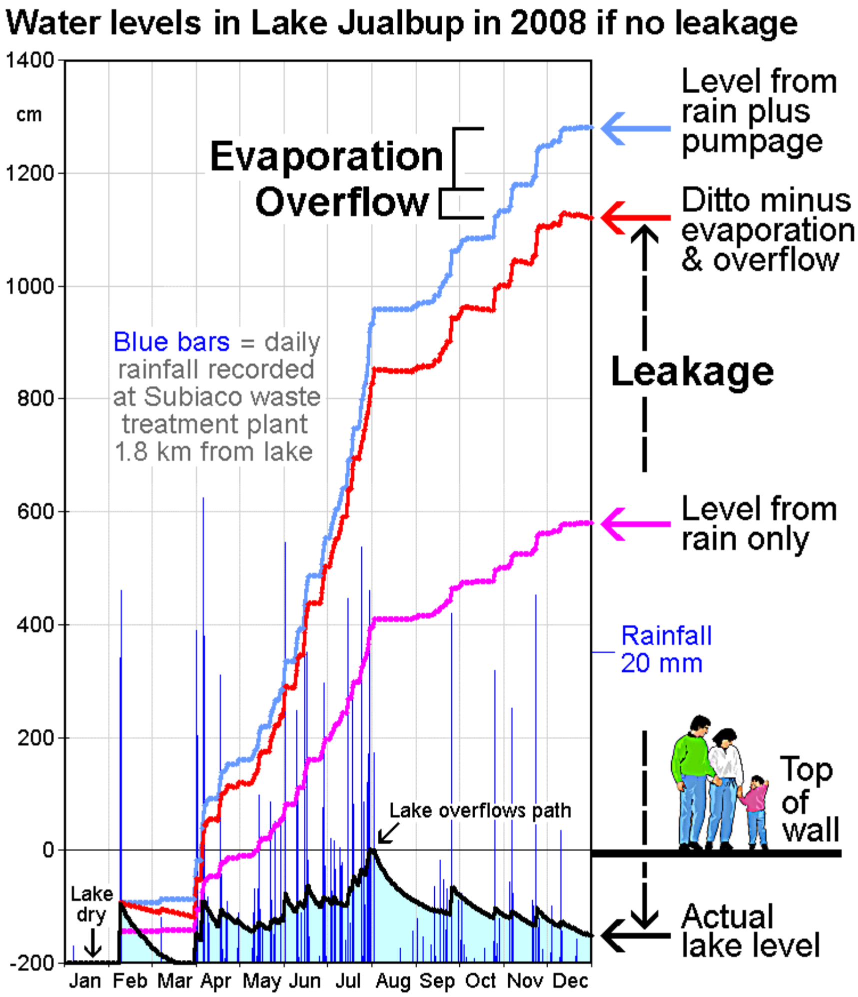
The secret life of water in Lake Jualbup

An illustrated digest of the available scientific information by Geoffrey Dean PhD DIC BSc ARCS, a local resident for over 20 years and formerly with the Soil Bureau, Wellington NZ, and CSIRO Soils Division, Perth. February 2012

April 2009. Road runoff from a storm discharges eastwards into a near-empty Lake Jualbup

Changes made for this 2011 update

I have corrected typos and any unclear figures. The new material includes (1) summaries of five more theses and commissioned reports, (2) more on evaporation and climate change, (3) actual versus predicted lake levels from 2005 to 2011, (4) levels during a 100-year event. The changes incorporate helpful comments from Dr Roger Passmore, principal hydrologist, Rockwater Pty Ltd, and Dr Don McFarlane, hydrogeologist, CSIRO. The pictures of the 2010 hailstorm that were included in the 2010 update now appear in the 2011 update of my *A chronological history of Lake Jualbup*.



Lake Jualbup in Shenton Park is a holding pond for road runoff that would otherwise overwhelm the road drains.

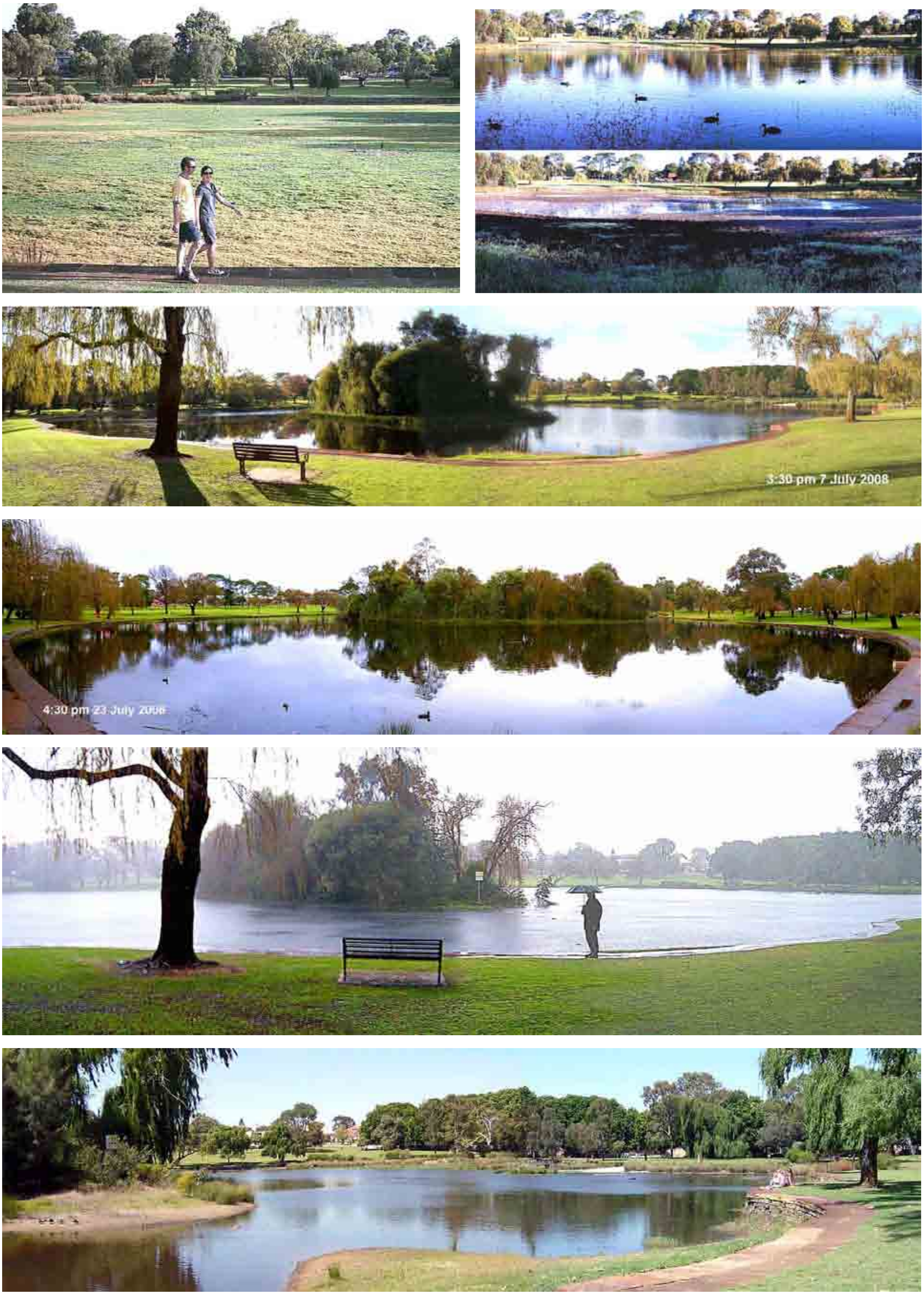
It receives runoff from roads in Shenton Park and southern Subiaco, and from the QEII hospital site. The QEII runoff is called *pumpage* because it is pumped from the holding pond at Aberdare Road.

The total runoff received each year is enormous – enough to fill the lake 8 times. So why does Lake Jualbup dry up?

If there were no leakage and no overflowing past the lake boundary, the water levels in 2008 would be roughly as shown opposite. The culprit is leakage, not evaporation.

But leakage tends to be a neglected topic in the official reports to date. So I have been measuring it almost every day for over 4 years.

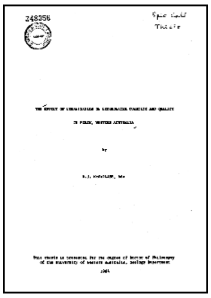
In what follows I bring together my results and a summary of previous scientific work on the lake.



Lake Jualbup during 2008: Top left, January 2008, lake is dry and overrun with weeds. Top right, February, half full after heavy rain, then becoming dry again in March. Middle two, July. Second from bottom, overflowing in August. Bottom, early December, 20 cm deep over causeway.

Previous studies

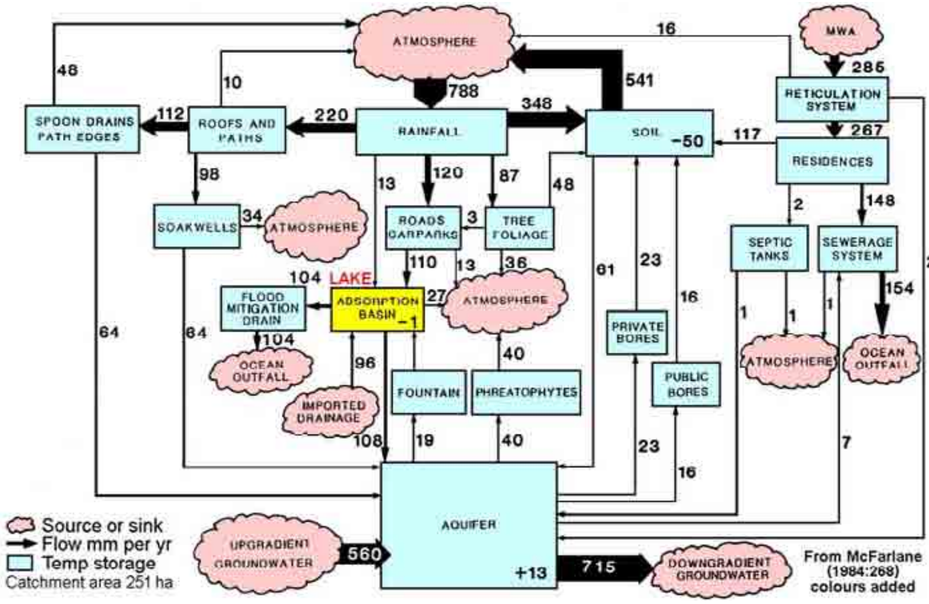
Don McFarlane's pioneering study of Lake Jualbup 1981-1982



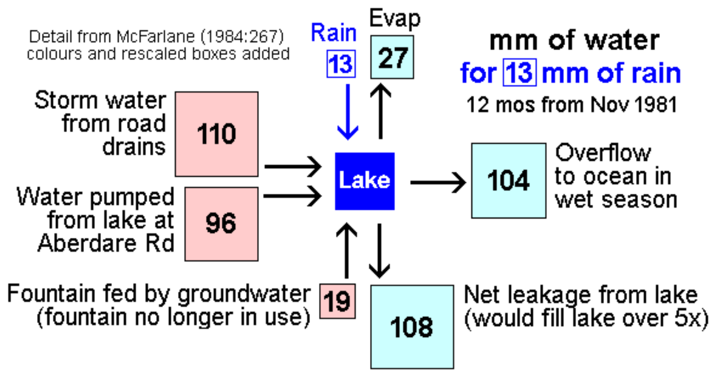
DJ McFarlane. *The Effect of Urbanization on Groundwater Quantity and Quality in Perth, Western Australia.* PhD thesis, University of Western Australia, Geology Department, 433 pp, 1984. One of the two external supervisors was Rockwater's Dr AD Allen, now retired.

The subject of this massive thesis (over 50 mm of A4) is Shenton Park Lake, now Lake Jualbup, and the lake one-eighth the size of Lake Jualbup at Mason Gardens in Dalkeith. They were chosen because the former is surrounded by small blocks with few bores, the latter by large blocks and many bores. The two lakes were studied from April 1981 through November 1982, a total of 86 weeks.

McFarlane looks in detail at where the water goes after it falls on each lake's catchment area, and its quality. His measurements include lake levels, rainfall, pumpage, drainage, evaporation, water table levels, catchment areas, lake size, lake bed composition, stormwater and groundwater quality, and the effect of roads, houses, lawns, trees, and bores. His results for the Lake Jualbup catchment area for twelve months from November 1981 are shown in the diagram below (which has been updated):

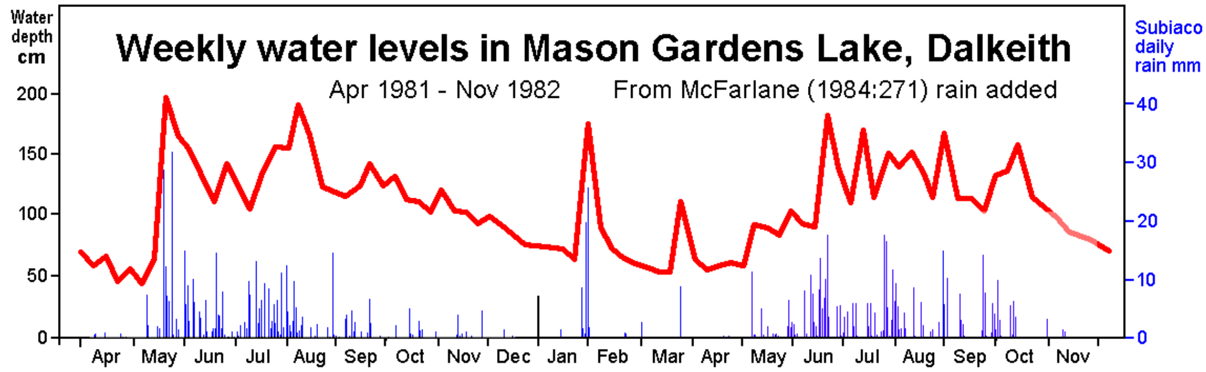


Above, start at the top. Of the 788 mm of rain falling on the catchment area, 348 end up in soil, 220 on roofs and paths, 120 on roads and car parks, and 87 on trees. Lake Jualbup (shown in yellow) gets 13 directly from rain, plus 110 as runoff from roads and car parks. Just below centre, *phreatophytes* represents the water transpired by catchment trees with roots that reach the water table or close to it. When the lake's water balance is extracted from the detail, it looks like this:



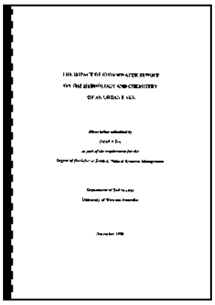
Above, for the 13 mm of rain (of the 788 falling on the catchment area) that fell directly on the lake in the twelve months from November 1981, twice as much (27) evaporated, and sixteen times as much (110 + 96) arrived via drainage and pumpage. Net leakage (108) was enough to fill more than five lakes. Other years will be different, but the above results give an idea of the likely scale.

Since the 1980s, Lake Jualbup's eastern end has changed, the fountain has disappeared, and the island has been enlarged. But McFarlane's findings still provide a good starting point, and I shall be quoting them often. Unfortunately his measurements of water level in Lake Jualbup were spoilt by equipment failure and vandalism, but at Mason Gardens they looked like this:



Above, comparing weekly water levels with daily rain involves some blurring. Nevertheless, as for Lake Jualbup on page 1, the link between rainfall and water level is readily apparent. The level rises with each rain and then falls due to leakage and evaporation.

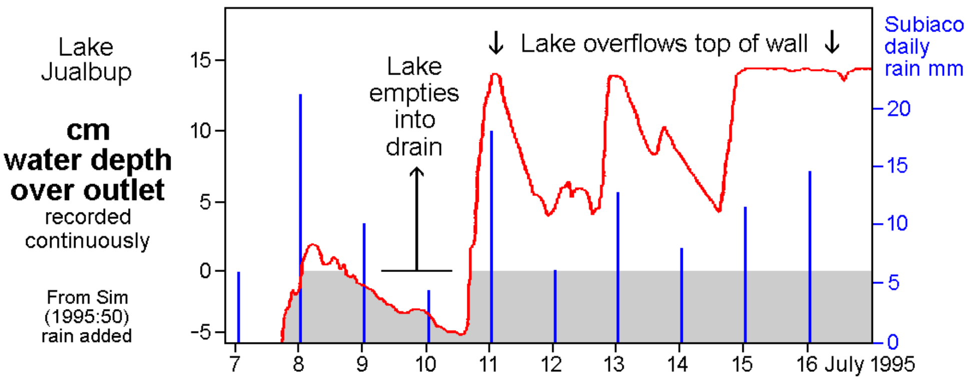
David Sim's follow-up study 1995



DA Sim. *The Impact of Stormwater Runoff on the Hydrology and Chemistry of an Urban Lake.* BSc Dissertation, University of Western Australia, Department of Soil Science. 97 pp, 1995.

The "urban lake" is Lake Jualbup. During July and August 1995 when the lake was often overflowing, the author monitored water quality, lake level, pumpage, drainage, and water-table levels next to the lake. His computer analysis confirmed McFarlane's findings and disentangled the leakages into and out of the lake, for which McFarlane's own measurements were insufficient. The stormwater was low in contaminants and had no adverse effects on the groundwater.

Sim reports the following interesting changes in lake level when the lake was overflowing into the outlet drain that eventually runs into the ocean (see diagram on page 11 and picture on page 19):



Above, when the lake water rises above the level of the outlet drain, water overflows into the drain. The rate of decrease in lake level then immediately increases (look at the slope), here to about 15 cm per day. Stormwater runoff from roads reaches the lake within minutes, which means that any variations in rainfall intensity readily show up as peaks and troughs in the lake level.

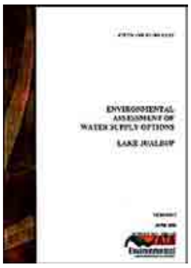
The findings of McFarlane and Sim answer almost any question about the behaviour of water in Lake Jualbup. In addition, in response to the controversy about the removal of the eastern wall in 2001, the City of Subiaco commissioned no less than eight reports on Lake Jualbup during 2005-2008 totalling 330 pages at a cost of $111,580. So the amount of scientific information about Lake Jualbup is now extensive. My summaries of these and later reports occupy the next four pages.

Commissioned reports on Lake Jualbup 2005-2008

Rockwater, *Hydrogeology of Lake Jualbup, Shenton Park, and options for maintaining lake levels.* January 2005. By Dr AD Allen Principal Hydrogeologist. 44 pp for $10,000

Dr Allen was one of the two external supervisors for Don McFarlane's PhD thesis on Lake Jualbup, and his report reflects the intimate knowledge thus obtained, But for some reason he reports the thesis date as 1983 when it should be 1984, a mistake repeated by every later commissioned report that cites McFarlane, which suggests that they are citing his work without actually consulting it.

Lake Jualbup was once a swamp. Now a holding pond for stormwater. Groundwater moving south from Gnangara Mound towards Swan River seeps in along the lake's northern side and out along the southern side. Options for maintaining lake levels are: (1) Add groundwater from bores. (2) Inject grout along southern side to reduce outflow. (3) Add groundwater via vegetated waterbird ponds built of concrete on northern lawn area. (4) Raise walls one metre to increase winter storage, top-dress lake bed with 100 mm of sand and eg bentonite to decrease outflow. (5) Excavate lake bed to below summer water table. Feasibility of each option is unknown and needs to be determined.



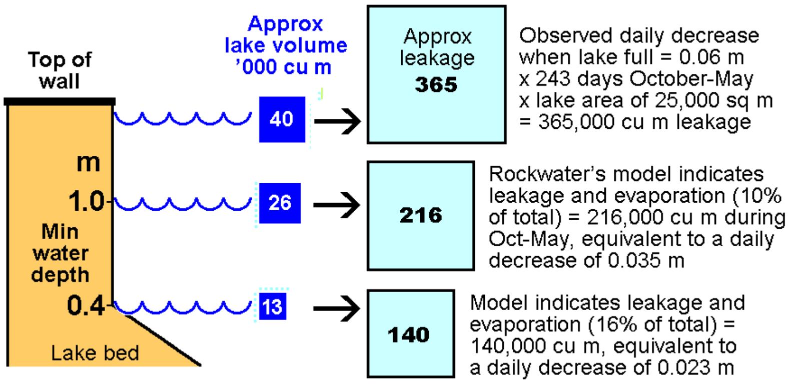
ATA Environmental. *Environmental Improvement Assessment – Stage 1, Lake Jualbup, Shenton Park.* February 2005. By G Martinez, H Van der Wiele. 27 pp for $10,680.

Assesses the environmental effects of removing the eastern wall of Lake Jualbup in 2001 and the planting of reeds, sedges and other natives on the resulting sloping bank. The effects are generally acceptable except on the island where foreign species such as willows could be replaced with natives, at the eastern end (needs more reeds and sedges), and around the lake edge (paperbarks could be planted).

Rockwater. *Water Requirements for maintaining lake level, Lake Jualbup, Shenton Park.* August 2005. By PH Wharton Principal Hydrogeologist. 13 pp for $14,500 (here the costliest page rate)

Unlike the briefly acknowledged work of McFarlane and Sim, who quantified the effects of rain and leakage on lake levels, the aim here is to estimate via a computer model how much water is needed during summer to keep the lake level with the base of the wall (minimum depth 0.4 m) and also slightly deeper (minimum depth 1.0 m). This is east of the island. Depths west of the island are about 1 m deeper.

The computer model was based on known or estimated values of water table levels, rainfall, evaporation, and lake bed permeability. The model was adjusted until the calculated decrease in lake level agreed with decrease of 0.06 m per day observed in May and June 2005 after heavy rain had filled the lake. I have summarised the results in the diagram below.



Above, the first result is calculated by me using the data shown. The other two results are from the computer model. The first result is for a wet winter and is therefore not strictly comparable with the computer model results for a dry summer. Nevertheless in each case the leakage is enough to fill the lake 8-10 times. The author stresses that his results are approximate since based on limited data.

The above computer results show that huge amounts of water are needed to keep the lake at the summer levels indicated – enough to fill about 60 or 90 Olympic pools respectively. In other words topping up the lake is like topping up a sieve. Reducing leakage was not in the report's brief.

Lake Jualbup resembles a postage stamp

One point not readily apparent in any of the reports is the extreme shallowness of the lake when compared to its area of roughly 160 x 230 metres at high water. Water one metre deep spread over such an area makes its cross section similar to that of a postage stamp.

Above, a decrease in lake level quickly reveals weeds and reeds to remind us how thin the water layer is, and how large the area is through which it can leak.

Ecoscape (Australia). *Lake Jualbup, Shenton Park, Proposal for Consulting Services.* April 2006. By D Kaesehagen, N Markham, P Hillman. 46 pp for $12,140.

Presents proposals for three educational features linked to Lake Jualbup. The features explain the water cycle (estimated cost $90k), water table ($75k), and water gauge ($75k). The diagrams and photographs in the website version are numerous but of very poor quality, so the reader is generally left none the wiser. Includes a schedule of hourly charges: $35-$60 junior, $90-$120 senior.

