

# **LAKE-GROUNDWATER EXCHANGE: Using The Capel Wetlands For Managed Aquifer Recharge With Discharge To Artificial Wetlands MARDAW**

Bill Scott , Song Qiu and Arthur McComb

*School of Environmental Science, Division of Science and Engineering,  
Murdoch University, Perth, WA 6150*

Email: [B.Scott@murdoch.edu.au](mailto:B.Scott@murdoch.edu.au)

## **Abstract**

A chain of mining-created wetlands in Capel, southwestern Australia, was maintained largely by an inflow of mineral processing water from the 1980s. Now the inflow has ceased and the mining site should allow the reclamation of wastewater from the townsite as 'Managed Aquifer Recharge and Discharge to Artificial Wetlands' (MARDAW).

The biology, lakes and groundwater have been managed and monitored since 1991; the wetlands are surface expressions of the local superficial aquifer. Various lake-groundwater models have evolved, especially to predict and interpret the impact of cessation of the mining inflow. With MODFLOW the recharge at the onset of heavy rains was shown to be absorbed by the local aquifer, with little change between the middle of June and late August. The diversion of inflow and the dry period in 1995-1996 created a 1.5 m drawdown in northern lakes, Swampen and Island. More drawdown is also predicted at the middle to southern part of the system, Tigersnake and Plover lakes.

Design variations also come from modelling the effects on flows of tree removal upstream and vegetation planting, including an analytical element model and a simplest model based on Excel. Design calculations suggest that the lake system will be nutrient-saturated in about 5 years. However, groundwater throughflow was ignored; it allows displacement, dilution and confinement of the wastewater; effects that may remove 85% of the nitrogen and 70% of the phosphorus in a 10 year period. It is possible that a chain of three lakes could be sustainable as a receiver for wastewater. Proper implementation of MARDAW may reclaim the wetlands as suitable ecosystems that require minimal intervention.

Keywords: groundwater, wetlands, aquifer, lakes, recharge, discharge, MAR, DAW, reclamation, inflow, diversion, displacement, mining, rehabilitation

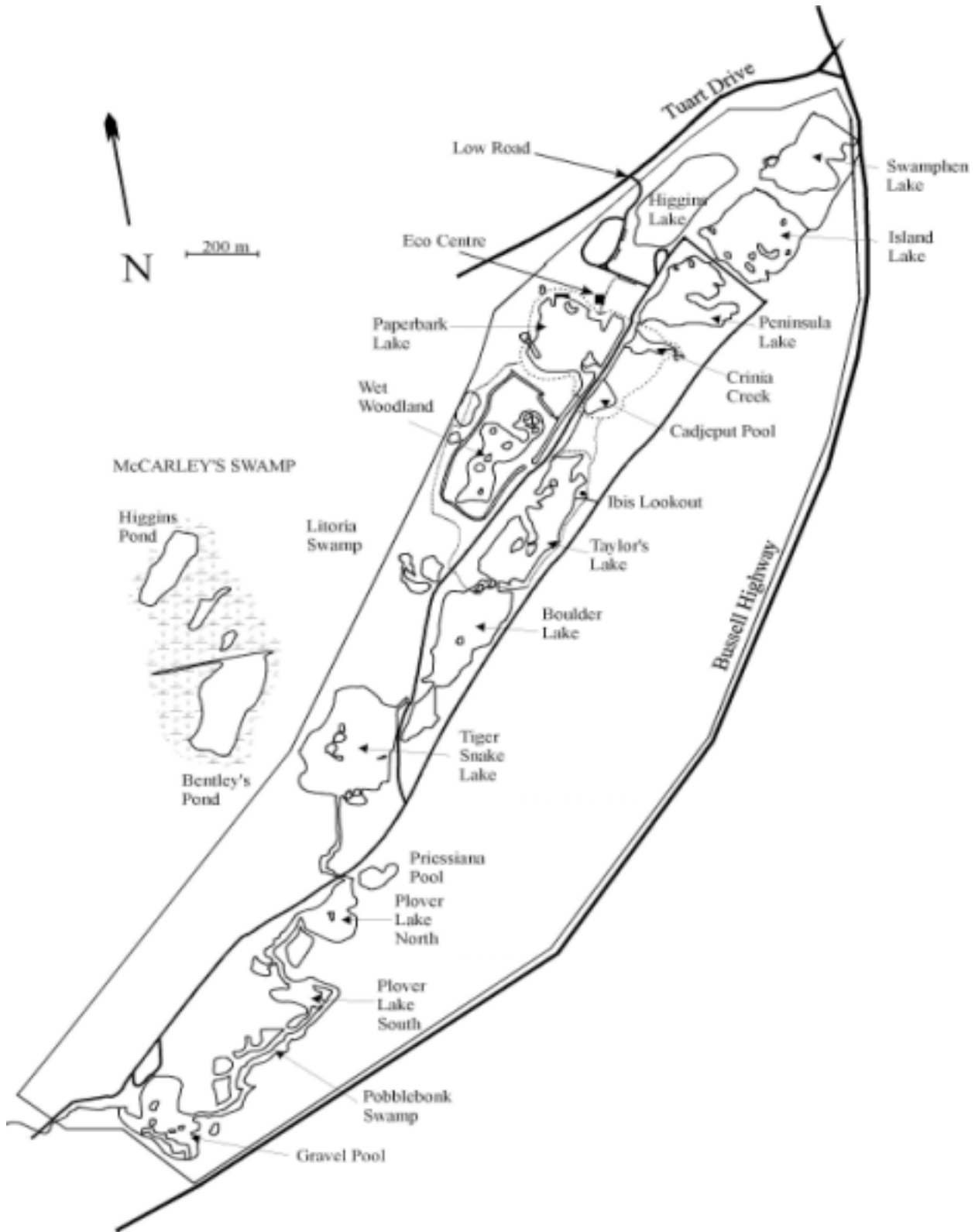
## **Introduction**

Wetlands cycle nutrients, support life in many forms, and deposit carbon as detritus. Small wonder that we look to use them to treat wastewater. In this case we seek to reclaim processed sewage water from the town of Capel and capture it for future use of the environment and people, using 'MARDAW', Managed Aquifer Recharge with Discharge to Artificial Wetlands.

The wetlands that make up the Capel Wetland Centre (CWC) are a series of approximately 15 lakes, swamplands and sumplands (see Figure 1, next page). The Centre has been developed from mining pits created by sand mining (Davies 2002). From around 1980 the CWC wetlands were artificially recharged by effluent water from the nearby ore-processing plant. The effluent water was acid (high in ammonium and sulphate and low in phosphorus) but was treated in the 1990s with lime to reduce the acidity. The water levels continued to be maintained by the effluent

water through 2000 though the discharge was moved from Swamphen Lake (the uppermost lake to the Northeast) down the chain into the adjoining creek system and Peninsula Lake (see the accompanying maps; Figure 1, Figure 2 and Figure 10).

Figure 1. Planar view of the Capel Wetland Centre. Before 2000 plant effluent discharged into Swamphen Lake.



There has been almost continuous monitoring of the CWC since 1980. Intense research efforts (more than 50 refereed papers with many reports and postgraduate theses) have investigated the biological and physical state of the CWC (see Bennetts 1998; Chambers et al. 1998), including surveys of birds, reptiles and mammals as well as the progression of revegetation, including special efforts to propagate near stream, emergent vegetation, macrophyte and microphyte communities (Davies 2002; Iluka Resources Limited 2004). Surveys of indicator species, flora and fauna, including invertebrates and microbiological communities, algae and carophytes. Detailed topographical surveys of the land and lakes have been completed. Nutrient studies have emphasised the general deficiency of phosphorus, with a tendency for the 'metasediments' to absorb added phosphorus within days. The metasediments are slimes deposited from the mining operations; in some of the lakes the metasediments may be more than 10m deep.

