A Preliminary Assessment of Water Resource and Environmental Management Issues Associated with the Fresh Groundwater Lens on the Cottesloe Peninsula

By S. Appleyard, June 2004

1. Introduction

The narrow strip of land between the Swan Estuary and the coast known as the Cottesloe Peninsula (Fig. 1.1) includes some of the most valuable real estate in the Perth metropolitan area. As a result of this, this area has a high demand for pumped groundwater to maintain gardens, public open space, school grounds and sporting grounds.

However, the peninsula only has a limited groundwater resource which is highly susceptible to saltwater intrusion. This factor coupled with an increasing demand for groundwater is generating a considerable amount of concern in the local community about how groundwater is being used, particularly by large groundwater users. Additionally, it is possible that groundwater discharge from coastal seepage faces and offshore springs has an important role in sustaining biological diversity on wave-cut platforms that fringe part of the coastline of the area. Limited evidence that high nitrogen concentrations in groundwater discharge are triggering the growth of weedy algae that are contributing the degradation of ecosystems on wave cut platforms in the area.

The absence of comprehensive groundwater monitoring data and a detailed assessment of the groundwater flow system is limiting the effectiveness of groundwater management on the Cottesloe Peninsula. Given the current community concerns about groundwater management in the area, and the importance of protecting nearshore marine and estuarine environments for nutrient discharge, it is timely that available information about groundwater resources is summarised together with predictions of how the flow system might respond to changes in groundwater pumping on the peninsula. This discussion paper undertakes these tasks, and also presents some generic guidance on measures that could improve groundwater management in the area.

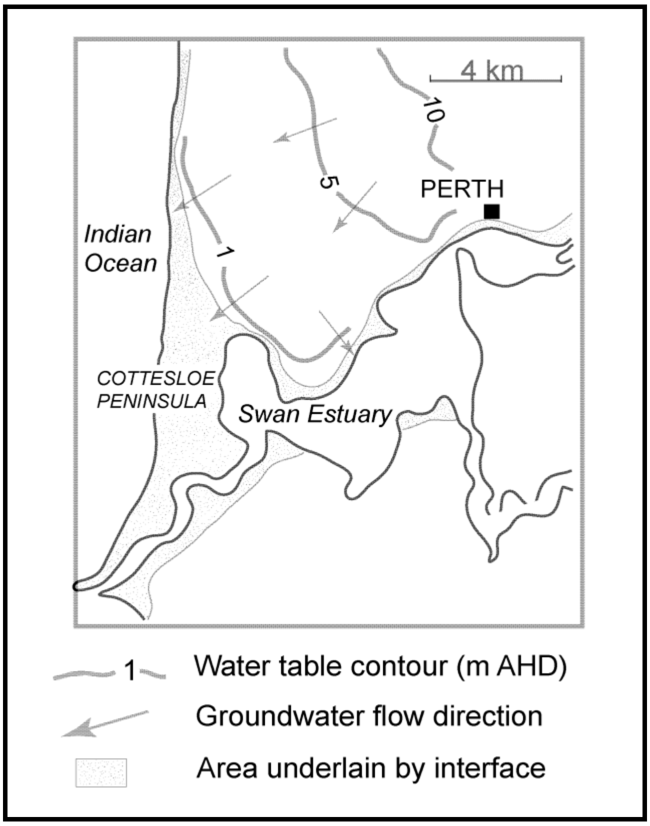


Figure 1. Location of the Cottesloe Peninsula

2. Groundwater resource

2.1 Geological setting

The Cottesloe Peninsula is underlain by recent aeolian sediments of the Tamala Limestone. These sediments consist of medium to coarse grained sands with shell fragments. These sediments have been variably lithified to form a sandy limestone (calcarenite) which is exposed in coastal cliffs and in rocky headlands. The dissolution of lime along former root channels and on joint surfaces and bedding planes has created a network of preferred flow paths which make the limestone highly permeable, and highly variable in its hydraulic properties.

2.2 Groundwater flow

To a large extent, the Cottesloe Peninsula has been isolated from the regional Gnangara Mound flow system by the Swan Estuary, and a local groundwater flow system has developed on the peninsula that resembles those on oceanic islands and coastal peninsulas of comparable size. The entire peninsula is underlain by saline water upon which "floats" a "lens" of fresh groundwater (Fig. 2.1). Limited historical information (Cargeeg et al., 1987; Davidson, 1995) indicates that the lens has a maximum thickness of about 20 metres near Cottesloe Beach, although this area may be receiving some inflow from the Gnangara Mound flow system to the north east. The lens thins substantially near the coast and may have a thickness of less than 5 metres in most coastal areas. In some areas, the saltwater interface moves inland on a seasonal basis, and garden irrigation bores near the coast often become saline in late summer.

