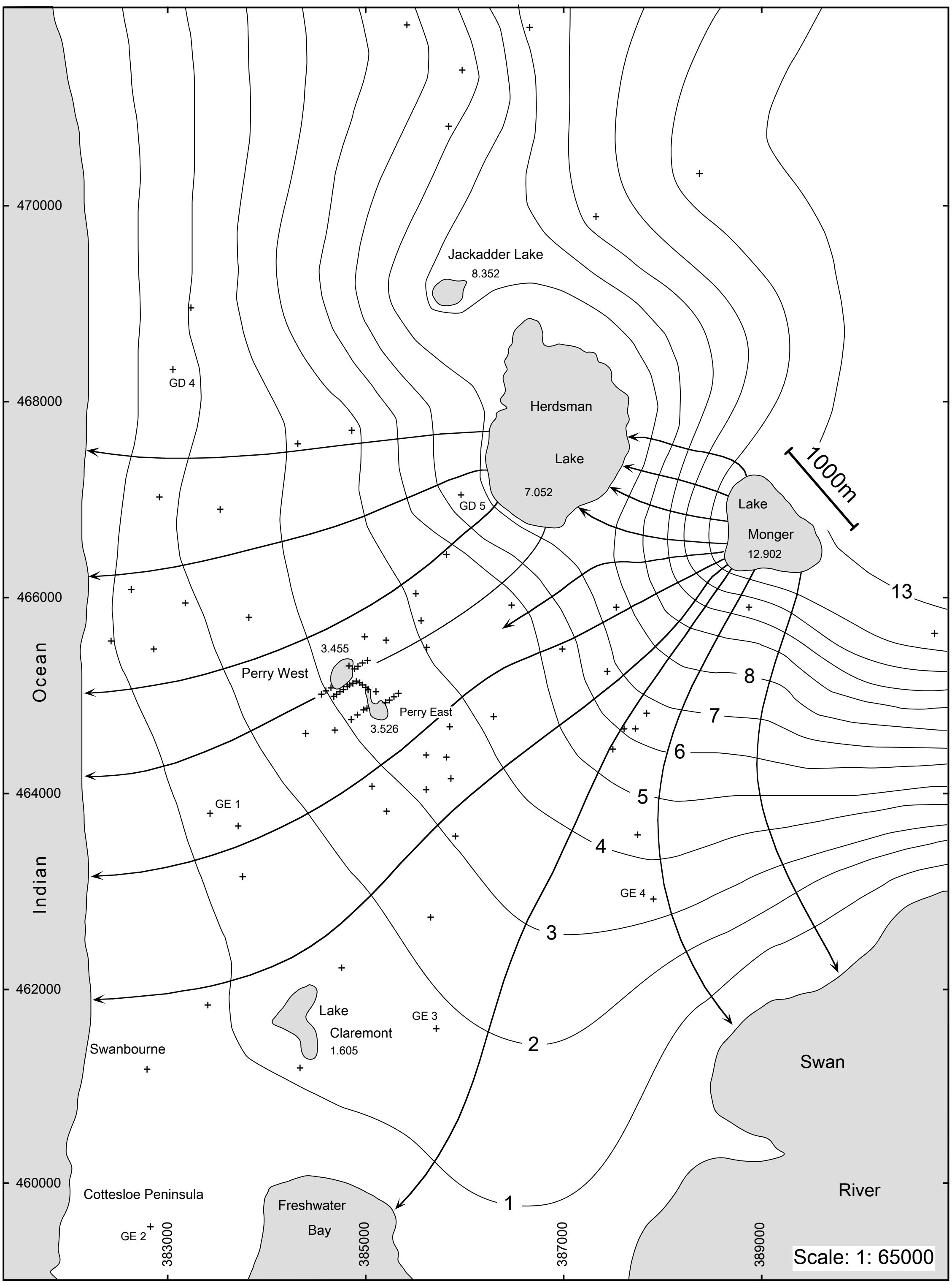

Figure 13.5 Groundwater Flow in the Perry Lakes Sector

Flownet showing pattern of groundwater flow for water recharging the aquifer from Lake Monger in flow through conditions. Lake Monger represents an aquifer section approximately 1000m in width. Water within this section spreads out into a massive fan discharging into the Swan River and Indan Ocean. In so doing it must suffer a decrease in velocity. The flow net also demonstrates that groundwater discharging to Perry Lakes may have passed through Lake Monger or both Lake Monger and Herdsman Lake, thereby explaining the large variations in groundwater isotope and chloride chemistry within Perry Lakes Reserve (refer Chapter 6).