GHD (civil engineering, mining and environmental consultants)**.** *Lake Jualbup Water Source Investigation.* June 2006. By G Tandle, I Munir, R Connolly (see last page). 41 pp for $14,500.

Feasible water sources for topping-up lake are: (1) Treated waste water from the Subiaco Waste Water Treatment Plant. (2) Stormwater from the Herdsman main drain. In each case the capital costs approach $1m. Topping-up with groundwater is not feasible because groundwater is already fully allocated.

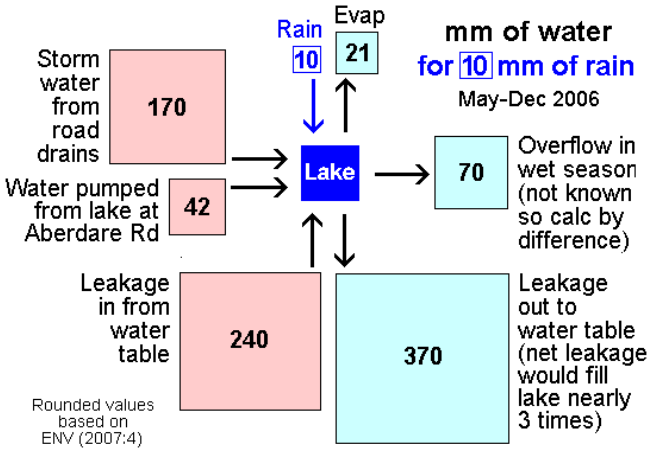
ATA Environmental. *Environmental Assessment of Water Supply Options Lake Jualbup.* June 2006. By K Hunt, B Van der Wiele, H Van der Wiele. 34 pp for $4830

Looks at the environmental impact of the GHD options. Conclusion: Treated waste water needs further treatment to achieve acceptable quality. The amount available from Herdsman main drain is unknown. Recharging groundwater (by whatever means) during winter may be better than topping-up the lake in summer.

ENV Australia. *Feasibility Study for Maintenance of Permanent Water in Lake Jualbup.* September 2007. By M Dunlop, B Woodward, K Lane, D Newsome. 121 pp for $39,930.

Looks at fifteen options for keeping the lake full in summer. Ten top up with water from various sources. Five conserve water by raising the walls, lowering the lake bed, or preventing leakage by treating part or all of the lake bed. The authors prefer topping-up with groundwater even though unlikely to be allowed. They reject leakage prevention because it might reduce water quality. *Continued next page.*

ENV's authors include a water balance for May-December 2006 based in part on Rockwater's computer results, which I have rescaled below in the same format as for McFarlane:.



Above, look at the bottom two boxes. Here the authors show not just the leakage out but also the leakage in, which happens when the water table is higher than the lake level. The net leakage out during May-October would fill the lake nearly three times, which is comparable with the earlier result of more-than-four-times found by McFarlane during the 12 months from May 1981

But overall the above water balance is not plausible. The authors state that evaporation was calculated using Penman's equation, which seems unlikely since it would require daily measurement of wind speed and saturation vapour pressures, all two metres above the lake surface. They assumed January-April 2006 was mostly dry, but according to records kept by the Subiaco Waste Water Treatment Plant (the official weather station nearest Lake Jualbup) it provided one-third of the year's rainfall. The wet season overflow (62,000 cu metres) was assumed to be the difference between estimated inputs and estimated outputs, but the 2006 rainfall was only 445 mm, 38% below average, and the lake never actually overflowed, certainly not for the 3-4 weeks that would be consistent with their figure. If nothing else an error rate of 100% illustrates the caution needed when confronted by recommendations based on bold estimates in lieu of actual observations, especially as their fragility may be unsuspected when blinded by what they cost

At the end of 2007 the above report was released for public comment. The result was two petitions against its terms of reference or its recommendations, and 42 individual responses from ratepayers, perhaps an indication that the lake is more about community issues than environmental issues. The City of Subiaco sent the petitions and responses to ENV's senior author for assessment. The results appeared in a report dated 27 February 2007 (should have been 2008) appended to the Subiaco Council minutes of 22 April 2008. My summary is as follows:

ENV Australia. *Technical Response to Comments on the Lake Jualbup Feasibility Study.* By Margaret Dunlop, Senior Environmental Engineer. February 2008. 6 pp for $5000

There were 42 responses. *Go for permanent water?* Yes 25, No let it dry up 14. *Reduce leakage?* Yes 7, No 2, Investigate further 4. *Preferred vegetation?* Native 6, Existing 4. *The effect on wildlife of the lake drying up is . . . ?* Bad 7, Good 1. The two petitions of 50 and 362 signatures were respectively in favour of permanent water or for obtaining more information on leakage prevention.

This concludes my original survey of previous scientific studies and commissioned reports on Lake Jualbup. Since then two relevant Rockwater reports have appeared, one on soakwells for the Subiaco catchment and the other for the Town of Vincent on the hydrogeology of Hyde Park Lakes, with options for restoring permanent water. Dr Don McFarlane kindly alerted me to two previously missed PhD theses, and to other relevant reference material. These new theses and reports are summarised on the next page (note the temporary change in pagination, which resumes at page 8).

Further theses and reports (new to this update)

JF Rich. *Integrated Mass, Solute, Isotopic and Thermal Balances of a Coastal Wetland.* PhD thesis, Murdoch University, Division of Environmental Science, 765 pp, 2004. Available online 46 Mb.

The "coastal wetland" is Perry Lakes. The various balances allow groundwater components to be quantified very accurately. What has happened to these lakes is illustrative for Lake Jualbup. Especially useful are the accurate determination of conversion factors to correct Perth airport evaporation data to lake evaporation, and hydraulic conductivity measurements of the lake bed and surrounding areas.

SL McHugh. *Holocene Palaeohydrology of Swan Coastal Plain Lakes, Southwestern Australia: A Multi-Proxy Approach Using Lithostratigraphy, Diatom Analysis and Groundwater Modelling.* PhD thesis, University of Western Australia, School of Earth and Geographical Sciences, 387 pp, 2004.

Reconstructs the hydrology of Lakes Gnangara, Jandabup and Mariginiup over the past 25,000 years. Shows how the decline in water levels since the 1970s, and now an annual drying up of the lakes, has led to acidification of the lake waters (pH as low as 3) and production of acid sulphate soils. Relevant to a dry Lake Jualbup.

Rockwater. *The Hydrogeology of Hyde Park Lakes, Town of Vincent, Perth,* February 2006 for the Town of Vincent, by Dr AD Allen Principal Hydrogeologist, 60 pp. Not available online, my copy was kindly provided by Jeremy van den Bok, Manager Parks & Property Services, Town of Vincent.

Hyde Park lakes are closely similar to Lake Jualbup in history, design, iconic status, Aboriginal significance, use as a holding pond for road runoff, and drying up in summer. The report includes options for restoring permanent water. Restoration has been officially adopted in response to community views. For more see next page.

Rockwater. *Hydrogeological Evaluation to Guide Stormwater Management Principles in the City of Subiaco,* July 2009 for the City of Subiaco, by Dr JR Passmore Principal Hydrogeologist, 50 pp.

Installing (more) soakwells in the drainage system would send runoff back to the groundwater instead of sending it to the ocean, and would raise groundwater levels by 13-22 cm. Installation in the drainage feeding Lake Jualbup is not needed since the lake already acts as a giant soakwell. The report includes height measurements for the footpath and lake bed that allow improved estimates of lake depth when full.

Town of Cambridge. *Perry Lakes Groundwater Management Project.* Undated brochure c.2008.

The Town of Cambridge, with the Water Corporation and CSIRO, have proposed using treated wastewater to maintain groundwater levels and thereby raise the level of water in the now-dry-in-summer Perry Lakes by about one metre over time. The design is unusual – treated wastewater will not go directly into the lakes but into an underground trench to block the downhill flow of groundwater, which will then back up into the lakes. This diagram from the brochure shows how it will work:

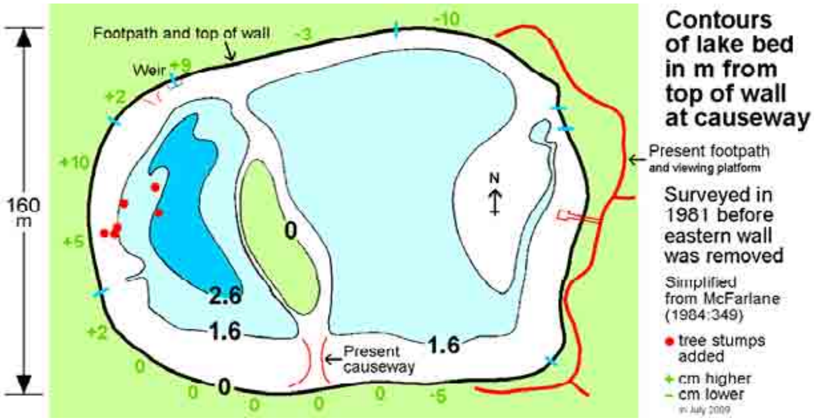
A series of underground trenches will be placed near the lakes and filled with 2% of the treated wastewater from the Subiaco Waste Water Treatment Plant. Modelling by CSIRO has shown that the trenches will block the flow of groundwater towards the sea, thus causing it to back up into the lakes and eventually areas beyond. Despite these advantages the Town of Cambridge eventually voted to not go ahead.

Rockwater. *Review of Lake Jualbup Evaluations*, January 2012 for the Save Our Jewel group, by Dr JR Passmore Principal Hydrogeologist, 15 pp.

Gives a general thumbs up to the hydrology in this report and the Save Our Jewel proposals for restoring Lake Jualbup (www.saveourjewel.org) but questions the extent to which grassed areas could soak up flood water. This point is modelled to Rockwater's very conservative specification on pages 40-44 of this update, which replace the text on the outlet drain that appeared on the previous page 41.

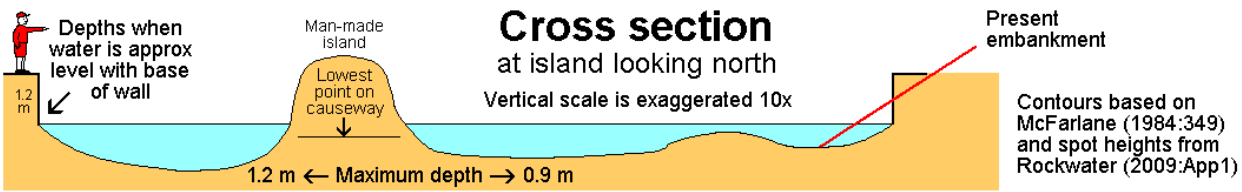
Lake Jualbup area and volume

To determine the water balance for Lake Jualbup, McFarlane (1984) needed to know how much water the lake contained. So in 1981 he surveyed the lake bed using standard surveying equipment sensitive to at least 1 cm in height across the width of the lake. In 1977 the reed beds next to the perimeter wall had been removed, so he had free access to all parts of the lake, reaching the deeper parts by boat. His map of the lake bed shows contours at intervals of 0.5 metres above Australian Height Datum (AHD), mean sea level in 1966-1968. To make the contours easier to follow, I have converted them below to metres from top of wall, and have included only the more useful ones:



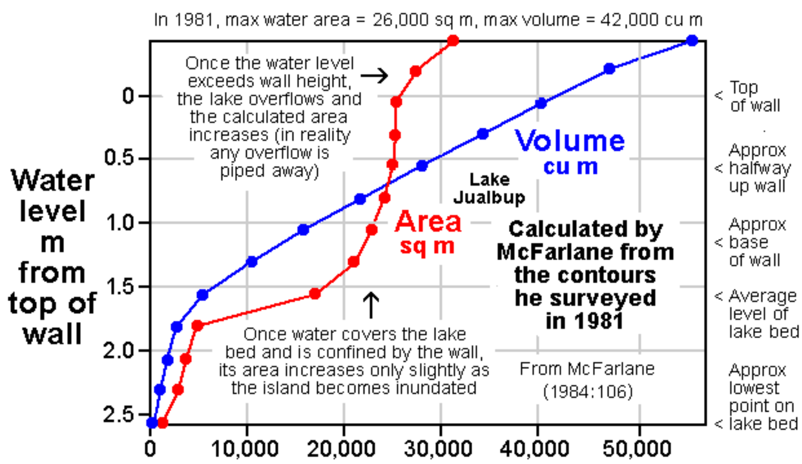
Above left, the tree stumps and 160 m distance are as surveyed by me with a 50-m surveying tape. One circuit of the present footpath is about 697 m around a lake roughly 160 x 230 m at high water. Average footpath height (shown in green relative to height at causeway) is uneven and can vary by ± 10 cm. **Right**, but along the southern side as here at causeway it is generally level within ± 1 cm.

The lake is very shallow for its width, and in cross section it is very similar to a postage stamp:



Above, even when the vertical scale is exaggerated ten times as here, the thinness of the water layer is still evident. Compared to its volume, the area through which water can leak is extremely large.

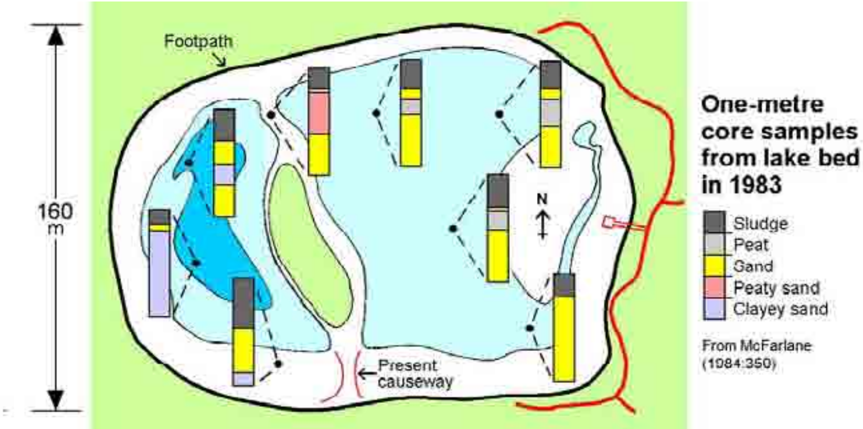
When his survey was complete, McFarlane was able to calculate the area and volume of the lake for various depths of water, with the following results:



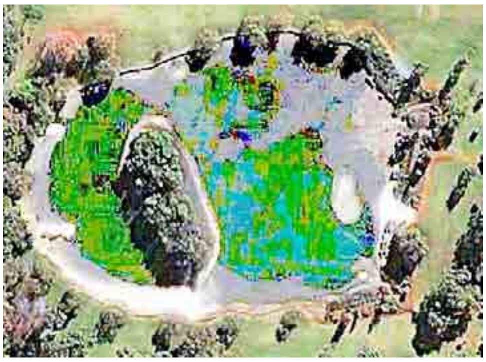
Above, in 1977 and 1986 the lake bed was dredged to remove accumulated silt (uniform removal of 10 cm would increase the maximum volume by about 6%), and in 2001 the eastern wall was replaced by a sloping embankment (which increased the area when full by about 3% but with little effect on the volume). Nevertheless McFarlane's calculations remain our best starting point.

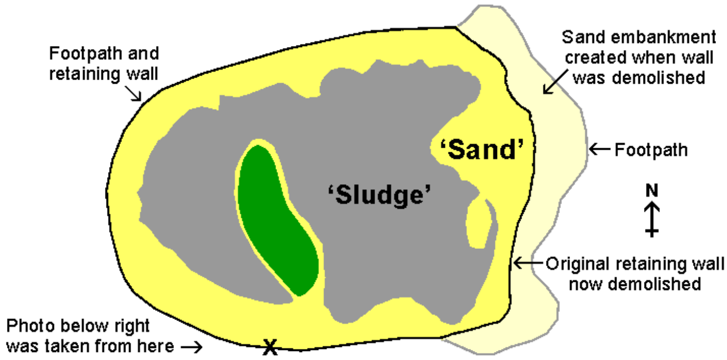
Composition of the lake bed

McFarlane (1984) took one-metre core samples from the lake bed, with the following results:



The edges of the lake were mostly sand while the central parts were mostly sand covered by about 30 cm of sludge rich in organic matter, typical of the sludge that accumulates at the bottom of lakes. Unlike the eastern basin, the deeper western basin tends to be slightly clayey under the sludge, and should therefore be slightly less permeable to leakage. In general terms the surface of the lake bed can be divided into 'sand' and 'sludge' as shown below on the right:





Above left is from Google Earth taken in 2008 and manipulated to emphasise the difference between sand (grey) and sludge (green) lake areas. **Right**, it broadly confirms the 1983 survey results, which suggests that the silt dredged in 1986 has largely returned.

Rockwater's (2005:4) model of the lake matched observations when the lake bed permeability K was about 4 to 6 cm per day, equivalent to silty sand (see table on page 26) in agreement with the above. When dry the sand and sludge areas are easily distinguished as shown in the pictures below.

Above, a week after surface water has disappeared. **Right**, the sand areas tend to be either visibly sandy as on the left or covered in weeds as on the right, and the sludge areas tend to be dark grey, bare and damp, although a week after becoming dry they too become covered in weeds. **Left,** when dry the sludge areas show cracking typical of a clay soil, but the clay content is low – when wetted the clumps are crumbly and (unlike potter's clay) impossible to shape.

When dry the grey clumps are remarkably firm and brick-like, but when wet they are transformed into dark black mud that is remarkably slippery, adherent, and difficult to wash off.

Above, side view of three clumps, two dry and one wet. The white bands are salt residues left when the last surface water evaporates. The middle sample is fragile and swollen by water.

Above, the exposed mud is deepest in the western basin. **Left,** near the edge it is generally ankle deep with knee-deep pockets (photo by Mark Wilshusen). **Right,** a long-necked turtle burying itself in the mud in order to survive the lake drying up. The presence of so much mud makes it difficult to say exactly where the lake bed is, so the previous lake bed contours can only be approximate.

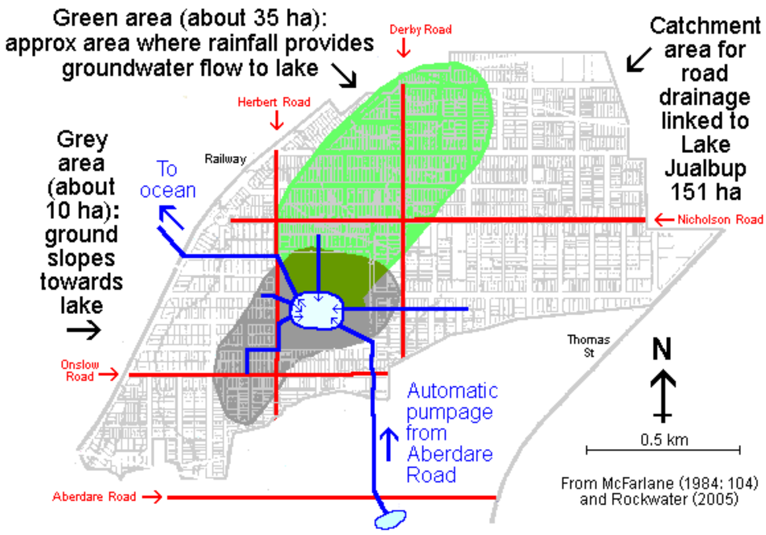
Above, when the last surface water has disappeared and only dampish mud remains, it means that the surrounding water table has fallen below the level of the lake bed. Although you cannot see it, it is still there, as a small excavation (here 20 cm deep) will quickly reveal.

McFarlane (1984:128) notes that the presence of sludge and silt on the lake bed helps to reduce leakage below that produced by sand (see the table on page 26 where silt is midway in permeability between sand and clay). This means that dredging the lake bed to remove accumulated silt, or replacing the walls with sloping sand embankments, must inevitably increase leakage.

Above, when the last surface water has disappeared, the weeds take over

Lake Jualbup catchment area

The catchment is the area from which all road drainage goes to Lake Jualbup. From drainage maps supplied by local and metro authorities, McFarlane (1984) identified the catchment area and the drains going into and out of the lake, which he verified by inspection of the lake's edge. Later Sim (1995:40).identified updates since 1981, but these require no change to McFarlane's map below:



Above, before white settlement the only runoff (as opposed to seepage) reaching the lake was from the surrounding slopes shown in dark grey. Today runoff comes from an area about fifteen times larger, or twice this if the Aberdare Road catchment area is included, see below.

By tediously counting from aerial photographs, McFarlane (1984:88) estimated the catchment to consist of *roofs and paths* 28.0%, *roads and car parks* 13.1%, *trees and large bushes* 11.0%, *small bushes, lawns and bard ground* 46.3%, *free water surfaces including Lake Jualbup* 1.6%. But the measured runoff was more than these figures allowed (p.111), suggesting that overhanging trees had lowered the first two values, which he estimated might be more like 30% and 16%.

Pumpage is the water pumped into Lake Jualbup from the lake at Aberdare Road, identified on some maps as Kilgor Park lake, which like Lake Jualbup is a holding pond for road runoff. The lake is at the same level as Lake Jualbup but has no outlet, so pumpage is essential to prevent flooding (it has nothing to do with trying to top up Lake Jualbup). Pumpage is triggered automatically by lake level, so it is not necessarily related to the amount of rain that triggers it. Also, when the water table is high, the pumps may switch on automatically for a short time to accommodate incoming seepage regardless of any rainfall. They may also be run during maintenance checks.

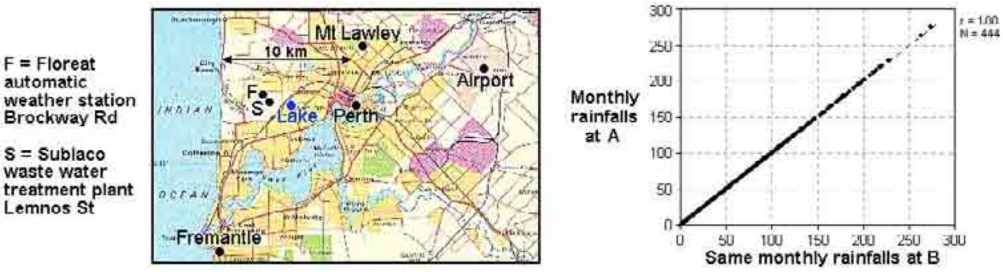
Pumpage volume

The lake at Aberdare Road receives all runoff from the QEII catchment area, which is about 139 ha (Sim 1995:41), slightly less than the Lake Jualbup catchment area of 151 ha (Rockwater 2005:12). But it has roughly 50% more shedding area such as roads and car parks, so it delivers about a third more runoff, all of which (minus leakage and evaporation) eventually goes to Lake Jualbup.