Here we use the combined measurements of lake levels and groundwater to estimate the effect of adding a nutrient stream from wastewater. The special feature of the CWC is the tendency to be nutrient deficient. Figure 3 illustrates the relative responses of lake and groundwater levels; they respond together showing the hydraulic connectivity between the wetlands and the superficial aquifer. The level of

Figure 2. The topography of the CWC. The lakes occupy pits along the 'ridge' in a roughly N-S direction, draining to the south and into the Ludlow river; the river 'wraps around' the southeast and turns west and into the Indian Ocean at Geographe Bay.

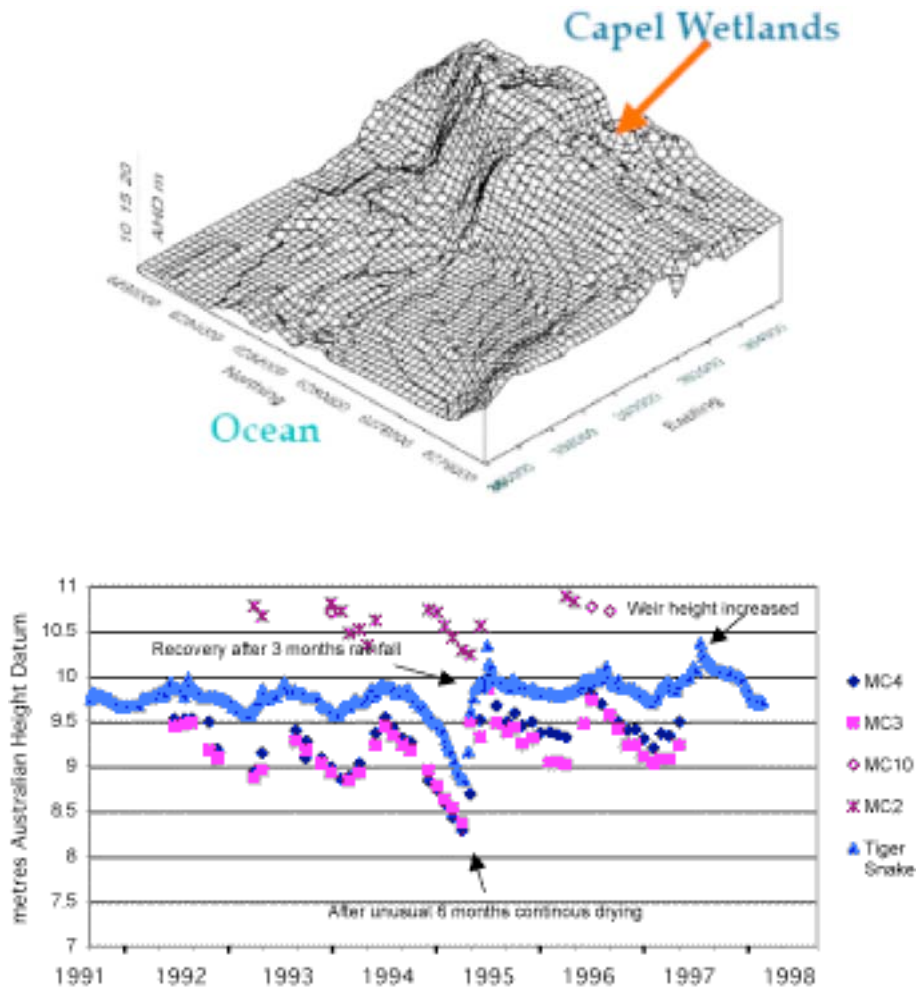


Figure 3. The lake level in TigerSnake Lake follows water levels in nearby bores.

water in TigerSnake lake, particularly, shows that groundwater responses 'follow' lake levels. As a whole, the lake responses show some correlation and grouping, an observation used by Staaden (2002) to complete a minimalist model, with three lake groups. Figure 4 presents these variations and how they grade from the top (north, Swamphen) to the bottom (south, Gravel Pool). Some lakes are effectively 'topped up' by groundwater flows or process water addition (Peninsula and Cadjeput) or simply because of the location of weirs; other more isolated lakes depend on the annual variations in rainfall and evaporation. Note Swamphen before and after 1995 when the process water supply was moved.

The early work of Nield and Townley (1985) simulated the groundwater responses to watering/dewatering from the nearby plant and possible natural fluctuations, using finite differences on a triangle grid, a planar version of what became the AquaFEM and Flowthru Models\*. The model treated the lakes as expressions of the water table. With little data on the properties of the aquifer or historical data, they concluded that the lakes would be more or less preserved with or without the effluent from the plant.

## MODFLOW

Qiu et al (2000) repeated the calculation including more than 10 years of historical data and estimates of topographical and hydraulic properties, using MODFLOW, the standard, layered model produced by the USGS\*\*, a model used in court cases as a basis for judgement. The model requires numerous adjustments and calibration with real data to reproduce groundwater isopotentials; this includes some judgements on boundary conditions and flows, transmissivities and storage coefficients of the different layers, as well spatial variations in topography and hydraulic barriers. In this case, it was necessary to place an aquitard between Island and Peninsula Lakes and to the west of these lakes. The results show an almost perfect fitting of piezometric data from boreholes.

With the model running in a predictive mode, several scenarios were considered; runs were initiated with a mean rainfall of 800mm/yr for 10 years, followed by a dry

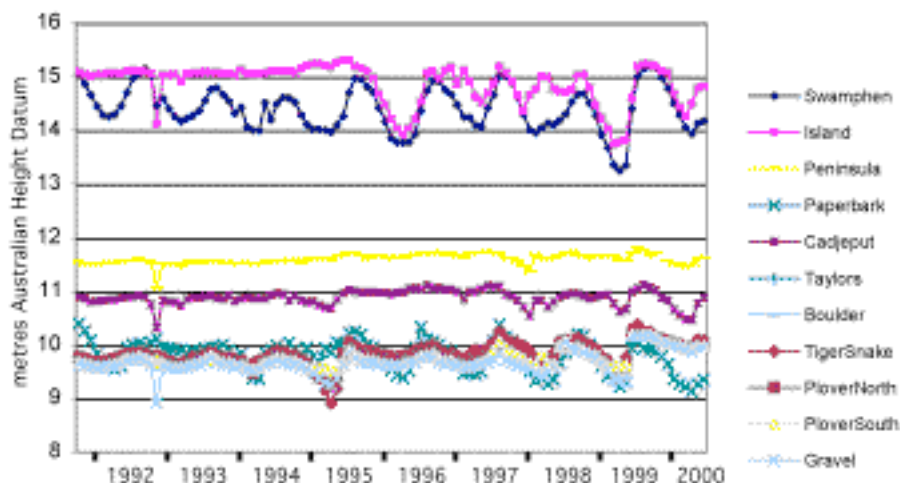


Figure 4. Lake level variations with climate and an altered discharge of effluent.