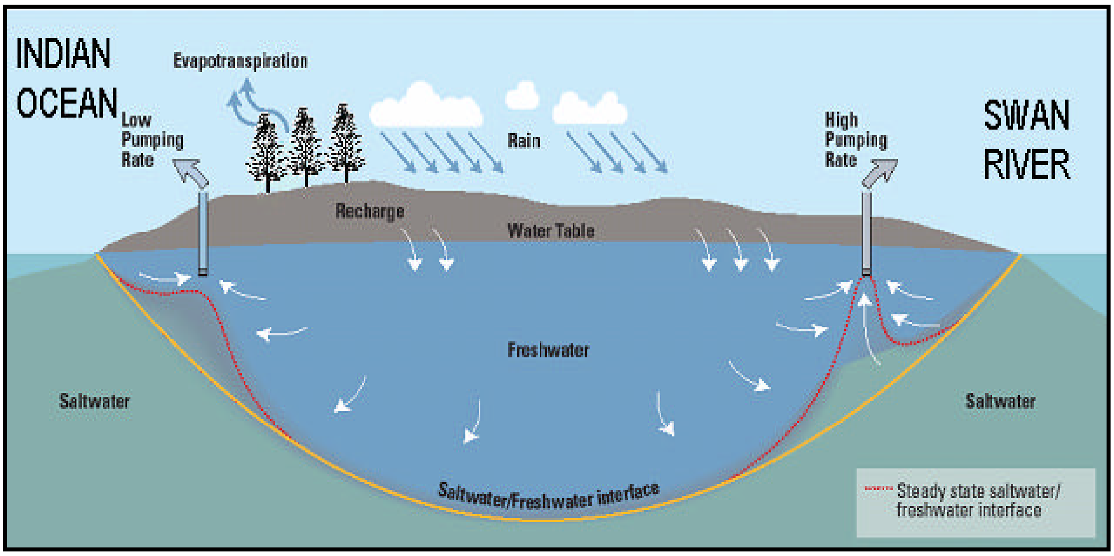


Figure 2.1 Schematic cross-section of the Cottesloe Peninsula showing the fresh groundwater lens.

Limited historical water level data (from 1984 – there are no more recent regional data) indicate that groundwater on the peninsula flows both towards the Swan Estuary and the coast, and that a groundwater divide extends along the peninsula in the vicinity of Stirling Highway (Fig. 2.2). The water level data suggest that suggest that the northern section of the peninsula (as far south as at least Muderup Rocks) receives some groundwater inflow from the north and east. This factor may explain why bores on the Cottesloe Golf Club can maintain high yields with no indication of saltwater intrusion or upconing, but there are no data to indicate whether this pumping is sustainable in the longer term.

2.3 Groundwater recharge

The freshwater lens is sustained by recharge from local rainfall. This has been recognised by Local Government Authorities in the area who have modified stormwater drainage systems in the area to ensure that as much runoff as possible is diverted into infiltration basins rather than being allowed to discharge to the coast or the Swan Estuary. The proportion of rainfall that infiltrates through the soil profile to recharge groundwater is highly variable and depends on a number of factors including variations in soil properties, land slope, vegetation density and the density of urban land use. Typically, recharge in undeveloped areas is of the order of 15% of average rainfall, and up to 35% in urbanised areas in Perth (Appleyard, 1995; Davidson, 1995). The average annual rainfall on the Cottesloe Peninsula is about 800 mm.

The peninsula also receives recharge from water imported through the reticulated scheme water supply through excessive watering of gardens with scheme water. In some cities in the world, leakage from water pipes and sewers is the dominant source of recharge (Foster et al, 1998), but this is unlikely to be the case on the peninsula because of the high level of construction and maintenance of these systems in Perth.`

