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Australian Government

National Water Commission

THE UNIVERSITY OF NEW SOUTH WALES

water research laboratory

Manly Vale N.S.W. Australia

PRE-FEASIBILITY ASSESSMENT OF MANAGED AQUIFER RECHARGE IN THE BOTANY AQUIFER

A REPORT FOR THE NATIONAL WATER COMMISSION

by

W A Timms, R I Acworth, N Merrick and A M Badenhop

Technical Report 2006/33
November 2006

THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
WATER RESEARCH LABORATORY

IN ASSOCIATION WITH
UNIVERSITY OF TECHNOLOGY SYDNEY

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1. INTRODUCTION

Due to on-going drought, integrated water management projects such as managed aquifer recharge (MAR) are being developed in many Australian cities including Sydney. The only significant large aquifer in the Sydney region is the Botany sand aquifer located between Centennial Park and Botany Bay.

Sydney's second water supply was sourced from the upper Botany catchment and delivered to Hyde Park via Busby's bore. Griffin, who surveyed the Botany Basin in 1963, warned:

"*Unless the main recharge area is protected from further encroachment and the water from stormwater drains fed into open areas (artificial recharge) instead of the sea, the future history of the Botany Basin sandbeds will be one of low yields and pollution.*"

Storing of water underground during times of plenty, for use in times of scarcity is known as water banking. Water banking, also known as MAR is practiced around the world and increasingly in Australia. MAR includes enhanced recharge, intentional storage and treatment of water in aquifers. There are many types of MAR systems that may be suitable for the Botany aquifer, including infiltration tanks and galleries, recharge ponds, aquifer storage recovery (ASR) and aquifer storage transfer recovery (ASTR) using separate or combined recharge wells and injection bores.

1.1 Background

Water from the Botany catchment, sourced from constructed ponds and Busby's bore was Sydney's second water supply from 1827 to 1869 (Figure 1). For over 130 years, sandstone lined stormwater channels have diverted stormwater into inadvertently leaky ponds constructed in Centennial Park. In 2006, a new MAR scheme was commissioned at the UNSW campus to counter-balance increased abstraction of groundwater for beneficial use that is 'fit for purpose'.

The possibility of large scale MAR schemes in the north-eastern Botany aquifer was recently highlighted by a team of experts from the University of New South Wales (UNSW) and the University of Technology Sydney (UTS). Various ideas for MAR schemes have been presented at meetings by personnel from the Water Research Laboratory (WRL), and the Centre for Water and Wastewater (CWWT), both of which are part of the UNSW School of Civil and Environmental Engineering. Presentation slides from these meetings are provided in Appendices of this report.

1.2 Scope of Works

The National Water Commission commissioned UNSW-WRL, in association with UTS, to prepare this pre-feasibility assessment of MAR for the Botany aquifer. The intention was to provide a first-pass summary of current knowledge about the Botany aquifer and the opportunities for MAR.

This concise report was prepared as a desktop assessment, focused on groundwater issues related to the possibility of MAR schemes in the Botany aquifer, whilst also touching on wider technical issues and context. Whilst key studies of relevance to MAR have been included in this report, a comprehensive review is beyond the scope of this engagement. No new data or updated hydrograph information have been sourced due to time constraints.

This review focuses primarily on the north-east section of the Botany aquifer, an area broadly defined as incorporating the suburbs of Daceyville, Kingsford, Randwick, Kensington, Moore Park and Centennial Park. It is noted that this area is a subset of DNR's Northern Zone of Groundwater Management Area, GWMA018. A large volume of information regarding contaminated areas of the aquifer towards the west and near Botany Bay has not been included in this report.

1.3 Report Structure

The report is structured in three main parts. Section 2 outlines current knowledge of the Botany aquifer resource, opportunities for MAR and water quality for beneficial use. Section 3 of the report provides recommendations for the next steps in assessment of technical feasibility for MAR. Suggested scopes of work are outlined and prioritised for each phase of work. A summary of the pre-feasibility assessment for MAR is presented in Section 4.

Broadly indicative budgets and possible timeframes for some of these recommended scopes of works are to be provided in a separate WRL Letter Report.

2. REVIEW OF AVAILABLE TECHNICAL INFORMATION

This desktop review has been prepared based on numerous unpublished university thesis studies, the findings of recent groundwater modelling, geophysical surveys of bedrock, pond-groundwater relationships and water quality assessments. Investigations for various projects since the most recent formal status report that was prepared by the Department of Natural Resources (Bish et al. 2000) have benefit for our understanding of the aquifer system and response to increased urban pressures. However, no new data or updated groundwater hydrograph information has been obtained for this pre-feasibility assessment due to timing constraints.

2.1 Mapping of the Botany Catchment and Extent of Aquifer

Catchment maps of the Botany Basin are shown in Figures 2 and 3, compared with the extent of the Botany aquifer from Griffin (1963) and recent updates on the aquifer boundary. The catchment boundary was identified in ArcView Geographic Information System (GIS) on the basis of 2 m contours obtained from a Digital Terrain Model (DTM) at a spatial resolution of 5 m (Department of Lands, 2006).

GIS analysis shows the area of the Botany aquifer is likely to be about 5314 hectares, compared with an area of 5547 hectares based on Griffin's aquifer boundary (1963). The aquifer extent, as currently defined, represents approximately 84% of the Botany catchment area (6,356 hectares).

2.2 Groundwater Resource Assessment

2.2.1 Geology of Botany Aquifer Sediments

The Botany Basin is a sediment filled topographic depression, lying between Port Jackson and Port Hacking. During the Tertiary period, a system of steep sided valleys (palaeochannels) were eroded into the Hawkesbury sandstone. These valleys were filled during the Quaternary period with approximately 30 metres of unconsolidated aeolian sands, intercalated with minor clay and peat deposits (Griffin, 1963; Bish et al. 2000). Geological sections from the top of the Botany Basin to Botany Bay are shown in Figure 4A, with a detailed geological section through Queens Park (Figure 4B). Sediment thickness is highly variable, with a maximum over the palaeochannel axes and reducing to a thinner veneer of aeolian sands between the channels.

Aquifers within these sediments are bounded by thick clay deposits in the west and numerous rock outcrops in the east. Palaeochannels within these sediments are important groundwater flow conduits. For example, a palaeochannel more than 45 m deep is oriented north-south between Southern Cross Drive and Anzac Parade-Bunerong Road. These channels extend into the area that is now Botany Bay. The channel system was partially flooded when sea levels rose about 10,000 years ago, reaching present levels about 6,000 years ago.

Three to four vertical stratigraphic units are identified within the sediments beneath Botany Bay by Albani (1981). Each of these units have distinctive hydrogeological properties. In summary, the units are characterised as follows listed from oldest to youngest:

- Unit 1 (up to 30 m thickness) - Basal unit of fluvial sand with associated minor gravel, marine sands, shells and interbedded peaty estuarine mud
- Unit 2 (5 to 15 m thick) – Composed of clay and clayey quartz sands containing minor peat beds
- Unit 3 (up to 30 m thickness) – Clean, well sorted, medium grained sands with low carbonate content, interbedded with discontinuous lenses of peat and silty clay
- Unit 4 (a few metres thick) – Holocene age fine to medium grained sands with silt and clay becoming dominant close to Botany Bay.

The units identified by Albani beneath Botany Bay have been extended by later workers (eg Yu, 1994). Geological sections show that the northern zone of the basin to the north of Botany Bay, is dominated by aeolian sands (Units 3 and 4 of Albani, Figure 5). A zone of intermittently cemented and organic rich sand known as “Waterloo Rock” or “Coffee Rock” frequently exists in the upper part of the sands. The unit has reduced hydraulic conductivity and may control local groundwater flow where it exists.

Governmental responsibility for the Botany aquifer has been anomalous in that responsibility has always been vested in the Geological Survey of NSW, rather than the government agency responsible for water resources. Responsibility passed to the Water Resources Commission (WRC) in the mid-1970s. At that time, WRC implemented a monitoring network of 20-28 bores down the central north-south axis of the basin, with very few monitoring sites near the edge of the aquifer.

The geology of the Basin has been described by three main methods, that are described in the following sections:

- Drilling and coring of sediments and rock

- Geophysical logs of existing bores using sondes lowered down on a winch cable
- Geophysical surveys along the ground surface such as resistivity and gravity methods.

Geophysical bore logs are a cost-effective method to obtain detailed information if cores are not obtained during drilling operations. For example, logs such as conductivity induction and natural gamma provide an indication of sediment type and the salinity of porewater (Acworth, 1998). Example of geophysical logs in the area indicate a dominance of fresh groundwater in clean quartz sands, although shallow contaminated groundwater (ie high electrical conductivity) was evident at some locations (Figure 6). Advanced geophysical sondes such as heat-pulse flow and Hydrolab sondes have recently been used to measure flow rates and in-situ water chemistry in deep sandstone bores near Bondi Junction.

The depth and lateral extent of the northern Botany sand aquifer was recently re-examined on the basis of 96 bore records and mapping of rock outcrops (Higgins, 2004). The northern Botany aquifer mapped in Figure 3 is somewhat smaller than that reported by previous studies (eg. Griffin, 1963) because the eastern boundary of the aquifer does not always extend to the catchment boundary. Although much of the upper catchment is underlain by shallow rock rather than saturated aquifer, the area remains an indirect source of recharge to the aquifer.

Although the general shape of the basin has been determined from limited drilling, a detailed bedrock profile is yet to be defined. In 1976, the WRC instigated a geophysical resistivity survey in the basin to better define the aquifer extent and depth (Merrick, 1977). Many soundings, however, were affected by cultural noise (pipes, fences) and the survey was not therefore useful.

The most successful surface geophysical method has been measurement of gravitational field to detect changes in sub-surface density, as this technique suffers minimal effect from a built environment. A significant gravity contrast is found between dense Hawkesbury Sandstone bedrock and overlying unconsolidated sediments that comprise the Botany Aquifer. A total of 1500 gravity measurements were used to define palaeochannel systems such as The Lake's Valley and Shea's Valley. The most comprehensive survey was carried out by Tho (2002), who was able to produce a bedrock topography map for the eastern half of the basin that has higher resolution than that derived by drilling. Tho's study included 980 measurements and was combined with 258 gravity stations occupied by Holzschuh (1994) along Foreshore Road and Botany Road. However, another 600 sites measured by Daniels and Palmer (1998), with a lot of detail at the airport, were excluded. Coffey

Partners also collected gravity data in 1993-1994 during investigations for the Airport Link railway. Existing gravity data should be collated where possible, and further gravity data should be collected in the northern area in particular, to define the palaeochannel between Centennial Park and the Lachlan Lakes.

Occasional seismic refraction, resistivity sounding, resistivity imaging and transient electromagnetic surveys of short duration have been run by UTS and UNSW students. There is a need to collate existing data sets and results, and combine them into a consistent interpretation.

Apart from irregular monitoring of groundwater levels, there has been no serious investigation by government of the groundwater resource in the past 30 years. Any investigations that have been done since that time have been uncoordinated and conducted by university staff and students or by consulting companies, the results in university theses or in confidential company reports.

2.2.2 Overview of Groundwater Resources

Groundwater management zones and flow directions within the Botany aquifer (GWMA018) are shown in Figure 7. Groundwater flow is generally from north to south, and south-easterly towards Alexandra Canal. Approximately 28% of the Botany aquifer area is currently subject to a ban on domestic groundwater use (Zones 2 - 4), while an abstraction exclusion area has been declared for about 9% of the aquifer (Zone 1).

Bish et al (2000) provided a summary of aquifer characteristics of the Botany aquifer from Botany Bay to the northern edge of the catchment. This was based upon Government records and is presented in Table 1.

2.2.3 Groundwater Level Fluctuation

Groundwater levels fluctuate over time in response to recharge, groundwater pumping and, where the watertable is shallow, due to evaporative transpiration losses. Groundwater levels are monitored in 35 bores by DNR (2000), of which 11 are located in Daceyville or northwards (Table 2). The locations of groundwater monitoring bores, are shown in Figure 8. The locations of licensed bores as reported by DNR (2000) is shown in Figure 9. GIS mapping of registered bore locations requires further data collation, processing, validation that is outside the current scope of engagement.

Table 1
Summary of Groundwater Resources North of Botany Bay, GWMA018

Parameter	Value
Area	6,150 hectares
Sediment thickness	<65 m*
Aquifer thickness	<35 m
Yield	1-41 L/sec (ave 5 L/s)
Depth to watertable	0 to 35 m, av <5 m
Salinity	130-600 μS/cm (very fresh)
No. of Licensed Abstraction Points (98/99)	491
No. of Licenses (98/99)	430
Usage (98/99)	Not available
Allocation (98/99)	4182 ML (11.5 ML/day)
Sustainable yield	14297 ML (39.2 ML/day)

Source: Bish et al. (2000). * Modified maximum depth (Section 3.1.1 of this report)

A number of multi-level bundled piezometers were installed by WRL in 1999, with one bore located in the north-eastern area (Realica, 1999). In addition to bores monitored by DNR, there are a number of private monitoring bores that were installed for specific projects such as the Eastern Distributor, Centennial Park and at research sites (eg. Dudgeon 1993, Acworth and Jankowski 1994). It is not known whether all these private monitoring bores remain functional and are actively monitored.

Groundwater levels over the long term appear to be in dynamic equilibrium, although there is evidence of groundwater level increases and decreases over several years. In 2003, DNR reported that there is evidence that groundwater levels in parts of the Botany Basin aquifer in Sydney have risen since the early 1970s. Available data is patchy and incomplete (Table 2).

No trend is evident in the hydrograph between 1974 and 1997 during which time the bore was monitored manually at infrequent intervals (Figure 10). Since 1999, more frequent groundwater level data are available from several bores, except periods when the automated logger malfunctioned. Figure 10B shows a fluctuating trend in groundwater levels between 1999 and 2003 at monitoring bore 42158 and two others in the north-eastern Botany aquifer. Although the groundwater level in 42158 may have declined by several centimetres during this period, other monitoring bores in the region do not show any significant downwards trend. A detailed evaluation of complete groundwater level hydrographs is yet to be undertaken.

Table 2
Groundwater level monitoring bores in the Botany aquifer
(Daceyville northwards only)

Bore No.	Easting	Northing	Depth (m)	SWL (m)	Date of SWL	Data available[#]
42518	335212	6247697	35.0	5.26	7/10/95	M 1974 to 1997 L (~12 hr intervals) 1999 to 2002 with missing data intervals.
40219	331990	6244970	6.30	2.13	7/5/95	M 1986 to 1994
51729	334160	6245990	8.5	2.57	7/6/95	M 1986 to 1994
75017	335109	6246100	28.5	2.15	7/7/98	L March to Oct 1999
75018	335896	6246576	43.0	1.55	8/7/98	L (~12 hr intervals) 1999 to 2002
40223*	336130	6246210	7.0	3.11	7/10/95	M 1986 to 1992.
40224**	336330	6246400	7.0	3.86	7/10/95	M 1986 to 1994
75021	336488	6242026	44.50	7.70	13/7/98	L (~12 hr intervals) 1999 to 2002
24368	334845	6244405	12.9	5.47	7/5/95	M 1986 to 1994
42169	335810	6243961	8.81	6.67	7/5/95	M 1975 to 1993
75025	336201	6243808	24.7	8.46	20/7/98	M Feb to Oct 1999

# It is unknown whether DNR data is available beyond the dates reported by Bish et al (2000).
M = infrequent manual dip measurements, L = automated logger with high frequency data

There is evidence for hydraulic connection between ponds and groundwater in Centennial Park, depending on relative water levels (Figure 11A). The series of cascading ponds are generally connected to groundwater, depending on the permeability of pond sediments and leakage through the walls (Figure 11B). The linkage between surface and groundwater in Centennial Park has been described by Dudgeon (1993) and Acworth and Jankowski (1998). Detailed hydraulic testing around the Kensington park area, including installation of a new irrigation bore and associated monitoring well were reported by Turner et al. (2002) and Timms (2003a,b).

2.2.4 Water Balance

A water balance accounts for changes in storage due to differences between inflows and outflows. Groundwater level fluctuations reflect changes in storage over time. Inflows to groundwater in the Botany area could include rainfall recharge and leakage from ponds, leakage from sewers and mains supply and throughflow from other parts of the aquifer. Outflows from groundwater in the Botany area could include evapotranspiration losses, discharge to ponds and Alexandra canal, discharge to Botany Bay and possible discharge to leaky sewers where there is a high watertable.