\* Numerical models for the simulation of lake-groundwater interactions generated by the CSIRO and Lloyd Townley and Associates, see <http://www.townley.com.au/flowthru/>

\*\* The United States Geological Survey. [http://water.usgs.gov/software/ground\\_water.html](http://water.usgs.gov/software/ground_water.html)

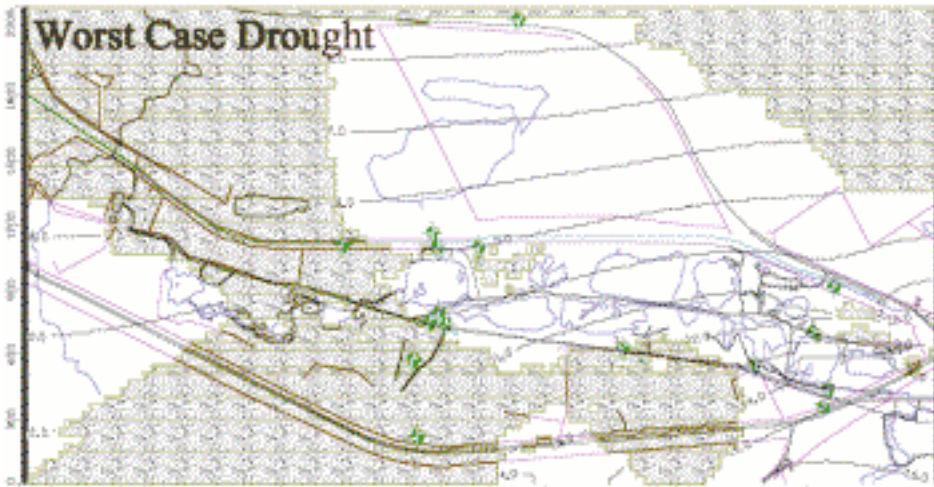
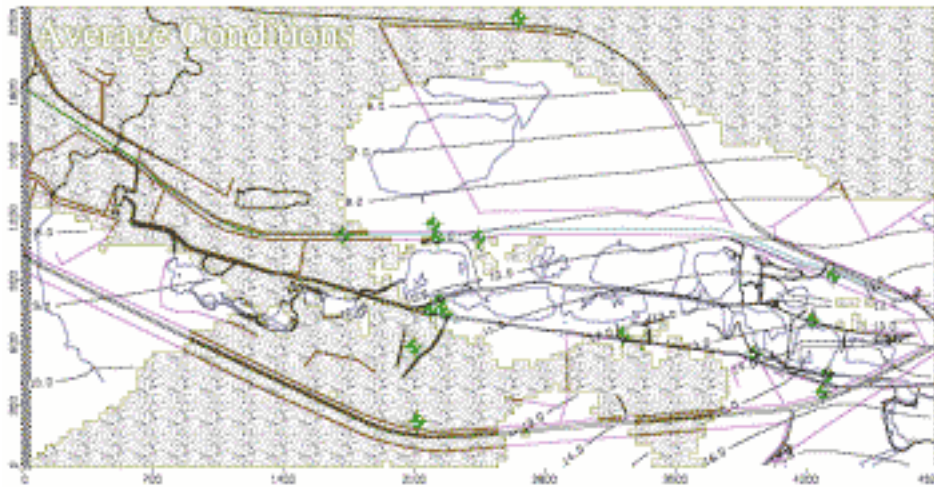


Figure 5. Planar view of the Capel Wetland Centre CWC. MODFLOW simulations from Qiu et al. (2002). North is to the right. Dry areas are textured; wet areas, white. Top-Early Wet Season; Middle-Average Conditions; Bottom-Worst Case Drought. The lakes and various cadastral features, boundaries and roads, are outlined. Boreholes are half-filled, circled crosses. Axes are distances in metres from an arbitrary SE position.

period of 1200mm/yr for 10 years, with the inflow of mineral processing water removed as well, equivalent to 2600mm/yr. The results were similar to those of Nield and Townley, that is, the fluctuations were within known climate fluctuations. See Figure 5 on the previous page. Generally, the lower lakes were fully maintained through the drought but the upper lakes diminished in height, some near to drying. In the bottom case the (textured) dry areas have invaded the lake system, but the lakes have not dried.

### Vegetation

Staden completed a vegetation study of the CWC and surrounding catchment using ground transects and Geographical Information Systems GIS; Figure 6 shows how the vegetation density has changed with time. Figure 8 shows the detail; almost independent of the CWC, the catchment is recovering from clearing surrounding the CWC that occurred around 1994. Apart from revegetation at the Centre, the largest effect was from logging of state forest in the vicinity, the lighter areas being those with little vegetation.

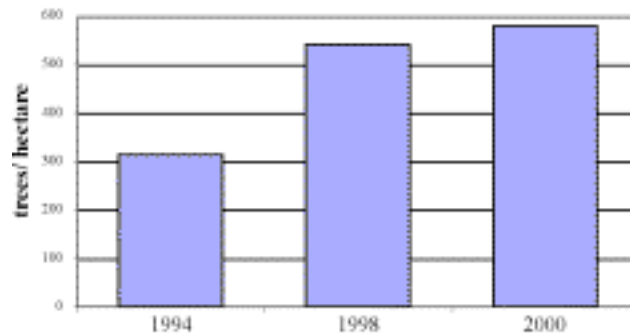


Figure 6. Stand Density, the vegetation coverage in the catchment of the CWC. From Staden (2002)

The pine forests around the CWC, notably up-gradient to the east, were logged around 1994. There was a large increase in flows in the Ludlow River (Figure 7), especially just downstream from the Happy Valley Gauge. Though there have been many spikey runoff events since, the overall increase in base flow receded around 1999, with the forest regrowth. The CWC has also been revegetated (Figure 8) but the small area of the CWC is not expected to significantly impact on regional flows.

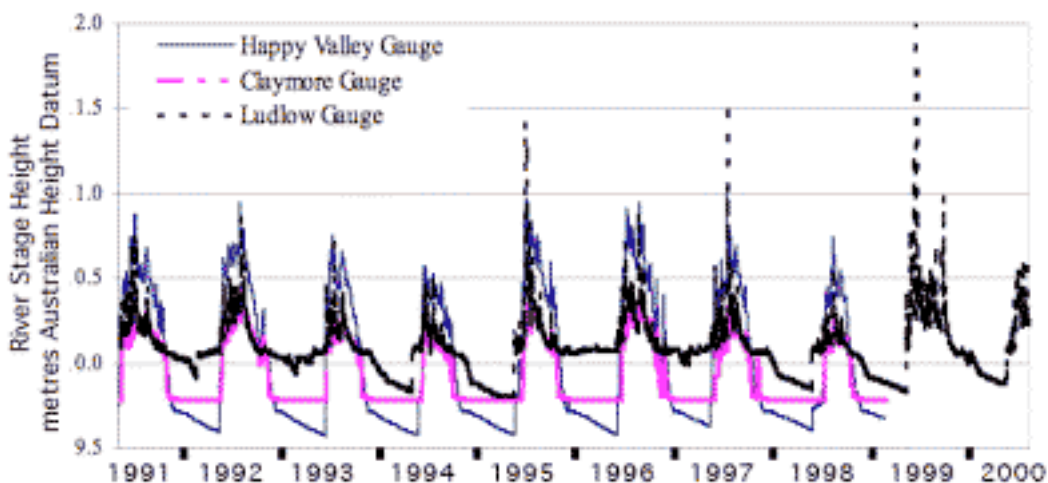


Figure 7. The stage of the Ludlow river during a period of Pine Forest Logging. From Staden (2002)