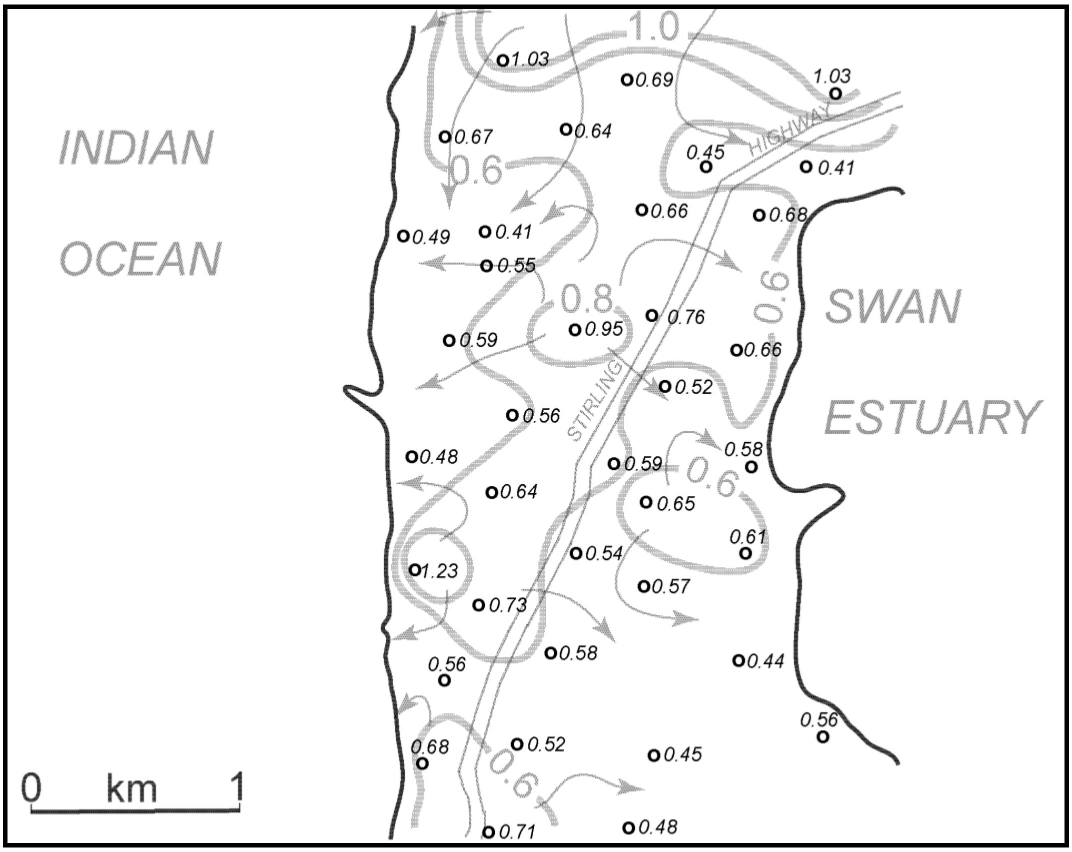


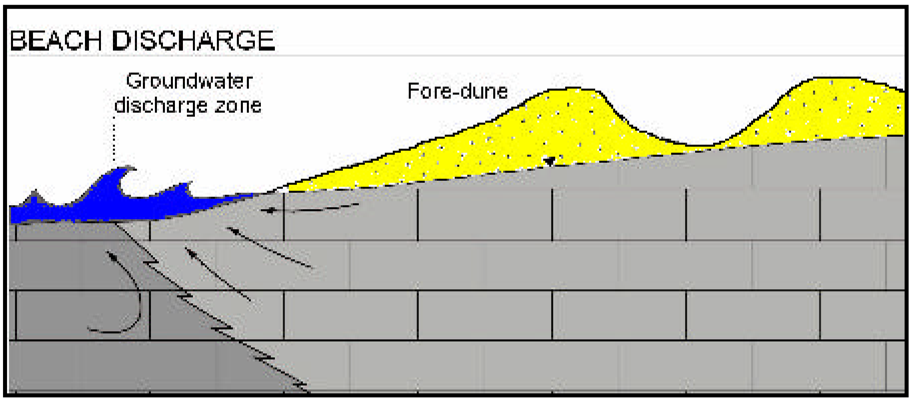
Figure 2.2 Elevation of the water table (m AHD), water table contours and groundwater flow directions for the Cottesloe area in June 1984

2.4 Groundwater and nitrogen discharge

The manner in which groundwater discharges to the coast and the Swan Estuary is controlled by the lithology of the aquifer and the position of the saltwater-freshwater interface.

In sandy areas, fresh groundwater is forced to ride over a more dense saltwater wedge and discharge at a seepage face on the shoreline (Fig. 2.3 a). In areas where limestone cliffs form the shoreline, discharge will take place near the base of the cliff and often in offshore springs on fringing wave-cut platforms (Fig. 2.3 b). Although rates of discharge to wave-cut platforms may be low, the fact that fresh groundwater is discharged directly into a benthic ecosystem with little or no dilution by mixing with seawater is likely to make their impact disproportionately larger than flow rates would suggest. It is possible that some biological communities on the platforms and in karst features beneath the platforms require a certain degree of discharge to maintain their viability, and are therefore groundwater dependent ecosystems. Although this is known to be the case for some marine ecosystems on fringing reefs in some parts of the world, there is very little known about the interaction of nearshore marine ecosystems and groundwater discharge in Western Australia.

a



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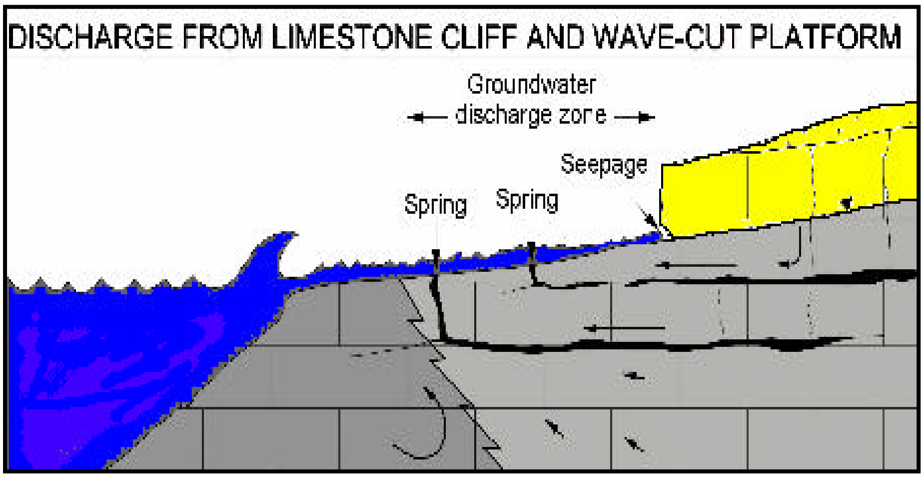

Figure 2.3 Groundwater discharge at (a) a seepage face on a sandy beach, and (b) to offshore springs on a wave-cut platform

The offshore springs are also likely to be important conduits for contaminants that are discharged by groundwater to the wave-cut platforms. The contaminant of most concern is nitrogen from fertiliser use on gardens and open space.

Apart from isolated samples from specific bores, there are no recent groundwater quality data to indicate the distribution of nitrogen in groundwater on the Cottesloe peninsula. However, historical data from the 1980s (Cargeeg et al, 1987) indicate that nitrate concentration in groundwater in the area vary from about 3 to 25 mg/L- N. Sampling from similar hydrogeological environments in the Perth region suggest that nitrogen concentrations in groundwater on the peninsula before development were likely to have been less than 1 mg/L (Appleyard, 1995).