The whole-of-basin model documented in Merrick (1994) gives the most comprehensive water balance analysis, based on eight years of transient calibration. The area covered by the 1994 model, compared with other groundwater flow models is shown in Figure 12. The model has been improved conceptually since that time but only for steady-state simulation, and recent modelling by Laase (2005) for Orica suggests that some water balance components are in need of further revision. Nevertheless, the results reported by Merrick (1994) for a representative dry year (1980) and a representative wet year (1990) are reproduced in Table 3 and illustrated in Figure 13. The rainfall recharge is expected to range from 22 ML/day to 44 ML/day (8 to 16 GL/year).

Good recharge of the groundwater store occurs in the more elevated northern region, particularly in open space areas such as Centennial Park and Moore Park, and on the golf courses flanking the Lachlan Lakes. Stormwater discharge into the Centennial Park ponds persistently tops up the aquifer by slow leakage through the base of the ponds, and more rapid recharge through the pond banks during wet events. Additional recharge occurs from street runoff in urban and industrial areas after heavy rain and sideslope runoff from sandstone borders onto the lower elevation sands.

Table 3
Water balance snapshots for a dry and wet period
(for whole aquifer north of Botany Bay)

Component	**Dry Period (ML/day)**	**Wet period (ML/day)**
Recharge		
Rainfall Infiltration	22	44
Lakes (net)	9	0
Lateral Flow*	17	17
Storage Increment	0	1
Discharge		
Pumpage	30	24
Lakes (net)	0	9
Alexandra Canal	9	12
Botany Bay	8	16

*Source: Merrick (1994) * Now expected to be an overestimate*

Shallow regional and local groundwater discharges into the Lachlan Lakes and Alexandra Canal which drains into Cooks River. Deep groundwater discharges to Botany Bay. Modelling by Merrick (1994) suggests that discharge to the Bay and Cooks River is in the order of 8 ML/day in a dry year and double that in a wet year. A similar volume of groundwater discharges into Alexandra Canal, but with less seasonal variation.

A comparison of the water balance components from the most recent groundwater flow models shows significant differences (Table 4). These models covered roughly the southern half of the Botany aquifer as shown in Figure 12. Although the models were specifically developed to address contaminant management issues near Botany Bay, the results indicate uncertainty in groundwater recharge and flow that are of relevance to assessing the feasibility of MAR schemes in the north-eastern part of the aquifer.

For example, through flow from the northern part of the aquifer (including Centennial Park) is modelled at ~0.6 to ~1.3 ML/day. These surprisingly low groundwater flow rates may be related to adoption of a constant head boundary and calibration that was limited to steady state. There are also significant differences in pond leakage rates of ~1.1 to ~2.1 ML/day. Rainfall infiltration of 13 ML/day is consistent with a whole aquifer estimate in excess of 30 ML/day. Further field investigation and revised groundwater flow modelling is required to resolve these discrepancies in modelled water balances.

Table 4
Comparison of steady state groundwater flow models
(for part of the Botany aquifer between Eastlakes and Botany Bay)

Groundwater flow component (ML/day)		**Model A**	**Model B**
Groundwater Inflow	Northeast zone	8.625	2.580
	Southeast zone	9.810	0.034
	Northern Constant Head Zone (Eastlakes)	0.567	1.313
Recharge Inflow	Aeolian Residential Zone	3.676	5.085
	Lacustrine/Industrial Zone	2.188	1.073
	Aeolian/Residential Parkland Zone	3.789	6.278
	Lacustrine Parkland Zone	NA	0.528
Inflow from Lakes		2.085	1.078
Outflow to Botany Bay		8.114	3.640

Source: Laase, 2005 (Model B) after Merrick, 2004 (Model A)

2.2.5 Rainfall Recharge

All estimates of rainfall recharge in the Botany aquifer have been made as part of groundwater modelling. There appear to be no model-independent estimates of rainfall recharge based on detailed site correlation of rainfall and groundwater levels, or using advanced hydrochemical or isotopic methods.

The proportion of rainfall that recharges shallow sandy aquifers can be relatively high. Although there has been no local assessment of recharge rates, studies in the Tomago aquifer and sandy aquifers in Perth have reported recharge factor of 30%. Recharge of up to 30% of rainfall into sandy aquifers compares with about 4% recharge to areas underlain by sandstone and a global average of 1%. Considerable confusion occurs with the recharge rates reported as many are associated with modelling calibration studies and are in fact the balance between rainfall recharge and evapotranspiration rates or net recharge to the aquifer.

Merrick and Barratt (1981) used rainfall infiltration percentages of 36% on sandy parkland, 18% on sandy residential and industrial areas, and 6% on estuarine deposits. During the 1940s drought, Mulholland (1942) estimated average rainfall infiltration at 33%. Modelling by Merrick (1994) suggests rainfall infiltration percentages of 37% on sandy parkland, 19% on sandy residential and industrial areas, and 6% on estuarine deposits and on parks adjacent to lakes.

Modelling by Laase (2005) suggests rainfall infiltration percentages of 96% on sandy parkland (including an irrigation fraction), 26% on sandy residential and industrial areas, 9% on estuarine parkland sediments, and 8% on estuarine industrial areas. The disparity between the rainfall recharge rate of 36% and 96% is considerable and will have a major impact upon groundwater conditions in sandy parts of the aquifer. Model independent investigations are required to determine the most realistic recharge rate.

2.2.6 Groundwater Flow

Groundwater flow rates in the Botany aquifer are relatively high, due to high recharge, hydraulic gradient and hydraulic conductivity. Groundwater velocities can be estimated using Darcy's Law, or measured using various chemical and isotope tracer techniques. A flow rate of 150 m/year can be calculated based upon Darcy's Law and assumed aquifer thickness and hydraulic gradient. A drop of water would therefore take approximately 50 years to travel from the recharge area near Centennial Park to discharge at Botany Bay. However, a groundwater velocity of 0.32 m/day (117 m/year) was reported from a tracer test at the Eastlakes experimental site (Jankowski and Beck, 2000), so it is possible that the regional estimation overestimates the actual velocity. Groundwater slows down a little as it nears Botany Bay (about 100 m/year).

2.2.7 Sustainable Groundwater Yield and Current Usage

A summary of currently available estimates of sustainable yield, allocations and usage is provided in Table 5. The official DNR estimate of the long-term abstraction limit for the northern aquifer zone between Botany Bay and Centennial Park is 39 ML/day (14.3 GL/year) (Bish et al., 2000). The sustainable yield is defined as 70% of the estimated annual average recharge, a standard approach for groundwater systems in NSW to allow for the water needs of groundwater dependent ecosystems. Annual average recharge was estimated for the aquifer between Botany Bay and Centennial Park assuming 30% of rainfall as recharge over an area of 61.5 km^2.

The official licensed allocation is 11.5 ML/day (4.2 GL/year), but this excludes pre-1972 licences held by major industrial users and pre-dates the Orica pump-and-treat extraction. A more realistic figure of current legitimate use would be nearer 28 ML/day, ignoring use made by backyard domestic bores (most of which are not licensed). The volume of groundwater being abstracted from the aquifer is unknown as there is no compliance system in place. However, it is likely to be less than 25 ML/day, about the same as was drawn from the Botany Swamps scheme more than a hundred years ago. Usage peaked at 55 ML/day in the late 1960s (Merrick, 1998). Despite the lack of detailed records, it is possible that the Botany Sands aquifer could support higher rates of abstraction, particularly to the north where recharge is concentrated and there is very little extractive use.

Table 5
Estimated Groundwater Sustainable Yield, Usage and Allocations

Zones	**Groundwater**		**Source of estimate**
	(ML/day)	**(ML/year)**	
Whole of GWMA018 – northern, southern and western zones			
Sustainable yield	61.6	22,515	DNR, 2000
Usage	27 15-25	9,855	1989 estimate from 90 bores Merrick estimate (1994)
Allocation		4,860	1989 data
Northern zone of GWMA018 – north of Botany Bay			
Sustainable yield	39.2	14,297	DNR, 2000
Usage	26.7	9,745	1989 data
Allocation	11.5	4,182	1989 data

The relationship between sustainable yield and usage with regard to data and management requirements is illustrated in Figure 14. Management requirements clearly increase as allocation and usage levels approach the sustainable yield. Detailed investigations and monitoring is required to decrease the margin of uncertainty associated with estimated sustainable yield.

It may be argued that the Botany aquifer is currently under-managed, and may be classified as a Type 2 or Type 3 aquifer according to Figure 12. It is essential that uncertainty in sustainable yield and usage is addressed as part of a detailed feasibility assessment of MAR. Based on the volumes in Table 5, there is the possibility that the aquifer could support increased abstraction in the order of approximately 12 ML/day in the northern zone. There may therefore be the capacity to extract more water within the sustainable yield that has been defined by DNR as equivalent to 70% of rainfall. However, the latest groundwater status report is now several years old (DNR, 2000) and this volume of 12 ML/day of possible increased abstraction is probably within the error margin of estimated sustainable yield and therefore may not be available.

The uncertainty in sustainable yield is attributed to the following factors:

- Groundwater hydrograph data from 2000 to 2006 is yet to be reported to identify trends reflecting groundwater usage and varying climatic conditions. Groundwater levels indicate whether an aquifer is stressed and therefore provide a reality test for the estimated sustainable yield volume.
- The lack of groundwater usage data is a severe limitation in managing a volume based sustainable yield. There are known to be many unregistered bores, and large scale (>20 ML/year) licensed bores that are not metered, or do not report on volumetric usage.
- Limited data defining aquifer depth, particularly in the north-eastern aquifer area.
- Sustainable yield is defined as 70% of total recharge. The balance of recharge (ie. 30%) is reserved for environmental requirements. However, there is a serious lack of scientific information regarding local groundwater dependent ecosystems and their water requirements so this definition of sustainable yield may not be appropriate.
- It is estimated that 30% of rainfall recharges the catchment area. However, there is significant uncertainty as groundwater models have used recharge values ranging from 6-96% of rainfall. No field studies of recharge have been carried out to determine realistic recharge rates.
- Inherent uncertainty due to natural subsurface variability.

2.2.8 Groundwater Quality

Classed as a highly vulnerable aquifer, groundwater abstraction in the southern Botany aquifer is embargoed due to contaminant plumes (Zones 1-4, Figure 7). However, excellent groundwater resources are available in the north-east of the aquifer in the suburbs of Randwick, Kensington, East Lakes, Kingsford and Maroubra.

Available data indicates that groundwater quality in this area generally complies with drinking water standards with the exception of iron, and bacterial indicators, except in locations near leaking sewers and landfills. Degraded water quality near the top of the watertable, and where fertilizers are applied (eg. Randwick race course, golf courses) and for a full range of water parameters is yet to be assessed. Up to 70% of nitrogen in fertilisers can leach to sandy aquifers under Australian cities, although phosphorous in fertilizers is generally bound up in the soil zone (Sharma et al., 1996).

Baseline data on groundwater pH, salinity (EC and major ions), and nitrate concentrations is provided by Jankowksi and Yu (1998). Natural hydrochemical evolution of groundwaters were observed along the flow path in the aquifer due to interaction between water and sediments. Spatial patterns of major ion concentrations along the flow paths (Ca, Mg, Na, Cl, SO_4, HCO_3) were described by Acworth and Jankowski (1993). Major hydrochemical zones are shown in Figure 15, showing an evolution from fresh recharge waters in the north towards more chemically complex waters in the south.

Detailed hydrogeochemical studies have been carried out delineating a landfill-leachate contaminant plume at Astrolabe Park in Daceyville (Jankowski and Acworth, 1997, Jorstad et al, 2004, Acworth and Jorstad, 2006). These studies highlighted that the water quality can vary on a local scale and that contaminants are leaching from former municipal landfills. Numerous water quality assessments have been undertaken by WRL for various government agencies and private residents. These results have shown that nitrate and selected trace metal concentrations are generally very low, and that total coliforms and E. Coli concentrations are generally not detected.

2.3 Potential Water Sources for Additional Recharge

The feasibility for managed aquifer recharge depends on a range of technical, environmental and socio-economic factors. WRL have adapted a scheme for local use, based on a scheme for determining the sustainability of MAR feasibility is presented in Figure 16 (Dillon and Pavelic, 1994). This report provides a first-pass assessment of the availability of a suitable aquifer and the utility of stormwater and wastewater sources for MAR. It is not within the scope of this report to consider the demand for increased groundwater abstraction for specific beneficial uses.

2.3.1 Opportunity for Stormwater Harvesting

There is increasing awareness of the large volumes of stormwater, or urban runoff, that discharge from Sydney's coastal suburbs to the Pacific Ocean, Sydney Harbour and Botany Bay. Rainfall depths in the Botany Basin is significantly greater than in the inland catchments that supply Warragamba Dam. Total average annual rainfall declines significantly between Randwick (1220 mm) and Warragamba Dam (840 mm). There appears to be a clear opportunity for stormwater harvesting in the Botany Basin and adjacent catchments, however the utility of stormwater resources for MAR requires careful consideration.

It is uncertain how much stormwater currently recharges the aquifer and so it is not currently possible to quantify the opportunity for additional recharge. There may be opportunities in areas of the catchment that do not already drain to pond systems or cause overflows when the leakage rates of ponds to groundwater are exceeded. Groundwater modelling does not specifically consider stormwater inputs, but applies a lumped recharge factor, relative to rainfall for specific areas of the aquifer (eg. lacustrine versus sandy as in Table 4.

Urban development has altered natural hydraulic behaviour, leading to increased runoff and decreased infiltration. Urban development increases the proportion of impermeable areas in the catchment, leading to rapid, high volume runoff, flash flooding and potentially dangerous water velocities in stormwater channels. For example, GIS land use mapping in the Bondi catchment has indicated that only 103 hectares of the 180 hectare catchment is pervious (Timms et al 2004). Pervious factors were assigned to each land use as follows: 45% for high density residential and commercial, 50% for road corridors and 63% for low density residential (Zaman and Ball, 1994).

A rough estimate can be made of stormwater yield in a catchment. The volume of water runoff depends on the intensity and duration of a rainfall event, losses due to wetting of surfaces and therefore the history of rainfall prior to a specific event. For example, a 10 mm rainfall event is equivalent to a volume of 1000 L over an area of 100 m^2. A rainfall event of 30 mm rainfall event in a 120 hectare catchment could generate up to 36 ML, although actual yield is likely to be considerably less due to evaporative and infiltration losses within the vadose zone (ie. the unsaturated zone above the watertable).

Water levels in the stormwater channel entering Musgrave pond in Centennial Park from a 120 hectare catchment were reported by Ball (2002)[1]. Water levels were monitored automatically at a high frequency between 1994 and 1999, although the channel was dry or had very low water levels for most of the monitoring period. Following a 1 in 10 year ARI event (Average Return Interval), the peak water depth (mid-April 1999) was approximately 0.9 m which was equivalent to 6 m^3/second of discharge based on the reported rating curve.

Water levels of 0.2 m (discharge of 0.7 m^3/s or 60 ML/day) were maintained for approximately 3 months with follow on rains. It is possible that a proportion of base flows maintained for that period represented gradual drainage of the sand layers on the edge of the catchment that was near to or fully saturated by this large rainfall event. A detailed analysis of event duration was not reported, so it is not possible to determine the total volume of stormwater runoff into the pond during these events. It should be noted that this was the largest, and most sustained period of stormwater runoff that was recorded between 1994 and 1999. The limited duration of stormwater flows may be a serious drawback to stormwater harvesting opportunities for MAR.

The opportunity for stormwater harvesting that, via MAR, could increase the yield of the Botany aquifer depends on many factors, including but not limited to the following:

- The catchment area that is not currently directed to aquifer recharge
- The quantity and spatial variability of rainfall and stormwater
- The frequency and duration of significant stormwater flow events
- The infrastructure required to divert adequate volumes of stormwater
- The area adjacent to the Botany catchment that where stormwater drainage could potentially be re-directed
- Appropriate management of first-flush stormwater which can often contain high suspended solids and contaminant concentrations
- Recognition of the useful cleansing role of urban runoff
- Maintaining environmental flows where required
- The volume needed to store via MAR between peak supply of stormwater and peak demand.

Potential areas for additional stormwater diversions are shown in Figure 17 and Table 6. These areas, defined by an elevation >60 m AHD are to the north and north east of Centennial Park in the Bondi Junction area. Further work is required to identify

[1] Monitoring equipment at this hydrographic station has since been removed (S. Wyllie, pers.com.)

infrastructure requirements for pumping or gravity drainage of diverted stormwater flows towards Queens Park and Centennial Park. It may be technically feasible, for example, to divert stormwater via gravity flow through a rock tunnel to the top of these parks (elevation ~45 m AHD).