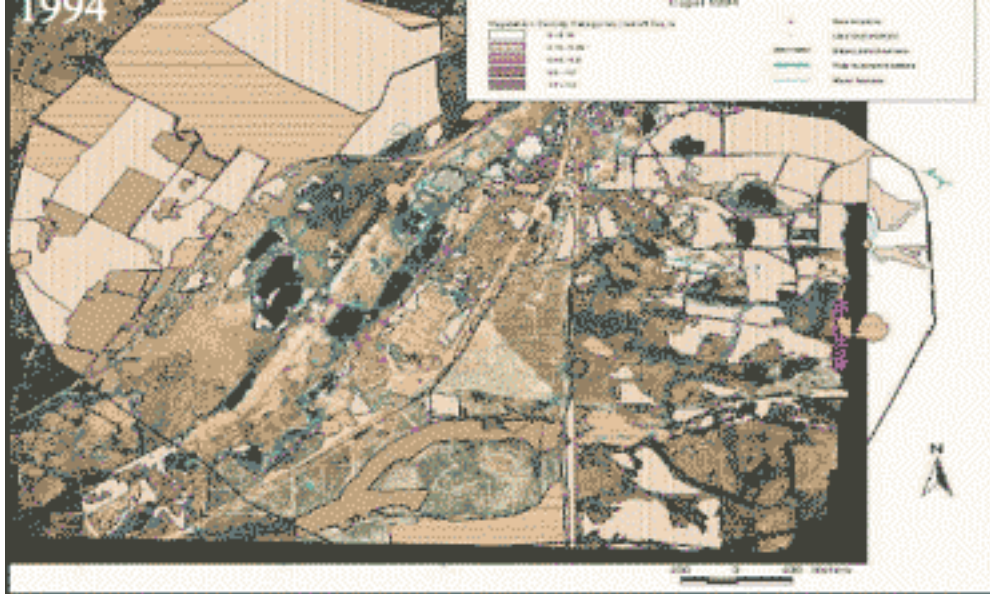


Figure 8. Plan view of the CWC with false colours interpretations by Stadden (2002); Top-1994; Middle-1998; Bottom-2000. North is at the top.

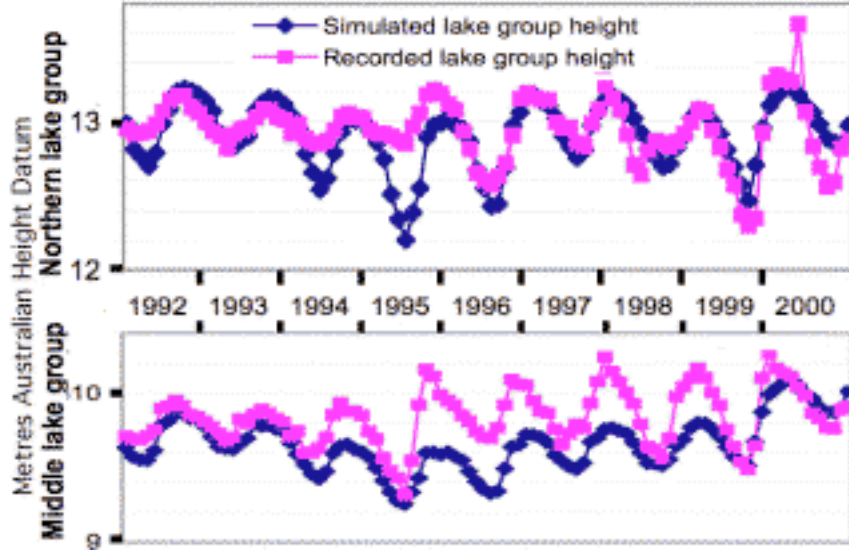


Figure 9. Responses of groups of lakes, from Staaden (2002). The diamonds are simulated values; the squares are recorded lake levels. Top-Northern lake group  
Bottom-Middle lake group

### Excel

Staaden evoked Occam's razor to produce a minimalistic model in terms of mathematics and parameters, using Excel. First, she looked at correlations of recorded lake levels; many were highly correlated; the ~15 wetlands could be grouped into 3 groups that were relatively uncorrelated; Southern, Middle and Northern. Further, she used single values of recorded measurements of the watertable at bores nearest to the lakes to measure the recharge or discharge from the lakes, using Darcy's law and estimated transmissivity values.

Figure 9 shows that the simulations were successful. With calibration and parameter adjustment, Staaden found that:

- a) Pine Harvesting increased the recharge around 1995.
- b) Regrowth since has significantly increased vegetation density.
- c) Groundwater flows remain sufficient for maintenance of the wetlands.
- d) Modelling of the wetland chain as three water bodies (groups) is adequate.
- e) Wetland levels are predicted to fall if the effective transmissivity around the wetlands is less than 5 m<sup>2</sup>/day.

Importantly, almost no flow measurements, as from pumping tests, or even the data from the weir that discharges into the Ludlow River, have been properly utilised in the assessment process. Since levels, as predicted by any of the models, can be altered overall by the ratio  $\frac{\text{recharge}}{\text{transmissivity}}$ , flow data is essential in any future calibration. Of course, it is flows that enter the wetlands at the start of the chain and which discharge into the Ludlow river. It is a mistake to continue modelling, especially complex modelling, without properly recognising these flows.

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\* Adrian Peck of Adrian Peck and Associates, private communication. Adrian's estimate of transmissivity from extended pumping tests at the plant site across the road is 50 m<sup>2</sup>/day; he also has developed Analytical Element techniques for use at Yanchep.

## Maple\* Algorithm

The lake and groundwater data were fitted into an interpolation function to get a 'best fit', a minimum of the some of the squares of the residuals, an Algebraic Element method. This is a superposition scheme (Bouwer 1978; Freeze and Cherry 1979) whereby the groundwater heights (isopotentials) respond in a mathematically-linear fashion to individual physical mechanisms. Significant elements in the water balance are considered and real locations, lake levels and groundwater levels; minimising the sums of the squares of the residuals, maximum likelihood, obtains best values of the parameters:

1. The lakes are considered as 'pumps'. That is, they act to supply or take up water (recharge or discharge) surface and boundary points at a single isopotential head. That head varies with time depending on the inflows and outflows and the lake storage characteristics. The pumping is in a quasi-steady state, that is, within a time scale of weeks and close to the lakes, the cone of depression follows the Theim equation, the logarithmic form in Equation 1. The term  $B_i$  is effectively the classic term  $Q_i/2\pi T_i$ , the recharge  $Q_i$  divided by the transmissivity  $T_i$ , for lake  $i$ .
2. The groundwater flow follows the Dupuit-Forscheimer Approximation with primarily horizontal flows. The regional groundwater flows are driven by the regional gradients in the  $x$  and  $y$  directions,  $C_x$  and  $C_y$ . Regional variations of hydraulic conductivity are cared for by a cross term,  $C_{xy}$ .
3. Regional recharge is determined by the convergence or squared terms  $x^2$  and  $y^2$ ,  $C_{x2}$  and  $C_{y2}$ ; the double derivative (Laplacian) and the  $x$ ,  $y$  directions; the  $xy$  terms do not influence the recharge.
4. The local direct lake rainfall, runoff and evaporation at the CWC is cyclic on a yearly cycle, perhaps with a trend; see the terms with  $b$ ,  $c$  and  $d$ .
5. There is a separate linear and cyclic regional or climatic trend characterised by coefficients  $C_l$ ,  $C_s$ , and  $C_t$ .

$$\sum_{i=1}^{NL} \{LR (1 + b \cos(t) + c \sin(t) + dt) \pi R_i^2 + B_i \ln(r_i/R_i)\} + C_\theta + xC_x + yC_y + yxC_{xy} \\ + \frac{(C_{x2}x^2 + C_{y2}y^2)(1 + b \cos(t) + c \sin(t) + dt)}{2} + C_l + C_s \cos(t) + C_t \sin(t)$$

Equation 1. The interpolation equation from Maple. Broadly, the terms  $\{ \}$  represent rainfall/evaporation and inflow (recharge) to each lake  $i$  where  $R_i$  is the effective radius. The terms premultiplied by  $x$  or  $y$  are gradients in the groundwater, postmultiplied by  $x^2$  and  $y^2$  are recharge or convergence, and the last three terms are linear and cyclic trends in rainfall/infiltration.  $LR$  as well as the small and large  $b$ ,  $c$  and  $d$  values are parameters that recognise the cyclic rainfall/evaporation and lake geometry at the CWC.