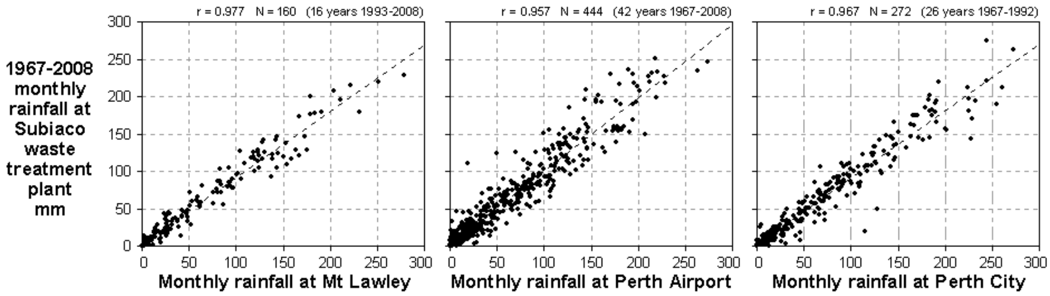
Today the Water Authority records pumpage times only monthly or quarterly, depending on season, but in the 1980s they were recorded weekly. This allowed McFarlane (1984:353-354) to compare the weekly runoff into Lake Jualbup with the weekly pumpage from Aberdare Road. From April 1981 through November 1982 (86 weeks, roughly two winters and one summer) the total pumpage was 88% of the total runoff, which is consistent with the respective catchment areas. Pumpage occurred in 45% of the 86 weeks, and on average raised the lake level by 18 cm, range 0.1 cm - 59 cm. Only on three occasions did the accumulated rain exceed 30 mm without triggering pumpage. In weeks with more than 5 mm of rain, pumpage varied from 0 to 2.5 times the runoff, average 0.9 times, Development of the QEII site since the 1980s may have increased these proportions.

Rainfall

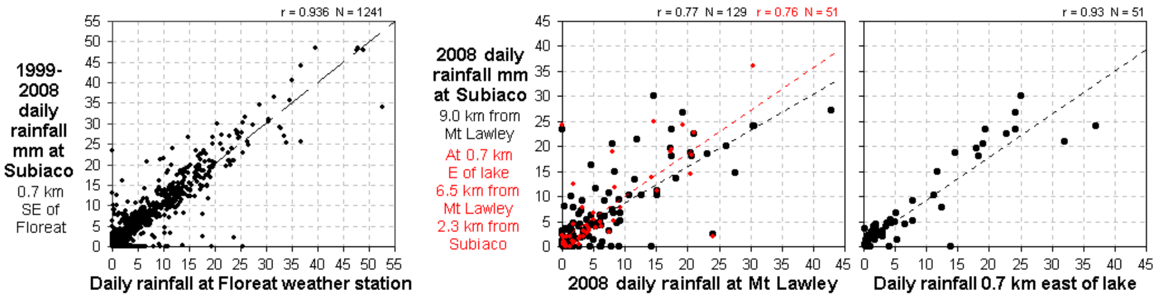
Even within the Perth area, rainfall varies with location due to: (1) The finite size of rain clouds, which is why one suburb can be drenched while another stays dry. (2) The Darling scarp, which causes a marked increase in rainfall from the coastal plain to the higher land. To see how it works, consider the locations on the map below. If say 444 monthly rainfalls (37 yearsworth) at A and B were exactly the same, plotting A vs B should give the result shown on the right:



But in fact local variations produce much scatter as shown by the plots below. The Subiaco plant is the official weather station closest to Lake Jualbup, being only 1.7 km away. It records only rainfall.



The plots above are for monthly rainfalls. The scatter for daily rainfalls is even worse:



Above left, the scatter for ten years of daily rainfalls at Subiaco vs those at the automatic Floreat weather station is marked even though they are only 0.5 km apart. Indeed either can record over 20 mm while the other records nothing. **Middle,** daily rainfalls between Subiaco and Mt Lawley show more scatter than monthly rainfalls. **Right,** reducing the distance apart can help.

If we look at the average difference between stations for daily rains of 5 mm and 20 mm, and compare them with the (very few) published studies of scatter, we get these interesting results:

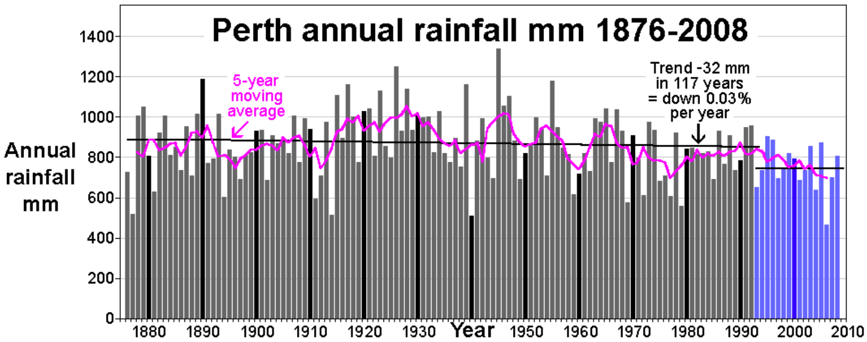
Location	No of stations	Mo of years	Av dist apart	No of rains	Av diff for rains = 5 mm	= 20 mm
New Zealand	41	2	50-100 m	102	rain/11	rain/15
Subiaco-Floreat	2	10	0.5 km	1241	rain/3	rain/5
Ohio USA	55	1	3-4 km	68	rain/2	rain/4
Subiaco-MtLawley	2	1	9 km	130	rain/1.5	rain/2

New Zealand = Jackson & Aldridge (1972). Ohio = Linsley & Kohler (1951)

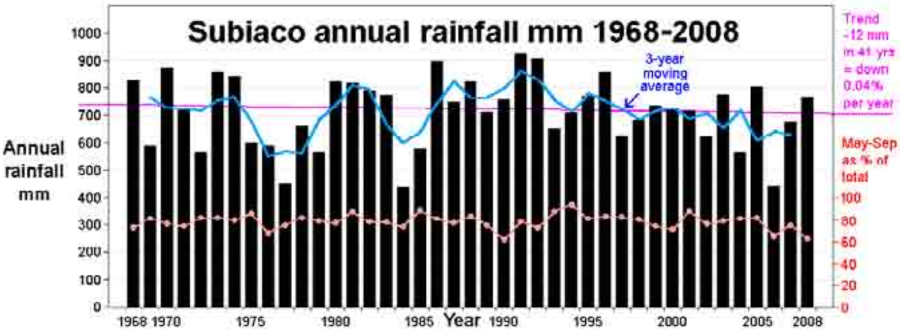
Above, as the distance between stations increases, the average difference between daily rains also increases. Wendy Swindell (1972) had Perth schools measure rainfall during 12-16 July 1971 when an average of 220 mm was recorded. The five schools closest to Lake Jualbup averaged 3.0 ± 1.0 km apart and the average difference in daily rain was a surprising 27 ± 13 mm (the period was too short to show a clear dependence on distance apart). The above results show that the rain falling on the Lake Jualbup catchment is unlikely to be exactly the same as at Subiaco or Floreat, and even less likely to be exactly the same as at Mt Lawley. Differences can of course arise due to human error and variations between gauges. But how important are they? Hutchinson (1969) estimated such differences for rainfalls up to 10 mm with twelve gauges 3-4 metres apart on an exposed 9 x 15 m site near Dunedin, and found an average difference equivalent to rain / 20. In addition, rain will not be accurately captured if the gauge is poorly located – the amount captured decreases with gauge height (typically by 10% at 2 metres) due to the increase in turbulent air flow. The gauge should not be closer to trees or buildings than at least half their height (HDR 2003).

Is annual rainfall decreasing in Subiaco?

Consider these official rainfall figures for Perth available from the Bureau of Meteorology:

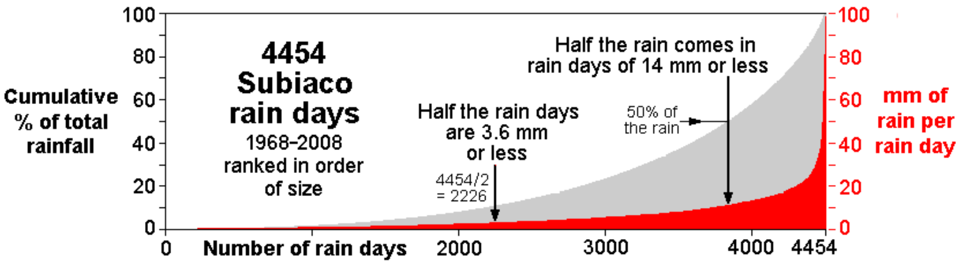


Above, it looks as if Perth's rainfall has shown a marked decline since 1993 (blue plot). But.in 1993 the recording station for Perth's rainfall moved from the city area to Mt Lawley. So what we are seeing is a change in location, not necessarily a change in rainfall. In fact Perth's rainfall in the 117 years to 1992 has declined on average only 0.04% per year. The same is true of Subiaco rainfall:



Above, Subiaco annual rainfall in the 41 years to 2008 has declined on average 0.03% per year. But this ignores important trends in climate (next page) and ground water (page 23).

How are Subiaco rainfalls distributed between light and heavy? If the 4454 Subiaco rain days recorded during 1968-2008 are ranked in order of size, the result looks like this:

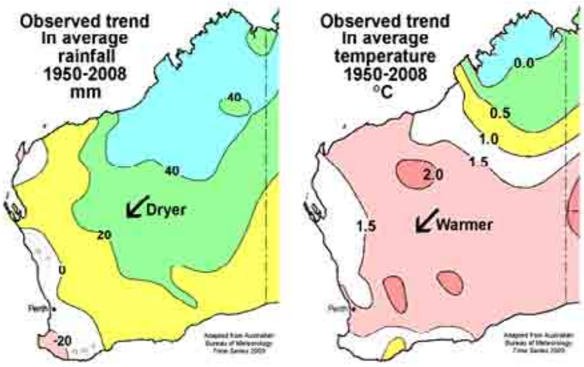


Above, there are many more light rains (nearly 500 are 0.5 mm or less) than heavy rains (just 100 are 30 mm or more). The proportion of rain from rainfalls up to any value on the red plot is shown by the value vertically above it on the grey plot. Half the rain comes in rainfalls of 14 mm or less.

Average monthly rainfall at Subiaco 1968-2008

	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
am	715	12	14	18	37	87	146	150	104	72	42	24	8
cv %	18	210	151	103	80	52	38	31	34	46	55	73	109
N	41	41	41	41	41	41	41	41	41	41	41	41	41

N = number of years. cv % = 100 x standard deviation (a measure of scatter)/average



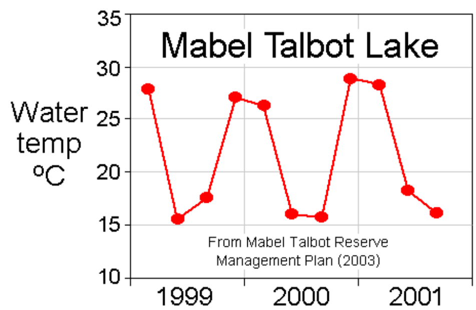
Left, the 0.03% annual decrease in Subiaco rainfall may be misleading because it reflects the amount, not the timing, which is just as important –useful falls in summer are becoming less frequent. Nor does it reflect the state-wide trends in rainfall and temperature shown opposite, where Perth and the SW are becoming drier and warmer, the opposite of that elsewhere in WA. Even if rainfall reverted to that of a century ago, it would take a long time to make good the backlog of lowered water tables.

Evaporation

Evaporation from open water in a lake is generally between 1 and 8 mm per day, depending on the weather, being highest on days that are sunny, windy, hot, and dry. In Lake Jualbup the losses due to leakage are about five times larger, so evaporation can almost be ignored. In 2008 the losses due to water overflowing to the ocean (see page 36) were even smaller than those due to evaporation.

Above, evaporation is made visible on calm frosty mornings when the evaporated moisture condenses as mist over the entire water surface.

The process is complex. Evaporation cools the water (which reduces evaporation), and is affected by the depth of mixing (which depends on lake conditions unrelated to weather), by turbidity (which creates a hot surface layer), and by any shade due to trees or vegetation. Reeds not only provide shade but also decrease mixing. At the dry edge of a lake, water close to the surface may evaporate as much as from open water, decreasing as it gets deeper. From a water table one metre below ground the evaporation may still be 50% of that from open water (Pollett et al 1979).

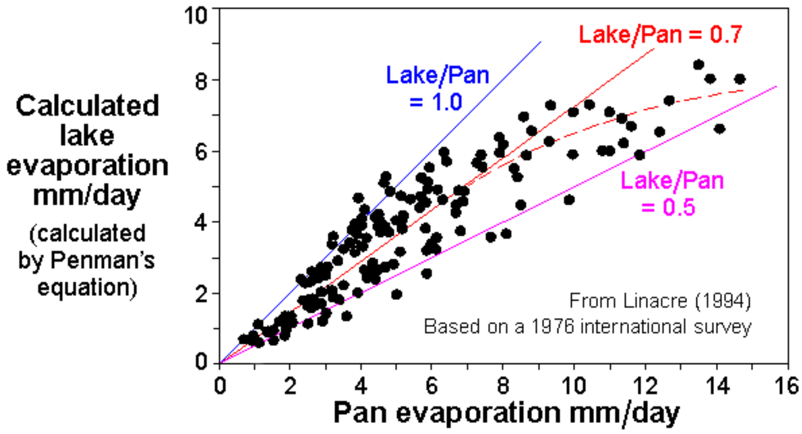


Above left, seasonal water temperatures at Mabel Talbot Lake generally vary between 16 and 28°C. My few measurements at Lake Jualbup indicate that the average water temperature is roughly the average of the prevailing maximum and minimum air temperatures. The day/night temperature 10-20 cm down was around 18/14°C in the deep water of winter and 35/25°C in the shallow water of summer. **Right,** the lake water stays much cooler among reeds than in the sun.

Many methods of calculation have been proposed, most of them requiring hard-to-get data such as vapour pressure and wind speed near the surface. So some workers have tried to predict evaporation from the only data routinely available, namely air temperature. For example Vining (2003) studied lakes in northern USA west of the Great Lakes and found that the monthly evaporation in cm was about half the average monthly temperature in Celsius. Here the use of monthly averages evens out the daily fluctuations. The correlation between calculated and observed evaporations was r = 0.80.

Pan evaporation

Perhaps the most obvious approach is to measure the evaporation from a large pan floating on the lake. But a floating pan is not easily accessible, measurement is difficult except in calm conditions, and the results can be uncertain due to the inward or outward wash of water (Wisler and Brater 1949:150) So lake evaporation is usually estimated from that of the nearest *Class A Pan Evaporimeter*, a galvanised pan 1.2 m in diameter, 25 cm deep, 15 cm above ground, and filled with water 20 cm deep. Ideally its evaporation should be the same as from a lake, but it is nearly always more due to the pan's greater exposure. Some comparisons are shown below:



Above, the lake-to-pan ratio varies from 0.5 to 1.0, with lower values being more likely when the pan evaporation exceeds 10 mm/day, as in hot dry weather The large scatter makes generalisation difficult, but 0.7 is commonly taken as a rule of thumb.

Estimating lake-to-pan ratios

As an alternative, Luke et al (1987) give estimated evaporation losses from WA dams based on

$$\text{Dam evaporation / pan evaporation} = 0.635\ \text{RH} + 0.000076\ \text{RF} + 0.474$$

which is said to give successful results for dams less than four metres deep. Here RH = average relative humidity at 3 pm and RF = average rainfall, both for the year or month. For 2008 at Mt Lawley, RH = 0.464 and RF = 808 mm, which gives average dam/pan = 0.83. For the winter months May-October the value is 0.84, and for the summer months November-April it is 0.75, both consistent with the above plot. However, there is no actual pan at Mt Lawley to which these figures could be applied, the nearest being at Perth airport 10 km to the east (which is also the pan nearest to Lake Jualbup 18 km west of Perth airport).

McFarlane (1984:45) reviewed the available evaporation data for the Perth area (only three sites were available including Perth airport) and concluded that evaporation at Perth airport was about 18% higher than in central Perth 10 km to the west, consistent with the later arrival of the sea breeze. Subsequently Rich (2004:Ch10) compared evaporation at Perth airport during 1997 with evaporation from a floating pan at Perry Lakes. Consistent with the previous findings, the lake-to-pan ratios were lower in summer and higher in winter, as follows:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
.54	.48	.54	.56	.66	.71	.69	.81	.86	.78	.74	.67	.67

The average of 0.67 is close to the rule-of-thumb 0.7, which overestimates evaporation in summer and underestimates it in winter. Putting Lake Jualbup evaporation = Rich's ratios x Perth airport, the period Nov 2007 to Apr 2009 gave the following average lake evaporations in mm per day:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
5.6	4.5	4.1	2.7	1.8	1.6	1.3	2.5	3.1	4.1	5.2	5.6	3.5

Errors hardly matter because leakage is so much larger than evaporation.

Predicting daily pan evaporation at Perth airport

How well does pan evaporation at Perth airport correlate with other weather variables? To find out, I correlated the main variables with each other for November 2007 through April 2009 (546 days).

The results looked like this (evaporation and sunshine from Perth airport, rest from Mt Lawley):

	Min	Max	Rain	***Evap***	Sun	AvRH	AvWS
Minimum temperature degC	1.00	.72	-06	***.74***	.19	-24	.33
Maximum temperature degC	.72	1.00	-28	***.77***	.51	-64	.14
Rain at Mt Lawley mm	-06	-28	1.00	***-26***	-29	.36	-05
Pan evaporation mm	***.74***	***.77***	***-26***	***1.00***	***.46***	***-57***	***.36***
Sunshine hours	.19	.51	-29	***.46***	1.00	-63	.25
Average Rel Humidity %	-24	-64	.36	***-57***	-63	1.00	-30
Average Wind speed kph	.33	.14	-05	***.36***	.25	-30	1.00

A correlation (denoted by r) is a number between 0 and ±1, where r = 1 is perfect correlation as between cm and inches or between any data and itself, and r = 0 is zero correlation as between tossing coins. Negative values indicate an inverse correlation, as between day length and night length. Look at the correlations for evaporation, shown in bold. As expected, those vs rain and relative humidity are negative (more of each means less evaporation) but neither is high enough to be useful. The highest correlations are vs temperature. Contrary to expectation, minimum (0.74) is almost as high as maximum (0.77), and. the actual relationship is remarkably simple – pan evaporation in mm per day = min temp ºC / 2, which on average is accurate within 2 mm per day. So actual evaporation at Lake Jualbup in mm per day is roughly min temp ºC / 3 (where 3 = 2/0.7).

Transpiration

Water is lost from plants and trees when the stomata in their leaves open in daylight to allow carbon dioxide to enter and oxygen to leave (the reverse of breathing in animals). This loss of water is called transpiration. It ceases when the plant is dormant or (with rare exceptions) at night, It is generally less than evaporation from open water but is otherwise much the same, being highest on days that are sunny, windy, hot, and dry. But leakage is still the major player.

Above, compared with leakage, transpiration is even less important than evaporation. Here the lake edge may seem dry, but with water so close to the surface, it may evaporate as much as open water.

As with evaporation, many methods have been proposed for the calculation of transpiration, some of them just as accurate (if you have the hard-to-get data) as field observations. Otherwise it can be estimated from class A pan evaporation. For example, for well-watered crops in the Perth area during the growing season, losses due to transpiration can be estimated by multiplying the pan evaporation by the following factors (taken from Penman 1963:53,64 and adjusted to the Perth area via the grass reference crop 12 cm high as per Grayson et al 1996:27):

Orchards 0.45-0.65m, *various crops* 0.55-0.75, *grass 12 cm high* 0.70, *rice* 0.95, *papyrus* 1.00
*eg beans, maize, potatoes, small veg, tomatoes, wheat

The above factors show that crops lose less than open water. Even orchards and swamps of papyrus (a grasslike sedge 5 m high that grows in water up to 1 m deep) do not lose more water than an open water surface. The factors are reduced if the water supply is reduced, and are close to zero outside of the growing season or (with rare exceptions) at night. Of course the above estimates may not be good enough when accuracy is essential, as for cash crops under minimum irrigation.

On the above figures, vegetation growing in Lake Jualbup is unlikely to increase evaporation even in the growing season, and is more likely to reduce it by shading the water surface and reducing convective mixing. Interestingly, the grassed area surrounding Lake Jualbup is almost exactly the same as the maximum water area. Even with reduced watering (equivalent to a crop factor of say 0.3) transpiration from the grassed area will lose as much water as evaporation from the lake.

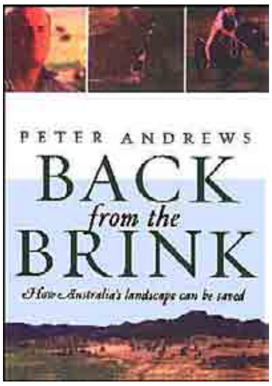
Willows

McFarlane (1984:127) measured the amount of water transpired by the three most common trees in the Lake Jualbup catchment area (Queensland Box *T.conferta,*, Peppermint *A.flexuosa*, and Willow *S.babylonica*), and by all other trees, and its variation with season. He found that the total loss of water due to transpiration by all trees in the catchment area was only 3.5% of the total loss by evaporation. During the summer months November-April the relative proportions of the water transpired were *Queensland Box* 17%, *Peppermint* 19%, *Willow* 16%, *all other trees* 48% (p.225).

Above, willows at the western end of Lake Jualbup in 2008. In 2001 the willows at the eastern end were removed together with the eastern part of the perimeter wall. One of the reasons for their removal was that their thirst for water was sucking the lake dry. But McFarlane's results show that this is offset by the willows' winter loss of leaves (and hence ability to transpire), see next picture.

Above, unlike most native trees, willows are without leaves in winter and transpire water only in the summer months. Field tests have shown that willows drop no more leaf litter than natives do.

Some people claim that any crusade against willows is short-sighted. In his best-selling book *Back from the Brink: How Australia's Landscape can be Saved* (ABC Books, Sydney 2006, reprinted nine times), Peter Andrews describes his lifetime of experience in reversing land damage caused by clearing, and in restoring water retention. He devotes two chapters to the advantages of willows. Although not directly relevant to lakes, his experiences are worth noting. Here is my summary:



During much of the year, willows consume very little water while shading the surroundings, thus preventing evaporation and encouraging organisms that break down organic matter. So instead of natives (which use photosynthesis to be a net producer of organic matter), the area becomes a net consumer, thus improving water quality. Willows and natives produce more biodiversity than natives alone. They also grow in areas where natives won't – and even if natives do grow, it could be 15-20 years before they provide the protection that willows do. Field tests have shown that willows drop no more leaf litter than natives do. Willows have a useful weakness, being less well adapted than native trees to Australian conditions, and natives will usually take over from willows once natural conditions are restored.

His methods have been so successful that he was persuaded to write a sequel *Beyond the Brink: Peter Andrews' radical vision for a sustainable Australian landscape.* ABC Books 2008. A copy is available at Subiaco Library. His methods were featured on ABC's *Australian Story* in July 2009.

Above, the lawns and willows were planted around the newly-bulldozed lake in 1957.

Recap so far

Lake Jualbup is not a natural lake. It is a holding pond for stormwater, which in the wet season it receives in unnaturally huge amounts. Most of the water in the lake is lost by leakage, with only 12-15% being lost by evaporation and transpiration. Indeed, compared with leakage, losses due to evaporation and transpiration are almost not important. It is leakage that decides the extent to which the lake will be watery as above, or dry as below (within a week of the first shower this dry area was green with weeds). But how large is the leakage? Is it constant or does it vary? What does leakage depend on? These crucial topics come next after a quick look at how I measured lake levels.