Water table data compiled September 10-15, 1997
Lake stands are approximate maxima during survey period, all data metres AHD
Indian Ocean and Swan River set as constant head boundaries at 0.000m
Contours created in SURFER on 100x100m kriged grid

+ Monitoring well used as water table data point (refer Chapter 2)

⟵ Groundwater flow line

recharge. In recent years many domestic bores have turned salty as extraction of fresh water has allowed the salt water wedges to expand (Cargeeg *et al* 1987, Davidson 1995). Again it represents a simple water balance problem where extraction exceeds recharge.

Variation in Aquifer Thickness

The thickness of the saturated section in the superficial aquifer is not constant but is a function of both the water table elevation and the surface of the Tertiary and Cretaceous units forming the basal aquiclude. Figures 13.6 b&c show aquifer isopachs and aquiclude geology. The aquifer section thickens over the Mullaloo sandstone by 10-20% further contributing to an expanded aquifer volume within the Perry Lakes sector.

Interaction with Underlying Tertiary and Cretaceous Formations

Northeast of Herdsman Lake the unconfined aquifer rests on Molecap greensand (Figure 13.6c) which is host to the Mirrabooka aquifer. In the Perth region, Davidson (1995) describes the Molecap as a glauconitic, fine to medium grained silty sandstone. The Perry Lakes area is underlain by early Tertiary age Kings Park Fm, comprising shallow marine to estuarine sediments (siltstone and shale) possibly deposited in the drowned valley of the ancestral Swan River (Playford *et al* 1976 p201). The Mullaloo sandstone member is incised into the Kings Park Fm. It consists of poorly sorted, fine to very coarse grained slightly glauconitic sandy clay. The Mullaloo Sandstone was deposited within deep marine channels incised into the Kings Park Fm and is considered to be a locally important semi-confined to confined aquifer (Davidson 1995).

Northeast of Herdsman Lake the unconfined aquifer receives water discharged from the underlying Mirrabooka aquifer. In the Perry Lakes area however scanty data suggests that while piezometric heads within the Mullaloo sandstone are positive, the bulk of the discharge occurs off shore close to the coast (Davidson pers com). Therefore northeast of Perry Lakes (and the Herdsman-Lake Monger barrier zone) there is recharge to the superficial aquifer which is absent within the Perry Lakes sector.

Rainfall Recharge

Northeast of Herdsman Lake the superficial aquifer comprises Bassendean sands with a predominantly shallow water table. Here natural recharge is estimated to be 15-20% of total rainfall (Davidson 1995) whereas to the southwest through Perry Lakes to the ocean, recharge estimates decrease to 10-15% (Figure 13.6d). Leaving aside the effects of urbanisation, the Perry Lakes sector receives reduced recharge. This is particularly so in elevated natural bush areas such as Bold Park where the distance from land surface