The effectiveness of the fit is broadly presented in the figures of Table 1. The figures emphasize the cyclic effects but the variability is generally much less than a metre. It is clear that lakes somewhat isolated from the groundwater system (SwampHen, Island, Paperbark, Wetwoodland, Litoria) show fluctuations to yearly rainfall and evaporation; the fitting algorithm shows about half as much oscillation. Peninsula

\* Registered Trademark of Waterloo Maple Inc., see <http://www.maplesoft.com/>

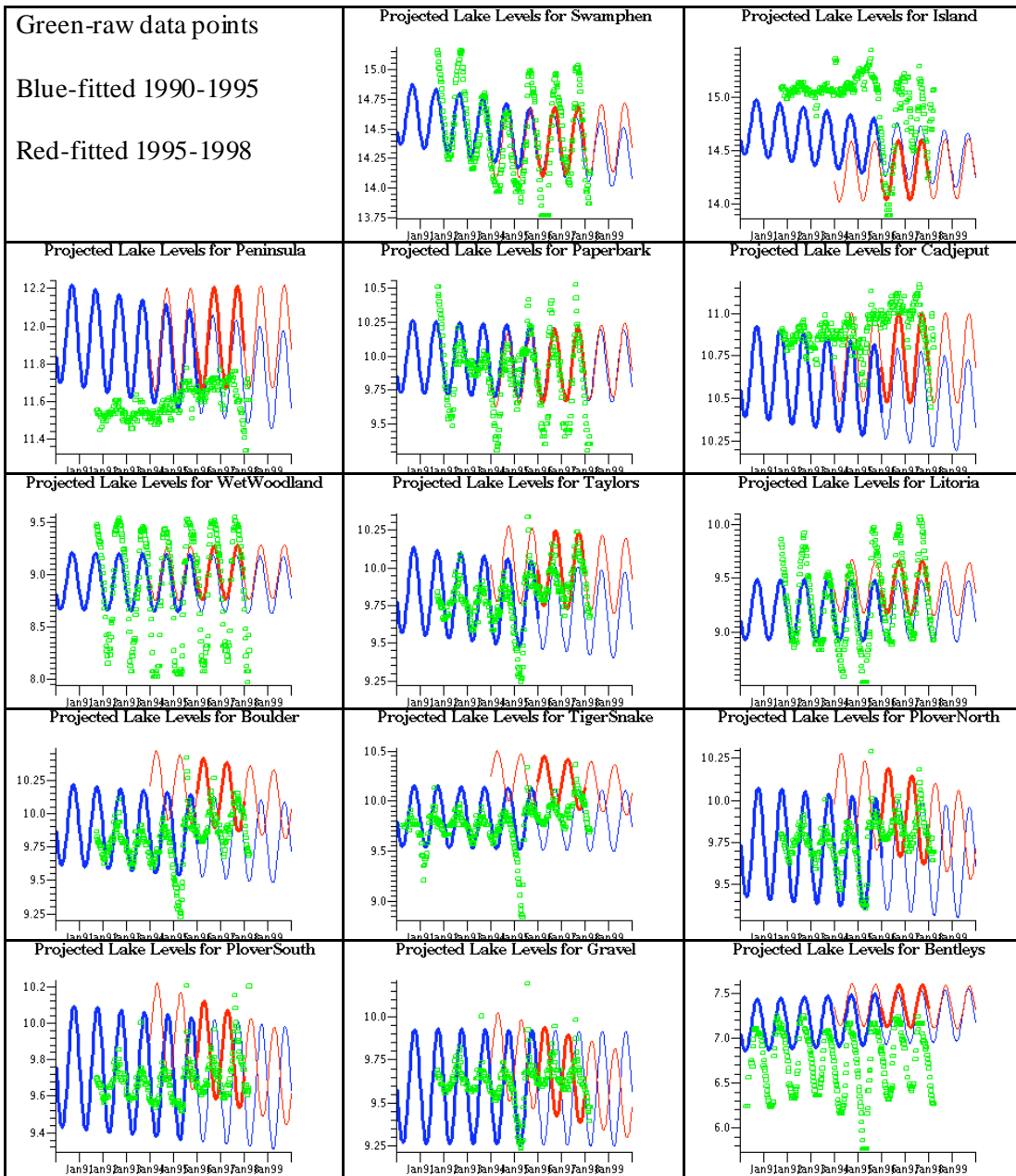


Table 1. Measured Lake levels and fitted, cyclic trends. The abscissa is unclear but corresponds to a time period of 1990 through 2000.

and Cadjeput were ‘topped up’ after 1995 with plant effluent and there was little change in levels the following years. Other lakes are not so directly affected and show a little less than the predicted change (Taylors, Boulder, PloverNorth, PloverSouth, and Gravel); these are all well-connected to the groundwater and respond closely to the groundwater fluctuations. Bentleys shows a lower water table than expected and also large fluctuations; it is a special wetland relatively unconnected to CWC, a ‘natural’ water body degraded by grazing; fluctuations are affected by drainage and it is broadly isolated from the CWC.

The fitting process gives, perhaps, first values of significant hydrological parameters for the CWC. Table 2 shows estimated recharge to individual lakes. Values of Q come forward, the water added to individual lakes through process water addition.

Surprisingly, values are nearly the same before 1995 as after 1995, despite the fact that the water was added further down the chain of lakes. There was some redistribution of water, however, with more loss from Swamphen and most of the gain to Paperbark and Cadjeput. Indeed, Staaden (2002) showed that water levels in Island, Peninsula, Paperbark, and Cadjeput are correlated and grouped them in her model; water added to one lake is conveyed to other, nearby lakes through surface or underground channeling. Adding the values for the gains to these lakes and using a effectively transmissivity T of 100 m<sup>2</sup>/day, the total added process water was 1500 m<sup>3</sup>/day. To match the actual process water addition of 2600 m<sup>3</sup>/day would require a T of 170 m<sup>2</sup>/day. Nield and Townley (1987) used a hydraulic conductivity of 50 m/day, in their model roughly equivalent to a T of 1000 m<sup>2</sup>/day. The referral document (Water Corporation 2003) uses a hydraulic conductivity of 55 m/day, T around 2000 m<sup>2</sup>/day. Qiu et al (2002) used an effective T of 1300 m<sup>2</sup>/day in the surficial aquifer with MODFLOW to fit the observed groundwater levels; however, hydraulic barriers were found to be necessary, particularly between Island and Peninsula lake. A T of ~200 m<sup>2</sup>/day seems low but all the literature values are based on calibration with groundwater isopotentials; it is well known that isopotentials are insensitive to T values<sup>\*</sup>; they are scaled with the ratio Q/T. Appropriate T values should properly stress the aquifer with long-term pumping tests; which have not been completed at the CWC. A significant, long-term pumping test<sup>\*\*</sup> near the plant site across the Busselton Highway, did yield a value of 50 m<sup>2</sup>/day.