Measurement of water level

Both McFarlane and Sim measured water level using continuous recorders, which were difficult to reach when the water was deep, and useless when the water has receded. They were also open to vandalism. So I measured lake levels by hand, either from the top of a small plastic drainage pipe in the wall near the causeway, or (when the water had receded out of reach) from the top of 40 cm of dowel inserted in the lake bed adjacent to the causeway, as shown in the pictures below.


Above left, the pipe is roughly halfway up the retaining wall. **Right**, the 40 cm of inserted dowel with two sticks to aid retrieval if submerged by rain, and to prevent dislodgement by ducks.

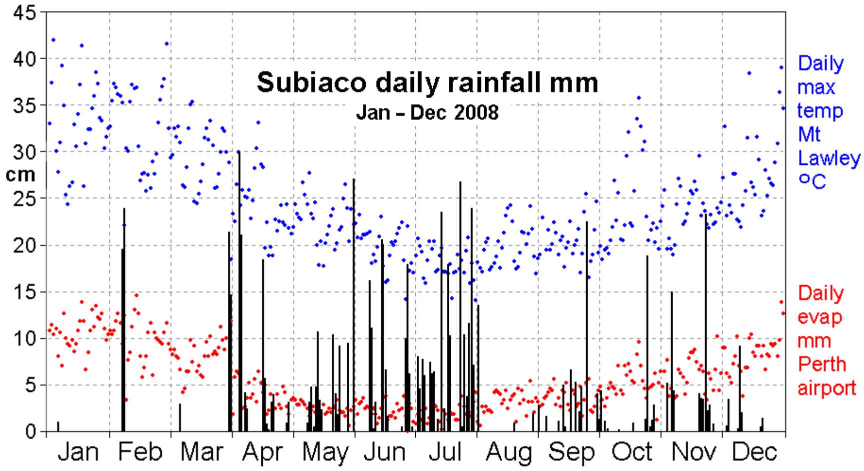

Above left, if water retreated beyond reach of the dowel, a small canal allowed measurement. The dowel was then relocated. **Right**, McFarlane's (1984) survey is not clear about the exact height of the wall. Sim (1995:46) re-surveyed the outlet and found the bottom of the weir to be at the level shown. By my own measurements the top of the wall at the outlet is 19 cm higher, but the height of the wall is not uniform enough for this to apply everywhere, see top left picture on page 8.

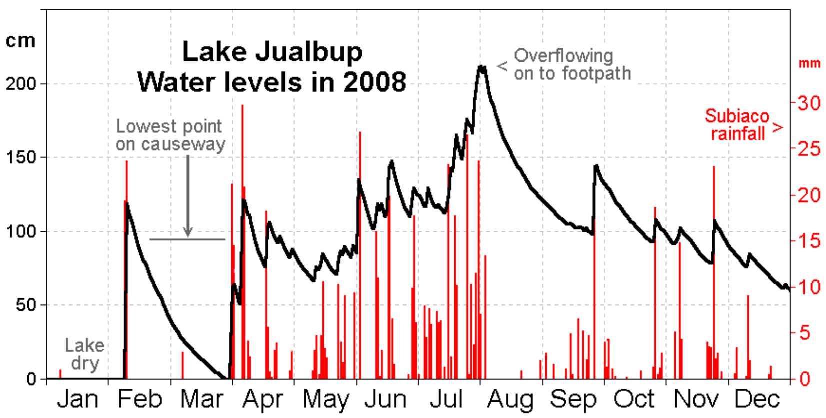
Above, the lake level can be roughly estimated from the depth of water over the causeway., which reaches 1.5 metres when the lake is full. In this picture the channel is 1 metre wide and 2 cm deep.

My measurements were made to the nearest mm with a Teflon-coated (ie non-wettable) metal tape measure; and were precise enough to detect the piling-up effect of strong winds (up to 5 mm in extreme cases), and wind-produced swell (up to ± 3 mm) usually in tune with the strongest gusts. Fortunately the lake is sheltered and only rarely did waves prevent precise measurement.

Effect of rain on water level

The rainfall recorded at the Subiaco waste water treatment plant (the weather station closest to Lake Jualbup) and the water level measured by me at Lake Jualbup during 2008 are shown below.

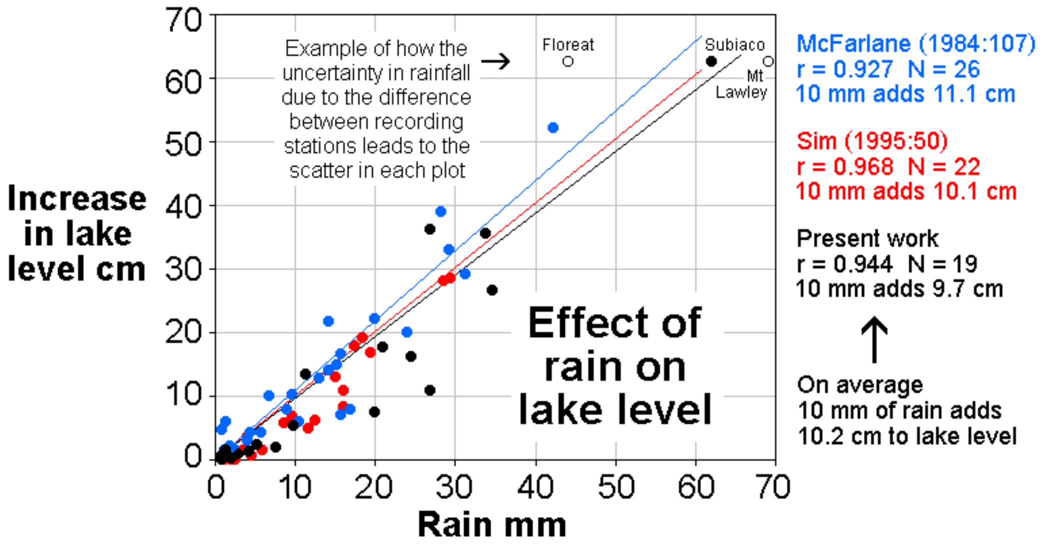




Above top, rain falls at irregular intervals but mostly in winter, and evaporation shows a strong dependence on temperature. **Bottom,** the water level rises with each rain and then falls due to leakage and evaporation. It seems simple enough, but the relationship is complicated . . .

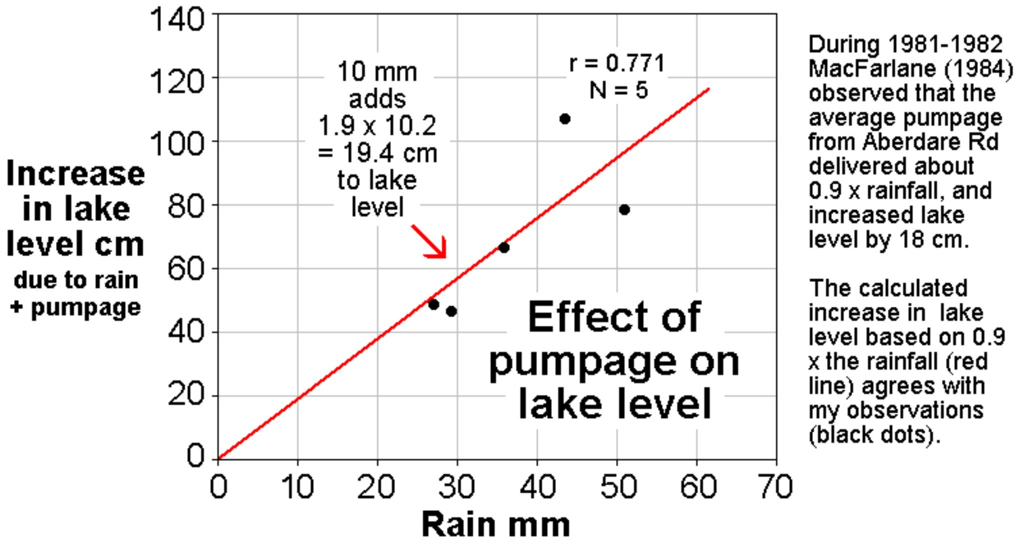
. . . because Lake Jualbup is not a natural lake. **Left**, the rain it receives is boosted by runoff from the catchment area. **Right**, and by pumpage from the QEII lake at Aberdare Road.

Accordingly, to determine the effect of rain on water level, we need to measure each rain, the water level before and after, and the leakage and evaporation that occurred while it was raining. We must also cope with likely snags – some rains are swamped by pumpage, others by too many rains before and after (which make it difficult to isolate a particular rain), others are too light to produce runoff, and we cannot know the exact rainfall anyway. But despite these difficulties the relationship was studied by McFarlane in 1981-1982, Sim in 1995, and me in 2008. As shown in the next diagram, our results agree quite well:



Above, each set of results shows considerable scatter about the trendline due to uncertainty in the rainfall. Rains seldom exceed 30 mm without triggering pumpage, which is why most rains are below this level (my single rain of over 60 mm is a rare and valuable exception). The above results indicate that on average 10 mm of rain increases the lake level by 102 mm or 10.2 cm.

Pumpage from Aberdare Road, when it occurs, is so dominant that care was taken to exclude it, so the results would reflect the effect of rain alone. The effect of including pumpage is shown below:



Above, my results agree with what the relative volumes of rain and pumpage predict:

Reaction time

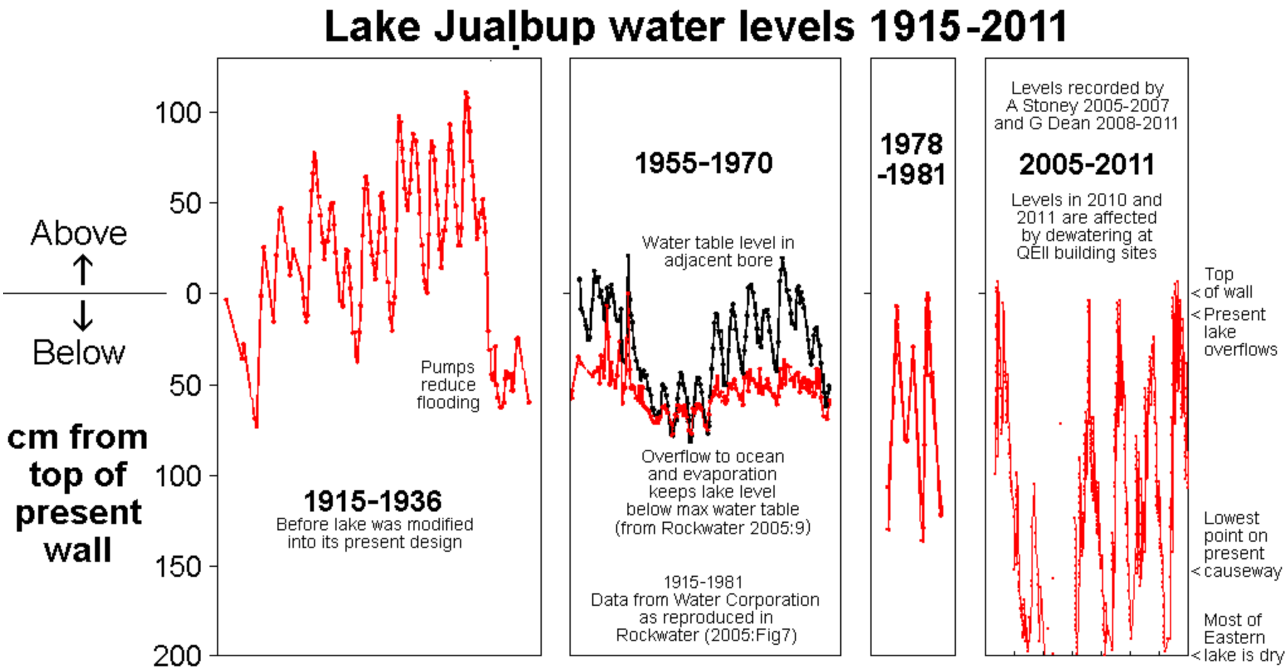
If roads are dry then about 2 mm of rain are needed to dampen the surface and fill drain pits enough for runoff to occur. Otherwise runoff reaches the lake very quickly – shown is the inflow five minutes after a ten-minute storm had dumped 6 mm of rain. It continued like this for ten minutes, reducing to a trickle after one hour.

Conclusion

The uncertainties in rainfall, evaporation, and the conversion from rainfall and pumpage to lake level are trivial compared with the huge volume lost by leakage. Even modest reductions in leakage could make a significant difference even if future rainfalls were to decrease. The technicalities of leakage are examined next.

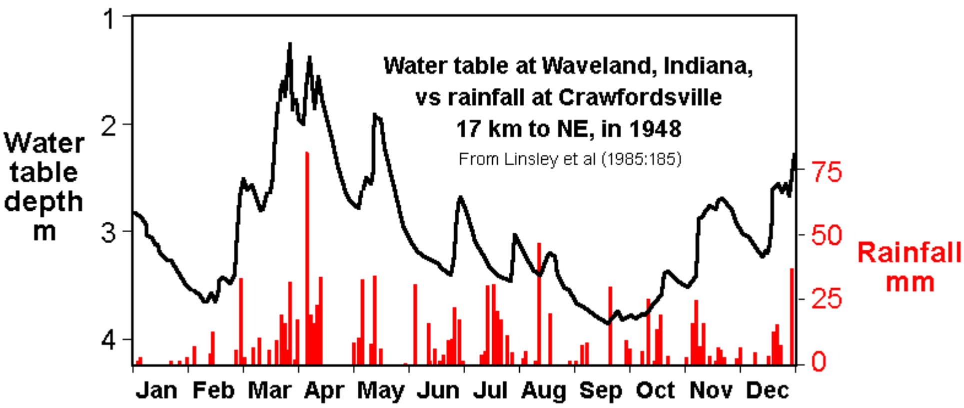
Historical water levels

The first officially recorded water levels at the lake began in 1915 when the area was subject to flooding, but were discontinued after 1936 once the flooding was under control. Records resumed in 1955 when bulldozers began removing the mountains of household and building waste that had been dumped over the years in an attempt to stop flooding. Grading and planting of the present lake area was completed in 1957. In 1973 the man-made earthwall around the lake was replaced by the present stone wall capped by the present footpath. The available records were collected by Rockwater (2005) and are reproduced below together with measurements for 2005-2011.



Above left, in winter the original lake reached from the west side of Herbert Road almost to Derby Road, more than twice what it is today, and reached a full metre above the present wall. Much of the original eastern end has been reclaimed, so the present lake is only partly in its original position. **Middle**, the water levels were lower than today due to the lower surrounding wall and a lower outlet to the ocean. The minimum lake levels are similar to the minimum water table levels, which shows that the lake and water table are connected. **Rest**, the 1978-1981 levels show that the lake was full-to-overflowing each year, as during 2005-2011, but was never dry as it was in 2005-2011.

The above seasonal variation in water table level is typical of how the water table reacts to seasonal rainfall. The example below (the only one I could find in this format) illustrates the connection:

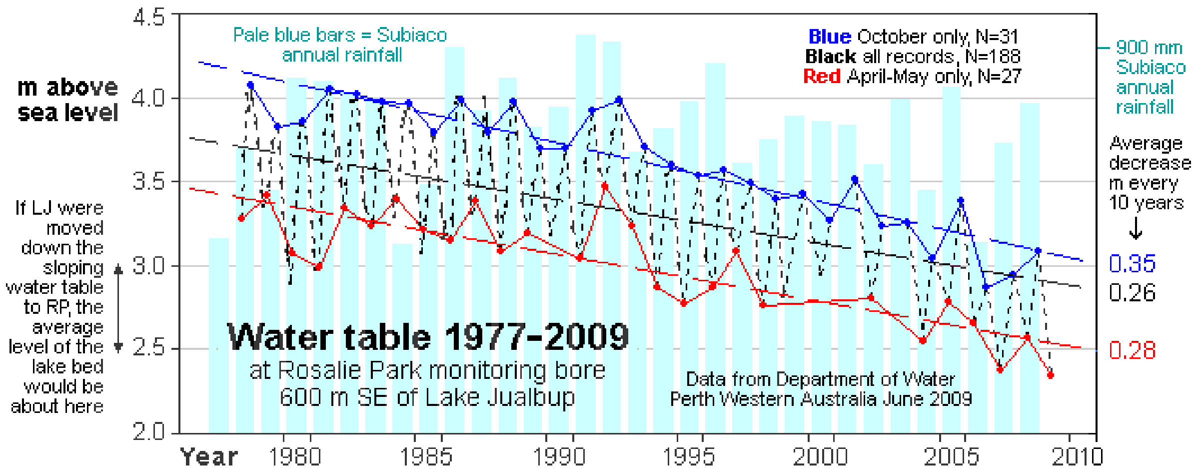


Above: This example is from Indiana in 1948. The measuring stations are 17 km apart, so the correspondence between rainfall and water table depth is not perfect. Nevertheless the plot clearly shows the water table rising in response to individual rains, superimposed on a general lowering during the hot summer months (in Indiana the seasons are of course the reverse of those in WA).

Ground water

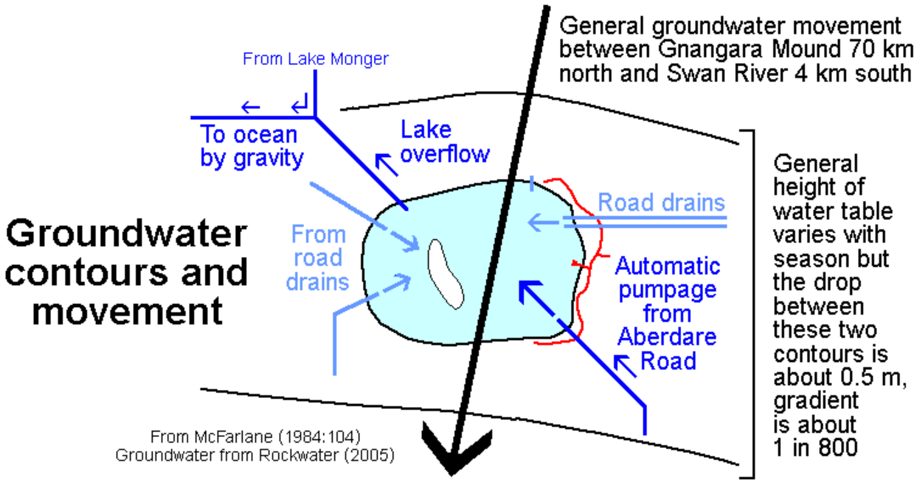
The sandy soils around Perth may contain from 10% to 15% water by volume near the surface (Stormwater Manual 2007:11). The *water table* is the depth below which the voids are completely filled with water. The water below the water table is called *ground water*. Ground water flows very slowly by gravity from where it is most elevated, in this case an area known as the Gnangara mound 70 km north of Perth, then into wetlands and rivers and eventually out to sea.

The water table varies with season, being naturally higher in wet weather when rain is replenishing the ground water, and lower in dry weather. If the water table is above ground level, water leaks out to form a wetland or lake, hence their description as a *surface expression of the water table*. If the water table then falls below ground level, the surface water disappears. As shown below, the drying up of Lake Jualbup in recent years can be attributed in part to a steadily falling water table:



Above, at Rosalie Park, the monitoring bore closest to Lake Jualbup, the water table varies with seasonal rainfall as expected. It is lowest at the end of summer (red dots), and higher by about 0.7 m at the end of winter (blue dots). Although the annual rainfall shows no evident decrease, thus 1977 and 1984 were just as dry as 2006, the water table is falling on average by about 3 cm every year. In the early 1980s it was always above the lake bed, so the lake was never dry, but today, given the present leakage rates, it is usually too low to keep the lake filled in summer. The relation depends on when the rain falls, so by itself annual rainfall is only a rough guide to water table level.

The direction and gradient of groundwater flow are shown below:

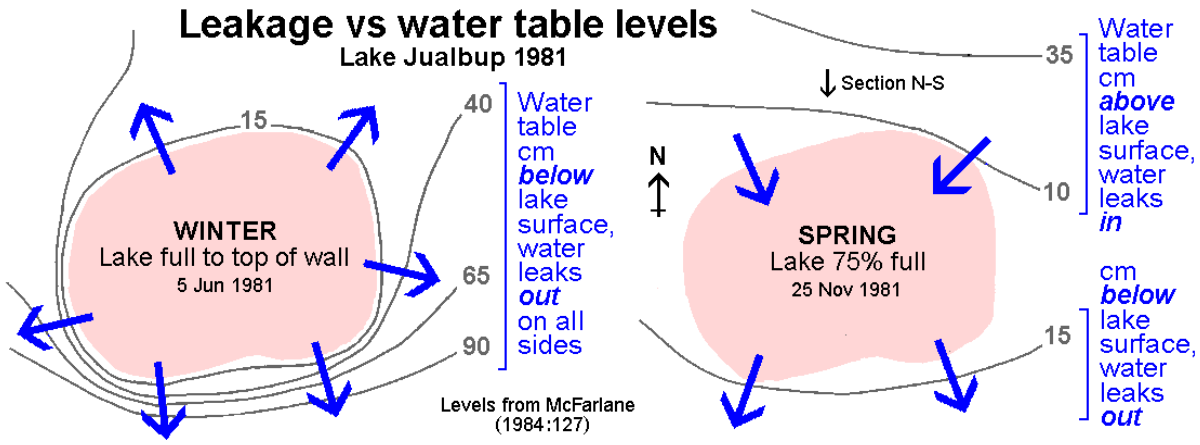


Above, the arrow shows the general direction of ground water flow.

The downhill flow of ground water at a gradient of 1 in 800 means that the water table is generally about 20 cm higher at the northern side of the lake than at the southern side, a difference that was examined in detail by both McFarlane (1984) and Sim (1995), see next.

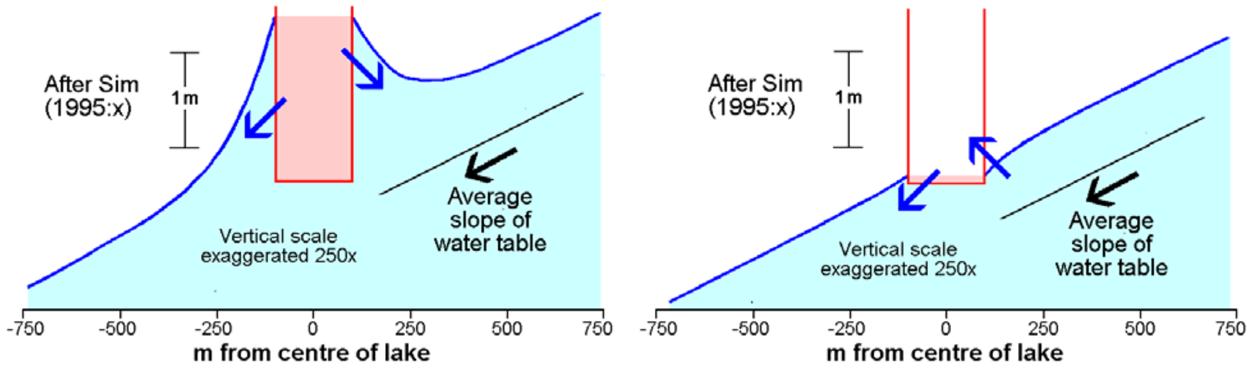
Water table

McFarlane (1984:127) found the following water table levels when the lake is 100% and 75% full: We are looking at the lake from above. The blue arrows indicate leakage to or from the water table.