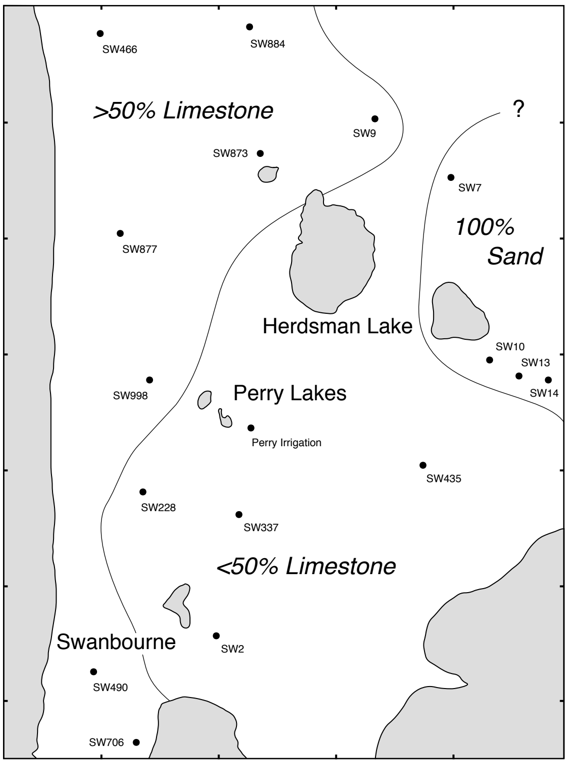

Figure 13.6A Variation in Aquifer Geology

Proportion of limestone estimated from drillers logs. Bore designations from Waters & Rivers Commision records

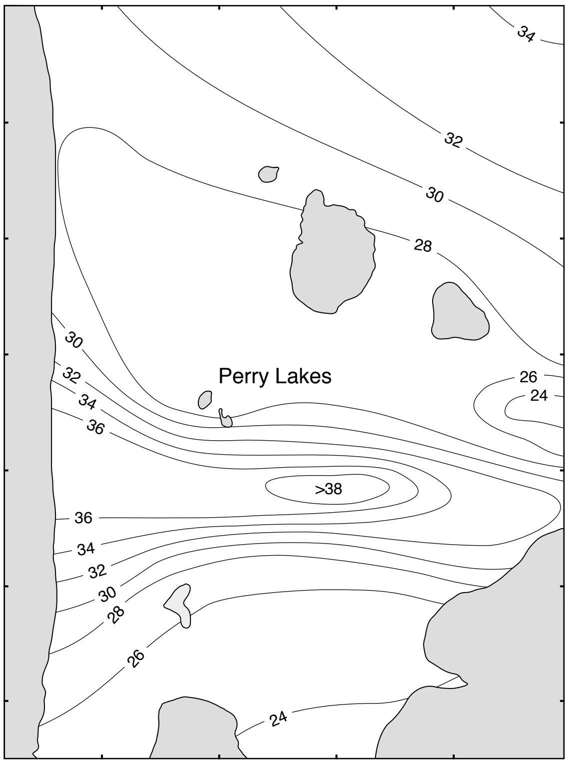

Figure 13.6B Variation in Aquifer Thickness

Unconfined aquifer isopachs in metres computed from basal aquiclude contour surface (Davidson 1995 p221) and water table levels September 1997

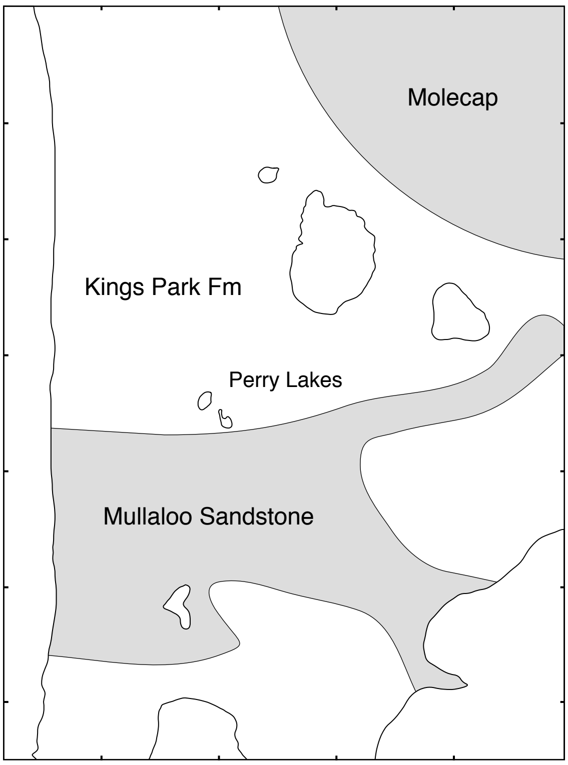

Figure 13.6C Geology at Aquifer Base

Mullaloo Sandstone member

Kings Park Fm (Tertiary)