	Q/T	Q/T	Avg Q		
Lake	1990 thru 1995	1996 thru 1997	With T=100 m <sup>2</sup> /day		Area
Swamphen	-3.04	-3.57	-331	Losing	0.034
Island	7.22	6.11	667	Gaining	0.052
Peninsula	2.12	2.11	211	Gaining	0.033
Paperbark	2.02	2.48	225	Gaining	0.041
Cadjeput	3.81	4.32	407	Gaining	0.029
WetWoodland	-8.65	-6.42	-753	Losing	0.023
Taylors	1.63	1.23	143	Gaining	0.044
Litoria	-.50	-.51	-50	Losing	0.0013
Boulder	7.61	8.53	807	Gaining	0.046
TigerSnake	1.27	2.04	165	Gaining	0.065
PloverNorth	-17.0	-26.3	-2163	Losing	0.018
PloverSouth	-.93	0.78	-7	Losing	0.010
Gravel	5.71	4.73	522	Gaining	0.030
Bentleys	-2.06	-1.49	-177	Losing	0.040

Table 2. Water added to individual lakes as suggested by the algorithm.

\* Adrian Peck, private communication.

\*\* Again, from Adrian Peck and Associates, Subiaco.

The present analysis uses the geometric features of the lake-groundwater system and the filling of the lakes acts as a pumping system. Perhaps  $T \sim 200 \text{ m}^2/\text{day}$  is a realistic value.

Further, the coefficient  $C_{xy}$  may represent a variation in the E-W transmissivity in the S-N direction; the factor is close to  $1 \text{ m}/\text{km}^2$  and suggests a lower  $T$  to the north. Hence, until long-term pumping tests can be completed, it is reasonable that a lower transmissivity is appropriate for Swampphen and Island Lakes; this information also fits with the knowledge that Swampphen and Island lakes have extreme loadings of metasediments.

The Capel townsite WWTP presently discharges approximately  $200 \text{ m}^3/\text{day}$  of secondary treated sewage water to infiltration ponds. There are continuing difficulties with clogging and maintenance of the ponds, and on several occasions they have overflowed into the Capel River. Additionally, the population of the area is one of the fastest growing in WA and in future the discharge may be more than  $1000 \text{ m}^3/\text{day}$ . For 25 years the CWC has been intensively developed and has attractive ecological features; however, it is clear that, without added nutrients, particularly phosphorus and nitrogen, the CWC is not a sustaining ecosystem. This is mostly because of the presence of the metasediments but also a lack of nutrients. The discharge is well



Figure 10. The catchment; the Capel and Ludlow Rivers with the CWC, lower left.

within the hydrological capability of the wetland system as the former plant discharge was around  $2600 \text{ m}^3/\text{day}$ .

Hence it was proposed by the Water Corporation (2003) that the discharge from the WWTP be pumped into the CWC. The three uppermost lakes would be used in series, with the initial discharge into Swampphen lake, with sequential flow to Island and Peninsula lakes. For flexibility the plan allows for discharge into any of the four uppermost lakes be controlled by manual valves. Additional treatment of the waste water is to include aeration, alum dosing and phosphorus adjustment, caustic soda pH adjustment, as well as chlorination to remove bacteria, before primary contact.

## MARDAW

Here is where Managed Aquifer Recharge with Discharge to Artificial Wetlands MARDAW comes in. It hinges on the idea that any water supplied to an aquifer adds to the water supply. It is less important where or how or maybe even the quality of the added water, provided the water can be added and the aquifer properties, transmissivity and storage coefficient, are not disaffected. In this specific example the Capel townsite uses deep and surficial aquifers for water supply. Capel sits south of the Capel River; the Ludlow River is, some, 5 km to the southwest, and wraps around the CWC (Figure 10, previous page). Between is a confused surficial system which approximates a groundwater mound. The Capel River is about 20m AHD; the topography rises to around 30m AHD halfway to the CWC and drops to around 10m at the Ludlow River, below the CWC and closer to the coast. The groundwater flow is distinctly west or southwest with mounding above the CWC. The CWC is in hydraulic connection with the aquifer mound, so importing wastewater into the CWC makes water available to the environment and the Ludlow River. Such groundwater recharge would slightly alter the mound to make the mounding more to the north and, in the long run, the Capel townsite would see more surficial groundwater. The waste water is effectively 'displaced' in MARDAW, processed by the groundwater inflow/outflow to the CWC and the surface wetland ecology. This natural process only requires a philosophy of 'water capture and storage' for the long haul. Natural systems, particularly wetlands, have been and continue to be effective this way, to allow sustaining living systems and survival with drought.

The pictures of Figure 11 show some historical variations of MARDAW. In the concept of Soil Aquifer Treatment, SAT (Bouwer, 1989) uses recharge ponds as infiltration basins that permit vertical or horizontal filtration through the soil to recharge the aquifer. SAT requires multiple basins for aeration and recovery because of clogging. Scraping or overturning regenerates the basins; phosphorus is removed with scraping and harvesting; nitrogen through drying/wetting cycles and the action of denitrifying bacteria.

The middle picture shows Aquifer Storage and Recovery; ASR recharges the Aquifer (lower part of picture) from either a pond (right of the picture) or recharge well (middle). Water is

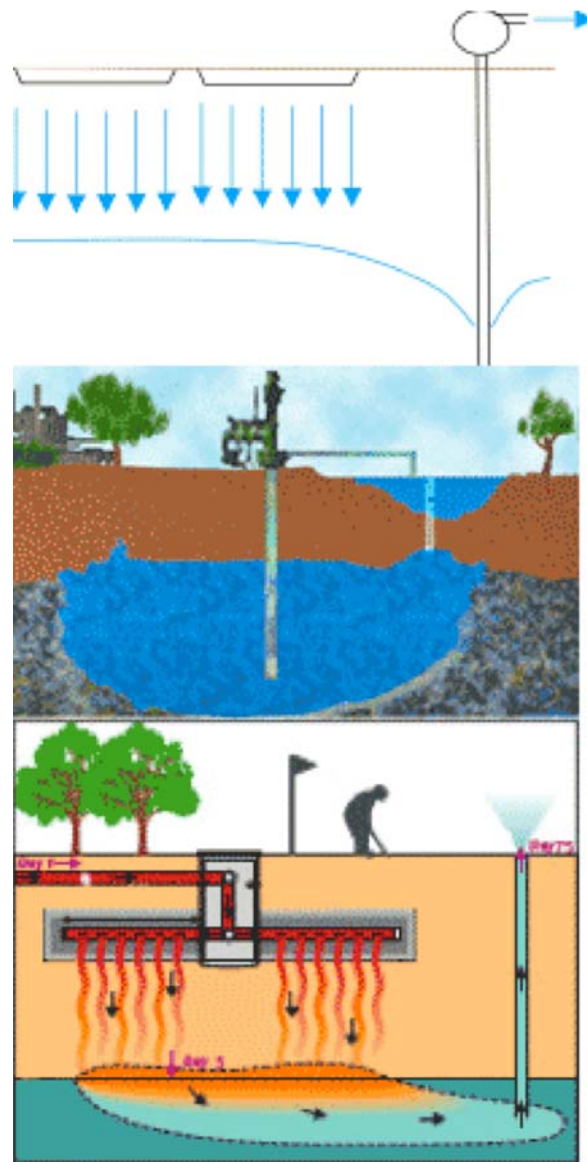


Figure 11. top to bottom: SAT, ASR and MAR

recovered from a similar pump screened for discharge, after some time in the aquifer (below), perhaps months, perhaps 10s of years. Nutrients and contaminants are removed during infiltration or through the filtering, absorption and biological actions of the aquifer, and long resident times.