It should be emphasised that this first pass assessment has utilised relative elevations for identifying areas for further investigation that may gravity flow towards Queens Park. Detailed feasibility assessment within the context of local stormwater management plans, including costings, are required for each subcatchment within the general area that has been identified in Figure 17.

Table 6
Stormwater Catchment Areas

Catchment	Area (hectares)	% of total Centennial Park catchment	Stormwater flow (ML/day)	Comments
Musgrave Pond	120	22	~60	Flow for 3 months after a 1 in 10 year ARI event. Generally dry or very low flows observed between 1994 and 1999.
Centennial Park	540	-	Unknown	
Botany aquifer	5,547 5,314	-	-	Griffin, 1963
Botany catchment	6,356	-	Unknown	
Potential additional catchment	<420	78	Unknown	Defined in GIS as areas >60 m AHD in catchments to the north-east of Botany catchment, that could gravity drain through a tunnel to Queens Park. Pending detailed feasibility assessment.

Major stormwater harvesting works require significant areas of land for capture, cleansing and retention storage. At Parafield in South Australia for example, a stormwater harvesting system including ASR wells was optimised for volumes of 1100 ML/year, representing about 70% of the average yield of the 1580 hectare catchment (Marks et al. 2005). The objective of the ASR scheme is to bank 2,000 – 3,000 ML of harvested water into a confined aquifer (about 200 m depth) to provide supply through a series of dry years. Several hectares of ponds and diversion weirs were constructed. The limited availability and high land values in the north-eastern Botany catchment may preclude large above-ground detention storages as part of MAR.

Stormwater harvesting from neighbouring catchments would need to be assessed in the context of local stormwater management plans. Local councils manage stormwater systems <900 mm in diameter, while Sydney Water is responsible for stormwater systems >900 mm diameter (Ball, 2002). Waverley Council's Integrated Stormwater Management Plan (2001-2006) outlines strategies and targets in the area. Catchment maps including stormwater reticulation systems are reportedly in progress for the Waverley council area.

Opportunities for stormwater harvesting for MAR appear to warrant further evaluation, including detailed stormwater and urban hydrology studies. The potential drawbacks of stormwater harvesting for MAR include, but may not be limited to: limited catchment areas, highly variable stormwater flows and the lack of water during extended dry periods.

2.3.2 Opportunity for Sewer Mining

Sewer mining is the process of extracting wastewater from a sewerage system and treating it for a specific end use (Sydney Water, 2006). Extraction of wastewater can occur before or after the sewage treatment plant (STP). There are a number of sewer mining projects under development in Sydney following the success of the schemes at Olympic Park and at Kogarah, however no sewer mining has yet been developed in NSW in conjunction with MAR.

Sewer mining generates recycled water for beneficial use, grit and screenings and other by-products including a more concentrated version of the extracted sewage. In addition to an extraction connection, a connection is also required for return of approved concentrated wastes to the sewer.

Sewer flows are maintained year-round, in contrast to infrequent and limited duration of stormwater. Since sewers are operated using mains supply imported from catchments outside the Sydney CBD, the use of sewer mining combined with MAR would represent an importation of water to the Botany catchment. Although sewer mining volumes would vary somewhat diurnally and seasonally, this water source would be relatively reliable and independent from climatic factors (Table 7).

Table 7
Comparison of MAR Water Sourced from Stormwater and Sewer Mining

Characteristic	Stormwater harvesting	Sewer mining
Security of supply	Not reliable	Reliable
Available volume	High coastal rainfall but flashy urban runoff. Available volume could be supplemented with stormwater from adjacent catchments.	Constant volumes of water imported from outside the catchment. Available volumes from nearby sewer lines currently unknown.
Infrastructure requirements	Diversion and relatively large retention storage of stormwater to match MAR capacity	Access to Sydney Water sewer mains, treatment plant and balancing storage
Treatment required	None or basic treatment for suspended solids, nitrate and metals, particularly for first flush.	Advanced wastewater treatment technologies
Relative cost	Moderate	High

The Kogarah pilot sewer mining scheme successfully produced 0.1 ML/day of Class A water for irrigation usage and is now proceeding to a full scale plant. The Water Reclamation and Management Scheme (WRAMS) at Olympic Park was Australia's first large scale urban recycling scheme to source wastewater through sewer mining for irrigation and residential non-drinking water uses (Sydney Water, 2006). Up to 7.5 ML/day of wastewater is treated by WRAMS using micro-filtration to filter bacteria, reverse osmosis to reduce salinity and chlorine disinfection (Sydney Olympic Park, 2006). The system includes a 300 ML water storage for stormwater and treated wastewater and freshwater wetlands that catch the first-flush of stormwater.

Treated wastewater from the Subiaco STP near Perth is to be used to counteract saline intrusion in the coastal aquifer through managed recharge (Radcliff, 2004). The possibility of indirect potable re-use is being investigated using the Gnangara groundwater system that provides a significant proportion of Perth's water supply. Wastewater from the Beenyup STP is to be injected at 27 GL/year following micro-filtration and reverse osmosis treatment.

There is limited publicly available information on opportunities for sewer mining in the north-eastern Botany basin. Sewer mains are located along three main corridors as indicated in Table 8. The volume and characteristics of sewage that may be harvested from these sewers would require an assessment by Sydney Water in regard to minimum flow rates that are required in the sewer mains. Sewer discharges in the area would be mainly residential at an average rate of 250 L/day/person and 2.2 persons per residence. This equates to 1 ML/day from approximately 10,000 residences.

Table 8
Sewer Mains in the North-eastern Botany Basin

Sewer mains	Locations	Sewer diameter (mm)
Anzac Parade and Robertson Road	West of Centennial Park to David Philips/Astrolabe Park	>350mm in the north and then mostly >500mm
York Road and Denison St	Between Centennial Park and Queens Park	>350 mm
Bourke St	Moore Park north	>350mm in the north and then mostly >500mm

Source: Sydney Water

If concept development and testing of sewer mining appears favourable, and it is decided to proceed with a sewer mining scheme, then council approval and an agreement with Sydney Water is required prior to construction, connection and operation. Sewer mining schemes that generate more than 1.5 ML for irrigation purposes require approval from the Dept. of Planning and an Environmental Impact Statement (Sydney Water, 2006).

At the concept development stage, further investigation would be required of potential sewer mining sites, suitable treatment technologies, the volume of extraction required, end uses and water quality requirements.

2.4 Managed Aquifer Recharge Systems

2.4.1 Potential Types of MAR

Managed aquifer recharge is already practiced, often inadvertently in the Botany aquifer since a proportion of stormwater already recharges groundwater. Schematics of the types of MAR in the Botany aquifer are shown in Figure 18. It is probable that downpipes from many buildings in the area are directed to soakage pits. At a larger scale, rainwater harvesting similar to that depicted in Figure 18D is now practiced at the UNSW campus. Infiltration tanks were installed in mid-2006 that capture runoff from the campus. Increased recharge has enabled increased abstraction for beneficial uses including irrigation, toilet flushing and cooling water (UNSW, 2006).

For over 130 years, sandstone lined stormwater channels have directed runoff to ponds that were constructed in Centennial Park (Figure 18B). Some of these ponds leak to groundwater, depending on the hydraulic head difference and the hydraulic conductivity of pond sediments and pond walls (Dudgeon, 1993). Surface and groundwater are closely connected in this area, with a dynamic relationship over time and space. For example, detailed field experiments have shown that Kensington Pond number 2 often recharges the aquifer, however, at very low stages, the pond water level is maintained by groundwater discharge to the pond (Turner et al 2002). It is possible that the recent construction of an irrigation bore near Kensington Pond may have increased leakage of Kensington pond to groundwater (Timms, 2003a). This would mean that MAR similar to that shown in Figure 18C (bank filtration) is practised.

There are other potential types of MAR that could be developed in the Botany aquifer, subject to detailed feasibility assessment. These MAR systems are shown in Figure 19. The key features of each of these systems and potential applicability to the Botany aquifer are outlined in Table 9.

In some cases, there are similarities between technologies used for MAR and for water sensitive urban design (WSUD) although the objectives of MAR and WSUD projects can be quite different. There has been significant recent interest in using porous pavements, soakaway swales, leaky pipes and infiltration tanks as components of WSUD. Although primarily designed to mitigate stormwater issues in the catchment, WSUD could assist in restoring natural infiltration in highly urbanised areas with a high proportion of impermeable surfaces. By contrast, MAR projects are typically larger scale and specifically designed to maximise recharge above natural rates, even in sandy areas. Tradeoffs between widescale WSUD that reduces runoff and efficiency of stormwater harvesting may require further consideration.

Table 9
Features of Potential MAR Systems

Type	Features	Comments
Infiltration tanks	Using porous structures often using recycled plastics to maximise porosity.	Used for WSUD or MAR depending on design intent. Protection of water quality over the long term requires assessment.
Recharge pits	Using natural porous media such as graded gravels and course sand to increase recharge.	Long term hydraulic performance (eg. clogging) and water quality protection requires assessment.
Ponds or basins	A spreading type of MAR usually with a number of basins used in rotation. Clogging problems can be managed by smart design, intermittent drying and scrapping of the pond and primary sedimentation treatment of source water.	Large area of land may be required. There are already many ponds with variable leakage rates in the area.
Porous pipes	Technology yet to be assessed for large scale MAR projects.	Long term capacity for contaminant removal requires assessment.
Filtration media	A range of natural and recycled porous media that could be incorporated with other MAR types (eg pond liners) that would be designed to enhance hydraulic performance and water quality treatment.	Long term capacity for contaminant sourcing and removal requires assessment.
Soil aquifer treatment	A spreading type of MAR using treated wastewater. Infiltration through soil and sediments decreases concentrations of nitrogen, phosphates, metals and organic carbon.	Attenuation capacity of the soil and unsaturated sediments in the Botany aquifer is unknown but maybe limited. Advanced wastewater treatment would be required to protect groundwater quality.
Underground dam	An in-channel modification that detains water in alluvial channels. A trench is constructed across an underground channel, keyed into basement rocks and backfilled with low permeability material.	Required further assessment. May be suitable in a few locations, particularly where there is unused storage (ie. relatively low watertable)
Drilled wells and boreholes	Advantageous when land is scarce. Aquifer storage recovery (ASR) where the well/borehole is used for both recharge and abstraction. Aquifer storage transfer recovery (ASTR) where water is injected and recovery some distance away to take advantage of water treatment and delivery capacity of the aquifer.	Either ASR or ASTR could potentially be developed and would be advantageous in terms of minimum land footprint required.

After Dillon (2005) and Gale and Dillon (2005)

The characteristics of the Botany aquifer that favour injection were reviewed (Table 10). MAR using injection techniques appear generally favourable, although aquifer clogging and maximum injection heads would require careful consideration.

ASR is considered to be a form of technology for collecting and treating stormwater (Radcliff, 2004). It is a relatively untried technology in NSW, although an ASR scheme is operated by Mid Coast Water at Tea Gardens to supply irrigation water.

Table 10
Characteristics of Aquifers Which Favour Aquifer Injection Compared with Properties of the North-eastern Botany Aquifer

Characteristic	Comment	Botany aquifer
High bore yields	Allows for high injection and recovery rates so more water can be stored and recovered per bore	Moderately high yields of ~15 L/s from suitably designed bores.
Low native hydraulic gradient	So that water can be stored locally and more easily recovered	Moderate gradient of 40 m in 8 km (0.5%)
High storage capacity	Aquifers that are thick and/or have a high porosity	High porosity of 0.25 to 0.3
Aquifers with a large grain size	To minimize the potential for clogging	Fine to moderate grain size indicates clogging may be an issue
Homogenous aquifers	To maximise the volume of recoverable water	Relatively homogenous aquifer, although heterogeneity observed even in Botany sands.
Unpolluted aquifers	Are preferred so as not to mobilise contaminants within an aquifer	Generally non-polluted, low salinity water quality in north-east part of the aquifer
Aquifers with compatible mineralogy or water quality	Biogeochemical reactions between injected waters and native groundwater can for some sites result in mobilisation of constituents	Largely unknown and would depend on recharge water used, however iron and manganese are known to be mobilised
Watertable level in unconfined aquifers	Watertable (m below ground) 0 to 2 – too shallow for injection. 2 to 5 – injection not recommended 5 to 10 – max of 5 m injection head 10 to 20– max of 10 m injection head	Watertable range of 1.6 to 8.5 m below ground (average = 4.4 m below ground, based on Table 1). Injection may be possible in most areas, however other types of MAR should be considered for areas with high water tables.

Modified after Dudding et al. (2006).

A recent study of ASR potential in Melbourne found that 24% of the city's water supply could be met with ASR with 93 GL/year from confined aquifers and 15 GL/year from water table aquifers (Dudding et al., 2006). However, areas with very shallow watertables (<2 m below ground) were not suitable and sandy aquifers had the lowest storage capacity compared with limestones and volcanic aquifers.

The capacity of an aquifer for injection, as commonly defined is the volume of water that could be injected through a single bore that fully penetrates the aquifer and is operated continuously for 180 days (Dudding et al., 2006). The capacity for aquifer injection is compared with potential water supplies and applicability to the Botany aquifer in Table 11. Based on available information, there is potential for high capacity aquifer injection schemes (>180 ML per year per bore), pending source water availability.

A detailed feasibility assessment is required to determine the aquifer capacity on the basis of site investigations, analytical estimates such as the Theis solution for transient flow and numerical groundwater flow modelling.

Table 11
Capacity for Aquifer Injection Compared with Potential Water Supply

Category	**Average injection rate per bore**	**Annual injection volume per bore (ML)**	**Potential Water Supply**	**Applicability to Botany aquifer**
High	> 1 ML/day (>11.6 L/sec)	>180	Moderate size stormwater catchments, detention pond and treatment plant or sewer trunk main and treatment plant	Possible. High aquifer capacity at some locations Limited stormwater volumes available within catchment.
Medium	0.5 – 1 ML/day (5.8 – 11.6 L/sec)	90-180	Small size stormwater catchments, detention pond and treatment plant or sewer main and treatment plant	Widespread applicability
Low	0.1 – 0.5 L/day (1.2-5.8 L/sec)	18-90	Rain water or storm water from small housing, commercial or industrial developments with detention storage and treatment	Widespread applicability
Very Low	<0.1 ML/day (<1.2 L/sec)	<18	Rain water from individual houses or cluster developments	Inadvertently practiced in many locations ?

After Dudley et al (2006), Pyne (1995) and CGS (2004)

There are considerable advantages to groundwater development in the Botany aquifer that warrant further consideration for MAR:

- Accessible in many locations for drilling and infrastructure
- Relatively inexpensive drilling and bore installation in shallow sandy aquifers
- Relatively inexpensive pumping and operational costs for relatively shallow groundwater levels
- Low salinity water for high-end beneficial uses if treated for iron and bacteria

- Close to variety of water users including golf courses, industry and residential areas.

2.4.2 Potential MAR Capacity in the Botany Aquifer

The capacity of MAR schemes in the Botany aquifer could be determined by groundwater flow modelling with additional data. However, approximate estimates can be made based on Darcy's Law which relates groundwater flow to cross-sectional area, hydraulic gradient and hydraulic conductivity of porous sediments. In this manner a first-pass estimate of 5 ML/day of additional groundwater flow may be possible in the palaeochannel below Alison Road. Additional groundwater recharge and abstraction could be several times higher than this estimate if the extent and depth of suitable sediments is confirmed. A typical large irrigation bore in the area can yield 1 ML/day, so a MAR scheme in this local area could support at least an additional 5 irrigation bores pumping a total of about 2 GL/year.

Given the uncertainties and knowledge gaps, it is not possible at this stage to estimate how many MAR schemes would be possible in the north-eastern Botany aquifer. The combined capacity of MAR schemes in the Alison Road area and at other locations in the north-eastern Botany aquifer could be substantial. If an ASTR scheme is designed to achieve a water residence time in the aquifer of 1 year, then an abstraction bore could be installed several hundred metres down-gradient from a recharge facility. Multiple MAR facilities could be installed in north-eastern Botany aquifer, each with a capacity of up to 5 ML/day. Importantly, this yield would be available continually, with groundwater levels maintained or recovering rapidly between abstraction cycles.

MAR schemes balance increased abstraction with increased recharge, the schemes would not result in any stress to the aquifer. At current estimates of sustainable yield and usage it appears that increased abstraction of about 12.5 ML/day is possible (Table 5). However this value is likely to be within the error margin of estimated sustainable yield and usage and may not be available. If these values are verified, increased groundwater development could therefore occur to a certain extent prior to the need for MAR. Thereafter, MAR schemes would effectively increase the sustainable yield.