Above left, when the lake is full, the water level is everywhere above the water table, and water leaks out in all directions. **Right**, even when the lake is 75% full, the water level remains above the water table only along the south side, and is below it along the north side where the water table is higher due to its slope from north to south. So water leaks in and out, respectively.

Sim (1995:x) modelled lake and water table levels more precisely than McFarlane did, with the following results. In this case we are looking at a cross section of the lake. The groundwater gradient is shown and the vertical scale is exaggerated by a whopping 250x:



Above left, as before, the water level in a full lake is everywhere above the water table, and water leaks out in all directions. In technical terms the lake is a *recharge system*. **Right**, when the lake is less full, or (as here) nearly empty, the lake level stays above the water table only on the downhill side, and falls below it on the uphill side. So water leaks both out and in. The lake is now a *flow-through system*. Of course, if the uphill water table falls everywhere below the lake bed, no leakage in can occur, and the lake dries up. Even with the vertical scale exaggerated 250x, the difference in summer between lake level and water table (typically about 10 cm) seems tiny. But when water is contained in sand, it does not need much of a difference to produce much leakage.

Sim (1995) compared his variations in lake level with computer models that used pre-set values of groundwater gradient and lake bed permeability, which avoided most of the assumptions necessary for direct interactive modelling. For a permeability typical of sand, a gradient in winter of 1:500 fitted the observed water levels better than 1:1000. The gradient in summer may be steeper, and may be better described by one value on the downhill side and another on the uphill side (p.58). Like elephants at a waterhole, a greedy lake distorts the water table most when water is scarce.

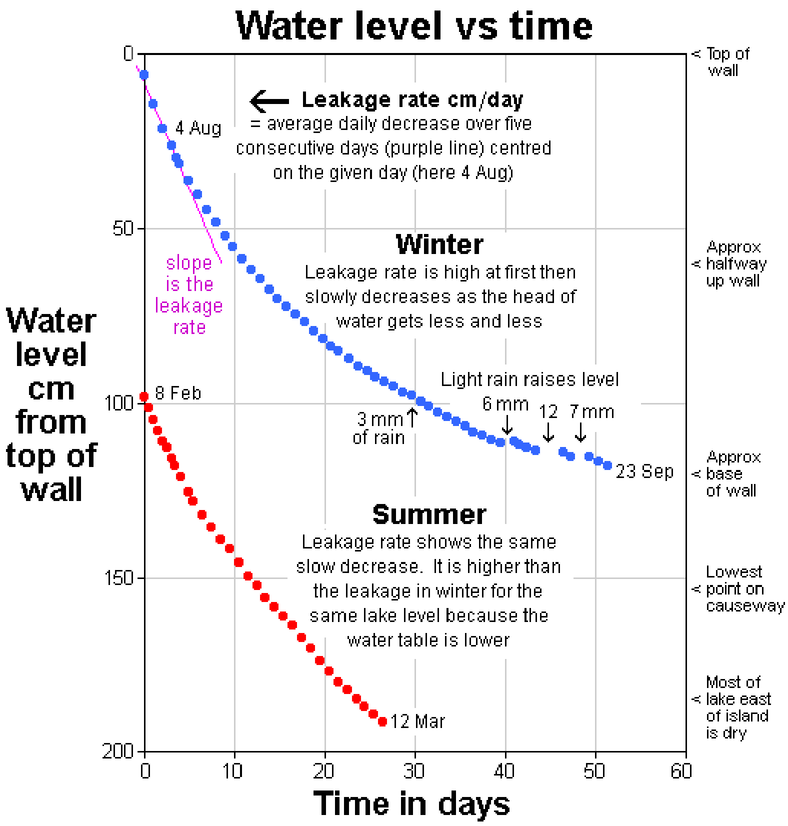
A follow-up study by Rockwater (personal communication) found the gradient in summer 2009 to be 1 in 370, and the direction of ground water flow to be about the same as in their 2005 report.

Leakage

The water level in Lake Jualbup rises with each rain and then falls due to leakage and evaporation. As illustrated by the picture below, both the rise and fall can often be surprisingly rapid.

Above, just 30 mm of rain is enough to convert the picture on the left to the picture on the right. But without further rain, all of the increase will leak away in less than a month. Turn your back for an hour and you can measure the difference in water level.

In 2008 the heavy rains in early February and early August were each followed by an unusually long period without rain, during which time the decrease in level with time looked like this:



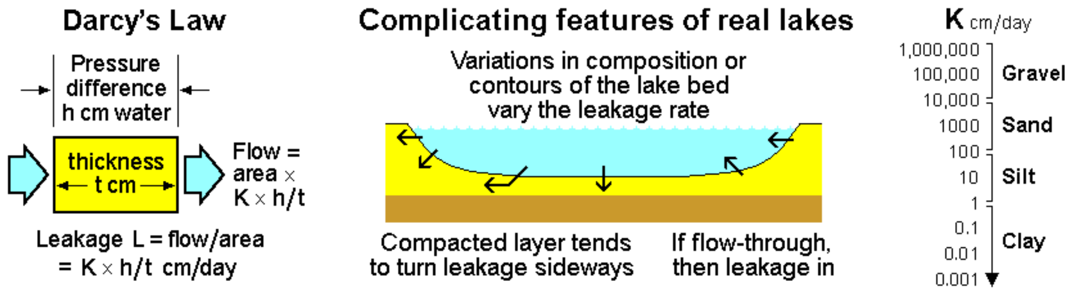
Above, the daily decrease in water level is high at first, then gets less and less. Except where interrupted by rain, the decline is smooth and continuous.

The leakage rate of water through a permeable soil layer under a pressure head is generally described by Darcy's Law, discovered by Frenchman Henri Darcy in 1856, which says

leakage rate L = K (a number describing soil permeability) x pressure head h / soil thickness t

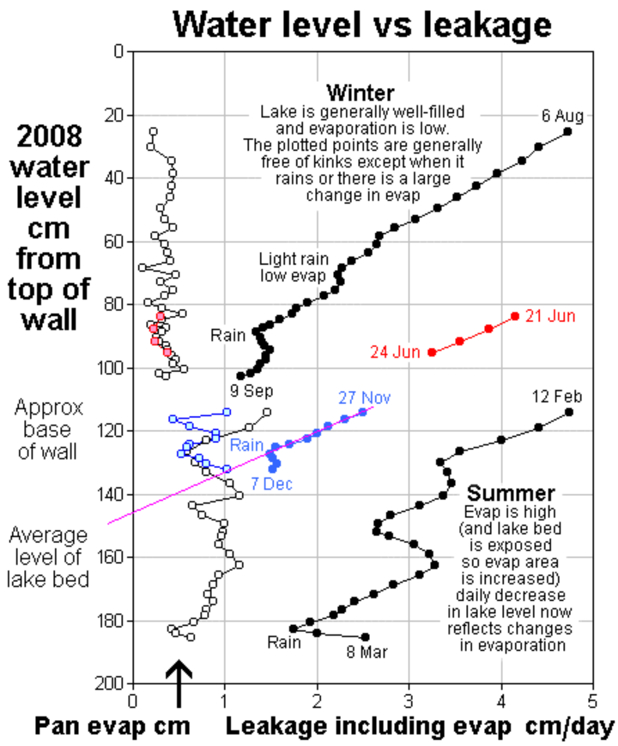
This tells us that the leakage rate (ie the slope of the above curves) is proportional to the pressure head (ie the depth of water as measured by the water level). So halving the head halves the leakage rate, which is why the slope gets less and less as the water level decreases. However, as explained next, the application of Darcy's Law to a lake is more complicated than the above might suggest.

Darcy's Law is shown schematically in the diagram below:



Above left, Darcy's Law says leakage across a soil body is proportional to the pressure difference h and inversely proportional to the thickness t. **Middle**, leakage from a lake can be horizontal as well as vertical, inwards as well as outwards. The relevant horizontal and vertical values of K, h, and t usually vary with location and will be generally unknown. Computer models avoid these problems by (1) subdividing the lake and surrounding area into hundreds of sub-areas in which the flow can be more accurately followed, (2) assuming reasonable values for each variable, and (3) adjusting everything until the calculated daily decrease in lake level agrees with tho observed decrease. **Right**, values of permeability K in cm/day taken from the literature. Their huge range (many orders of magnitude) is the largest range of any property of construction materials (Cedergren 1989:20).

Even though K, h, and t are variable and unknown, we might reasonably expect leakage from Lake Juabup to *approximately* conform to L = Kh/t. Since K/t is largely constant if the lake bed is not being exposed (which would change t), a plot of leakage L vs water level (as a measure of h) should tend to be a straight line. As shown below, this expectation is confirmed:



Above, reasonably straight lines are observed except when (as expected) there is rain, or a large change in evaporation, or the lake bed is being exposed (when it will still be evaporating water). Thus evaporation from a water table 1 m down may be 50% of the evaporation from open water (Pollett et al 1979). In their computer model Rockwater (1995a:5) assume a linear decrease to 0%.

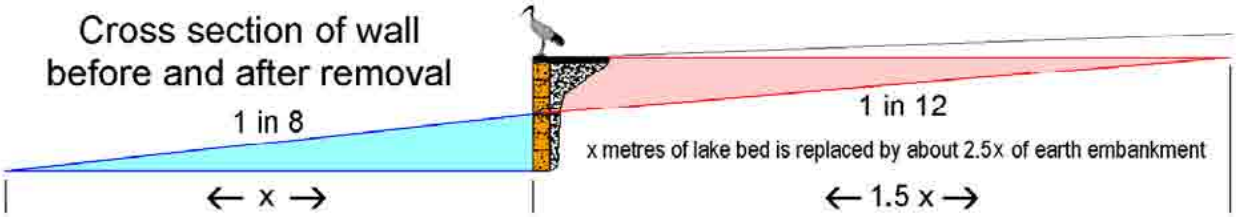
Since leakage tends to conform to L = Kh/t, the above straight lines should tend to have the same slope K/t as illustrated by the purple line – and they do, except in summer when the lake bed is being exposed (which changes t), but even here the trend is not too different. This finding will be put to good use later when I look at ways of predicting leakage

Did removing the eastern wall affect leakage?

In November 2001 the eastern wall was removed and the banks regraded to a sloping embankment. According to local residents, the lake then started to dry up completely each summer, which it had not done before (it had been very low but not completely dry). Do the figures support this?

Replacing the eastern wall required considerable earth moving and the removal of eight mature trees that were in the way. The resulting large areas of bulldozed embankment provided a rare glimpse of what underlies and surrounds the lake, as shown in the picture below right:

Above left, December 1988. Even with late rains the lake is no longer this full in December. **Right,** this black-and-white picture from the Subiaco POST (24 November 2001 page 14) shows the eastern end of the lake during the changes. Mature trees are gone, and earth embankments are where the wall used to be. The area was immediately used by long-necked turtles to lay their eggs, but the lack of cover made the eggs an easy target for hungry crows. The inset shows the area today.



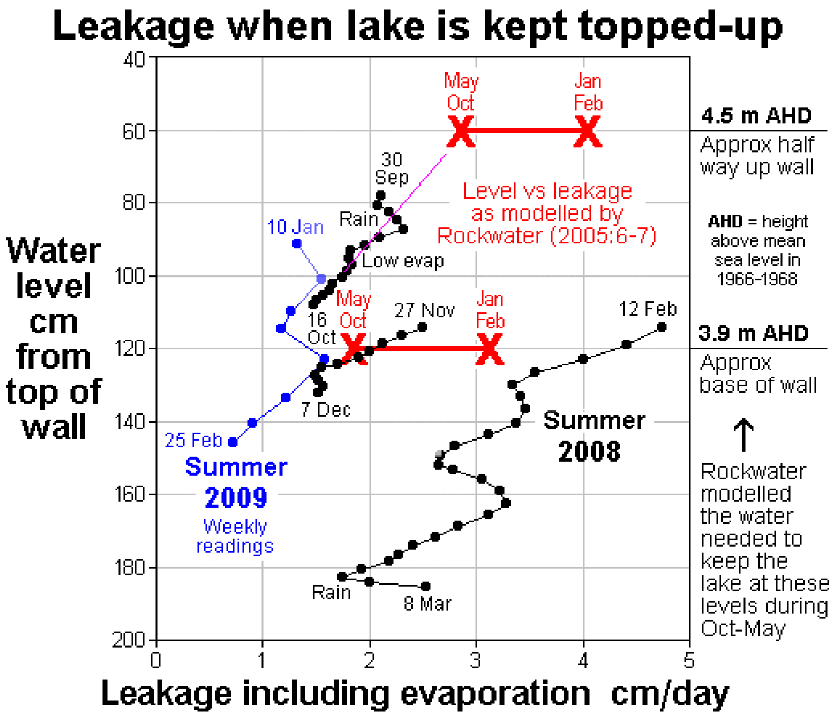
Above, the slopes are averages based on my own measurements. They do not continue beyond the footpath into the lawn area, which averages about 1 in 30. Removing the wall effectively replaced x metres of lake bed with about 2.5x metres of earth embankment to the level of the previous top of wall. So the embankment width averages about (8 + 12) / 2 = 10 times the wall height, which is about 1.2 metres above the immediate lake bed, or say 1.4 metres above the excavated level.

The embankment length is about 180 metres, so its area is roughly 1.4 x 10 x 180 = 2520 square metres, or nearly 10% of the lake area of 26,000 square metres inside the old wall. If we knew the relative permeability of this 10%, and thus its relative leakage rate, we could estimate the effect on leakage of removing the eastern wall. Rockwater (2005:10) notes that the lake wall has too many gaps left by eroded mortar to significantly retard the flow of water through it, so removal of the wall should not have much effect. But this does not consider regrading and relative permeabilities.

According to Rockwater (2005a:4), based on their various hydrological studies in the Perth area, the vertical or horizontal permeability of local sand is likely to be respectively 20 or 50 times that of the lake bed. Reduce each to say 10 times to allow for the mixing in of some silt during grading. The result is that 10% of the lake bed at high water might be leaking 10 times faster than the rest, which in effect doubles the overall leakage rate. This would not apply if clay existed beneath the workings, but McFarlane's cores (page 9) give no hint of this. So removing the eastern wall has increased the leakage out at high water, and the tendency to become dry in summer. Since the embankment is more or less parallel to the groundwater flow, benefits from increased leakage in seem unlikely.

Observed leakage vs Rockwater model

Rockwater (2005a) calculated the water required to keep it at two levels in Lake Jualbup during the eight dry months (October-May) assuming no rain. Their model was based on an estimated lake bed permeability of 5-6 cm per day for vertical flow and 20 cm per day for horizontal flow (reflecting the effect of compaction), and average water table levels, adjusted to give the leakage rate of 6 cm per day that they observed in May and June 2005, a year with good rains. Their results are given in cubic metres per day, which I have converted to a daily decrease in level by dividing by the lake's water area (26,000 sq m, see McFarlane 1984:106) for the comparison shown below:



Above, I have included the relevant observations from the previous plot, plus those for Sep-Oct (which show kinks for the reasons indicated), and Jan-Feb 2009 based on weekly measurements (which show kinks for the same reasons as in Feb-Mar 2008). The comparison to be made is between the modelled leakages in red, and observed leakages at the same water level in the same months. **Upper red results**: the lake was never at the same level in the same months, so there are no observations to compare them with, although there is good agreement with the extrapolated Sep-Oct observations (purple line). **Lower red results:** the predictions for the cooler months are fairly close to the observations. But those for Jan-Feb, even though they assume no rain since October, are notably less than those I observed in 2008 when the water table was low due to lack of rain (only 15 mm after October 2007), and easily twice those I observed in 2009 when the water table was high due to good rains (nearly 60 mm after October 2008). In other words, and as expected, the model is accurate only to the extent that the water table and rain can be accurately predicted.

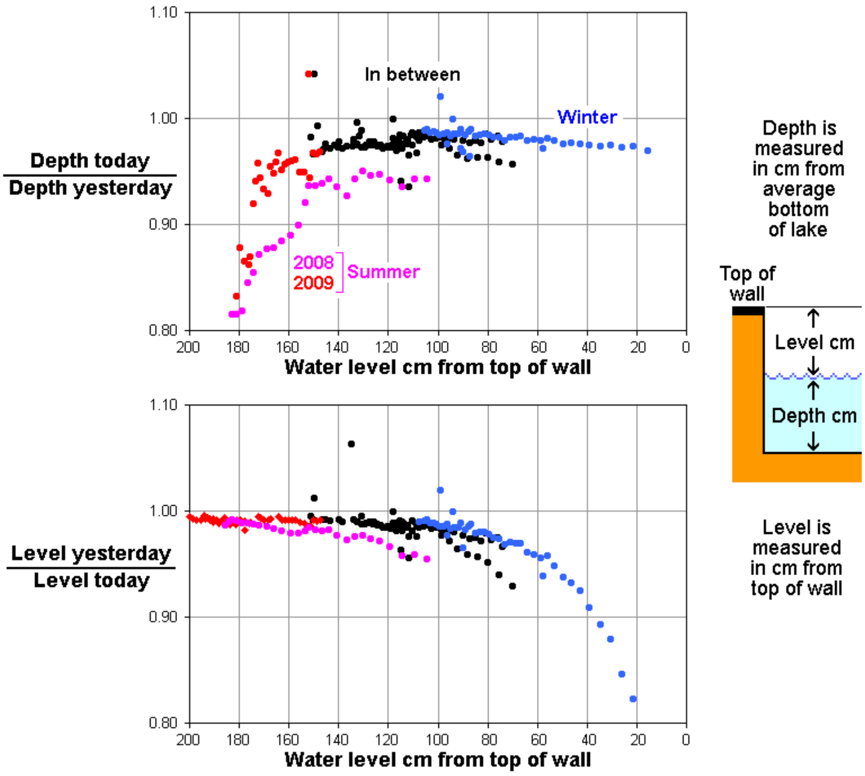
Predicting leakage

We saw earlier that leakage tends to follow L = Kh/t, and that K/t can be estimated, so we can in principle predict the leakage for any value of h, provided we know what h is. But we don't. All we know is h measured from an arbitrary reference point (here top of the wall), which is not the same thing. We could break h down into H the true reference point and h the measurement on our arbitrary scale, where H is the level at which the extrapolated leakage is zero, see the purple line on the previous page, which by difference will give us the h we want. But this isn't much help because H is highly variable, for example during 2008 it varied by about two metres, three times the average seasonal variation in the water table observed at the Rosalie Park monitoring bore 600 m away.

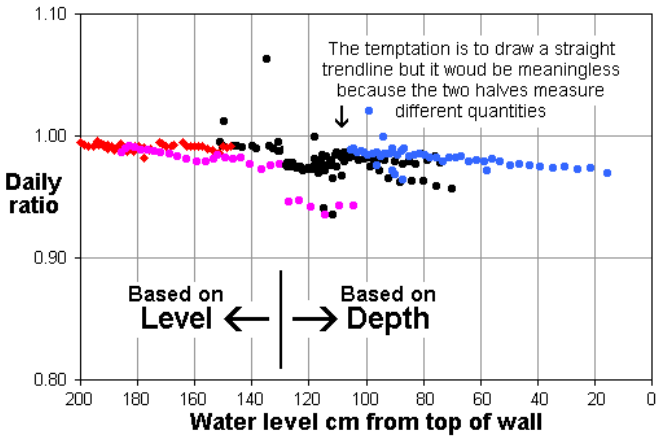
But suppose we measure the leakage on two consecutive days without rain. On day one $L_1 = Kh_1/t$. On day two $L_2 = Kh_2/t$. The leakage during day two is the difference $h_1–h_2$. So $L_2 = Kh_2/t = h_1–h_2$, which simplifies to $h_1/h_2 = 1 – K/t$. If we know the difference $h_1–h_2$ we don't need to know h_1 or h_2.

That is, level yesterday (which we know) / level today (which we want to predict)
= 1 – K/t = constant if the lake bed is not being exposed

The value of H (the elusive true reference point for measuring levels) applies to both h_1 and h_2 and therefore tends to cancel out. But it still varies too much during a year to be ignored. The best we can do is try different ways of measuring level to see if any give usable results, as follows:



Above right, water level can be measured (1) as a depth from the average lake bed, and (2) as a distance from top of wall. **Top** is a test of (1). The position of the average lake bed was not critical, and 190 cm from top of wall gave good results. The ratio depth today/yesterday is fairly constant in winter when the lake is full, and in the adjoining months (black dots), averaging 0.97-0.98. But in summer when the lake bed is being exposed and depth becomes highly variable, the ratio is all over the place. **Bottom**, the reverse is true when the water level is measured from top of wall. Here the ratio averages about 0.99 and the previous large difference between 2008 and 2009 disappears. The difference in scatter is easily explained – the scatter is low when the measured distance is large compared with daily differences, and high when the measured distance is small. Combing the best parts from each plot gives us this usable result:



Above, the daily ratio is now reasonably constant for all lake levels, which means we now have a simple way of predicting today's level from yesterday's level, and hence the leakage. To put these levels into context, at 130 cm the water has receded nearly 3 metres on average from the wall, and is barely 20 cm deep over the causeway. At 180 cm the east and west basins are no longer joined.

Predicting lake level from rainfall

At this point we can predict the rise in water level due to rain, and the fall in water level due to leakage. So if we know the rainfall and make an allowance for pumpage, we should be able to predict water level. But as noted, it is surprisingly difficult to know the rainfall because we cannot be sure that the rain falling over the catchment is accurately measured by a particular nearby rain gauge, the average difference being typically one quarter of the measured rainfall. Nor can we know when pumpage will occur, or the amount, only that over a year the pumpage and road runoff should be roughly equal, effectively doubling the rainfall. So we have difficulties before we even start.

Nevertheless, using rainfall data from Subiaco and Floreat, and pan evaporation data from Perth airport corrected by x 0.7, I was able to adjust the calculations to give the best fit with observations during 2008. Surprisingly, the variables taken together were not overly critical because changes in one could often be compensated by changes in another. Two examples show how it works:

Example 1. Starting level L = –100 cm, ie 100 cm below top of wall.
Since –100 cm is above –130 cm, calculate tomorrow's level "Based on Depth".
Depth D = 190 + L = 190 + (–100) = 90. Let leakage factor LF = 1 and daily evaporation = 0.5 cm.
Then (and here we introduce the observed "Based on Depth" conversion shown in the previous diagram),
tomorrow's depth = D x (1 – 0.0214 x LF) – evaporation
= 90 x (1 – 0.0214 x 1) – 0.5 = 87.6 cm above nominal base of –190 cm
= 87.6 – 190 = –102.4 cm, ie 102.4 cm below top of wall.
So in 24 hours the water level in the lake has dropped from –100 cm to –102.4 cm, a drop of 2.4 cm.