In Managed Aquifer Recharge MAR active and fitted infiltration basins, percolation chambers and/or recharge wells store water in the aquifer. There may be no immediate plans for recovery. Nutrient and contaminant removal occurs through actions of the aquifer.

Constructed Artificial Wetlands CAW are storage ponds or lagoons used to treat water to acceptable standards. Wetlands are usually only used for the later stages of treatment; reeds, bullrushes and waterweeds form part of the treatment.

Discharge to Artificial Wetlands DAW allows that input water is processed in wetlands isolated from the aquifer and naturally deviant features; plants, sediments and turbulence may be used to process the water. Nutrients and chemicals are added or removed to maintain the wetlands. Intervention is through removal of plants, sediments and alterations in the flows (through weirs).

MARDAW is all inclusive; it interlaces surface water systems which process the water either before or after it enters or leaves the aquifer, and should produce the equivalent of a restored natural wetland system.

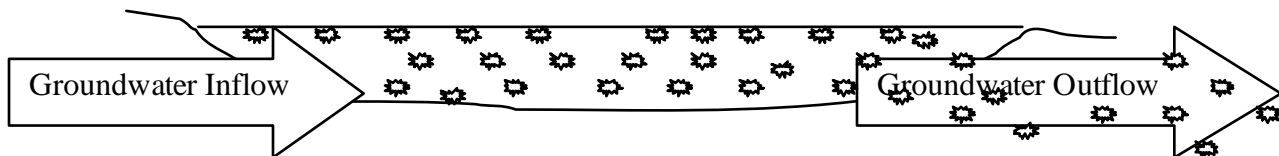


Figure 12. The displacement, dilution and confinement effects of MARDAW. The horizontal groundwater inflow mixes with the lake water and captures the nutrients in the outflow, even if the inflow and outflow are the same. The nutrients are stored in the aquifer downstream and are processed in the long time frame of the aquifer.

### Swamphen Lake

The referral document from the Water Corporation (2003) has detailed modelling that suggests that discharge to an individual lake; SwampHen, Island or Peninsula; would not be viable. A combined, serial arrangement, however, is workable with increased flows. Tables 3a,b,c present indicative summaries for Swamphen Lake\*. The other lakes show diminished effects going to zero for about a five year period. The N and P concentrations in the lake approach that of the wastewater in one to three years of operation. Thereafter it will be necessary to have intervention, perhaps harvesting, overturning the sediments or dredging. Remember that the lake sediments have a large capacity for sorption of N and P; without overturning, however, absorption may only penetrate into the first few mm of metasediment.

The referral document (Water Corporation 2004) indicated that water quality improvements come primarily from vegetative uptake and denitrification (for N) and

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\* Tables 3 and 4 are redone and include horizontal groundwater flows.

sediment uptake (for P). The balance considers vertical infiltration with seepage through sediments, conveying nutrients to groundwater. However the balance doesn't consider the full consequences of groundwater interchange; the Horizontal Inflow and Horizontal Outflow from groundwater. This feature is the heart of MARDAW; see Figure 12 on the previous page.

Table 3a. Water budget\* in ML for Swamphen Lake with 10 mg/L input to swamphen.

Water	Inflow	Rainfall	Evaporation	Seepage	Overflow	Ground water Inflow**	Ground water Outflow**
2002	60	23	19	8	48	80	88
2004	61	23	20	11	33	80	88
2006	88	23	20	9	62	80	88
2008	128	23	20	7	104	80	88
2010	140	23	20	7	116	80	88

Table 3b. Projected nitrogen budget in Swamphen Lake. Tonnes unless noted.

Nitrogen	Input	Seepage	Vegetation Uptake	Denitrification	Discharge	Ground water Output	Average lake level mg/L
2002	1.79	0.06	0.18	0.3	0.3	0.5	7
2004	1.85	0.11	0.18	0.3	0.2	0.6	9
2006	2.63	0.11	0.18	0.3	0.5	0.7	10
2008	3.83	0.10	0.18	0.3	1.0	0.9	12
2010	5.03	0.12	0.18	0.3	1.4	1.1	16

Table 3c. Projected phosphorus budget in Swamphen Lake. Tonnes unless noted.

Phosphorus	Input	Seepage	Vegetation Uptake	Absorption	Discharge	Ground water Output	Average lake level mg/L
2002	0.60	0.26	0.02	0.08	0.10	0.19	2.9
2004	0.61	0.33	0.02	0.07	0.07	0.18	2.7
2006	0.88	0.39	0.02	0.10	0.18	0.26	3.9
2008	0.93	0.31	0.02	0.11	0.31	0.26	4.0
2010	1.06	0.35	0.02	0.12	0.38	0.29	4.3

The spreadsheets, Tables 3a,b,c (above) and 4a,b,c (next page) are repeats of the tables in the referral document including groundwater inflows and outflows. The numbers are not entirely the same; the nutrient outflows are all considered to depend on the concentration in the outgoing flow, including the seepage and absorption. Still, the tables are 'calibrated' to give roughly the inflows and outflows predicted in the document. The lakes were considered to be at the decant level at the start of the simulation and the start time is notionally 2002 for comparison. The time is extended to 2010; the calculations are done on a yearly basis though only even years are shown.

\* These tables are variations of the indicative tables in the GHD referral document (Water Corporation 2003)

\*\* Calculated from the Maple algorithm. The divergence of the flux is calculated between pairs of points on the lake perimeter and is the lake loss per unit volume. The extra loss is taken as a portion of the seepage so the water balance is maintained.

\*\* Also calculated from the Maple algorithm. The inflows can be separated from the outflows to give detail of the flow pattern around the entire lake.

The N levels in the original table in 2006 were 25 mg/L; P, 10 mg/L. Table 3a,b,c shows that there is some advantage through groundwater throughflow and displacement of N in Swamphen Lake, though there are still rather high levels of nutrients. Similar values are found on the spreadsheet if the wastewater is put directly into Peninsula Lake. With the groundwater flows, the chain of lakes still works more efficiently than a single lake. Considering Peninsula Lake as a third member of the chain receiving water from Island Lake, and that Swamphen received wastewater at 10mg/L P, the large throughflow of groundwater to Peninsula Lake has stretched the time for the lake system can process both N and P (see Table 4b,c). The N levels from Peninsula lake start to become high only after about 2010 (8 years). Surprisingly, there is sufficient dilution by the groundwater that the P levels actually stabilise before 2010. Note that, (ignoring overflow or discharge), the fraction of N directly removed by groundwater is ~48%; P, ~40%. Other than overflow, seepage is the other significant removal mechanism for nutrients. Here seepage is a vertical component that flows through to the aquifer; hence the total N removed by groundwater is 85%; P, 70%.

Table 4a. Water budget in ML Peninsula Lake. Lakes in series. 10 mg/L Input P to Swamphen

Water	Inflow	Rainfall	Evaporation	Seepage	Overflow	Ground water Inflow	Ground water Outflow
2002	36	21	36	36	139	360	230
2004	39	22	39	39	136	360	230
2006	57	22	54	54	132	360	230
2008	61	23	58	58	165	360	230
2010	70	23	66	66	162	360	230

Table 4b. Projected nitrogen budget in Peninsula Lake. Tonnes unless noted.