The rate at which groundwater is likely to have discharged to the coast and the Swan Estuary before development took place on the Cottesloe Peninsula can be estimated by the following relationship:

$$q = a.f \qquad \text{(Nunes et al, 2002)} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where q is the discharge rate per unit length of shoreline, a is the distance from the coast the groundwater divide of the freshwater lens (about 700 to 1000 mteres), and f is the recharge rate (about 15% of 0.8 metres rainfall).

Substituting these figures in equation (1) gives a discharge rate of groundwater of about 0.1 m^3 per year per metre length of shoreline (0.1 m^3/year/m) for the Cottesloe Peninsula before development.

Consequently, assuming an average nitrogen concentration of 0.5 mg/L, the discharge rate of nitrogen to the coast and the Swan Estuary before development took place was likely to have been about 0.05 g/year/m.

2.5 Current water balance

Although there are only limited hydrogeological data for the Cottesloe Peninsula, a **preliminary** estimate of the inputs to and outputs from groundwater can be made based on land uses on the peninsula and research that has been undertaken in Perth to determine water use patterns in different urban settings (Metropolitan Water Authority, 1985) and groundwater abstraction data for the area. Table 2.1 summarises the predicted water balance for the peninsula based on this information.

Tab1e 2.1 Estimated water balance for the Cottesloe Peninsula (in units of L/year/m^2, or mm/year)

Component	Magnitude (L/year/m^2)	Assumptions
INPUTS		
Rainfall recharge	250	25% of 800 mm annual rainfall is recharge
Scheme water recharge	20	75% of land is residential, 80% of households use scheme water at 3 L/day/m^2 for 100 days. 10% of this water recharges groundwater
Groundwater inflow	80	Hydraulic gradient is 0.0003, permeability is 150 m/day, cross-sectional area of 30 000 m^2, inflow redistributed evenly over land area
TOTAL =	**350**	
OUTPUTS		
Domestic bores	140	75% of land is residential, 20% of houses use bores at a rate of 12 mm/day for 100 days. Roughly 20% of water returns to the water table
Licensed bores	75	
Transpiration by large trees and discharge to coast and Swan Estuary	135	Water not accounted for in the above output data
TOTAL =	**350**	

It is not known how much water is transpired by large trees such as Norfolk Island Pines on the peninsula. However, if this is assumed to be a very small component of the water balance, the overall rate of discharge of groundwater to the coast is currently at about the same level as it was before development, although the distribution of discharge may have been altered by groundwater pumping.

Much of the groundwater discharge is probably taking place in the northern part of the peninsula where there is some groundwater inflow as the saltwater interface is likely to be inland from the coast for a significant proportion of the year elsewhere. If the groundwater discharge rate has not changed significantly in coastal areas to the north of about Muderup Rocks, it is possible that the rate of discharge of nitrogen to wave-cut platforms has increased by up to a factor of 100 in this area.

This is a major concern given the importance of ecosystems along this section of the coastline. This area includes the Cottesloe Reef Fish Habitat Protection Area which was proclaimed in 2001 to protect the biodiversity of communities on the wave-cut platforms near Cottesloe Beach. Nutrient management on land adjacent to the coast is seen as a key issue in the management plan for this Fish Habitat Protection Area (Fisheries Western Australia, 2001), and groundwater discharge has been recognised in the management plan as an important conduit for transporting nutrients to the reef ecosystems. The discharge of nitrogen by groundwater may be one of the causes of the excessive growth of weedy algae that are smothering some sections of wave-cut platforms in this area.

3. Predicted response of the freshwater lens to changes in groundwater pumping

3.1 Background

Predicting the response of coastal groundwater flow systems to changes in pumping is often difficult due to modelling complexities caused by large variations in groundwater salinity and because of the presence of an interface between fresh groundwater and denser, more saline groundwater.

The position of the interface between fresh and saline groundwater can be approximated using the Ghyben-Herzberg relationship (Fig. 3.1):

$$h = \frac{\rho_s - \rho_f}{\rho_f} H \Leftrightarrow h = \alpha H, \qquad (2)$$

where h is the potentiometric head with respect to mean sea-level, H is the depth of the saltwater interface below sea-level, ρ_f is the density of freshwater (1000 kg/m^3), ρ_s is the density of saline groundwater (typically 1025 kg/m^3), and α is the relative density difference between fresh and saline groundwater (typically about 0.025).

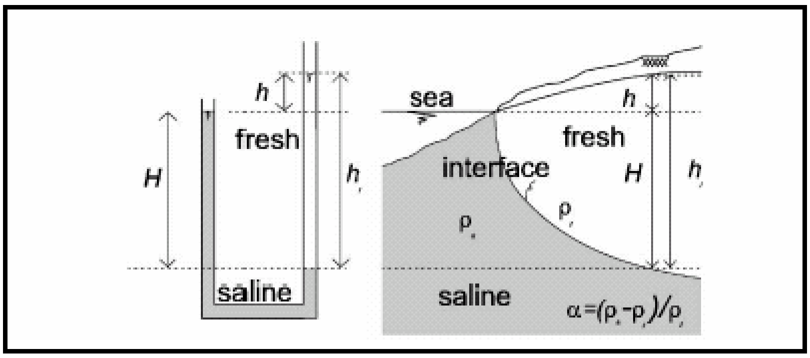

Figure 3.1 Gyben-Herzberg principle (see equation (2))

In situations where coastal peninsulas or islands are completely underlain by saline water, the interface between fresh and saline groundwater defines the boundary of a freshwater lens (Oude

Essink, 2001; Fig. 3.2 a). Otherwise, the boundary between fresh and saline groundwater in an unconfined aquifer adjacent to the coast forms a saltwater "wedge" (Fig. 3.2 b).