If there had been 10 mm of **rain** overnight, the level would have been raised by 10 x 1.05* = 10.5 cm, a net increase of 10.5 – 2.4 = 8.1 cm. *Annual pumpage and rain are roughly equal, but the correction is 1.05 and not 2 because pumpage is much less frequent than rain. To keep leakage (which depends on water level) on track between frequent small rises due to rain and infrequent large rises due to pumpage, the correction has to be smaller than otherwise expected, and spread out over the year. Examples of what happens when they get seriously out of sync are shown on the next page.

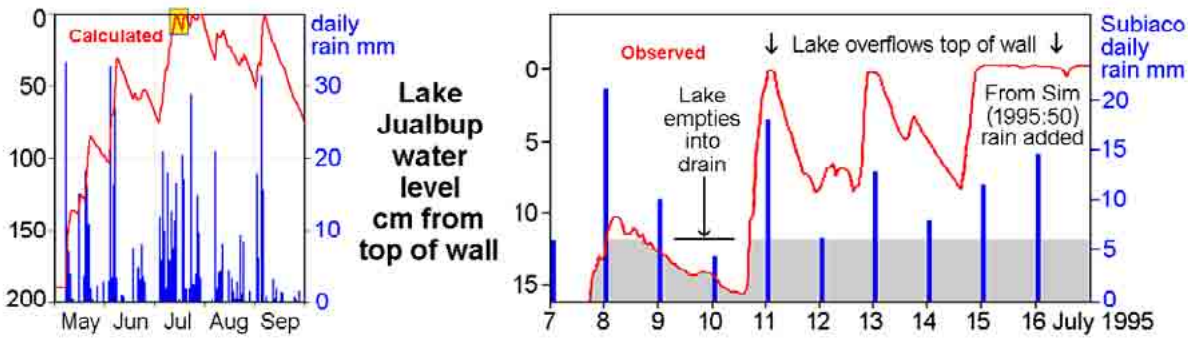
Example 2. Starting level L = –150 cm, ie 150 cm below top of wall.
Since –150 is below –130, calculate tomorrow's level, "Based on Level". Let LF = 1 and daily evaporation = 0.5 cm.
Then (and here we introduce the "Based on Level" conversion shown in the previous diagram)
tomorrow's level = L / (1 – 0.0052 x LF)
= –150 / 0.9948 = –150.8 cm, which evaporation will lower by a further 0.5 cm to –151.3 cm.
So in 24 hours the water level in the lake has dropped from –150 cm to –151.3 cm, a drop of 1.3 cm.

If the calculated level is below –190 cm, the lake is drying out, so **cap** the level at –190 cm. If the calculated depth is above 0 cm, the lake is flooding over the path, so **cap** the depth at 0 cm to simulate removal of water by the weir. In 2012 the accumulation of further data allowed this model to be refined, see page 43.

When the calculations are applied to the average of Subiaco and Floreat rainfalls, the calculated water levels are in good agreement with the observed levels, as detailed on the next page.

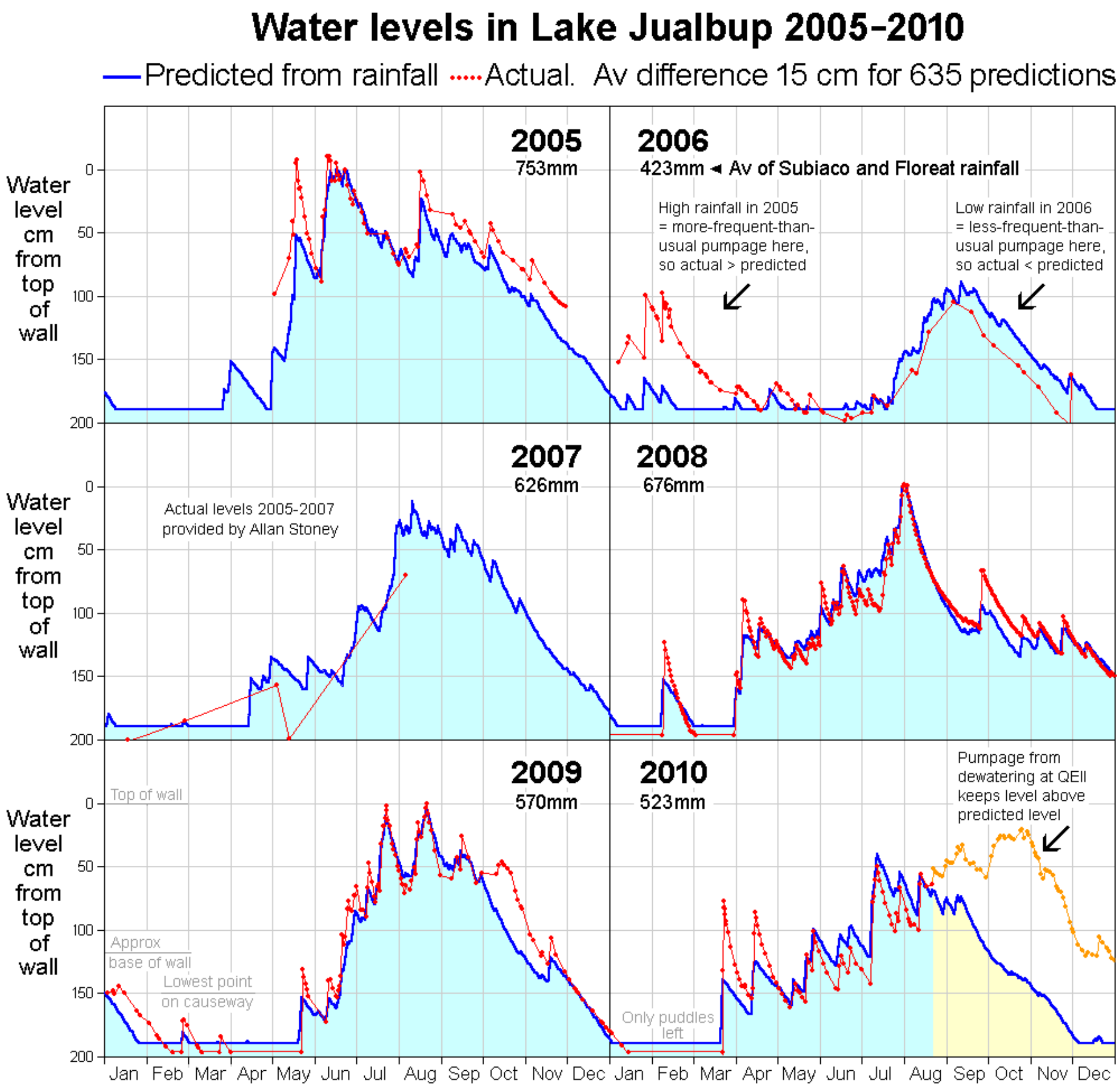
A check on the calculations vs daily lake levels in 1995

There was also good agreement with the daily lake levels observed in July 1995 by Sim (1995:50), at a time when the lake was overflowing, making this a severe test. The comparison is shown below.



Above, the calculations for 1995 based on Subiaco rainfall predict multiple overflowings during July in good agreement with Sim's observations. The small inset on the left is enlarged at right.

The lake levels predicted from rainfall during 2005-2010, and the observed lake levels for the same period, are compared in the diagram on the next page.

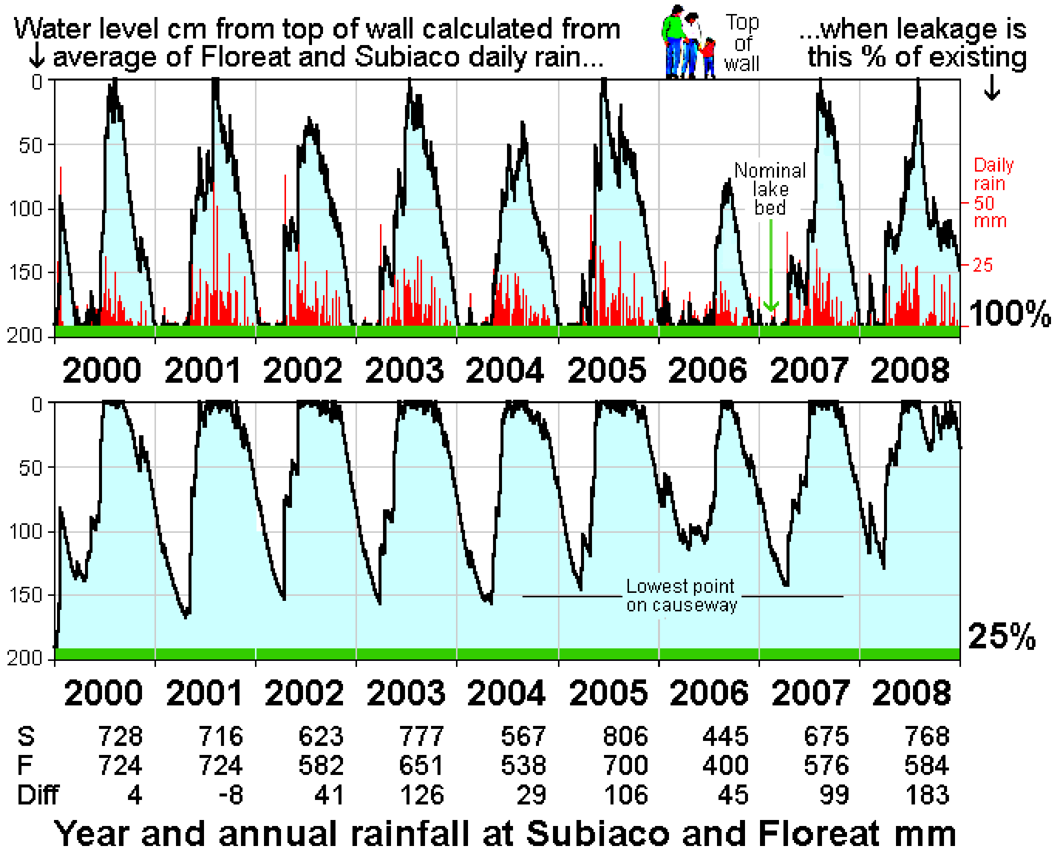


Above, the data for 2005 (good rains) and 2006 (poor rains) were independently provided by Allan Stoney after I had completed the previous edition of this work, so they provide a severe test of the calculations. Except when the balance between rainfall and pumpage is upset by dewatering, as in the last third of 2010, there is good agreement with all observations, the average difference for 635 predictions being only 15 cm. The predicted days for the highest lake levels are always close to those observed. So we can have some confidence in the predictions. When unusual levels of previous rain (high or low) upset the normal pumpage frequency, as in 2006, it temporarily sways the calculated levels, but eventually they get back in sync. When only puddles remain, the level is too low to mean anything, see below, which is why the calculations are capped at –190 cm.

Above, the first few months of 2009 were exceptionally dry, and water levels were often too low to be measurable, as here. Some of the ducks in mid-puddle are standing up.

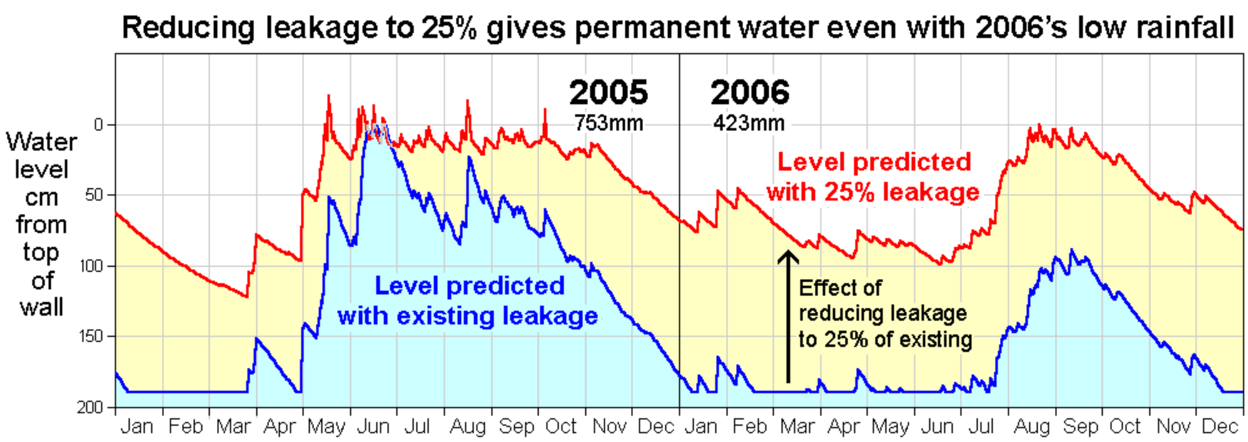
Predicting the effect of reduced leakage

In the above calculations, the decrease in level is partitioned between leakage, which is controlled by the leakage factor LF, and evaporation. When leakage is at the existing leakage rate, LF = 1. When there is no leakage, LF = 0. To predict the effect of reduced leakage, we simply run the calculations with values of LF between 1 and 0 for as many years as we have rainfall data. The results for 2000-2008 with LF = 1 (no reduction) and LF = 0.25 (leakage 25%) are shown below:



Above top, rainfall (red) and calculated lake levels (black) at 2008 leakage rates. The results are based on assumed pumpage and estimated evaporation, and on the average of Subiaco and Floreat rainfall that may differ from the catchment rainfall. Nevertheless the marked seasonal variation (low in summer, high in winter) is clearly evident. **Bottom,** with 25% of existing leakage the lake retains enough water to keep the island isolated in most years.

The years 2005 and 2006 are of especial interest because of their high and low rainfall, respectively. More precise results that take into account the variations in footpath height, the actual slope of the adjoining grassed area, and evaporation, are shown below:



Above, with 25% of existing leakage the lake again retains enough water to keep the island isolated in most years. The depth provided by the good rains in 2005 carries on through 2006.

Even 25% represents a sizable leakage averaging more than 0.7 cm per day (about twice the average daily evaporation) when the lake is half full, which will deliver to the groundwater nearly 200 cubic metres per day, or enough to fill an Olympic-size pool every fortnight. It is much more than the average observed leakage of 0.05 cm per day for farm dams in the NE wheatbelt of WA (Luke and Denby 1987:11). It is also more than the leakage from Mundaring Weir in the 1970s, which was up to 0.2 cm per day outwards in summer, and up to 0.04 cm per day inwards in winter, when the water table was respectively lower and higher than the lake level (Hoy & Stephens 1977).

A further check of the calculations.

Of the plots shown on the previous page, the year 2005 had the largest number of calculated overflowings over the top of wall (7, next was 2000 with 6), all of them in June. So the flooding of the lake surroundings should have been appreciable. And it was, as shown in the pictures below,

Above, the southern footpath in June 2005 was under 10 cm of water, enough for ducks to swim in. *Subiaco Post* 18 June 2005 p.6 shows the flood here even higher with swans swimming over path.

Above, the eastern footpath in June 2005 was similarly flooded, as was the northern footpath just visible in the distance. Note the debris washed up on the path. Photographs by Mark Wilshusen.

Methods of reducing leakage

Rockwater (2005:23) suggests that leakage could be reduced by top dressing the lake bed with bentonite or other clay product such as kaolinite, as routinely used for farm dams. Marais (1997:ch.3) and Coles (2003) describe methods for reducing leakage in holding ponds by clay and by geomembrane liners. Today synthetic polymers are available that are cheaper and better than bentonite, and do not require disturbing the lake bed (eg Polymer Innovations 2010). The amount required is determined by mixing various amounts with soil samples for laboratory testing. Rockwater (2005:21) also suggests that leakage out could in principle be reduced by inserting a physical barrier several metres deep along the southern edge of the lake where most of the leakage out occurs. If such a barrier was technically feasible, the lake bed itself need not be disturbed, but the cost would be high. Such a barrier using treated wastewater has been proposed for Perry Lakes.

Reducing leakage from farm dams is of course essential, because even a small leakage can greatly reduce the number of sheep that a dam can support. For example, Luke and Denby (1987:11) give the following estimates for a farm dam 25 x 25 x 3 m deep containing 2000 cu metres of water at the end of August, assuming there is no more rain:

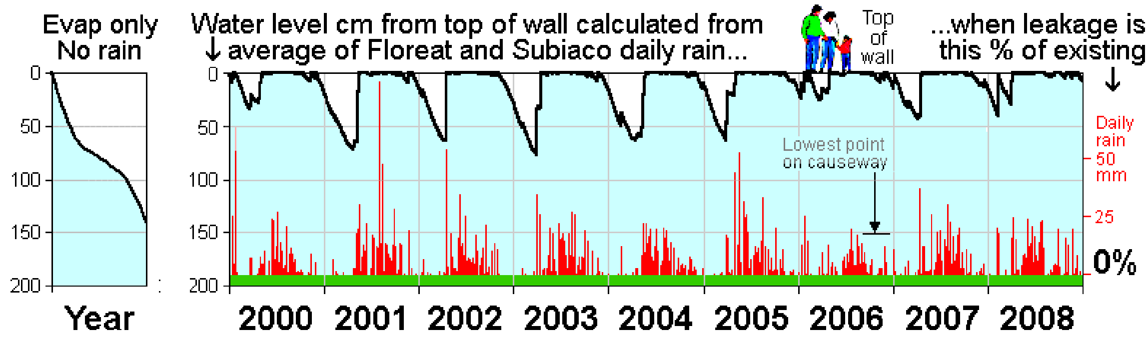
Each entry is the number of sheep the dam could support during 10 months without rain

Leakage rate mm per day	0	1	2	3	4
Southwest(Katanning)	1340	1070	800	540	270
NE wheatbelt (E of Dalwallinu)	640	430	220	0	0

The NE wheatbelt is hotter and dryer than the southwest, so evaporation there is higher and the dam's capacity to support sheep is lower. A leakage of only 2 mm a day reduces the capacity by between a half and two-thirds depending on area. Anything more would be disastrous in dry areas, even though it would be far less than the 20-70 mm a day typically observed at Lake Jualbup, As previously noted, the leakage of farm dams in the NE wheatbelt averages a tiny 0.5 mm a day.

If leakage were zero

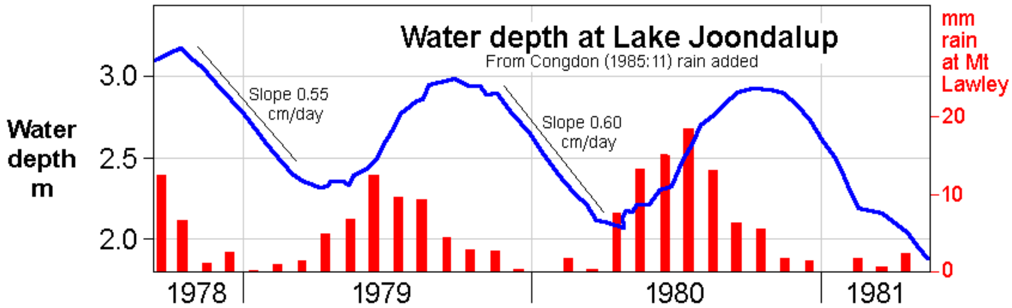
The previous plots have looked at the effect of reducing leakage. But what about evaporation? To reveal its effects, I ran the calculations for zero leakage. The results are shown below.



Above, calculated lake levels if no leakage. **Left**, if the lake was initially full to the top of wall, the losses due to evaporation would look something like this. After one year nearly 1.4 metres of water would have evaporated, and the water level would be 10-20 cm deep over the causeway. **Right**, the massive inflows of water from runoff and pumpage do not prevent some lowering in summer due to evaporation, but the lake is never less than half full.

Lake Jualbup vs Lake Joondalup

The spikes in the plots of water level at Lake Jualbup are directly the result of (1) massive inflows after rain of road runoff and pumpage, which together are about 20x the rainfall falling on the lake, and (2) substantial leakage, both of which are large compared with the lake volume. When runoff and leakage are small compared with the lake volume, as at Lake Joondalup (over 200x the area of Lake Jualbup with road runoff only one-quarter of the rainfall), the spikes are hardly noticeable against the broad changes between summer and winter, as shown below:



Above, these results from Congdon's (1985) study of Lake Joondalup show a smooth cycle between the rises due to winter rains and leakage *in* from the rising-due-to-rain water table, and falls due to summer evaporation and leakage *out* to the falling water table. There are almost none of the spikes observed in the water levels at Lake Jualbup. In the warmer months the average daily decrease of 0.55-0.60 cm (mostly due to evaporation) is about one fifth of that at Lake Jualbup.

A reduction in leakage would of course reduce leakage *in* as well as leakage *out*. It would also increase the amount of water piped to the ocean when the lake overflows into the outlet drain. This is an important loss to the groundwater, so the drain and its overflow will be examined in detail.

Overflow to ocean

The outlet drain is in the northwestern part of Lake Jualbup as shown in the pictures below.

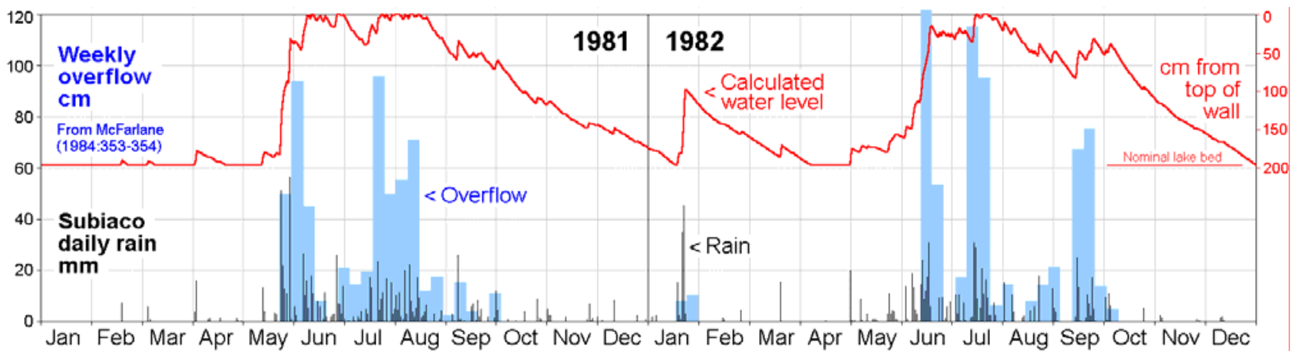

Above left, the outlet drain enclosure juts out from the lake edge. **Right**, the outlet drain consists of a weir protected by a grille to keep out leaves and branches (for this picture I have cleared away the accumulated debris). The rightmost third of the leading edge is uneven and up to 12 mm higher.

When water is 10 cm deep over the weir it represents a volume above weir level of about 2700 cubic metres, or enough to fill an Olympic-size swimming pool. The water level elsewhere in the lake is then generally close to, or just over, the footpath as shown below.