Additional movement of contaminated groundwater to Botany Bay due to a potential MAR scheme would not occur as a groundwater capture scheme is already in place to prevent this. The capture scheme has a capacity of 15 ML/day and is currently being used at below 50% capacity. Migration of contamination towards the north-east would not occur, provided that natural hydraulic gradients were maintained by preventing excessive abstraction in key locations.

2.4.3 Water Quality Issues with MAR

The benefits of segmenting the urban water market according to beneficial usage and water quality are beginning to be appreciated in Australia. Delivery of water that is "fit-for-purpose" provides an opportunity for smarter and more sustainable urban water systems.

Achieving water quality targets for beneficial usage requires attention to water quality at each step of the MAR process including:

- Recharge water quality
- Native aquifer water quality
- Attenuation capacity of the aquifer
- Extracted water quality.

Recharge water quality should be of a standard that does not degrade the beneficial use of the aquifer and that minimizes problems with clogging during managed recharge. It is assumed that MAR schemes would incorporate water quality treatment either prior to, or during the recharge process that is commensurate with the source water quality.

The NSW State Groundwater Quality Protection Policy (DLWC, 1998) stipulates that groundwater quality should be protected so that beneficial use is not downgraded. In practice, this policy has meant that many aquifers can be classified as drinking water beneficial use, even if disinfection is required to meet bacterial guidelines. By contrast, in the USA, all water recharged to aquifers must comply with EPA drinking water standards or similar criteria.

To protect native groundwater quality for beneficial use including drinking water, a comprehensive baseline data is required for a detailed suite of analyses, describing temporal and spatial variability. At the current time, groundwater quality data in the north-eastern Botany aquifer is generally limited to traditional geochemical parameters, sampled once or twice at few locations.

Classed as a highly vulnerable aquifer, groundwater abstraction in the southern Botany aquifer is embargoed due to contaminant plumes (Zones 1-4, Figure 7). However, excellent groundwater resources are available in the north-east of the aquifer in the suburbs of Randwick, Kensington, Eastlakes, Kingsford and Maroubra.

Available data indicates that groundwater quality in this area generally complies with drinking water standards with the exception of iron, and bacterial indicators, except in locations near leaking sewers and landfills. Degraded water quality near the top of the watertable, and where fertilizers are applied (eg. Randwick race course, golf courses) and for a full range of water parameters is yet to be assessed. Up to 70% of nitrogen in fertilisers can leach to sandy aquifers under Australian cities, although phosphorous in fertilizers is generally bound up in the soil zone (Sharma et al., 1996).

There is no baseline water quality data on some parameters that are of importance for managed aquifer recharge. For example, the occurrence and distribution of manganese, fluoride, dissolved organic carbon, suspended solids, various nitrogen, iron and sulphur species (eg. reduced forms such as NH_4 and Fe) and a broader suite of pathogens (eg. Faecal streptococci) is lacking. The extent to which aquifer sediments may release iron due to enhanced flow rates and changing pH and oxidising conditions requires a thorough assessment of iron and carbonate mineralogy within aquifer sediments.

The water quality required for irrigation and drinking water is summarised in Table 12 compared to the likely water quality of the North-eastern Botany aquifer.

Table 12
Water Quality Criteria for Various Beneficial Uses Compared with Water Quality in the North-eastern Botany Aquifer

Parameters	**North-eastern Botany Aquifer**	**Aquifer Sediments**	**Irrigation ANZECC (2000)**	**Drinking Water (NHMRC, 2004)**
Salinity	Low		Low-Moderate	Low
pH	~5.6		6.0-8.5**	6.5-8.5**
Dissolved Oxygen (DO)	Moderate	-	-	High
Suspended Solids (SS)	Low	-	Moderate (clogging of equipment)	Low
Bacterial load	Low	-	Moderate -High	Low (raw water may be treated)
Iron (Fe_{TOTAL})	Moderate	Moderate in sands, high in coffee rock	Low-Moderate	Low*
Manganese (Mn_{TOTAL})	Insignificant	-	Low-Moderate	Low
Nutrients	Low-Moderate	-	High	Moderate

* aesthetic reasons only
** prevent corrosion of fittings

It is assumed that MAR schemes would not increase contaminant loadings to the aquifer, however, natural filtering and attenuation of some existing contaminants occurs within the sand aquifer. Whilst the north-eastern Botany sand aquifer is comprised mostly of quartz sand, the sediment would also contain trace quantities of iron minerals, silt, clay and shell fragments. Geochemical reactions would therefore be expected during mixing of recharge waters with native porewaters. A water residence time of years is proposed in the aquifer, compared with a residence time <10 hours in typical sand filtration beds that are often used as part of conventional drinking water treatment plants. The sands would likely act as an effective filtration and attenuation medium for a range of constituents including trace metals and pathogens.

A methodology for predicting water quality improvements during MAR has been developed called ASRRI (Dillon et al in CGS, 2004). The screening tool ASRRI (ASR Risk Index) predicts breakthrough and contaminant attenuation for the worst case scenario. More complex reactive transport flow modelling (eg. using the PHREEQC and PHST3D codes) would provide additional confidence in predicted water quality impacts during MAR, provided that suitable input data were available for modelling.

3. KNOWLEDGE GAPS AND RECOMMENDATIONS

On the basis of this review of existing data, there appears to be a significant opportunity to extend the available water resources in the Botany Aquifer by some form of MAR. This section of the report recommends a scope of work for a detailed feasibility assessment. The recommendations have been formulated on the basis of the review, preliminary GIS mapping and typical MAR projects. Suggested studies would address operational uncertainties and unknowns, expanding upon issues that have been identified.

3.1 Knowledge Gaps

3.1.1 Aquifer Depth and Boundary Conditions

Despite the large number of references to the Botany Aquifer, it is clear from the compilation work presented above that little co-ordinated and systematic work has been carried out to date. There are numerous examples of unchecked data that have been often quoted and entered into the literature. This important observation is illustrated by the following examples:

- An estimate of the maximum depth of the aquifer of 80 m that is often used (Bish et al., 2000). This often quoted observation relates to the inclusion by Griffin (1963) of a reported bore by Australian Paper Manufacturers (APM) Limited at McCauley Street in Mattraville. This bore was test bore No 37 by APM and reached a depth of 78.9 m after passing through sand, clay, peat and sandstone. This seems to be the only bore in Griffin's records that penetrated the sandstone and was possibly drilled to check for additional water resources below the sands. Examination of other logs in the vicinity of this bore indicate that bedrock is at a much shallower depth in the immediate area and that a palaeochannel does not exist. Woodward Clyde (1996) report that the maximum depth of the Lake's Valley palaeochannel immediately to the west at Banksmeadow is approximately 65 m where it flows beneath the present Botany Bay coastline. In either event, the depth of the sands within the Basin is much less than 80 m.
- Another area of uncertainty is the large variation in fluxes through the aquifer reported by the various workers in the field, due to assumptions regarding recharge and other boundary conditions. Merrick (2004) and Laase (2005) have individually carried out detailed modelling of the southern part of the aquifer using the latest and most sophisticated groundwater modelling and optimising packages. They arrived at quite different estimates as shown in Table 4 (from Laase, 2005) where Model A relates to Merrick’s 2004 model and Model B relates to Laase’s 2005 model. The fact that these experts can arrive at such different solutions merely indicates that their conceptual

models are significantly different and require further detailed field investigation to reduce the current uncertainty.

Similar comments could be made concerning other critically important factors such as the actual abstraction rates and active abstraction and monitoring bore locations. It is essential that these areas of uncertainty are resolved if MAR is to proceed successfully. An additional 5 ML/day in the area would be a significant boost to resources and at present is within the uncertainty of currently available modelling.

This fairly basic hydrogeological information is not difficult to achieve but it is time consuming. State agencies have not given the aquifer a high priority from a resource perspective, while consulting companies have focused on specific project objectives, with reports not generally available. University students have frequently carried out research that has not generally been widely available and is sometimes of questionable quality. The result is that despite all the reference material, there remains a great deal that is unknown about the aquifer, and this includes fairly basic material such as the aquifer depth and extent. Without this data, any groundwater model remains a best guess based upon many untested assumptions.

A major and significant knowledge gap is therefore a comprehensive geological model of the aquifer. This will require accumulating and checking available data before entering it into a 3D data base and forming a representative 3D model. Further gravity survey work would help improve estimates of depth to bedrock in the upper part of the aquifer. The 3D model can then form the basis for a comprehensive and more accurate 3D groundwater model that can be used to obtain more concise estimates of groundwater flow and potential storage.

3.1.2 Sustainable Groundwater Yield and Capacity for Increased Recharge

It is essential that the groundwater model be calibrated against a representative data set acquired over a period of several years (ie. transient calibration). Ideally, this period should cover a major drought and a wet period. The aquifer does receive good recharge from the coastal rains and the current stormwater recharge. This probably explains why water levels in the aquifer are stable, notwithstanding the considerable abstraction. Monitoring points should be activated or established and data loggers installed so that the variation of hydraulic head and water quality can be recorded. Measurements of spatially and temporally variable rainfall and stormwater flow are required to calibrate the model.

The groundwater model can finally be used to estimate how much additional recharge and abstraction would be possible in the aquifer. This is unknown at present and although estimates can be made, they will be subject to large error margins given the uncertainty in aquifer hydraulic properties that exists at present.

3.1.3 Available Volumes of Additional Recharge Water

On the basis of this review it appears that additional recharge water from sewer mains may be the preferred option for a secure additional source of recharge water that does not depend on rainfall. However, the possibility of additional recharge water from stormwater sources from some areas not already diverted to ponds and areas located adjacent to the Botany catchment cannot be ruled out.

Five stormwater drains currently enter Centennial Park and discharge directly to the ponds. A proportion of this water then enters the aquifer. There appears to be significant potential (Figure 17) to redirect additional storm water by limited engineering works, perhaps involving new tunnels to divert stormwater from areas outside the Botany catchment (at >60 m AHD) via gravity flow to Queens Park. The cost of pumping stormwater from areas lower than this is likely to be prohibitively expensive. It would not be possible to harvest stormwater from all of these subcatchments. Furthermore, stormwater monitoring available from the Musgrave pond sub-catchment indicate that the volume and reliability of this water source may not be adequate for MAR. However, stormwater modelling is required to assess potential harvesting in other areas.

The suggestion is made that treated wastewater be used to further recharge the aquifer as wastewater appears to be the most reliable source of additional water for aquifer recharge. If the assumption is made that only tertiary treated wastewater is recharged, then there is little point in detailed studies of bacterial die off or virus transport. However, if secondary treated effluent were considered for recharge then these studies will be required.

3.1.4 Vulnerability of the Aquifer to Contaminants

Shallow sandy aquifers are highly vulnerable to contamination. Untreated urban recharge, sewer leakage and fertiliser usage may have caused local groundwater quality impacts, particularly at the watertable. The extent to which possible increased salinity near the watertable is due to urban impacts versus concentration by evapotranspiration, and the possible long term implications for aquifer water quality, is unknown. However, even a sandy aquifer has some capacity to absorb and attenuate specific types of contaminant, particularly if the sediments contain trace quantities of silt, clay, and carbonate such as shell fragments. The capacity of the Botany aquifer for de-nitrification and inactivation of bacterial loads is largely unknown.

It is assumed that MAR schemes would incorporate water quality treatment either prior to, or during the recharge process that is commensurate with the source water quality. For example, MAR schemes should be designed to prevent increased loads of trace metals, pathogens and nutrients. The capacity of the aquifer to remove existing contaminant loads (eg. from fertilisers) however, should be considered along with possible interactions between increased flux of fresh, oxygenated recharge water with the aquifer matrix.

The ponds in Centennial and Moore Parks are known to be connected to the groundwater system. The water quality in these ponds is poor during drought, due to a range of factors including nutrient inputs and re-suspension of pond sediments by carp. A significant knowledge gap exists in that it is not known how much of the surface contamination is transmitted to the aquifer. Hydrochemical studies are therefore required to establish the water quality in the aquifer associated with the ponds.

3.1.5 Operational Issues for Potential MAR Systems

There are several operation issues for potential MAR systems, that would need to be addressed should the outcome of detailed feasibility assessments be favourable. For example, technical operational issues would include management of bio-fouling in bore pumps and screens and preventing clogging of aquifer pore spacing. For example, detailed conceptual design of a proposed injection bore in coastal sands included an assessment of bio-fouling that was identified as the most significant risk to the operation (Glamore et al., 2005a, b). This work included geochemical mixing modelling that indicated significant mobilisation of iron from aquifer sediments could occur, and outlined a plan of management to minimize iron-biofouling.

The regulatory framework for operating MAR systems would also need to be considered in terms of right of access to additional recharge water that is recovered.

3.2 Recommendations

3.2.1 Project Stages

Detailed assessments are required to evaluate three primary issues that would determine whether or not MAR is feasible in the Botany area. These three issues are:

A. The suitability of the Botany aquifer for specific MAR systems

B. The availability of additional recharge sources

C. The demand for additional groundwater supplies and specific beneficial uses.

The following recommendations provide details specific to the Botany aquifer for the first part of a general assessment methodology outlined in Figure 16 (Dillon and Pavelic, 1996). It is possible that MAR in the Botany area is not feasible, is not required to meet current demand or is currently not economically viable.

MAR schemes could proceed to detailed concept design, preconstruction design and pilot testing should detailed feasibility assessment of each of the three primary issues appear favourable.

3.2.2 Detailed Feasibility Assessments

It is recommended that detailed feasibility assessments be undertaken of the available sources of additional recharge water, and treatment requirements, along with an assessment of demand (Issues B and C). These assessments would include, but not be limited to the following components of work:

1. Assessment of availability of treated waste water
    - Suitable locations to access sewer mains in the vicinity of MAR points
    - Possibility of diverting STP discharge from Bondi and Maroubra
    - Water quality treatment required for MAR
    - Balancing storage volume required as part of MAR scheme
    - Estimated costs and project timeframes.

2. Assessment of availability of stormwater
    - Stormwater modelling to determine harvestable volumes and reliability

- Assessment of diversion and transfer mechanisms
- Water quality treatment required for MAR
- Estimated volume of detention storage required as part of MAR scheme
- Estimated costs and project timeframes.

3. Assessment of demand for additional groundwater supplies
    - Water quality requirements for specific beneficial uses
    - Assessment of water demands and consumption patterns, and the technical and economics of delivery of water to potential consumers
    - Potential demand for industrial use, assuming that the demand for irrigation (eg. golf courses and domestic gardens) is already met.

Future consideration may be made of whether or not using groundwater as an additional buffer may provide increased confidence for providing treated wastewater to the mains supply.

It is recommended that a detailed feasibility assessment of the suitability of the Botany aquifer for specific MAR systems (Issue A) include the following components of work, listed in priority order:

1. Develop a database framework to facilitate detailed groundwater assessment
    - Data compilation and validation would facilitate modelling work
    - Data would include stratigraphy, geophysical surveys, bore construction, updated groundwater level hydrographs and water quality
    - An on-line database with appropriate levels of access and security is preferred.

2. Audit of existing groundwater monitoring bores and abstraction bores
    - Verification of monitoring bores that are still functional, and which require maintenance (eg. de-silting)
    - Re-activation of key monitoring bores where required, utilising data loggers recording water level and EC (salinity)
    - Assess the significance of groundwater abstraction rates from numerous unlicensed bores, where possible.

3. A 3D geological model should be assembled based upon verified available data
    - A 3D geologic model to be developed to define aquifer extent and support groundwater flow modelling
    - Limited additional geophysical survey to provide gravity data in parts of the north-eastern Botany aquifer that are not already surveyed
    - Limited additional drilling and geophysical bore logging to verify stratigraphy and depth to aquifer base in areas near important boundaries where there are no existing bore data.

4. Limited studies of aquifer recharge by rainfall
    - Installation of shallow nested monitoring piezometers, above and below the watertable
    - Correlation of groundwater level changes and vertical hydraulic gradient with high frequency rainfall data
    - Rainfall recharge factors determined for groundwater flow modelling.

5. A survey of water quality in the north-eastern part of the aquifer
    - Testing of water quality parameters of relevance to MAR and to better define baseline conditions (eg. suspended solids, oxidized and reduced iron and nitrogen species, bacterial indicators).

6. A revised groundwater flow model
    - Improved resolution and layering in the north-eastern part of the aquifer
    - Constructed on the basis of 3D geologic modelling
    - Determination of the optimum rates for increasing recharge with no further abstractions, and then to determine the optimum recharge to support additional abstractions.

7. Identification of suitable MAR technologies and constraints
    - Identify suitable MAR methods such as recharge ponds and ASR methods
    - Pond sediment management and permeability assessment, if required
    - Assessment of groundwater dependent ecosystem requirements in the area, including acceptable water table levels
    - Constraints to variable water table levels in key urban areas.