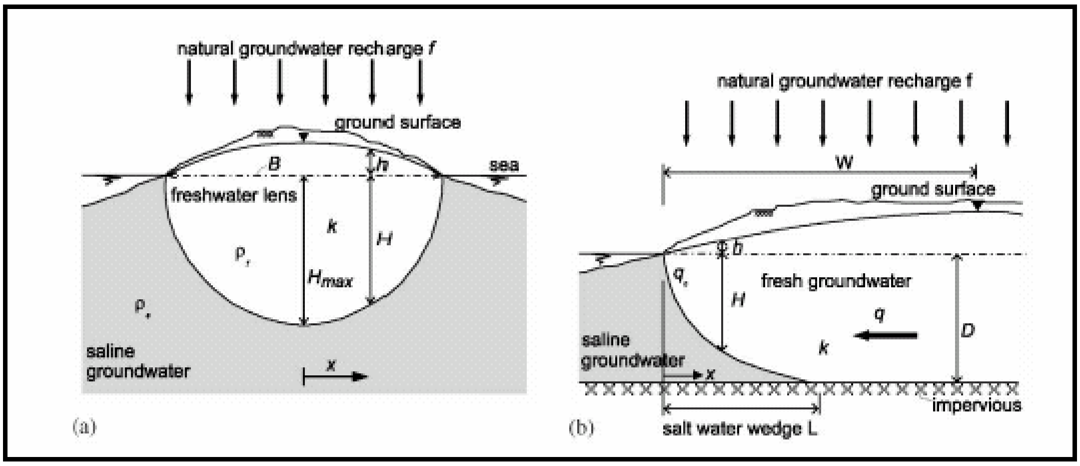

Figure 3.2 Schematic sectional view of the interface between fresh and saline groundwater, defining (a) a freshwater lens beneath coastal peninsulas and oceanic islands, and (b) a saltwater wedge in other coastal areas.

The Ghyben-Herzberg relationship assumes that there is a sharp interface between fresh and saline groundwater. In reality, this is rarely the case because of mixing caused by fluctuations in the position of the interface due to seasonal variations in recharge and discharge, tidal effects, and the impact of groundwater pumping. The presence of a mixing zone introduces a number of errors into analytical solutions based on this relationship, although in many cases, the errors are small.

Although a number of numerical codes such as SUTRA3D and MOCDENSE3D have been developed specifically to allow the simulation of freshwater-saltwater interfaces with mixing zones, the lack of groundwater data for the Cottesloe Peninsula does not yet warrant the time and effort required to set up and calibrate a model for this area, particularly if simple analytical solutions exist that can give some indication of how the freshwater lens in the area will respond to changes in groundwater pumping.

Such an analytical solution does exist that can be applied to the freshwater lens in Cottesloe. As a first approximation, the Cottesloe Peninsula can be assumed to be an elongated oceanic island for which the following solution for the elevation of the potentiometric head as a function of the geometry of the island was developed by Fetter (1972):

$$h^2 = \frac{f\left(a^2 - (a-x)^2\right)}{K(1 + 1/\alpha)} \qquad (3)$$

where h is the potentiometric head, f is the recharge rate, a is half of the width of the island, x is the distance inland from the coast, and K is the hydraulic conductivity of the aquifer. This relationship was developed using the Ghyben-Herzberg approach and making the Dupuit assumption that groundwater flow is mostly horizontal, although this does not strictly apply near the groundwater divide in the centre of the island and in discharge zones where there is a large component of vertical groundwater flow.

3.2 Cross-sectional model for the Cottesloe Peninsula

A cross-sectional model was developed for the Cottesloe Peninsula by discretising and solving equations (2) and (3) in 139 ten metre wide cells in an EXCEL spreadsheet. The elevation of the water table in each cell was calculated with reference to adjacent cells. The hydraulic conductivity of the aquifer was assumed to be 150 m/day based on information given in Davidson (1995).

The best match with 1980s water table data (Fig. 3.3) was achieved with a net recharge of 70 L/year/m^2, a value considerably lower than the estimated rainfall recharge rate of 250 L/year/m^2. This suggests that about 180 L/year/m^2 was being removed by groundwater pumping at the time, a pumping rate that is comparable with current rates estimated by the water balance outlined in Table 2.1. The depths of the saltwater interface simulated in the model are comparable with depths previously measured in multiport monitoring bores in the area (Cargeeg et al., 1987; Davidson, 1995). These results suggest that the current water table and saltwater interface elevations are similar to those measured in the 1980s on the peninsula.