Nitrogen	Input	Seepage	Vegetation Uptake	Denitrification	Discharge	Ground water Output	Average lake level mg/L
2002	0.11	0.00	0.08	0.15	0.00	0.00	0.0
2004	0.4	0.04	0.08	0.15	0.04	0.06	0.7
2006	0.79	0.19	0.08	0.15	0.15	0.22	2.4
2008	1.02	0.39	0.08	0.15	0.36	0.43	4.6
2010	1.32	0.67	0.08	0.15	0.54	0.66	7.0

Table 4c. Projected phosphorus budget in Peninsula Lake. Tonnes unless noted.

Phosphorus	Input	Seepage	Vegetation Uptake	Absorption	Discharge	Ground water Output	Average lake level mg/L
2002	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2004	0.11	0.03	0.00	0.04	0.03	0.05	0.42
2006	0.49	0.17	0.00	0.15	0.10	0.17	1.55
2008	0.70	0.25	0.01	0.21	0.17	0.23	2.11
2010	0.96	0.39	0.01	0.28	0.22	0.31	2.84

## Discussion

The Maple algorithm has composited the entire system with horizontal groundwater flow using separate data sets for 1990-1995 and 1995-1997. Considering Swamphen, the total groundwater inflow is around 80 ML/year; the outflow is about

the same, leaving a consistent loss to horizontal groundwater flow of about 8 ML/yr; this is using a transmissivity\* T of 200m<sup>2</sup>/day. There is almost no variation in groundwater input/output through the 7 year period 1990-1997. Staaden (2002) included groundwater flows and suggested that T needs to be greater than 5m<sup>2</sup>/day to maintain the upper wetlands; a common value she used was 25m<sup>2</sup>/day. Before 1995 Swamphen Lake was relatively constant in height at about 14.5 m AHD. With no plant discharge it seems overflow should happen only on rare, heavy rainfall events. The rather small amount of wastewater to be added would not significantly alter the overflow, unless the weir or pipelines used to connect the lakes is maintained at a low level.

Here we have used the algorithm and the volume-area relationships for Swamphen lake and Peninsula Lake to estimate the levels of nutrients that might be expected with the advent of wastewater addition. The scenario starts to add wastewater into the lakes in the year 2002 and (as far as possible) the conditions used in the referral document (Tables 3 and 4). That includes fluxes that are independent of concentration, except for the groundwater outputs, seepages and lake outflows. There is special detail in the specifics of inflow/outflow by groundwater flow. For each pair  $x, y$  following the perimeter of the lake a first consideration is the volume-area relationship. This was well done by Paul Fowler and Associates. Unfortunately the data do not show detail in the positioning of the edges of the lake, the perimeter as the lake height changes; we presume that the lake retains the same shape as it dries with the same centroid; values on the perimeter of the lake are recalculated to fit the known area values. The groundwater flux (Darcy flux) at an average position is used to calculate the flow through that length of perimeter. Vectorwise the flow estimate is the dot product of the vector flux and the  $\Delta x, \Delta y$  vector formed from the pair, multiplied by the effective aquifer depth. These flows are sorted into positive (inflow or recharge) and negative (outflow or discharge) and added for each pair of points around the lake.

## Summary

With extensive monitoring and understanding the CWC wetlands system is becoming attractive and progressing towards a natural wetland system. There is a need for a sustaining source of nutrients, and the use of wastewater and MARDAW will probably fill this need. As the plan evolves we need to monitor and adjust our management and research, and perhaps intervene to make sure the system remains macrophyte dominated, and not fall into a eutrophic, algal dominated state.

MARDAW emerges because of the rather ideal structure of the CWC. The upgradient, upland lakes have a minimal connection with the aquifer and will allow surface anerobic effects and the biology to start the processing of the wastewater without substantial contamination of the aquifer. Middle lakes have a strong connection with the aquifer and groundwater displacement, and dilution can easily take place. That leaves the other lakes to 'mop up' and fresh water, purified by surface processes, but mostly which has come from the aquifer, to flow into the Ludlow River. The nutrients and contaminants are used by the biology, both in the surface wetlands and below, within the groundwater matrix. The water may stay within the groundwater matrix for 10 or more years before any use by the environment or people.

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\* The flows are directly proportional to the effective transmissivity

Ordinary detailed and simple modelling supports this work but there is a continuing lack of proper, long-term pumping tests to ascertain the exact transmissivities and storage coefficients. Perhaps continuing monitoring and flow measurements, with detailed perimeter values and lake topographies, will serve the same purpose. But this requires an investment and continual records of physical and biological properties along with flora and faunal studies.

The wildlife studies are perhaps a forte of the CWC and it may well become the location of some endangered species. We would hope that the background physics and engineering will ensure a perpetual home for them.

## References\*

- Bennetts K (1998) The effects of cessation of wastewater input on water quality and the health of the ecosystem at the RGC Wetlands Centre, Capel. School of Environmental Science, Murdoch University. Technical Report 41.
- Bouwer H (1978) *Groundwater Hydrology*, Superposition, pgs 204-207, McGraw Hill Book Company, New York, USA
- Bouwer H (1989) Estimating and enhancing groundwater recharge, In *Groundwater Recharge*, M. L. Sharma, Ed. Balkema Publishers, Rotterdam, The Netherlands, pgs 1-10.
- Bouwer H (2002) Artificial recharge of Groundwater: hydrogeology and engineering, *Hydrogeological Journal*, 10, pgs 121-142.
- Davies SJJF (2002) *The Capel Wetlands Centre: A Survey of its Historical Developments, significance and Research Results*. Curtin University of Technology, School of Environmental Biology, Bulletin No. 22.
- Chambers JM, NL Fletcher and AJ Mc Comb (1998) The effect of hay addition on the algal productivity of Cadjeput Pool, RGC Wetlands Centre, Capel, Western Australia. Murdoch University, Institute of Environmental Science Technical Reports 43 and 44.
- Freeze AR and JA Cherry (1979) *Groundwater*, pgs 327-331, Prentice-Hall, Englewood Cliffs, N. J.
- Iluka Resources Limited (2004) Capel Wetlands Centre Management Plan, available from Iluka Resources Limited, Capel, Western Australia, ISSN 1443-7449
- Nield SP and LR Townley (1987) Study of water levels in the Capel wetlands. Report, CWC Technical Report No. 5.
- Qiu Song, Bill Scott and Arthur McComb (2002) Predicting effects of inflow diversion on future water levels in mining-created wetlands, CWC Technical report No. 53, 26 pgs.
- Staden SO (2002) An investigation into the water balance of the Capel Wetlands Centre, Honours Thesis, School of Environmental Science, Murdoch University, and CWC Technical Report 54, 92 pgs.
- Townley LR and MG Trefry (2000), Surface water - groundwater interaction near shallow circular lakes: Flow geometry in three dimensions, *Water Resources Research*, 36, 935-948.
- Water Corporation (2004) Capel Wastewater Treatment Plant Proposed Wetland Enhancement Program, Referral Document from GHD 61/1 1484/44842, 163 pgs with an A3 foldout, colour figures and data.

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\* Capel Wetlands Centre Technical Reports, books and book chapters are available from the Capel Wetlands Centre and Iluka Resources Limited, Capel, W.A. ISSN 1443-7449.