Further detailed investigations may be required at detailed concept design stage and as part of the regulatory approvals process, but are not warranted for detailed feasibility. These technical studies could include the following: aquifer hydraulic testing, optimisation modelling of bore fields, and geochemical assessment of source water compatibility with native groundwater. Advanced techniques such as groundwater age dating and tracer testing of recharge are not considered essential to detailed feasibility investigations.

Identification of regulatory issues such as licensing of MAR and rights to recovered groundwater would also need to be considered. It is noted that the above outline for detailed feasibility studies represents the minimum scope recommended to provide a realistic outcome that can be used for planning purposes.

It is recommended that a sustainability assessment be undertaken in conjunction with detailed feasibility assessment to ensure a best practice approach. A sustainability assessment would adopt a 'triple bottom line' approach that could compare various MAR options, or compare MAR with other water supply options such as emergency groundwater supplies from deep rock bores. For example, the WSAA (Water Services Association of Australia) Sustainability Framework includes life cycle assessment, quantitative risk assessment and cost comparison (G. Peters, pers.com.).

Broadly indicative costs, project time frames and agencies that are recommended to complete some of the recommended detailed feasibility assessments are to be provided in a separate WRL Letter Report.

4. SUMMARY

The only significant aquifer in the Sydney region is the Botany sand aquifer located between Centennial Park and Botany Bay. On the basis of this review of existing data, the hydrogeological characteristics of the north-eastern Botany aquifer are suitable for managed aquifer recharge (MAR) systems that could extend available water resources.

On the assumption that additional groundwater supplies are required, it is recommended that further detailed assessment of aquifer capacity for MAR be undertaken. Naturally high recharge rates and the permeable nature of the Botany sand aquifer are two factors which make the Botany Aquifer particularly suitable for MAR schemes. The north-eastern part of the Botany aquifer is generally excellent quality water, and is not associated with contaminated areas to the west and south. Available groundwater resources from the Botany aquifer could be increased by MAR. Such MAR systems could be designed within the constraints of an urban environment and operated in a sustainable manner and monitored to protect groundwater quality and dependent ecosystems. The source waters for MAR would be treated to ensure the beneficial use of the aquifer is unchanged.

This pre-feasibility assessment has identified knowledge gaps and uncertainties, particularly regarding estimated sustainable yield of the Botany aquifer. Groundwater usage data, particularly for the many unlicensed bores is not available. Recharge rates used in various groundwater flow models have varied widely and have not been verified by field studies.

Given the uncertainties and knowledge gaps, it is not possible at this stage to estimate how many MAR schemes would be feasible. This first-pass assessment suggests that multiple MAR schemes in the area, each with a possible capacity of up to 5 ML/day are possible. Priorities for further assessment of aquifer hydrogeology have been detailed.

The additional water for groundwater recharge could be provided by new stormwater diversions or by the addition of high quality treated wastewater (eg. sewer mining) or a combination of both. More detailed assessment is required to investigate these source options. It is probable that sewer mining and advanced water treatment will provide a more reliable source for continuous MAR operation than stormwater, particularly during extended dry periods.

Suitable MAR types may include infiltration tanks, galleries lined with porous media, existing ponds and injection bores. Selection of specific types would be subject to detailed site assessment. There has been significant recent interest in using porous pavements and leaky pipes as a component of water sensitive urban design (WSUD). Although primarily designed to mitigate stormwater issues in the catchment, WSUD could assist in restoring natural infiltration in highly urbanised areas.

The addition of extra water to the aquifer could have the advantage of maintaining water levels in lakes, ponds and the aquifer, allowing users the possibility of continuing abstraction during dry periods. This would potentially reduce the demand for drinking water and ensure the amenity of the many parks, gardens, playing fields and open spaces. Excess water in wet periods would be carried away down the existing drainage channels. The feasibility of abstraction for other beneficial uses such as industrial processes and possibly, indirect reuse to the mains supply requires further investigation.

Before embarking on a MAR scheme it is essential that groundwater sustainable yield is established with more confidence. The most recent estimates of sustainable yield and usage suggest that increased abstraction in the order of 12 ML/day is possible from the aquifer without additional recharge. There may therefore be the capacity to extract more water within the sustainable yield. However, the volume of groundwater available depends on the definition of sustainable yield and the proportion of rainfall that recharges the aquifer. Further studies are required to assess more accurately the sustainable yield. An updated status report that examines the response of groundwater levels to dry conditions and current usage rates would significantly assist in this regard.

To design a workable MAR scheme it is essential that the physical extent and properties of the aquifer be better defined with additional geophysical surveys and targeted drilling. It is recommended that this be achieved by the construction of a robust and validated geological model. The geological model can be used as the basis for an improved groundwater flow model that is calibrated with time-varying data and model independent recharge values. Such a groundwater flow model can then be used to determine the quantity of additional recharge that the aquifer can accept and transmit and the quantity of additional abstraction that is sustainable.

Integrated water management in this context may present an opportunity for providing additional water sources that are ‘fit for purpose’, ensuring the amenity of a significant part of central Sydney, and optimising water use from an important aquifer resource that has until recently, been overlooked.

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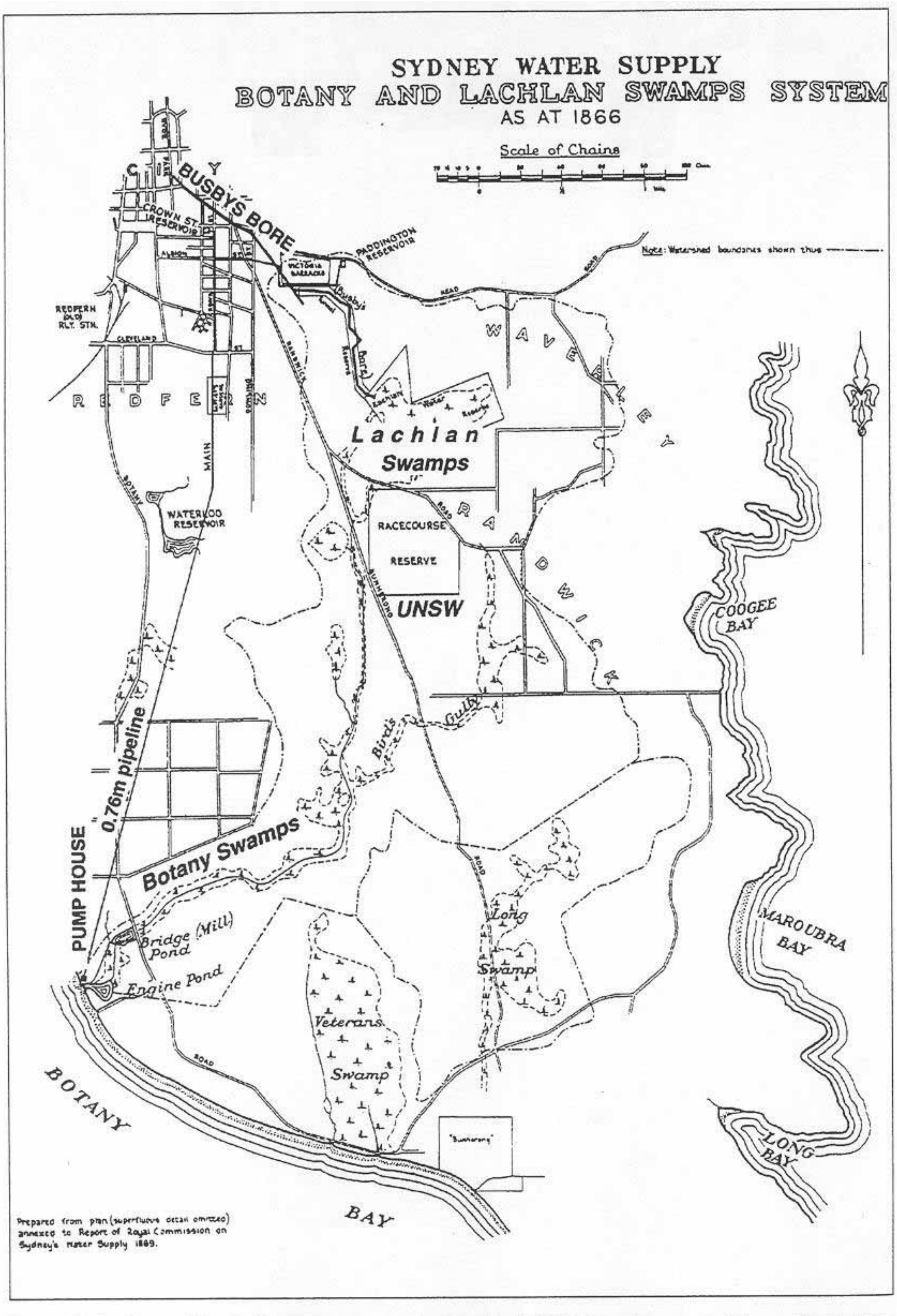
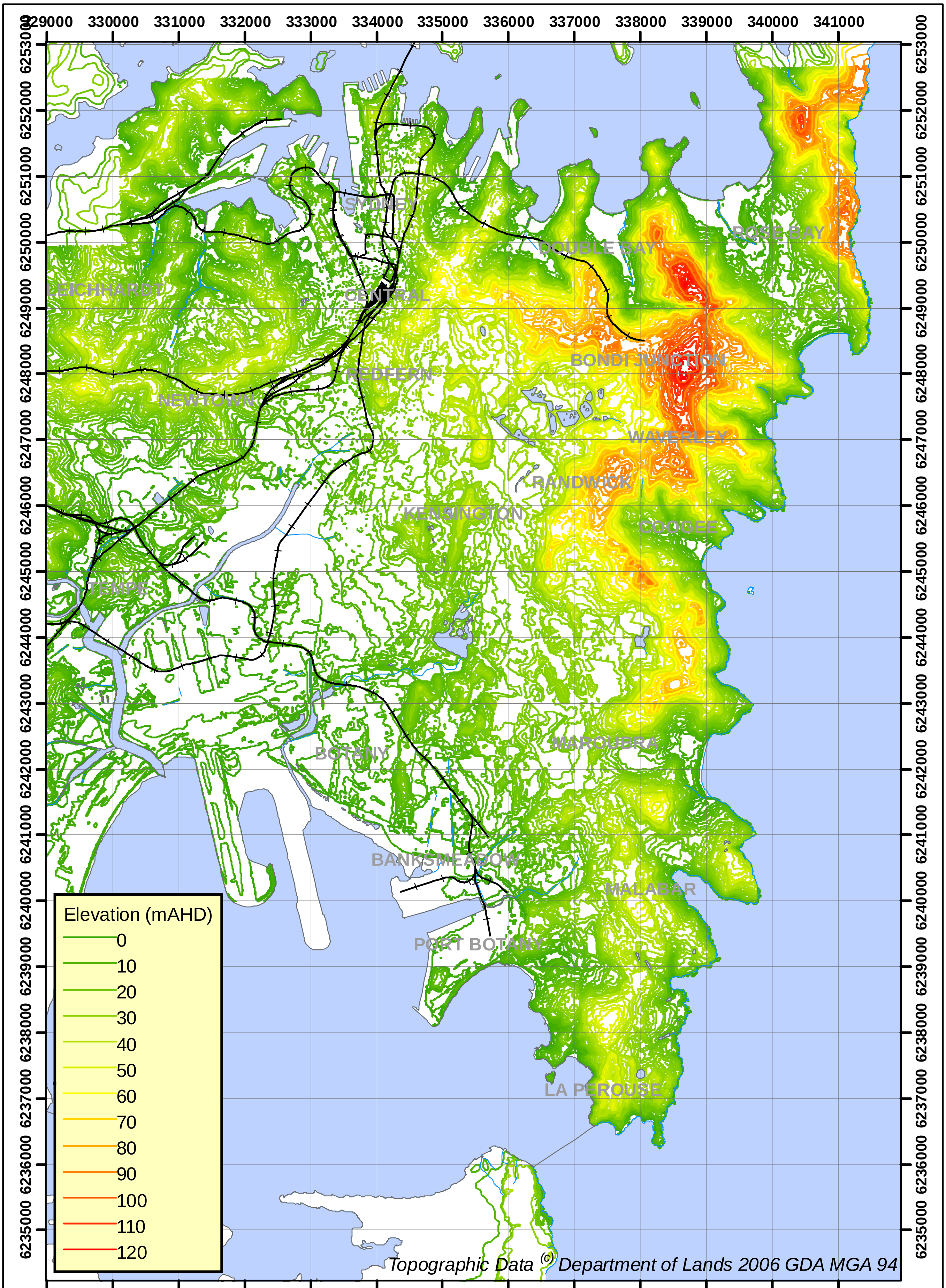
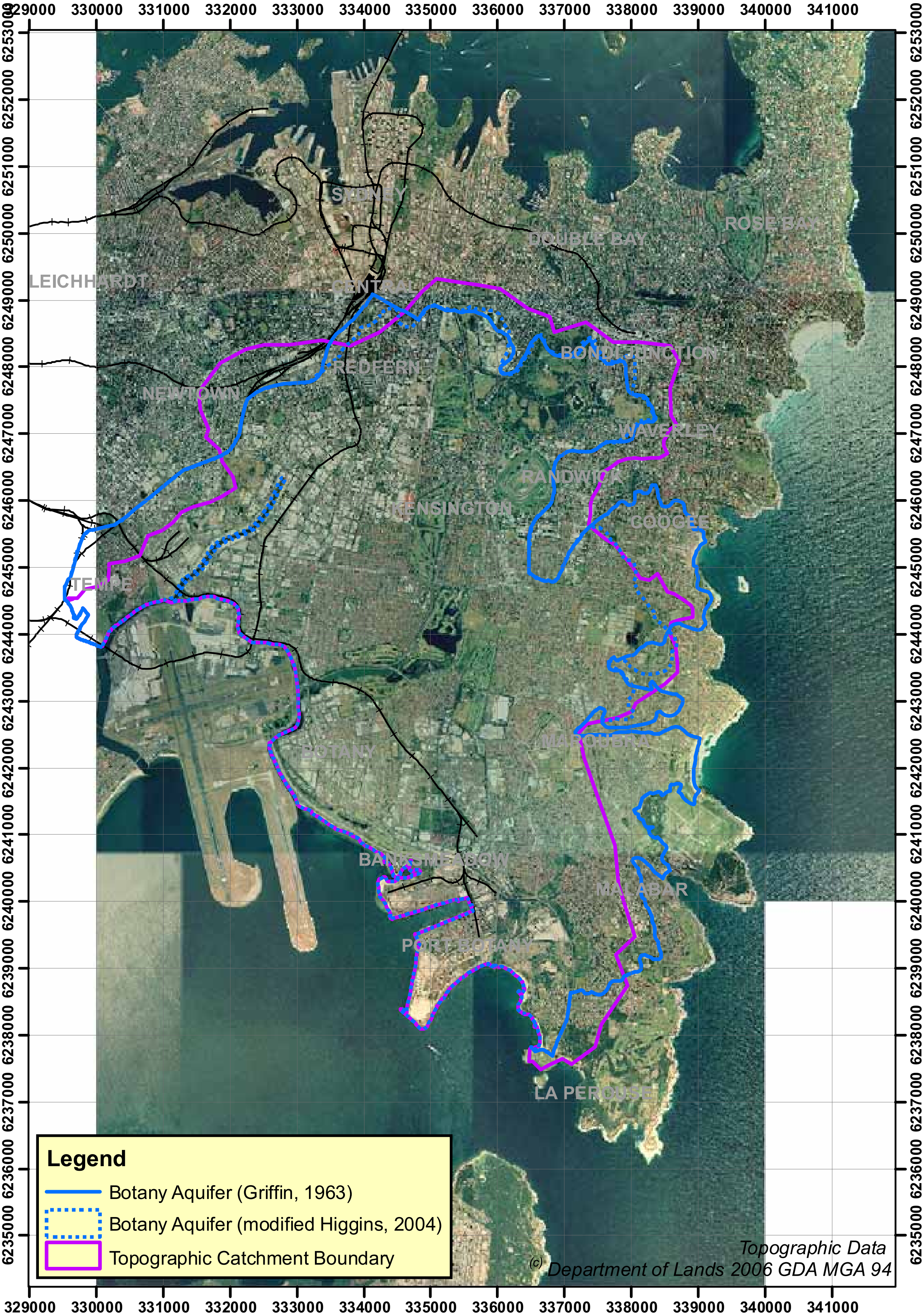


Source: McNally and Branagan (1998) after Aird (1961)