3.3 Effect of pumping on the storage of the freshwater lens

A simulation of the freshwater lens without groundwater abstraction suggested that the freshwater lens beneath the Cottesloe Peninsula used to have a total storage of about 41 000 m^3 of fresh groundwater per metre wide vertical slice of aquifer before this area was settled. This is about 16 000 m^3/m than the current storage of fresh groundwater. That is, the amount of fresh groundwater beneath the peninsula has probably been reduced by about 40% by groundwater abstraction.

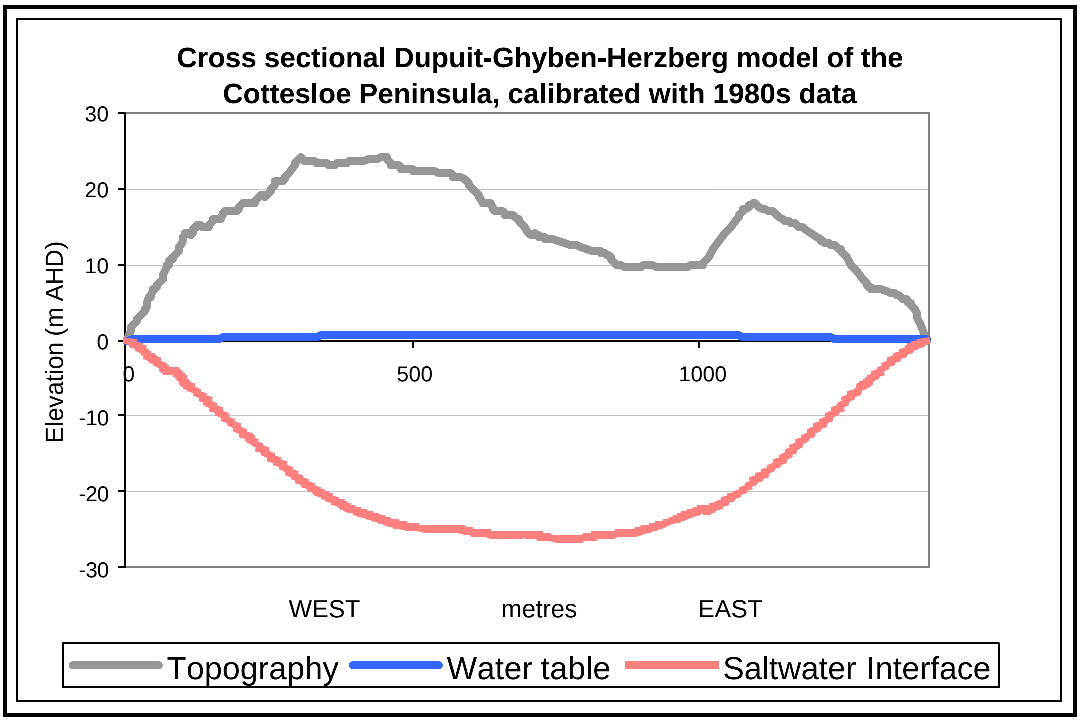

Figure 3.3 Simulation of variations in the water table elevation and the depth of the saltwater interface across the Cottesloe Peninsula.

The equations used in the cross-sectional model assume a condition of steady-state equilibrium, and cannot be directly used to determine how long it took for groundwater use on the peninsula to reduce the aquifer storage by this amount. However, the time taken for a freshwater lens to fully recover from the effects of groundwater abstraction can be estimated by the following expression (Van Dam, 1999):

$$T_r = \frac{\pi}{4}\phi(2a)\sqrt{\frac{1+\alpha}{4K\alpha}}\frac{1}{\left(\sqrt{f1}+\sqrt{f2}\right)} \tag{4}$$

where ϕ is the porosity of the aquifer (assumed to be 0.3), and f_1 and f_2 are recharge rates without and with groundwater pumping respectively.

Using this expression, it is estimated that it would take 390 days without any pumping for the lens to fully recover from the effects of groundwater abstraction. This is rapid compared to estimates made on many other coastal peninsulas (see e.g. Nunes et al., 2002) where recovery times may exceed ten years. The high rate of recovery predicted for the Cottesloe Peninsula is due to the large value of the hydraulic conductivity of the aquifer in this area.

While it would not be feasible to stop pumping altogether for a year, the same result could be achieved in ten years if the overall amount of groundwater abstraction in the area was reduced by 10% (provided that average rainfall was maintained over this period).

If groundwater abstraction on the peninsula were to increase above the current level, the thickness of freshwater lens would further decline. This would exacerbate the current saltwater intrusion problem in the central and southern parts of the peninsula: the saltwater interface would remain inland for a longer period each year, and coastal seasonally saline bores would remain saline for a longer time (or even permanently). The reduced thickness of the lens would also make bores throughout the area more susceptible to saltwater upconing, the issue that is discussed below.

3.4 Saltwater upconing

When a saltwater interface is located beneath a pumping bore, it will rise in elevation due to the pumping. The elevation of the interface will progressively rise with increasing pumping rates until a critical height is reached where it becomes unstable, and it may shoot upwards and contaminate the bore with saline water (Fig. 3.4).