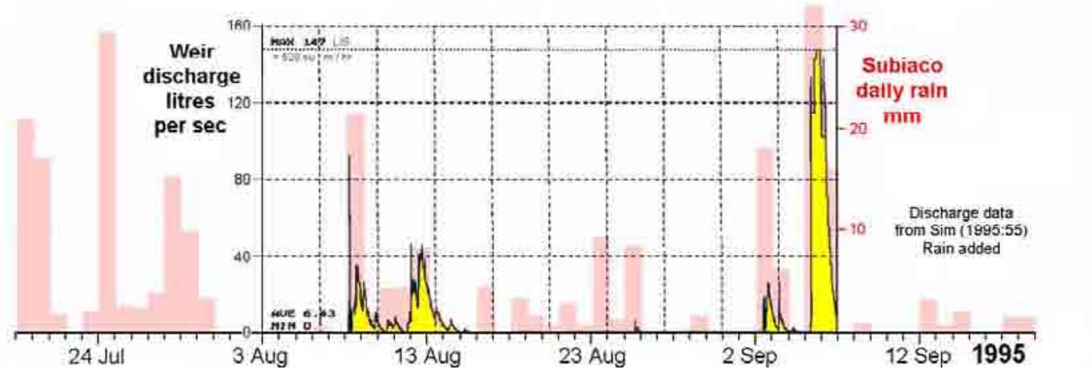
Above, when water is 10 cm deep over the weir it reaches nearly over the southern footpath (left), just over the footpath near the observation platform (middle), and well over the footpath at the NE corner (right). These pictures were taken in July 2009. When water is 10 cm deep over the southern footpath, as in June 2005, it is about 22 cm deep over the weir

The Water Corporation does not record the volume flowing into the drain. McFarlane (1984:121) estimated this volume as the difference in outflows (based on lake level and water table level) when the lake was overflowing and not overflowing. Both of his study years (1981 and 1982) had above-average rainfall, and the water table was around one metre higher than in 2012, so it is not surprising that he observed the lake overflowing for weeks as a time. His results are shown below:



Above, the blue bars show the weekly overflow estimated by McFarlane (1984:352-354), which I have converted to cm of lake level (1 cm = 260 cu m). 1981 and 1982 had above-average rainfall, and at peak times the lake level probably approached 30 cm deep over the southern footpath and 10 cm deep over the grille. See next page for volumes. Note how my calculated lake levels (shown in red) underestimate the overflowings due to the change in conditions between then and now.

Sim (1995:37-38) used an ultrasonic sensor to measure the depth of water in the drain itself, which when converted to cross sectional area and multiplied by flow rate (calculated via the pipe gradient taken from Water Corporation plans for an assumed pipe roughness) gave the discharge rate. The depth was monitored continuously from 3 Aug through 7 Sep, which gave the continuous discharge record shown below. Sim (1995:46) estimated the measurement error to be ±17%.



Above, discharge in litres per second over the weir as recorded by Sim (1995:55). 80 litres per second = 288 cu metres per hour = 1.1 cm of lake level per day. The red bars show the Subiaco daily rainfall (which in 1995 was above average) for a period extending beyond that monitored by Sim. His results are not without anomalies, for example the initial spike on 8 August is not followed by the decline shown by other peaks, as would be expected if it represented a genuine peak.

During the huge peak on 6 September (a day of high rainfall, and presumably pumpage as well, that followed high rainfall two days earlier), Sim estimates that 10,000 cu metres flowed over the weir and a further 10,000 cu metres flooded over the surroundings (p.46). Taken together they represent something like a half-metre rise in lake level above the footpath. But the above plot indicates that even this lasted no more than two days. In contrast, the three earlier and smaller peaks shown above were probably too small to reach above the footpath, which averages 12 cm higher than the weir. If we look again at my calculated levels for 1995 in the bottom left plot on page 31, this difference in height is probably one reason why my calculated levels (which count path overflowings but not weir overflowings) failed to register them, whereas they registered the path overflowings.

Summary of overflow discharges 1981-2008

Sim does not estimate the total discharge for 1995, but from his two plots and my calculated levels it seems likely to be around 60,000 cu metres. The equation derived in the next section indicates that the 2008 discharge was about 12,000 cu metres. The various estimates in detail look like this:

Source of results	Year	Discharge cu metres	Rainfall mm	% above average Jan-Dec	% above average May-Oct
McFarlane (1984)	1981	148,000	817	14	23
McFarlane (1984)	1982	164,000	789	10	8
Sim (1995)	1995	c60,000	771	8	18
This work	2008	12,000	768	7	-9

Above, the huge decrease in annual discharge since the 1980s is probably due to a combination of (1) above-average rainfall in May-October that happened to occur in the first three measured years, (2) increased leakage due to dredging the lake bottom and removing the eastern wall, and (3) a fall in the water table. The figures are consistent with the timing of rainfall being more important than the amount, especially when on average a single pumpage can add about 18 cm to the lake level (see page 21), or nearly 5000 cu metres. The above should not be taken to imply that lake overflow is now a rarity – in 2011 the lake twice overflowed the footpath for days at a time, see pic page 51.

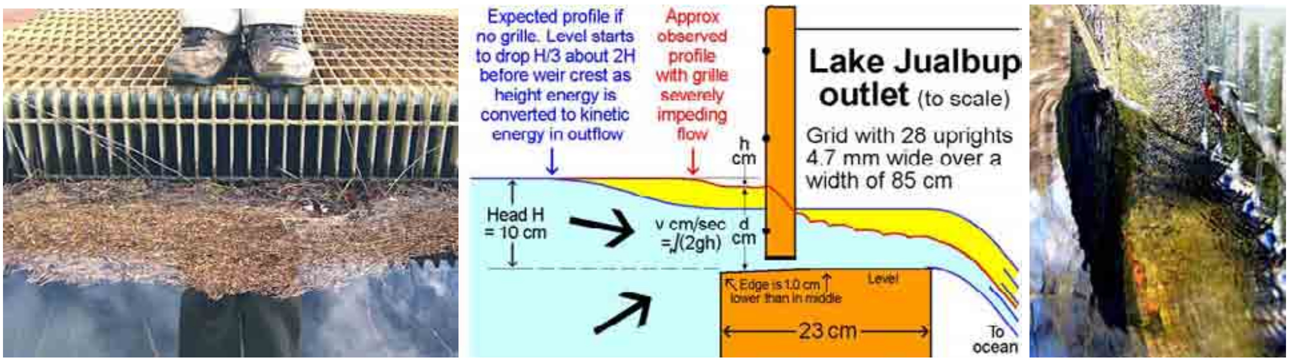
Because a reduction in leakage would increase the overflow and therefore the amount of water lost to the groundwater, I now look at the relation between them, starting with ways to measure the discharge that are easier and more convenient than those adopted by McFarlane and Sim. Among other things I discover that the outlet weir is initially less effective than allowing surplus water to flood.

Measuring discharge

The volume of water discharged by a weir has been extensively studied in experiments dating from the 19th century. Discharge is known to depend on a large number of variables including width and depth of water; the shape, sharpness and smoothness of the crest; turbulence in the approaching water; and whether the approach is open water or via a channel. If the Lake Jualbup weir had no grille, and no other obstructions, then according to a concise survey of published results by King (1940:314), the volume discharged per hour should be about

$$\text{discharge in cubic metres per hour} = 0.052 \times \text{width cm} \times (\text{head cm})^{3/2}$$

The dependence on width and head$^{3/2}$ is common to all weir equations and reflects the underlying hydraulics. But as we shall see below, the grille spoils everything. *Head* is the height of open water above the weir, not the depth of water passing over the weir, which is reduced due to its height energy being converted into the kinetic energy needed by the outflow. Sim's observations of an overflowing weir in July 1995 (see page 31) indicate that the average daily head was about 10 ± 5 cm. In 2008 and 2009 I observed 9 ± 4 cm. So we can take 10 cm as representative, for which the theoretical (no grille) and observed (with grille) profiles over the weir are shown below.



Above left, a strong flow will suck in any leaves and lawn clippings that are floating within range and thus reduce flow, in this case by about half. **Middle**, the outlet drawn to scale. The yellow areas show the reduction in flow caused by the grille when free of leaves. **Right**, close-up of flow as it enters the grille, dropping in level as the flow accelerates. Flow is from left to right. Early in 2011 the grille was replaced by a new design that made it impossible to measure or observe the flow, see picture on page 51. So what follows applies only to the old design.

Width is the effective width of the weir, which is not just the overall width minus the combined width of the grille uprights (which limits K to an upper bound of 3.7). It must also allow for the converging effects of water coming from all possible directions, for the blocking effects of the grille and any debris, for the losses due to friction and the (marked) turbulence, and for any unevenness in the weir itself. Also, the grille has cross bars and a gap at the bottom, so its effect will vary with depth. Overall there are so many unknowns that the effective width can be determined only by measuring the actual discharge, the idea being to evaluate K in the following equation:

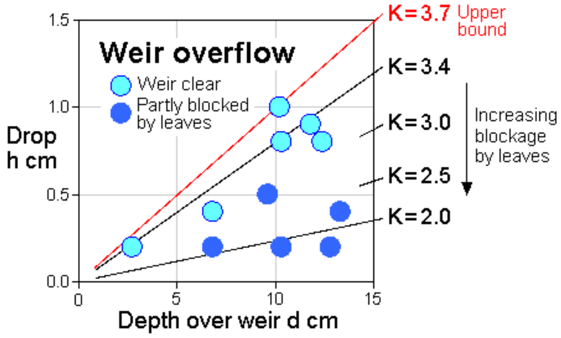
$$\text{Discharge cu metres per hour} = K \times (\text{head cm})^{3/2}, \text{ where } K = 0.052 \times \text{effective width cm.}$$

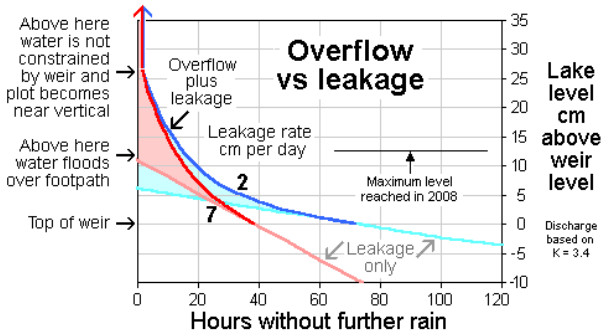
Once K is known, the discharge can be estimated for other heads. It is K along with leakage that determines the slope (ie decline) of the peak discharges recorded by Sim. Assuming the leakage rate for water just below weir level was the same in 1995 as it was in 2008-2009 (average 7 cm per day), the average of Sim's slopes indicate K = 3.4. Here an uncertainty in leakage rate of ± 1 cm per day equates to ± 0.7 in K. So the effective width is something like 3.4 / 0.052 = 65 cm, which is 20 cm narrower than the measured width of 85 cm. Of this 20 cm, about 28 x 0.048 = 13 cm is grille and the remaining 7 cm is due to converging and blocking effects present on those days in 1995.

Now K will still vary depending on leaf blockage, which introduces an unwelcome unknown into the calculation. But we can calculate the water velocity **v** over the weir from $v = \sqrt{2gh}$ cm per second, where **g** = acceleration due to gravity = 980 cm per second per second, and **h** is as shown in the diagram. The flow *into* the weir (which obviously equals the discharge *from* the weir) is then velocity x (cross sectional area = **d** x entrance width). Unlike the K equation, this measures the discharge directly, regardless of any blockages. Height **h** is most easily measured as the difference in **d** when the flow is temporarily stopped by a plastic sheet over the grille (clearly not an option for weirs such as Mundaring Weir). But here **h** is typically only a few mm in an inconvenient location, so its accurate measurement is difficult or (in choppy conditions) impossible. My observed values of **h** and **d** in 2008 and 2009 are shown in the plot below left, plus the corresponding values of K. The results suggest that K = 3.4 is a reasonable first approximation for a clear weir, so the discharge in cu metres per hour = 3.4 x (head cm) $^{3/2}$, which is 38 or 108 for head (**h**+**d**) = 5 or 10 cm.

Overflow vs leakage

As noted, a reduction in leakage would generally increase the overflow and therefore the amount of water lost to the groundwater. But a lake that is overflowing is also leaking. We cannot have one without the other. To put both into perspective, we can use K = 3.4 to calculate the discharge, and thus discharge-plus-leakage for various leakage rates. The results are shown below right:





Above left, despite the large errors likely in **h** and **d**, my results are consistent with the value K = 3.4 estimated from Sim's results, and with lower values between 2.0 and 3.0 when the grille is blocked by leaves. But even a severe blockage is not able to stop the flow completely. **Right,** the red and blue lines show how the lake level decreases when it is initially above the top grille, similar to Sim's (1995:55) observation on 6 September 1995, and assuming no further rain. Initially the level is so high that water bypasses the weir and flows directly into the drain, thus greatly increasing the outflow and giving a steep near-vertical plot. When water no longer bypasses the weir, the red and blue lines show discharge-plus-leakage for leakages of respectively 7 and 2 cm per day. The pale red and blue areas show the decrease due to overflow alone. (The plots do not allow for flood water soaking into the surroundings, which is considered on the next page.) At 7 cm per day the lake leaks as much water as overflows under a head of 8 cm, or 10 cm if blocked by leaves and K is say 2.5. When the level drops below the top of weir, overflow ceases, and the subsequent decrease is determined by leakage alone. Evaporation is generally too small to need considering.

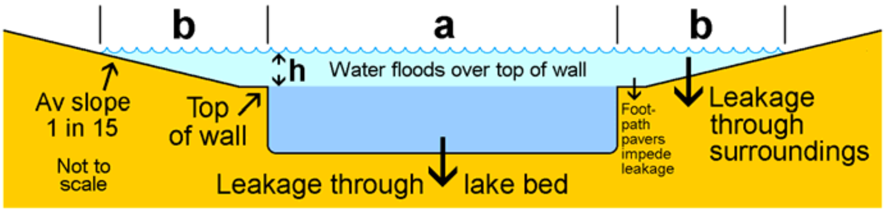
The plot above right is consistent with local opinion that even the extreme floods of the 1980s and 1990s lasted only a day or two, or somewhat more if heavy rain persisted. It suggests that raising the outlet above the flood levels likely today (just 15-20 cm might do), or even temporarily sealing the outlet except in an emergency, would not cause floods any worse or longer-lasting than those common in earlier years, and would return to the groundwater all water currently lost to the ocean. Indeed, raising the outlet by nearly a metre was one of Rockwater's (2005:23) several suggestions for retaining more water in the lake, albeit without the detail provided by the above plots, which would also require raising the footpath to avoid the possibility of being submerged by floods nearly one metre deep. Such changes would of course need the approval of the Water Corporation.

Soak pits

Soak pits typically 1.8 m diameter and 1.8-2.4 m deep at the end of each substantial road drain have recently been assessed for their boosting effect on groundwater (Rockwater 2009). Soak pits installed on drains leading into Lake Jualbup would reduce the runoff it receives, thus making it more likely to dry up, but would be pointless since the lake is already a giant soak pit. Nevertheless soak pits could be useful to reduce flooding if leakage was decreased in order to retain more water in the lake (Rockwater 2012). For starters, let us look at the effect of raising the outlet drain.

Effect of raising the outlet drain

If there is no outlet for excess runoff, the lake level will rise above the top of wall as shown below.



Above, as the lake level rises above the top of wall, water floods over the surroundings as shown in pale blue. The flood increases the lake area **a** by area **b**, whose size depends on the flood depth **h** and the slope of the surroundings. The flood will then leak into the ground water through both lake bed and surroundings. Leakage through the footpath is likely to be negligible. Except on the eastern side where the footpath is concrete 2.4 m wide, the footpath is two pavers wide (2 x 60 cm).

McFarlane's (1984:349) contours extend beyond the lake to the north and east, and indicate slopes roughly between about 1 in 7 and 1 in 25. For the grassed areas lining the footpath I found slopes varying from 1 in 6 to 1 in 70, average 1 in 15 for 98 measurements equally-spaced around the lake in a 2.2-metre wide strip, which translates to an average flood depth of 15 cm. The southern and eastern sides were generally the flattest. By independent autoCAD measurements the average slope is 1 in 19.3 for a flood depth of 30 cm and 1 in 25.7 for a flood depth of 80 cm.

Above, the grassed slope is steepest on the northern side, up to 1 in 6, but the footpath is lowest.

We can now estimate flooding by removing the upper cap in the calculation on page 30, which in effect stops water going down the outlet drain and allows it to flood over the surroundings. We can then calculate by simple geometry the extent of flooding and its depth, and thus how long the flood might last before it disappears into the surroundings, as shown next.

Duration of flooding

If water floods on to a lawn or grassed verge, the rate at which it drains away depends on the underlying soil, its wettability, its dryness, and to some extent how long the grass is. Dry sandy soil with grass 30 mm long can initially soak up water at more than 0.5 metres per hour (Carleton 1992), less if the grass is shorter, but the rate quickly drops as the voids fill and the soil becomes saturated. After 10-30 minutes the rate becomes constant at a rate determined by the soil permeability and the height above the water table. If the water table is close to the surface the rate will be slow.

McFarlane (1984:227) found permeabilities between 6 and 49 metres per day for lawns and verges in the Lake Jualbup catchment area, average 18 ± 14 for ten locations, and 25 ± 11 for five locations in nearby woodlands. These values are comparable with the 30 metres per day typical of the Swan coastal plain (p.245), the 14 metres per day estimated for sandy soils in Perth (Argue 2004:ch3), and the 1 and 10-11 metres per day assumed by Rockwater (2005a:4) for the vertical and horizontal permeability of compacted sands in the catchment area (they did not test lawns around the lake).

Argue (2004:3.2) warns that soils are variable, so the permeability of large sand areas can often be half that of a test hole. In what follows I use 6 m per day, the *lowest* value observed by McFarlane. The time taken for a flood to drain away corresponds to the emptying time of a storage pit following cessation of rainfall, which according to Argue (2004:3.1.1) is given by

Emptying time in days = J x depth in metres / K permeability in metres per day

where J is about 0.8 for cube-shaped pits, 0.2 for narrow extremely deep pits, and 2.0 for large very shallow pits similar in profile to a flooded lake. In this case the flooded depth varies uniformly from zero to **h**, which in effect halves both the depth and the emptying time, thus simplifying the equation to emptying time = **h** / K. The rate at which the flood drains away (ie depth / emptying time) is therefore **h** / (**h** / K) = K metres per day.

The above emptying time will obviously not apply if the storage pit extends below the water table, because by definition it can never empty. Nor can it be applied directly to the flood depths depicted on the previous page, because drainage rates per square metre for areas **a** and **b** are likely to differ, so water from the slower area will continuously replenish the water in the faster area. (Nor will it apply if the water table is close to the surface, as will tend to apply to an overflowing lake in winter, but for the moment let us ignore this complication.) We can proceed as follows:

First, to simplify the geometry, we treat the lake as a rectangular lake with the same shoreline (about 660 metres) and high-water area **a** (about 27,000 sq metres) as the actual lake, which gives a size of 150 x 180 metres. Second, we surround this rectangle with a footpath 1.2 metres wide and a grassed area **b** of slope 1 in 15. Two-thirds of the footpath are within ± 5 cm of its average level, so we can reasonably ignore variations. Finally we (1) pick an arbitrary starting value for depth **h** such as 0.2 metre, (2) calculate the corresponding volume as shown above in pale blue, (3) subtract the volume leaking through area **a** in a suitably small time interval such as 0.1 hour, at a given leakage rate through the lake bed such as 7 cm per day, (4) subtract the volume soaking through area **b** in 0.1 hour at a rate of 6 metres per day, the lowest value observed by McFarlane, (5) calculate a new depth **h** corresponding to this new volume, (6) repeat steps 3-5 until **h** is reduced to zero. Results obtained under these conditions are shown below. They suggest that floods as deep as 30-40 cm should not last much longer than a day or so:

Depth h m	Water extends over grass by m	Drainage rate when depth = h cu m per hr	Duration of flood days	Weir discharge when head = h cu m per hr
0.1	1.5	250*	0.7	110
0.2	3.0	495	1.0	300
0.3	4.5	745	1.2	560
0.4	6.0	990	1.3	1200 approx**

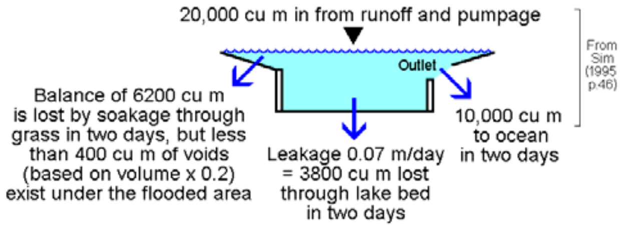
*Over 2 Olympic-size pools per day. **Boosted because water level is above grille.

Above, the wetted area increases with flood depth, hence the volume leaked also increases, so the flood duration (determined by volume leaked) increases less than proportionately – on average a 100% increase in flood depth increases flood duration by 40%. The last column shows what the discharge over the outlet weir would be (calculated as 3.4 x $(\text{head cm})^{3/2}$) under a head equal to the flood depth. At every depth short of covering the grille, the weir is always less effective at dealing with floods than allowing the same depth to soak naturally into the surroundings.

The above results are fairly insensitive to errors in lake area, perimeter, or slope (errors of ±20% change the flood duration by about ±10%). But they are sensitive to the soakage rate through the grass. For example, it may be less than 6 metres per day (according to Rockwater 2012:6 it might not exceed 0.2 metre per day). At which point we return to the complication ignored above.

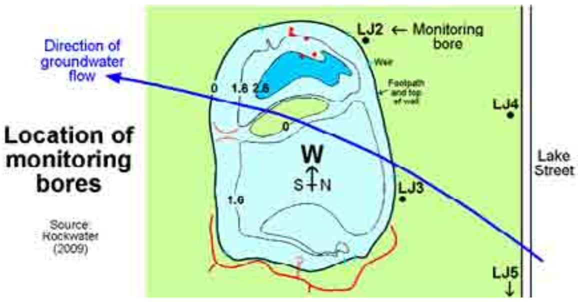
If the calculations are repeated with a soakage rate of 0.2 metre per day instead of 6, the above flood durations are 2-4 times longer. Rockwater (2012:7) also points out that soakage into the grass will be initially into the voids above the water table, and that once these are filled the soakage rate will be much reduced, perhaps to as little as 0.01 metre a day. But this further reduction has little effect on the new flood durations because they are now dominated by leakage through the lake bottom. Of course this will no longer apply if the leakage is sufficiently reduced.