WRL Report No. 2006/33	THE LACHLAN AND BOTANY SWAMPS WATER SUPPLY IN 1866	Figure 1
		03117-file

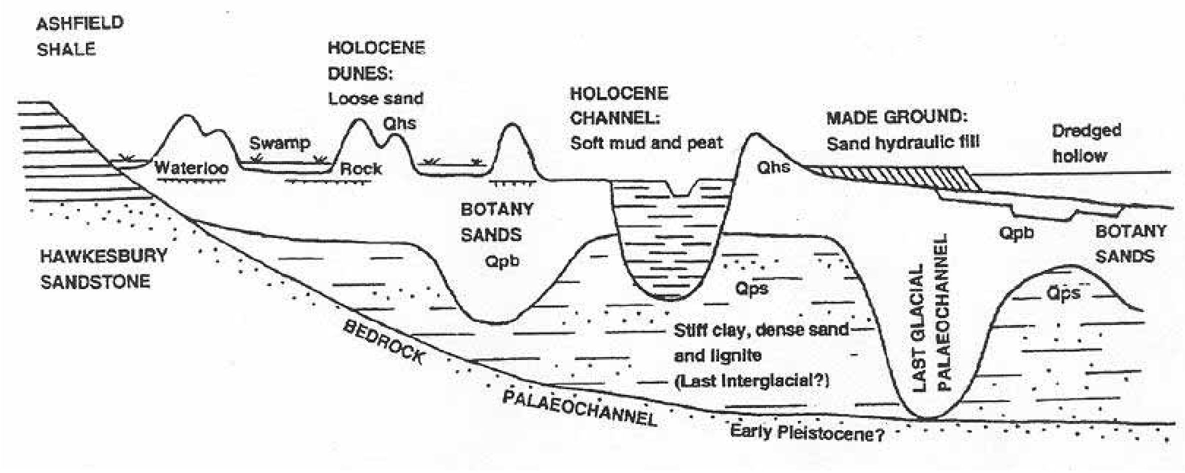


WRL Report No. 2006/33	SITE TOPOGRAPHY (2 m CONTOUR INTERVALS)	Figure 2
		insert filename



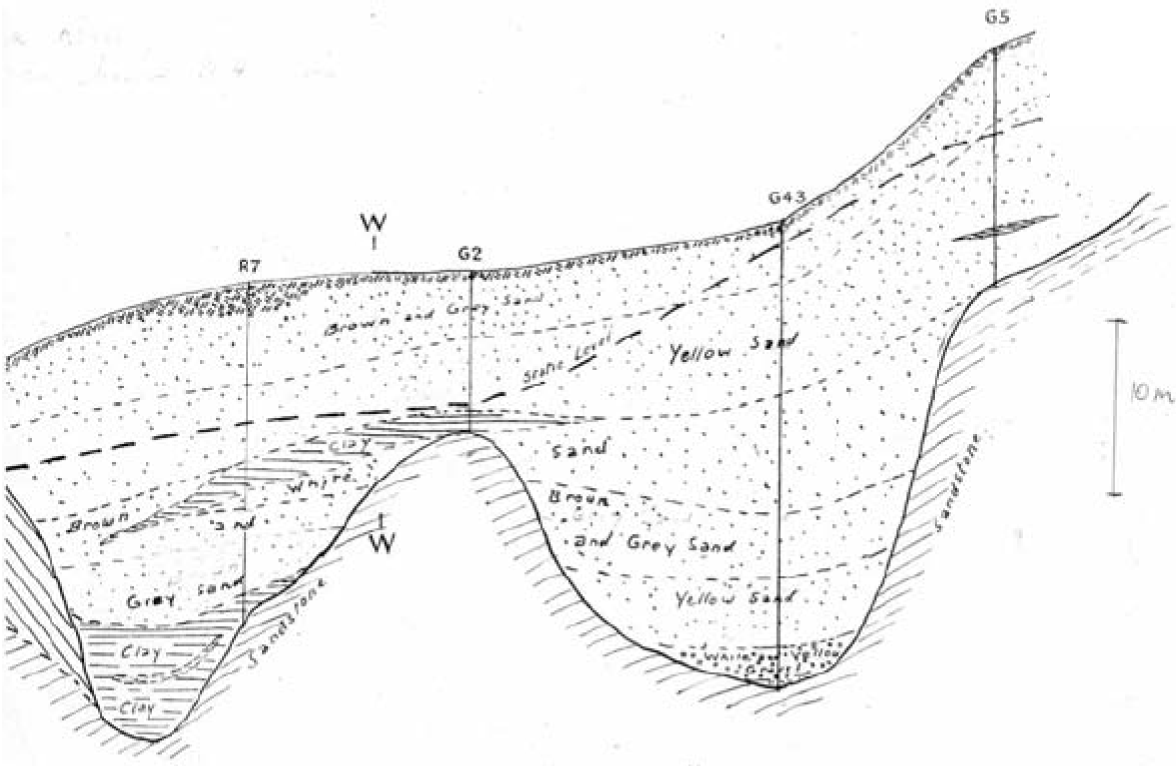
WRL Report No. 2006/33	MAP OF CATCHMENT AND AQUIFER BOUNDARIES	Figure 3 insert filename

A. Northwest to southeast section (Not to scale)



Source: McNally and Branagan (1998)

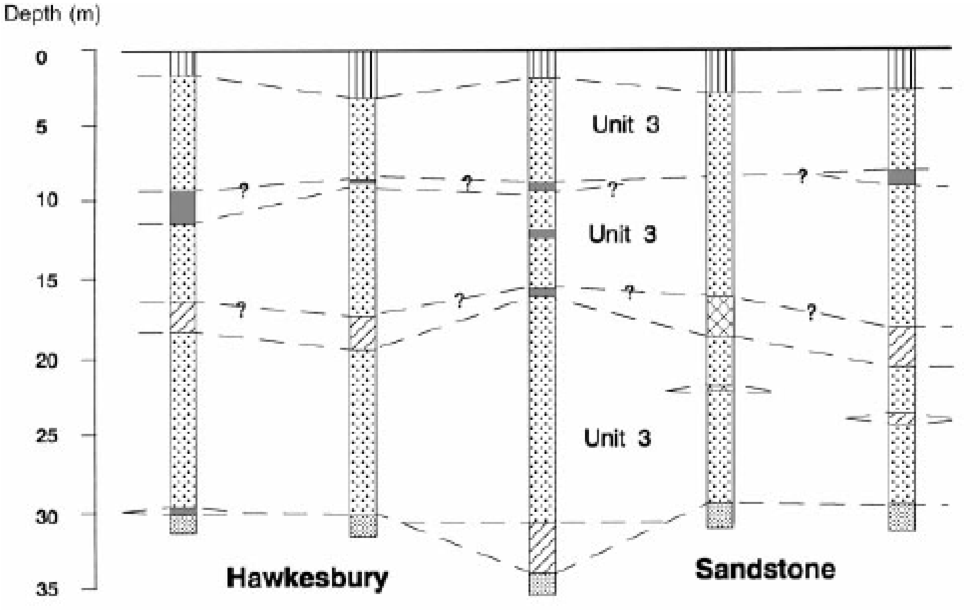
B. Queens Park



Source: Sheil (1942)

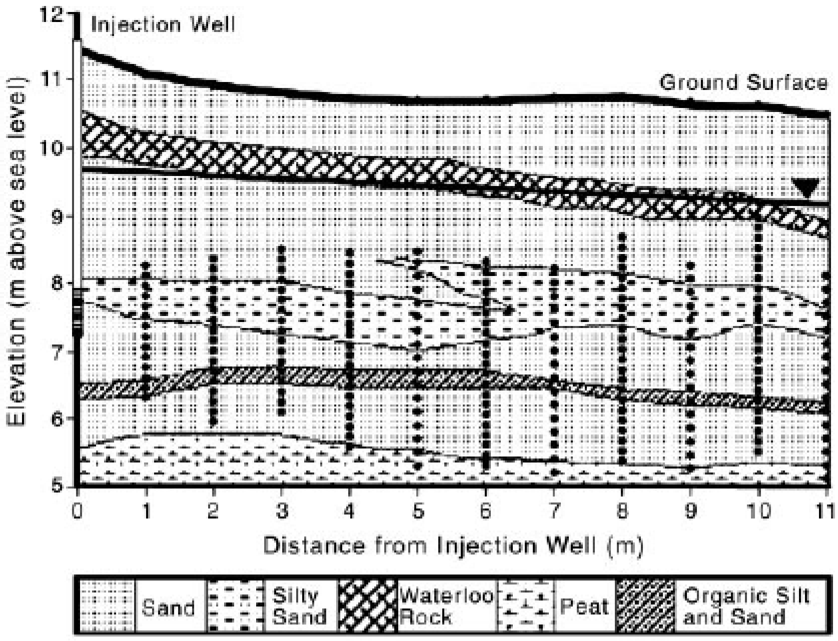
WRL Report No. 2006/33	GEOLOGICAL SECTIONS OF THE BOTANY AQUIFER	Figure 4 03117-file

A. UNSW David Philips Sports Field, Daceyville



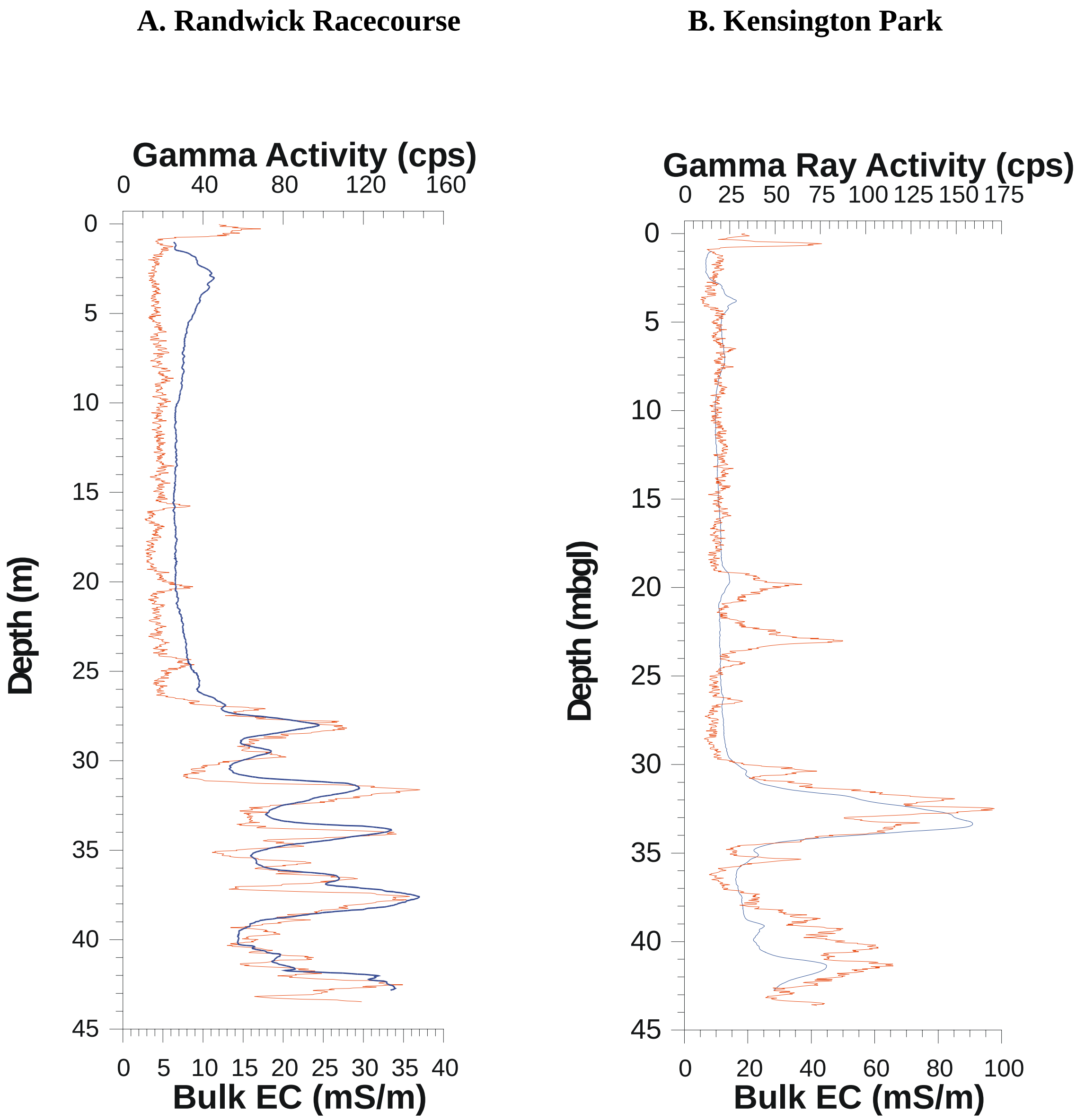
Source: Jankowski and Bedk (2000) after Webb and Waterson (1979)

B. Eastlakes Experimental Site



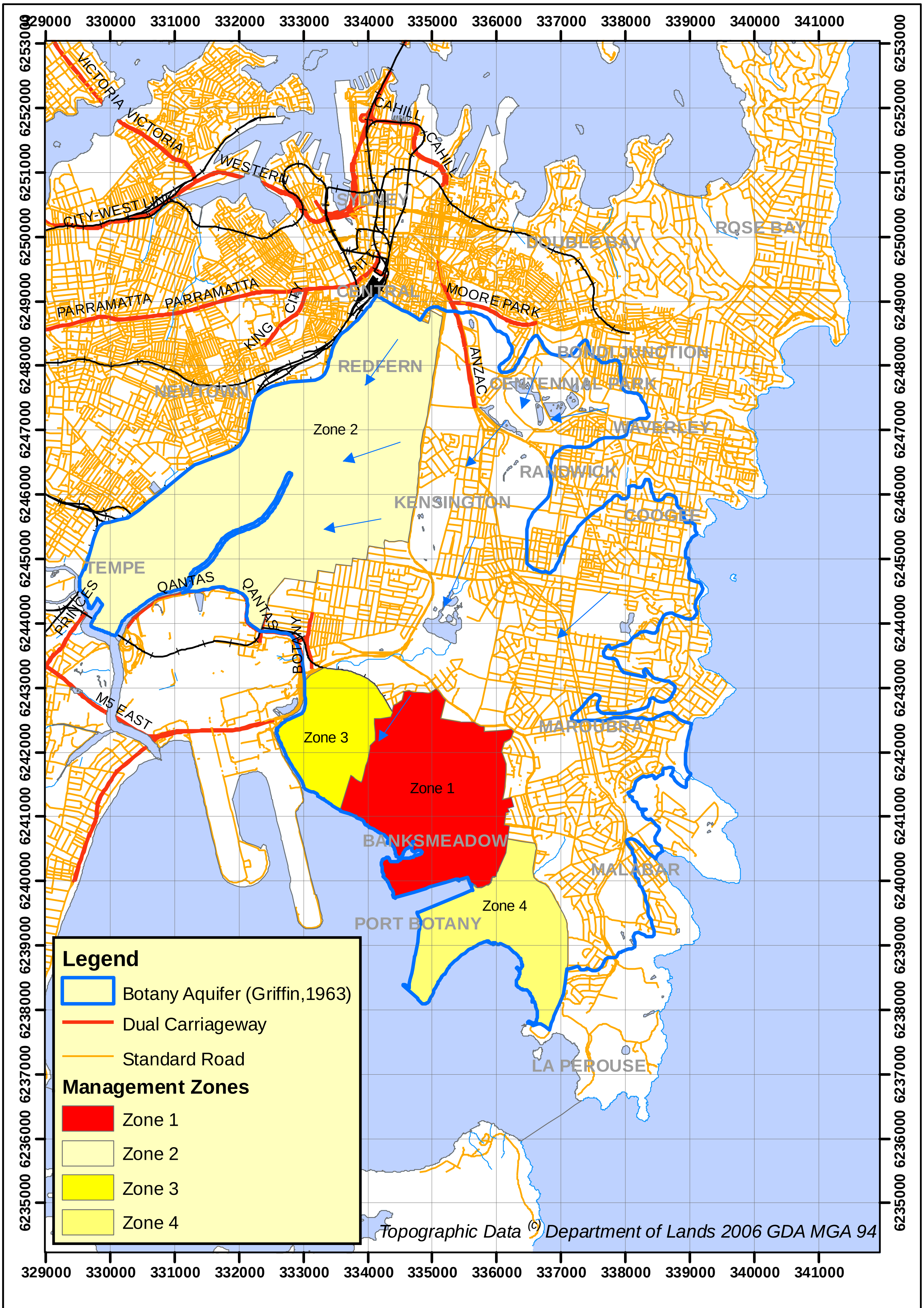
Source: Jankowski and Beck (2000))