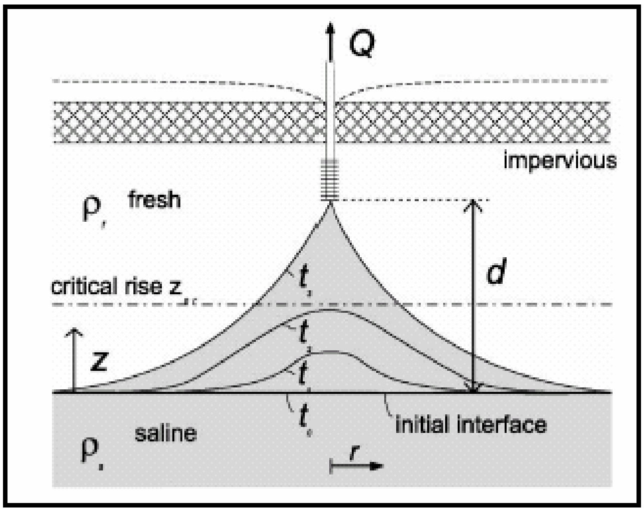

Figure 3.4 Saltwater upconing beneath a pumping bore (after Oude Essink, 2001)

The critical pumping rate can be approximated by the following relationship:

$$Q_{\max} \leqslant 2\pi\alpha k_x \theta d^2 \qquad (5)$$

where θ is about 0.3 and d is the distance between the bore screen and the interface before pumping (Fig. 3.4).

Assuming that d is 3 metres, the critical pumping rate for bores on the peninsula would be about 400 m^3/day. However, if the value of d was reduced to 1 metre, the critical pumping rate for a bore would be only 45 m^3/day. Critical pumping rates may be much higher in the northern part of the peninsula because of groundwater inflow from the regional Gnangara Mound flow system.

In general, the most effective way of managing groundwater abstraction in freshwater lenses is to use a large number of shallow, low yielding bores to spread the discharge and reduce the risk of upconing. There is a much lower risk of upconing if water is trickle-pumped into a storage reservoir over a long period (and water for irrigation is discharged from the reservoir rather than the bore), than if the same volume of water is pumped at a high rate for a short time period.

This principle is applied in managing groundwater pumping from a freshwater lens in similar sediments on Rottnest Island where production bores have screened intervals that only extend 1.5 metres below the water table (Smith, 1994). Each production bore is equipped with a low-yielding pump capable of being pumped at variable rates, and salinity and water levels are monitored on a continuous basis and the pumping rate is reduced when necessary to ensure that upconing does not occur. The total volume of groundwater abstracted from the Rottnest borefields is also set at 50% of the average recharge rate to ensure that sufficient groundwater is available to support groundwater dependent ecosystems and to minimise the risk of lateral saltwater intrusion.

4. Measures to augment groundwater resources in aquifers with a freshwater lens

The most effective way of reducing the risk of saltwater intrusion and upcoming in coastal aquifers such as the Cottesloe Peninsula is to reduce both the groundwater pumping rates from individual bores, and decrease the overall groundwater abstraction from the lens.

There are also a number of engineered measures that can be implemented to either increase the recharge of water to the lens, or retard discharge from the lens. These measures include (Oude Essink, 2001):

- ***Coastal freshwater barriers*** – the infiltration of treated wastewater near the coast can form a hydraulic barrier that can retard both the discharge of fresh groundwater and the ingress of saline water from the coast. However, if the wastewater contains high concentrations of nitrogen and phosphorus, there is a significant risk of environmental problems occurring in nearshore environments due to excess nutrients.

- ***Extraction of saline groundwater*** – the use of "scavenger" bores to pump water from below a saltwater interface (Fig. 3.5) can greatly reduce the risk of upcoming and can allow fresh groundwater to be pumped at higher rates. However, the disposal of anoxic saline water that may be contaminated with hydrogen sulfide and other toxicants may also cause environmental problems.

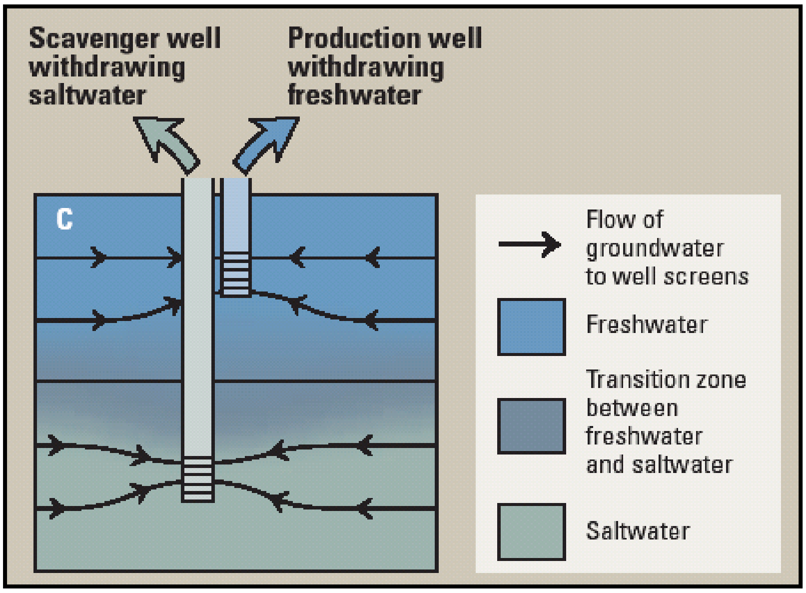

Figure 4.1 Use of a saltwater scavenger bore to prevent saltwater upconing into a bore pumping fresh water

- ***Land reclamation*** – increasing the width of islands or coastal peninsulas by land reclamation can increase the storage capacity of a freshwater lens and move the saltwater interface further towards the coast. However, such a project would also destroy the environmental and social values of beaches and fringing reefs around the peninsula.