Molecap Greensand (Cretaceous)
(area of discharge from Mirrabooka aquifer to unconfined aquifer)

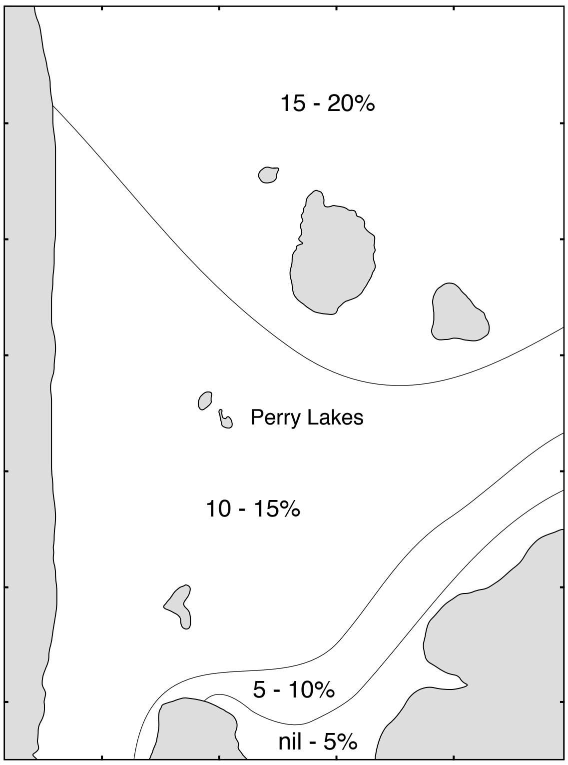

Figure 13.6D Variation in Recharge

Percentage of annual rainfall recharged to the unconfined aquifer (after Davidson 1995 p251)

Aquifer Geology
Figure 13.6

to water table is up to 80m. Vegetation here is non phreatic and therefore utilises a great proportion of vadose water.

In summary, natural factors have a substantial influence on the observed water table decline at Perry Lakes, in particular the damming effect to the east coupled with aquifer geometry which results in partial hydrologic isolation of the Perry Lakes sector from the Gnangara Mound, expanded aquifer volume terminating in constant head boundaries and reduced rainfall recharge. Aquifer geometry is not, in itself, the cause of the water table decline. Rather, its importance lies in the exaggerating effect it exerts on both natural and non natural factors. In particular, under the current regime of reduced rainfall and recharge:

- the effects on water table levels from bore extraction are increased because the damming effect impedes groundwater entering the area from the east
- the effects on water table levels from natural evaporative pumping around wetlands are similarly enhanced

13.9 SUMMARY

Wetlands are a fundamental feature of the Perth urban environment (Sadler *et al* 1988). When the climate that ultimately sustains them is significantly altered wetland managers are faced with difficult decisions. Which aspects (or even which wetlands) can or should be preserved become key questions. For example should West Lake simply be allowed to revert to sumpland as has already happened with South Lake and Camel Lake or should significant expense and effort be expended to rid it of invasive weed species and maintain more water in it over summer? Alternatively should all efforts go into maintaining East Lake as a permanent wetland? Should the whole lot simply be allowed to disappear?

Decreasing rainfall is a present fact and a future expectation. As Sadler *et al* (1988) point out history has shown that timely decisions on difficult resource management problems are difficult to achieve. Action is often precipitated only after the problem reaches crisis proportions. Concern over declining water levels in Perry Lakes has been on going for at least 30 years (Chapter 2). Unfortunately because any climate prediction includes uncertainties, decisions are likely to be incremental rather than pivotal. Easy (and we might add inexpensive) decisions are likely to predominate over difficult (and most likely more expensive) ones. In the case of wetlands, any realistic hope of preservation may be long lost by the time the problem reaches crisis point.