WRL Report No. 2006/33	DETAILED GEOLOGICAL SECTIONS AT EXPERIMENTAL SITES	Figure 5 03117-file



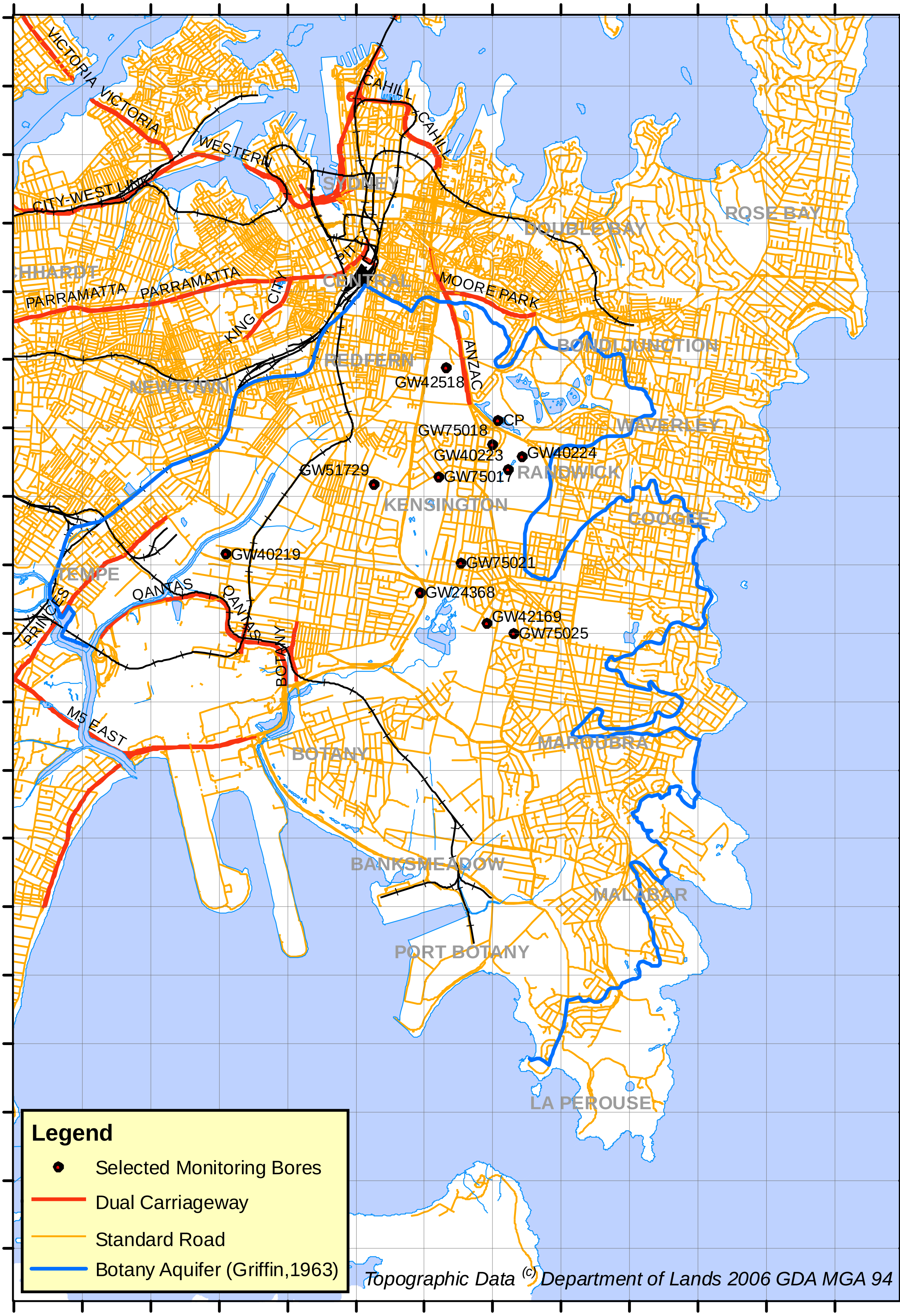
Data Source: Acworth (1998)

WRL Report No. 2006/33	GEOPHYSICAL BORE LOGS AT RANDWICK RACE COURSE AND KENSINGTON PARK	Figure 6 03117-file

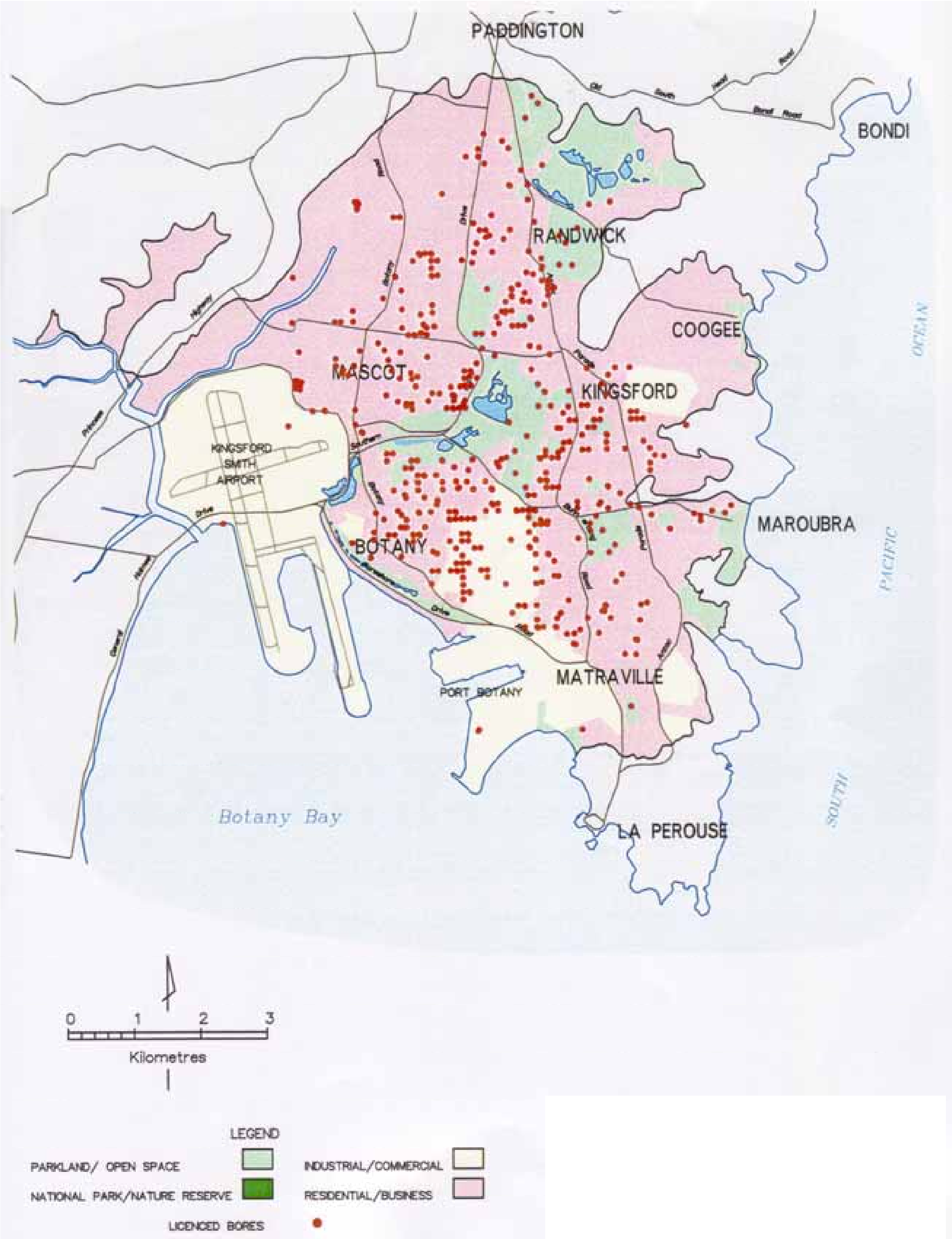


WRL Report No. 2006/33	GROUNDWATER MANAGEMENT ZONES AND FLOW DIRECTIONS	Figure 7

insert filename

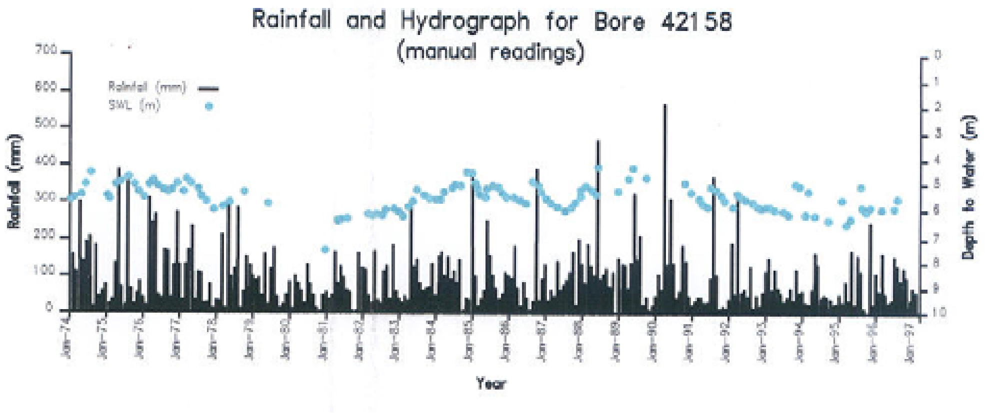


WRL Report No. 2006/33	LOCATIONS OF MONITORING BORES	Figure 8

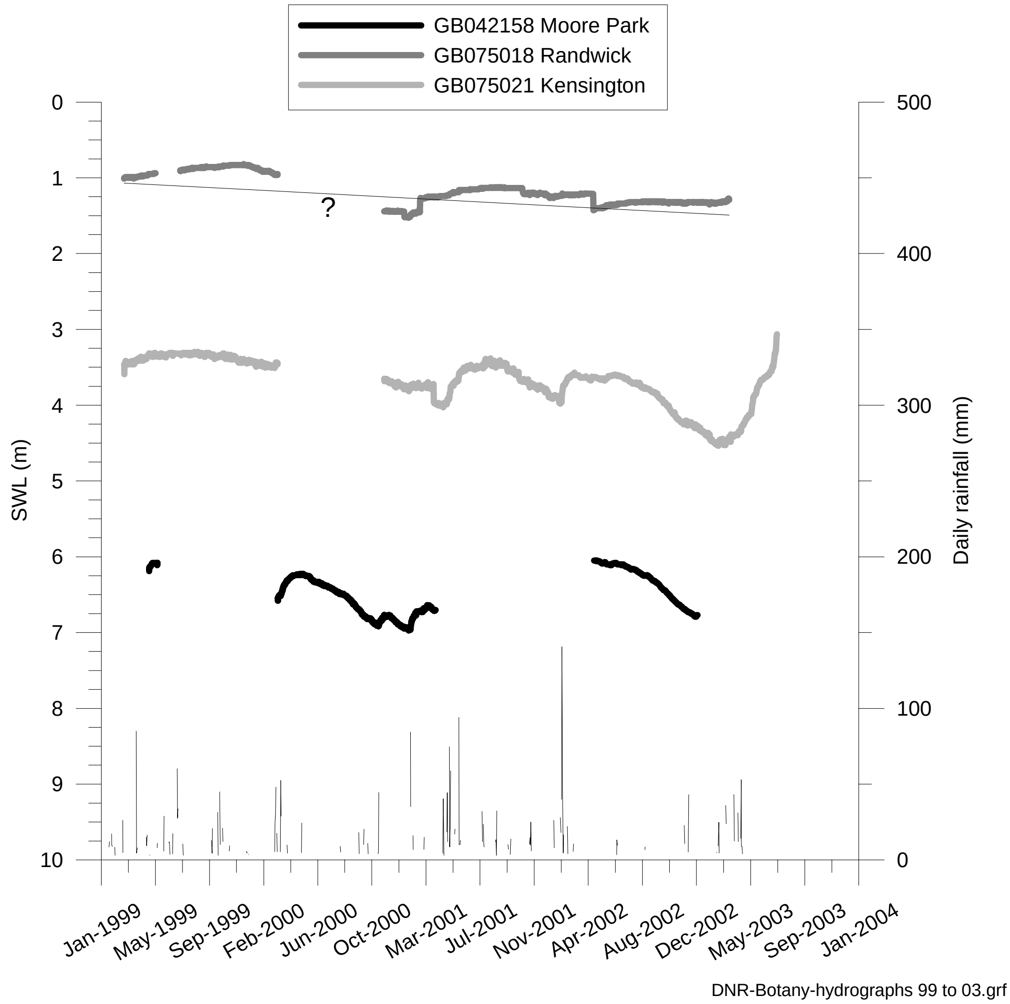


Data Source: Bish et al. 2000

WRL Report No. 2006/33	LICENSED BORES - 2000	Figure 9 03117-file



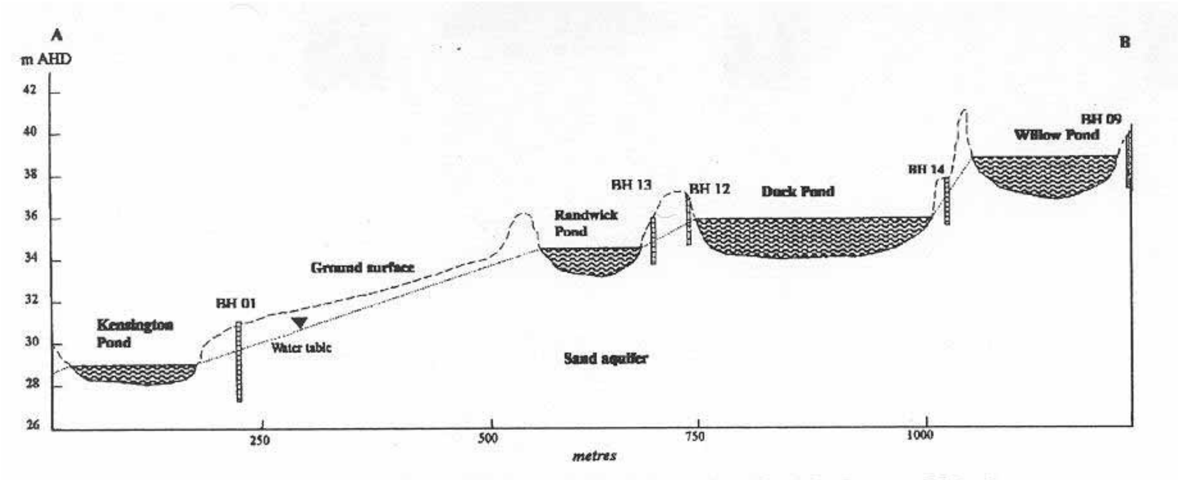
Source: Bish et al. (2000)



Data Source: DNR, Bureau of Meterology (Station 66160)

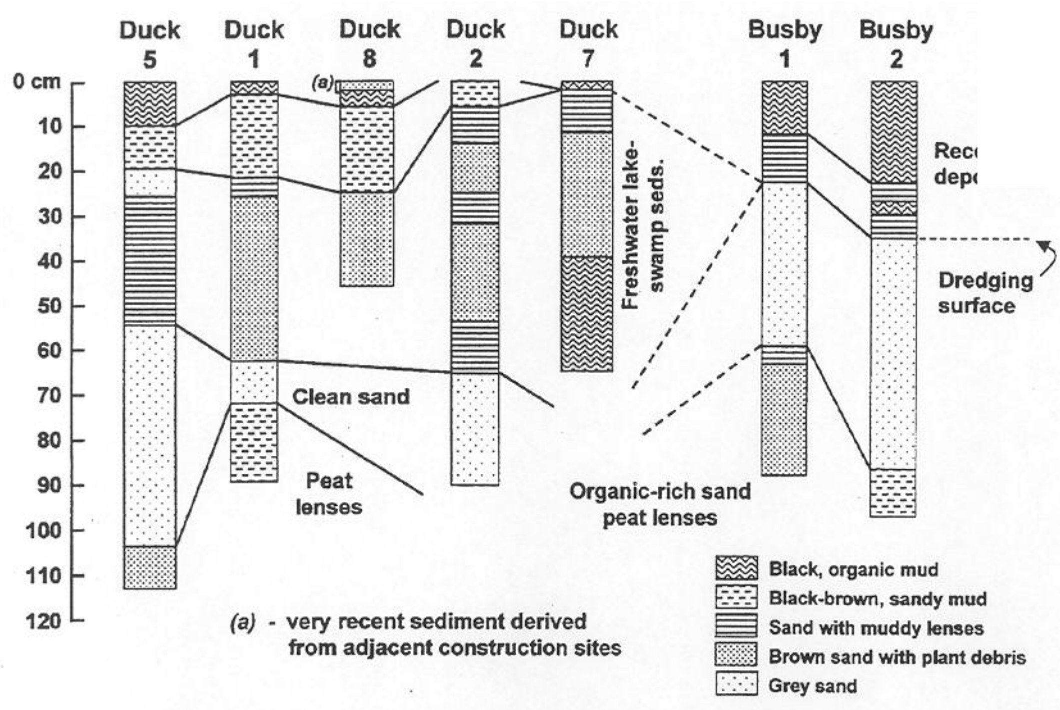
WRL Report No. 2006/33	SELECTED GROUNDWATER HYDROGRAPHS – 1974 TO 2003	Figure 10 03117-file