- ***Creation of physical barriers to discharge*** **–** Subsurface structures to retard the discharge of fresh groundwater can be created through the injection of polymers into the ground in coastal areas, or by the use of sheet piling or grout curtains.

- ***Artificial recharge*** **–** the effective recharge to a freshwater lens can be increased by infiltrating fresh water (usually stormwater or treated effluent) in inland areas.

With the possible exception of artificial recharge, most of these engineered measures are extremely expensive and are generally only considered where the lens is a sole drinking water source in remote areas.

The Water Corporation is currently considering using treated wastewater to increase recharge of the Cottesloe Peninsula. Although this could have the benefit of increasing the volume of freshwater stored in the lens, the high nitrogen concentration of wastewater (often about 15 mg/L N) could increase the discharge of nitrogen to both the coast and the Swan Estuary. This is of particular concern for the Cottesloe Reef Fish Habitat Protection Area which has been established to protect the biodiversity of an ecologically significant area. It is strongly recommended that the potential environmental impacts of such an artificial recharge scheme are carefully assessed in consultation with the community before such a scheme is implemented.

5 Possible measures to improve the management of the groundwater resource on the Cottesloe Peninsula

There are a number of measures that could be implemented to improve the effectiveness of groundwater management on the Cottesloe Peninsula. These measures include:

1. Creating a management framework for the peninsula

Although the Department of Environment (DoE) has the overall responsibility of managing groundwater resources in the Perth region, the fact that groundwater on the Cottesloe Peninsula is used only for the irrigation of gardens and open space gives the region a relatively low management priority, as much of the agency's limited groundwater management budget is focussed on managing groundwater that is used for public water supply and for protecting groundwater-dependent wetlands with a high conservation value.

However, the limited groundwater resource is extremely important to the communities that live, work and recreate on the peninsula, and so in line with the water management reforms that are taking place at both a State and national level, these stakeholders should have a much larger say in how the resource is used.

A possible way of doing this is for the DoE to set an overall allocation for the peninsula, but devolve the much of the responsibility of managing the local resource to a local groundwater management body that incorporates the interests of local government authorities and other large groundwater users, and the community. Although management may initially delivered through an LGA, from a groundwater management perspective, the management body should be responsible for the entire peninsula so that the entire groundwater flow system is managed rather than having artificial local government authority boundaries which could lead to conflict between adjoining LGAs.

2. Developing and implementing groundwater monitoring programs

The absence of a groundwater quality and water level monitoring program is a major impediment to the effective management of groundwater in the area. Although a number of multiport bores were constructed on the peninsula to monitor the saltwater interface in the 1980s, these have not been maintained and many of the monitoring ports on these bores are no longer operational. Replacing these bores will be very expensive, but in the longer term it will be important to construct new bores to be able to measure how the depth of the saltwater interface varies with time across the peninsula to ensure that groundwater use is sustainable.

However, in the short to medium term, it will be possible to establish an effective monitoring network using existing domestic bores. Such a network was previously carried out in the area during the Perth Urban Water Balance Study in the 1980s (Cargeeg et al, 1987) when the headworks of a number of domestic bores were modified to allow access for a water level probe. The elevation of the top of the casing of each of the selected bores was also surveyed to allow the height of the water table (in metres above Australian Height Datum, or m AHD) to be determined (see e.g. Fig. 2.2 for locations of domestic bores used for monitoring in the area at that time). Long-tem monitoring of the water table (on at least a quarterly basis) is an important indicator of how the groundwater flow system is responding to changes in rainfall and groundwater use on the peninsula. Testing of at least the electrical conductivity and nitrate concentrations (with field measurements and possibly some laboratory analyses) of water pumped from these bores would also valuable information about whether saltwater intrusion was occurring at a given time, and about the effectiveness of nutrient management in the area.

Such a network of domestic bores would also allow an opportunity for community involvement, which would in turn could greatly reduce the operational costs of monitoring. Given the widespread nature of internet access in the area, it could be possible to coordinate monitoring by email and have water table and water quality data for the region deposited into a web-based database at specific time intervals, making the information rapidly available for the whole community.

Another important monitoring need on the peninsula is to be able to track how the magnitude and distribution of groundwater abstraction varies over time in the area. Although some information is currently available for larger production, more needs to be known about the distribution and groundwater usage of domestic bores in the area.

Additional investigations and monitoring will also be required in groundwater discharge areas, particularly in the Cottesloe Fish Habitat Protection Area. It is important to identify whether groundwater dependent ecosystems occur in this area as new the new water management framework being implemented nationally requires sufficient water to be allocated to sustain these environments.

3. Creating a long-term plan for groundwater use

Currently the local communities do not have a shared understanding of the value of local groundwater and of its uses in the longer term. One possible way of addressing this is for a long term plan to be developed for groundwater management in the region in consultation with local communities and other key stakeholders. A useful tool to help with this process would be the development of a regional groundwater model to allow a variety of “what if” land use and groundwater management scenarios to be tested, and to demonstrate the implications of making various management decisions.

Developing a long –term strategy is important, as this will help influence planning and land use decisions to ensure that the groundwater resource is preserved. Without such a plan, decisions will probably continue to be made with little regard for groundwater management in the region.

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