At this point the outcome becomes critically dependent on the limiting soakage rate, for which no actual measurements are available. The nearest we have are Sim's (1995) findings as described on my page 36, where a likely flood depth of half a metre in a wet winter was all gone after two days, ie much quicker than if soakage was largely determined by voids. This diagram shows the situation:

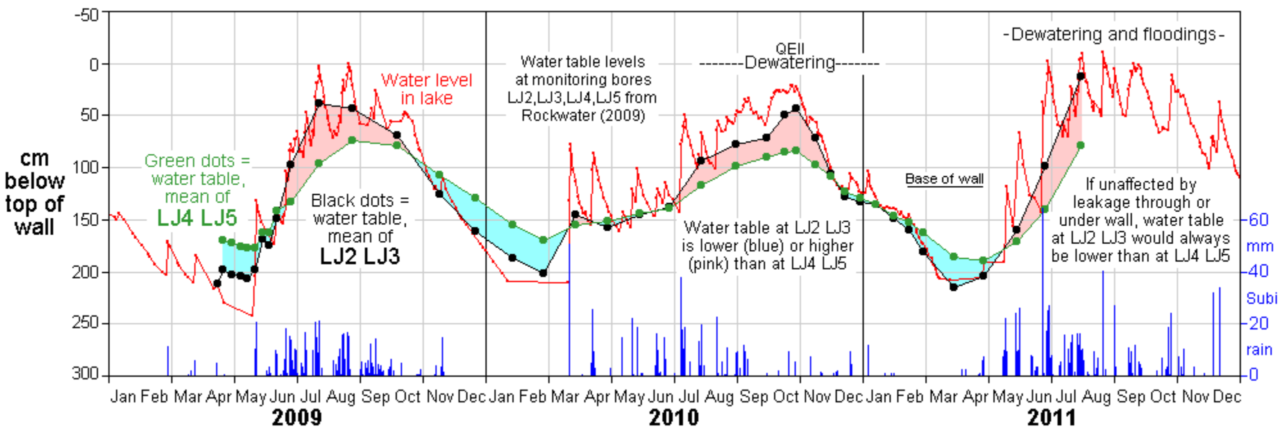


The above discrepancy might be explained if Sim had underestimated the outflow to the ocean. But it was measured by an ultrasonic data logger in the outflow pipe that bounced a signal off the water surface and calculated its depth from the return time. The sensor was almost impossible to foul with debris, and it recorded data continuously without any need for manual supervision. Sim estimated that the error associated with his inflow and outflow measurements was 17%, which is nowhere near large enough to explain the above discrepancy.

The discrepancy might also be explained if the voids and permeability under the grassed areas differ from the assumed sand, which is possible since the entire park was reclaimed from a rubbish tip in the 1950s. It would be consistent with local reports that even extreme floods of the 1980s and 1990s lasted no more than two or three days, even though the water table would have been higher than it is today. thus reducing the pressure head It would also be consistent with these observations of the water table by Rockwater (2009), reproduced without acknowledgement by RPS (2011:11 & 12):



Left, location of Rockwater monitoring bores, which are small bores that penetrate the water table in order to allow its level to be measured. LJ1+LJ2 are on the northern edge of Lake Jualbup. LJ3+LJ4 are next to Lake Avenue about 150m north of LJ2+LJ3.

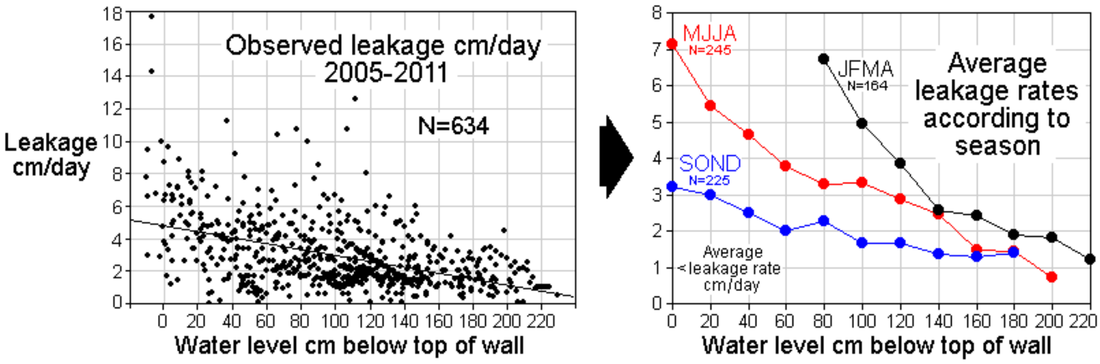


Above, When the lake is dry the mean water table at LJ2+LJ3 is lower than the water table at LJ4+LJ5, consistent with the downwards groundwater slope from north to south. These periods are shown with blue shading. When the lake is full, the former is higher than the latter, consistent with the former receiving seepage from the lake (pink shading). Notice how the crossover between blue and pink shading occurs when the lake is more empty than full, and is not too different between the filling and drying phases. In most cases it is when the lake level is below the visible base of the wall, generally 120 cm below top of wall, which seems to indicate that the travel time between lake and LJ2+LJ3 is quite short (so the permeability might be quite high). This relationship is not obvious in the original plot of the individual measurements, where the many measurements plotted at the same time make it hard to see the wood for the trees.

Regardless of how the discrepancy might be explained, it is clearly desirable to revise my model to conform with Rockwater's conservative estimates. The process and results are described next.

Revising the model to conform with Rockwater's (2012) estimates

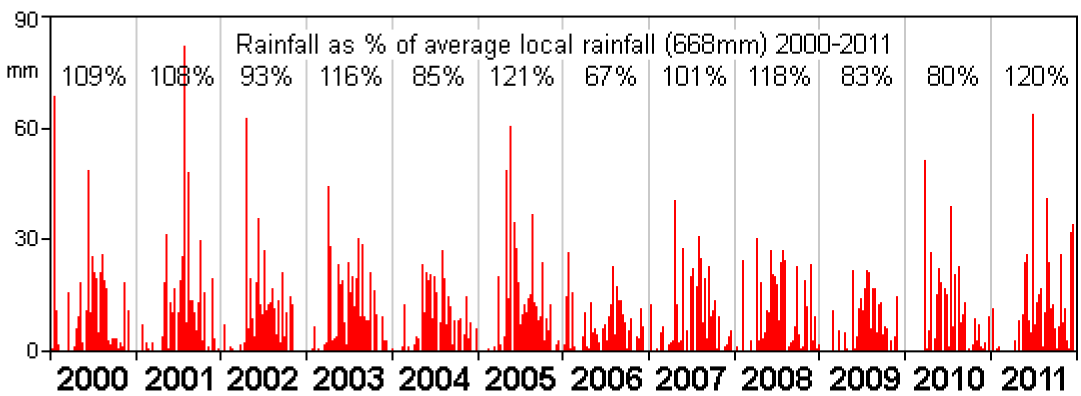
It was desirable to revise the model not only to conform with Rockwater's estimates but also to accommodate changes in variables such as outlet height. This required making use of the extensive data acquired since 2008, including better evaporation data, starting with leakage rates:



Above, when observed leakage rates are plotted against water level (**left**), the result is a confusing cloud of points. Leakage decreases as the water level decreases, but with too much scatter to be useful. But when the same data is divided according to season (**right**), the result is more orderly. As expected, leakage rates for a given level are highest when the ground is driest (JFMA), lowest when the ground is wettest (SOND), and in between when the ground is progressing from driest to wettest (MJJA). Division into smaller intervals, or with different dividing points, offered no improvement.

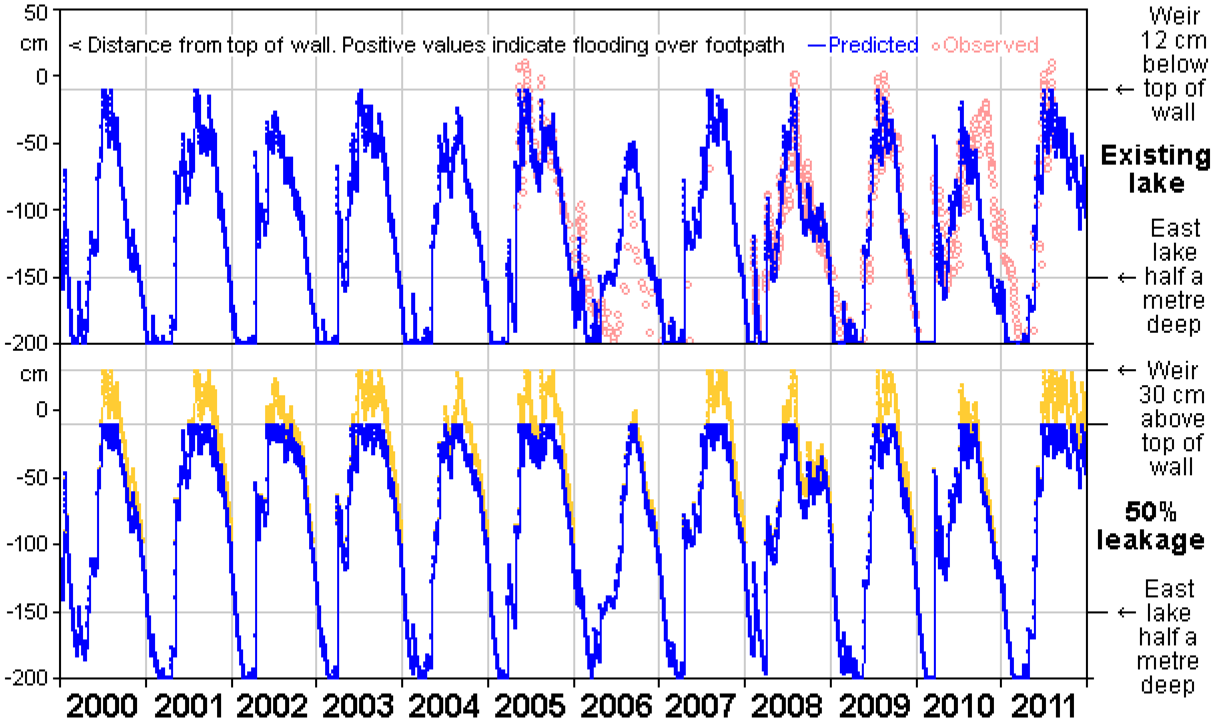
Trials using average leakage rates to determine lake levels instead of the previous approach (based on the ratio today's level / tomorrow's level, see page 30) were equally accurate in predicting lake levels (average difference between observed and calculated levels was again 15 cm), but were more accurate in predicting losses to the ocean. To conform with Rockwater's estimates, the soakage rate of flood water into grassed areas was set at 5 cm per day, and was reduced to zero once the voids beneath the flooded area were filled. The new model predicted water levels (including flood levels and water overflowing to the ocean) for 2000 through 2011 for any chosen combination of leakage, weir level, rainfall, and soakage. Predictions for earlier years will be increasingly unreliable because of changes in the water table, which has fallen by about one metre since 1980. The idea of course is to see what sort of compromise is possible between minimising loss of water to the ocean and maximising water levels in summer.

Some representative outcomes are shown below. They replace the data and discussions that appeared on page 41 of the previous version. First the Subiaco rainfall for the years 2000-2011:



Above, the main feature is the *variability* in both amount and timing. Look at the highest daily rainfall in each year. It can occur anywhere between January (2000, 2006) and July-August (2001, 2004). Significantly high years can be followed by significantly low years (2005, 2006) and vice versa (2010, 2011). These twelve years seem as good as any for their challenging diversity.

Next, examples of predictions for the years 2000-2011 that explore the effect of changing the leakage rate, weir height, and rainfall. An effective change in rainfall could occur through climate change or the installation of soak pits in the road drains, see bottom of page 38. To simplify modelling, water rising above the weir level is immediately lost (in reality it takes time, so the loss is overestimated), and falling water levels are capped at –200 cm (most of the water below –200 cm will occupy voids in the lake floor, so the model can no longer apply).

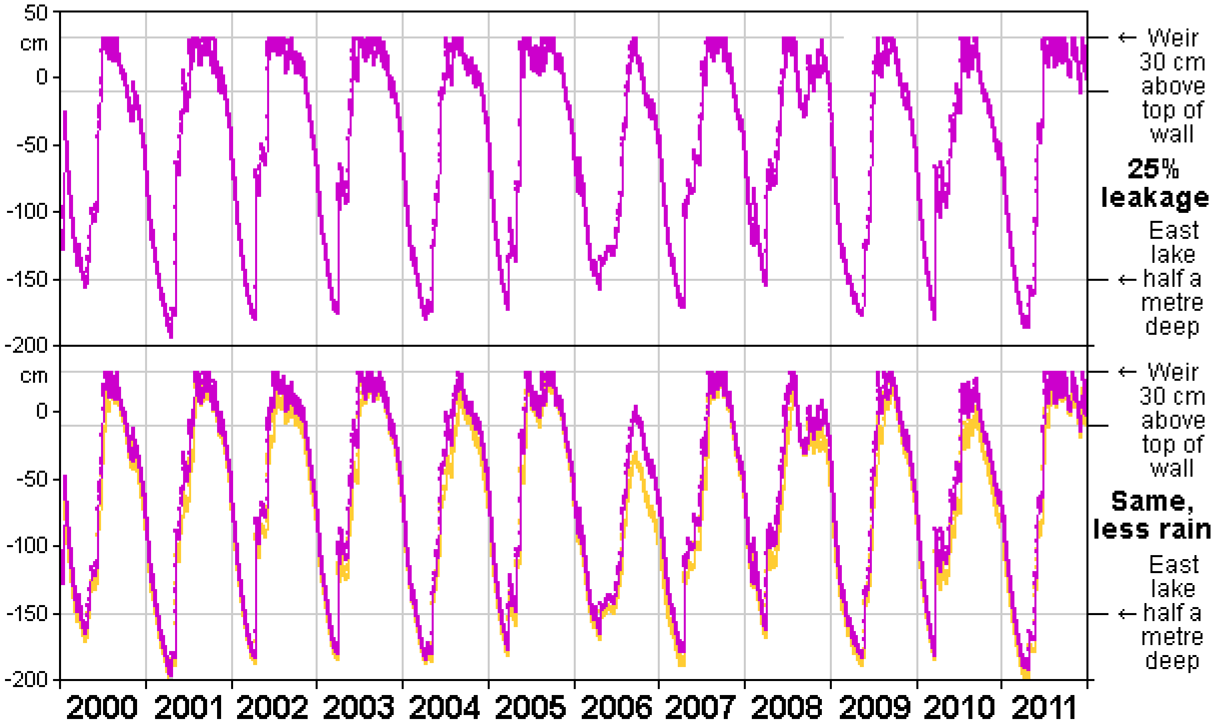


Above top, predictions for the existing lake. Average loss of water over the outlet during 2000-2011 is equivalent to 0.25m of water in the lake, just 19% of the average loss due to evaporation (1.34m) and 4% of the water lost by leakage. On average the runoff and pumpage received each year is equivalent to about 12m of water in the lake, or (depending on year) 6-10 lakefuls. In late 2010 and early 2011 there is a notable difference between observed and predicted levels due to dewatering at QEII building sites (the 2010 licence allowed removal of 90,000 cu m of groundwater, enough to fill the lake more than twice). **Bottom**, when leakage is reduced to 50% of the existing leakage, the average duration of half-metre depth is increased by more than six weeks and the average outlet loss is increased to 1.35m. This increased outlet loss can be offset by raising the weir to 30 cm above top of wall (yellow plot), which reduces the average outlet loss to 0.34m, or much the same as before, and increases the duration of half-metre depth by a further 3 days.

The above results show that a reduction of leakage to 50% and a small increase in weir height (both of which should be easily achievable at minimal cost) allow useful increases in water depth without a significant increase in the loss of water over the outlet. In most years the lake dries out to slightly more than shown in the picture below, where the water level is about 190 cm below top of wall.

Above, this picture is of the East lake. The West lake is deeper (see page 8) and is less affected.

However, as shown below, a further reduction in leakage to 25% has a major effect on drying out:



Above top, a reduction of leakage to 25% of existing leakage has a major effect on water levels – the average duration of half-metre depth is 13 weeks longer than for the existing lake, and the lake never dries out. Although leakage *rates* are 25% of existing leakage rates, water levels are higher, which (thanks to more pressure on the bottom) increases the actual *amount lost by leakage* above what it would otherwise be (here 84% vs 25%). But reducing the leakage to 25% increases the outlet loss to 1.25m (still less than the 1.34m lost by evaporation), which will also increase the frequency of flooding up to outlet height (30 cm). **Bottom**, the outlet loss and the frequency of flooding is much reduced by a decrease in runoff, as might occur through climate change or the installation of soak pits. Thus a 20% reduction in runoff reduces the average outlet loss to 0.47m, while a 35% reduction in runoff (yellow plot) reduces the outlet loss to almost nothing (0.09m). In each case there is a minor decrease of one week in the duration of half-metre depth, to respectively 12 and 10 weeks more than for the existing lake.

The above results suggest that reduced leakage, increased weir height, and runoff control via soak pits could, in the right combination, lead to almost any desired increase in permanent water while simultaneously maximising the return of water to the groundwater. If (as suggested by local reports, see page 41) soakage rates through the grass are higher than Rockwater's (2012) estimates, there might be no need for runoff control, which would of course allow much simplification. Because the model involves uncertainties (eg about rainfall, groundwater, leakage, soakage, outlet losses), the above results should not be taken too far. Trends should be more reliable than individual results.

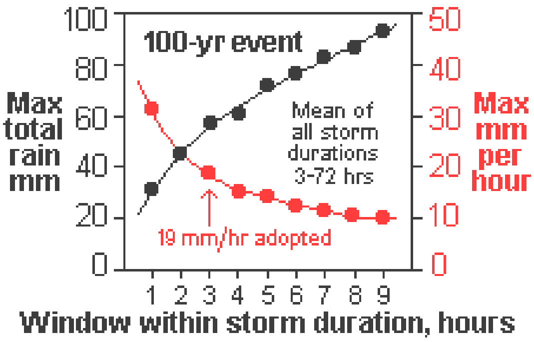
Above, in this picture the East lake is less than half a metre deep and the island is no longer isolated, but there is still plenty of birdlife and the lake is far from looking dry.

Behaviour of Lake Jualbup during a 100-year event

A 100-year event is the heaviest rain that can be expected in 100 years. For Perth the corresponding rain intensities for various storm durations (eg 0.5, 1, 24 hours) have been published by the EPA:

For storms lasting 6, 9, 12, 18, 24, 36 hour the average mm/hour is 13.5, 10.2, 8.36, 6.60, 5.57, 4.35.

During each storm the intensity will vary, and the variations for each duration have been published by Engineers Australia in *Australian Rainfall and Runoff* (1977), wholly revised (1997, reprinted 2001). In general their figures indicate that about 40% to 50% of the rain will fall in about 1/6th of the duration. To find the maximum mm/hour for various periods (and thus the worst case scenario) the data for storm durations of 3, 6, 9, 12, 18, 24, 36, 48, 72 hours were swept with a window of 1,2,3…9 hours to find the maximum rainfall falling inside each window. The results are as follows:



As expected, the maximum amount of rain falling inside a given window varied with storm duration, with a maximum when the window = storm duration. But the variation within typically six maximums was modest (standard deviation averaged 7% of the mean, the mean was typically 90% of the largest maximum), so to keep things simple the mean is plotted here. As expected, the maximum rain intensity (red dots) decreases as the total amount of rain increases (black dots).

It is not clear what the worst case scenario might be. High intensity is important, but it is needed for a sufficient duration to create flooding. Thus 32 mm/hr for just one hour (total 32 mm) might not be enough, whereas 19 mm/hr for 3 hours (total 57 mm) seems a reasonable starting point.

Calculation of 100-year flooding

From field measurements, we know that the amount of water being delivered by rain + runoff + pumpage averages 19.4 x rainfall intensity, so 19 mm/hour will deliver 18 x 19.4 = 370 mm/hour or 0.37 m/h over the lake area of 28,000 sq m, or 0.37 x 28,000 = 10400 cu m/h, enough to fill an Olympic-size pool every 15 minutes. Over a 3-hour period at this intensity we assume (1) the lake is full at the start, (2) flooding increases until soakage through the grass equals the rate of delivery, and (3) rainfall + runoff + pumpage are sufficiently in sync to not upset the calculations.

If the outlet is inundated it should permit the discharge of about 1200 cu m/h (see page 40), leaving about 9200 cu m/h for the grass to soak up. What effect does lake leakage have? Leakage through the lake bed will be around 8 cm/day or 0.003 m/h, which is negligible compared with a rainfall intensity of 0.37 m/h. So lake leakage has almost no effect on a 100-year outcome.

The area of grass needed to soak up V = 9200 cu m/h is V / soakage rate m/h. Measured soakage rates in the general area (no measurements have been made next to the lake) are around 30 m/day or 1.25 m/h, which will therefore need about 9200/1.25 = 7360 sq m of grass to soak up the above rates of flooding, which correspond to a depth above the footpath of about 0.7 metre. But if the water table is near the surface, the soakage capacity of the grass will be much reduced, see page 41. Clearly there are too many unknowns (rain, water table, soakage, lake and grass status at time of the 100-year event) to allow even a ballpark estimate. But that is not the end of the story.

Because (1) the Water Corporation will have necessarily approved the existing outflow size and position for a 100-year-event, and (2) lake leakage has almost no effect on a 100-year outcome, we can conclude that there is no point in trying to guess the various unknowns, especially when a drying climate seems likely to reduce 100-year intensities. That is, the existing outlet has already been deemed to cope, albeit at the expense of losing water to the ocean. Nor is there much point in trying to *precisely* estimate a new outlet position to accommodate any flooding due a reduction in leakage, because it is easier to try first and adjust later, especially as a trial outlet could be fitted with an automatic gate that opens in emergencies. Yes, there are many unknowns, but they need not present insurmountable problems.

Concluding remarks

The future of Lake Jualbup is a controversial issue. It always was – see my companion work shown opposite for a look at its history. But controversy thrives on incomplete or one-sided information. So in the present work I have summarised the relevant scientific information in plain English without urging any particular view of the lake's future. I have not looked especially at environmental or community issues, both of which are covered in the companion work.

Lake Jualbup is a holding pond for road runoff that would otherwise overwhelm the road drains. It receives far more water than a comparable natural lake, most of which is presently lost by leakage. Modest reductions in leakage would reduce the present drying-up in summer, even with continuing small falls in the water table. The outlet weir presently discharges surplus water to the ocean, yet may (or may not – it depends on whose assumptions you accept) be less effective at dealing with floods than allowing the same depth to soak naturally into the surroundings. Manipulating the outlet weir deserves attention, especially as it would cost almost nothing.

In summary, the volume of water received by the lake is so large that even dramatic falls in the water table and rainfall need not have dramatic effects on lake levels, although some drying up in drought years might be hard to avoid. Since these things can be calculated, nothing need be left to speculation, which should allow the future lake to be whatever the community chooses.

Above, a wet lake is arguably more useful to wildlife than a dry one.

Next page: Wraiths of mist on a frosty morning. Tranquil family weekends. Perfect reflections are rare due to wind eddies and wave-making ducks. Sunsets that light up the lake are almost as rare.

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The WA Department of Agriculture, Bureau of Meteorology, and Water Corporation provided data as cited in the text. I thank Stan Rudrum for help in obtaining official rainfall data, Leigh Alver for helpful comments, Mark Wilshusen for early lake photographs and proofreading, Allan Stoney for lake level measurements 2005-2007 and autoCAD contour areas, Dr Roger Passmore principal hydrogeologist of Rockwater for helpful discussion and technical advice, Dr Don McFarlane of CSIRO for reading the whole work and making helpful comments, Dr Sandie McHugh of the Department of Water for a copy of her PhD thesis on CD, Jeremy van den Bok Manager Parks & Property Town of Vincent for details of Hyde Park Lakes restoration, Professor Neil Coles UWA Department of Ecohydrology for information on bentonite, and Mayor Heather Henderson for encouraging this work's circulation (in 2009) to Subiaco councillors.

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Left, new outlet grille installed early in 2011 makes it impossible to measure or observe the flow. The badly deteriorating brickwork was not repaired. **Right,** flooding over footpath, August 2011

The secret life of water in Lake Jualbup

INDEX

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