A. Section showing pond and groundwater levels



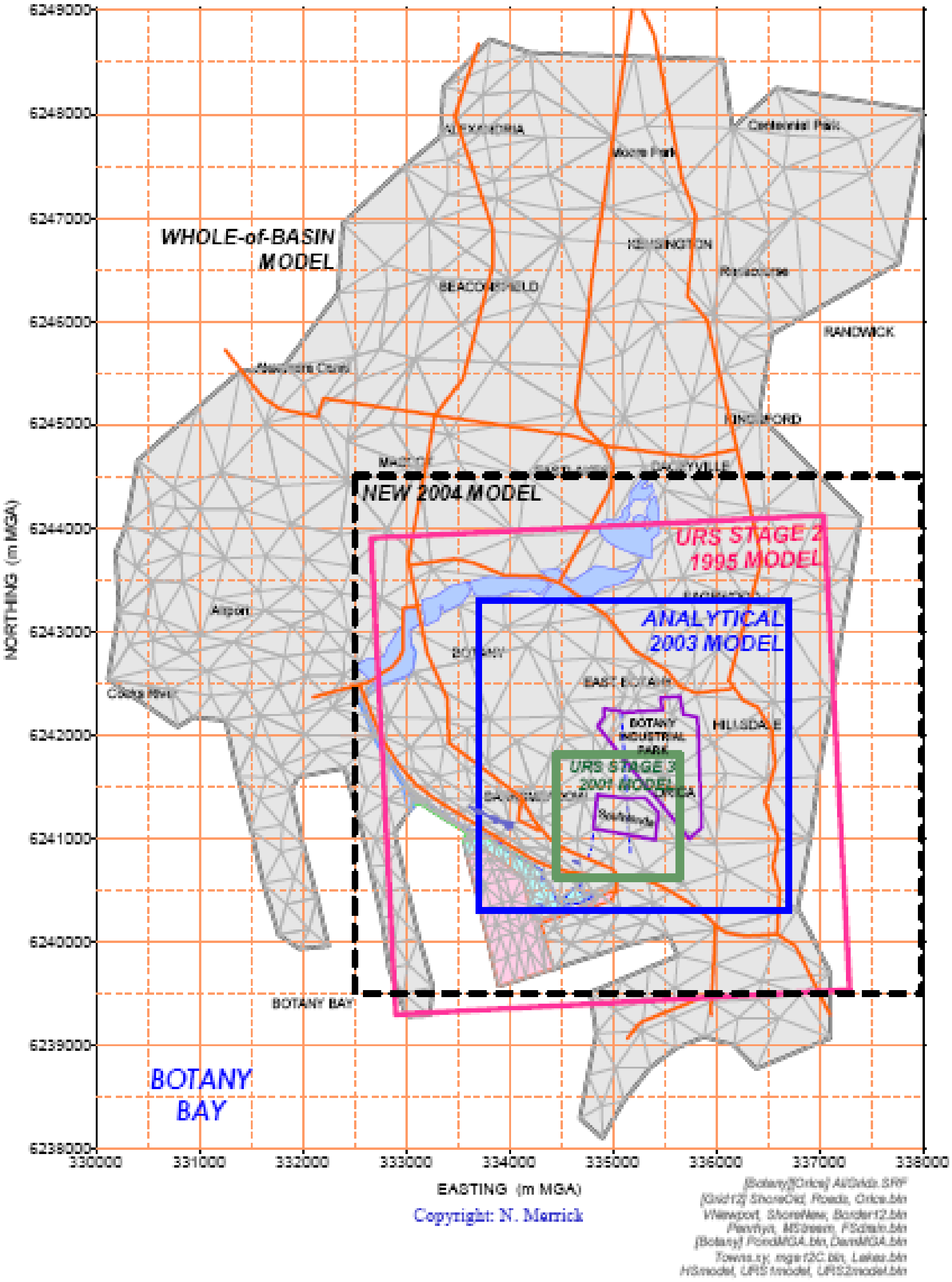
Source: Dudgeon (1993)

B. Core logs and interpreted stratigraphy for Duck and Busby ponds.



Source: McHugh et al. (1998)

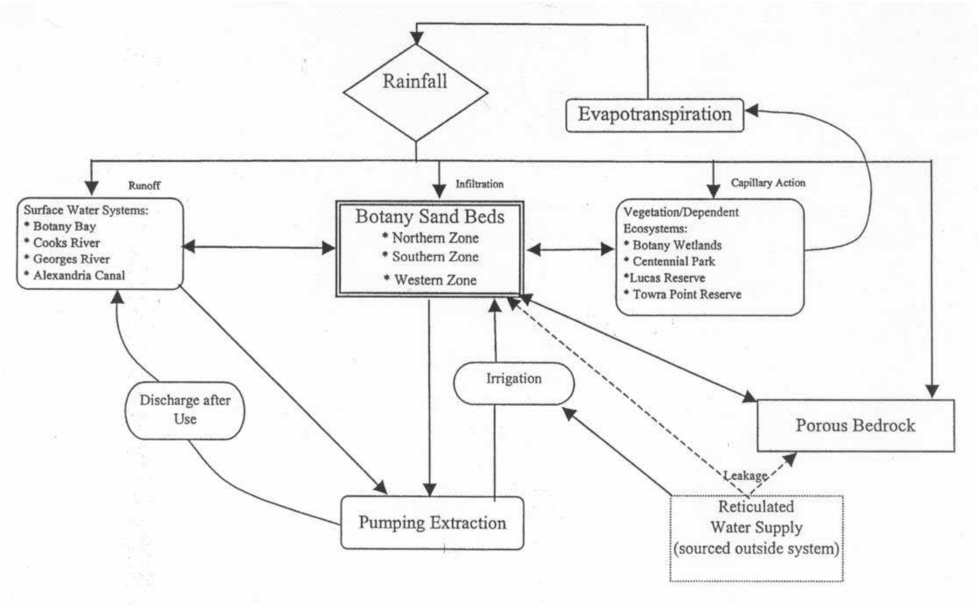
WRL Report No. 2006/33	CENTENNIAL PARK POND SECTIONS	Figure 11 03117-file



Source: Noel Merrick pers.com.

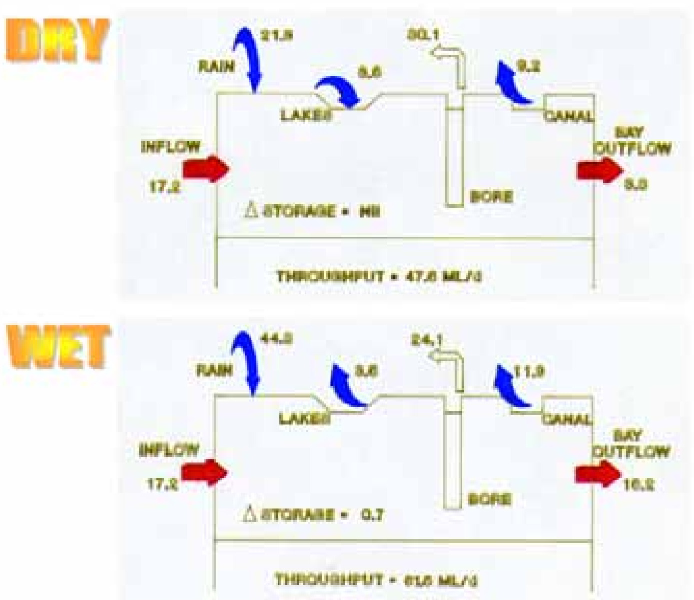
WRL Report No. 2006/33	GROUNDWATER FLOW MODELS	Figure 12
		03117-file

A. Water balance relationships



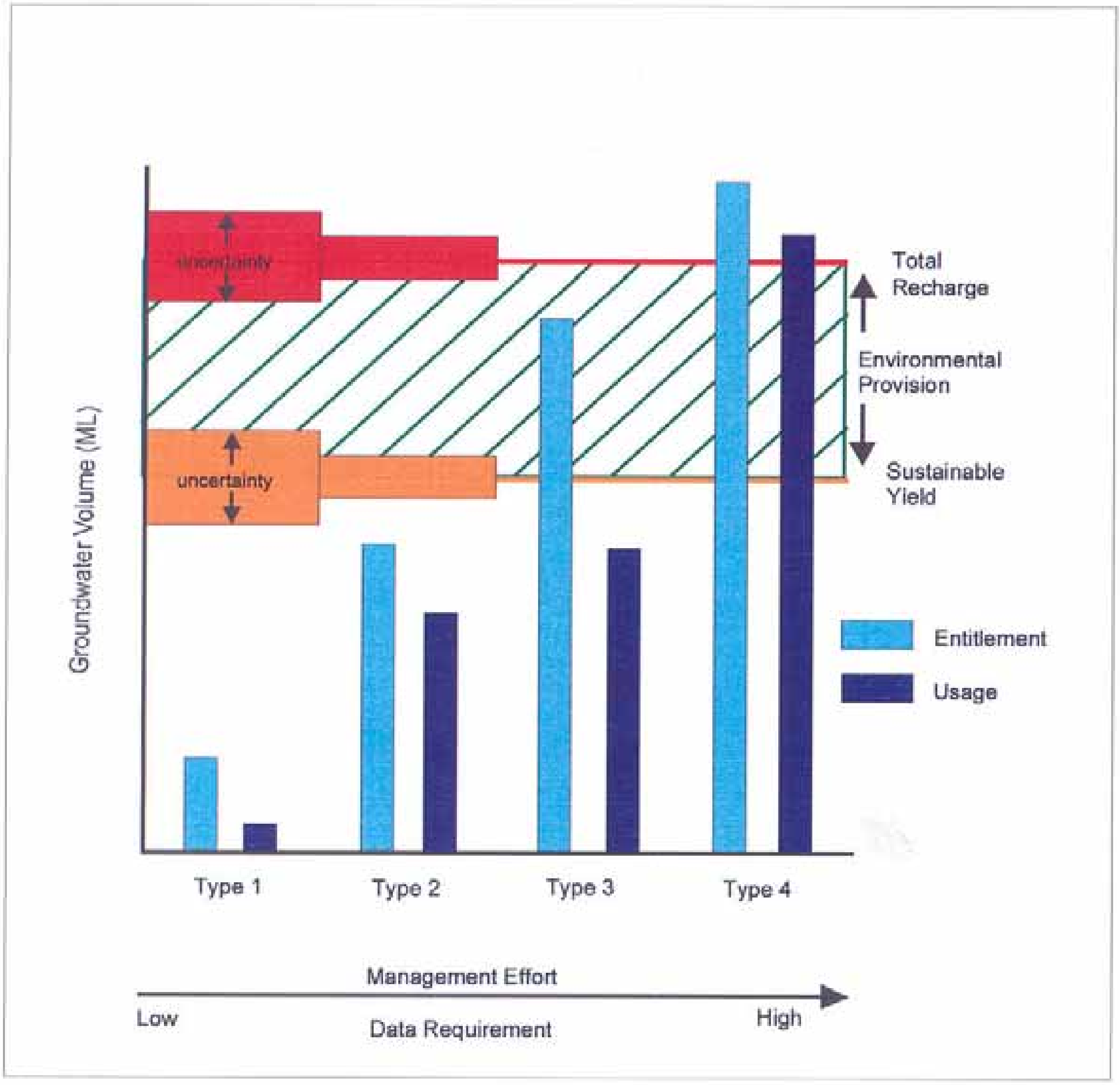
Source: Bish et al. (2000)

B. Water balance snapshots from numerical flow modelling



Source: Merrick (1994)

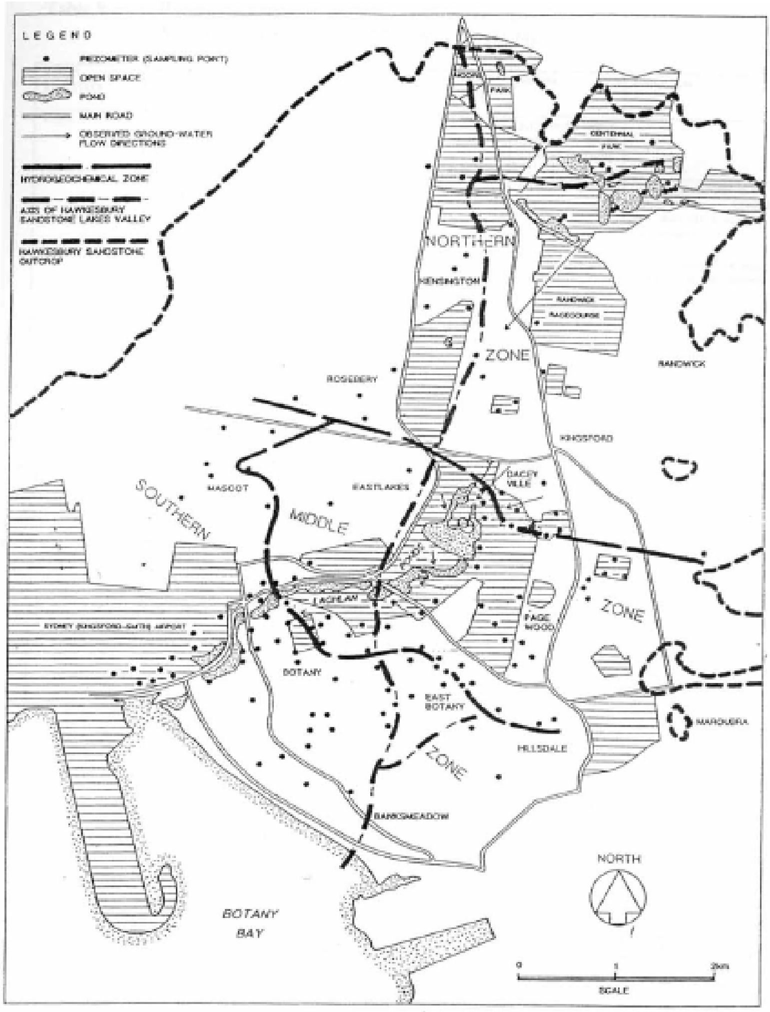
WATER BALANCE RELATIONSHIPS AND SNAPSHOTS



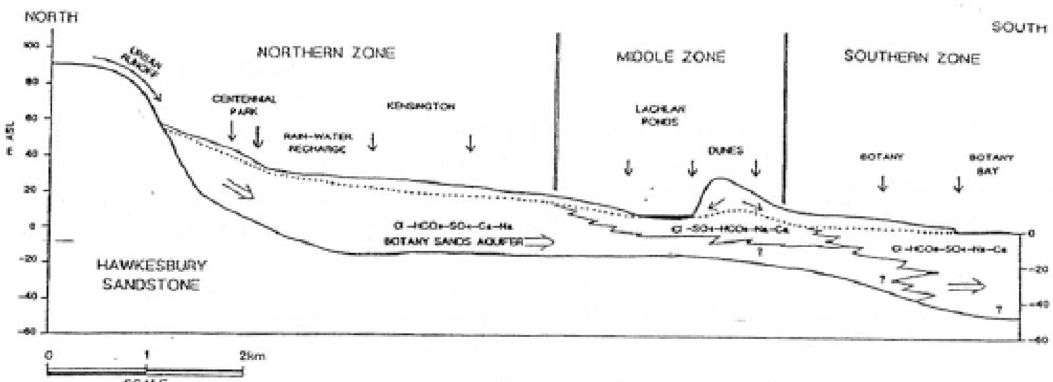
Source: Modified from DLWC (2001), The Draft NSW Groundwater Quantity Management Policy. Department of Land and Water Conservation.

WRL Report No. 2006/33	SUSTAINABLE YIELD UNCERTAINTY AND DATA REQUIREMENTS	Figure 14
		03117-file

A. Plan view

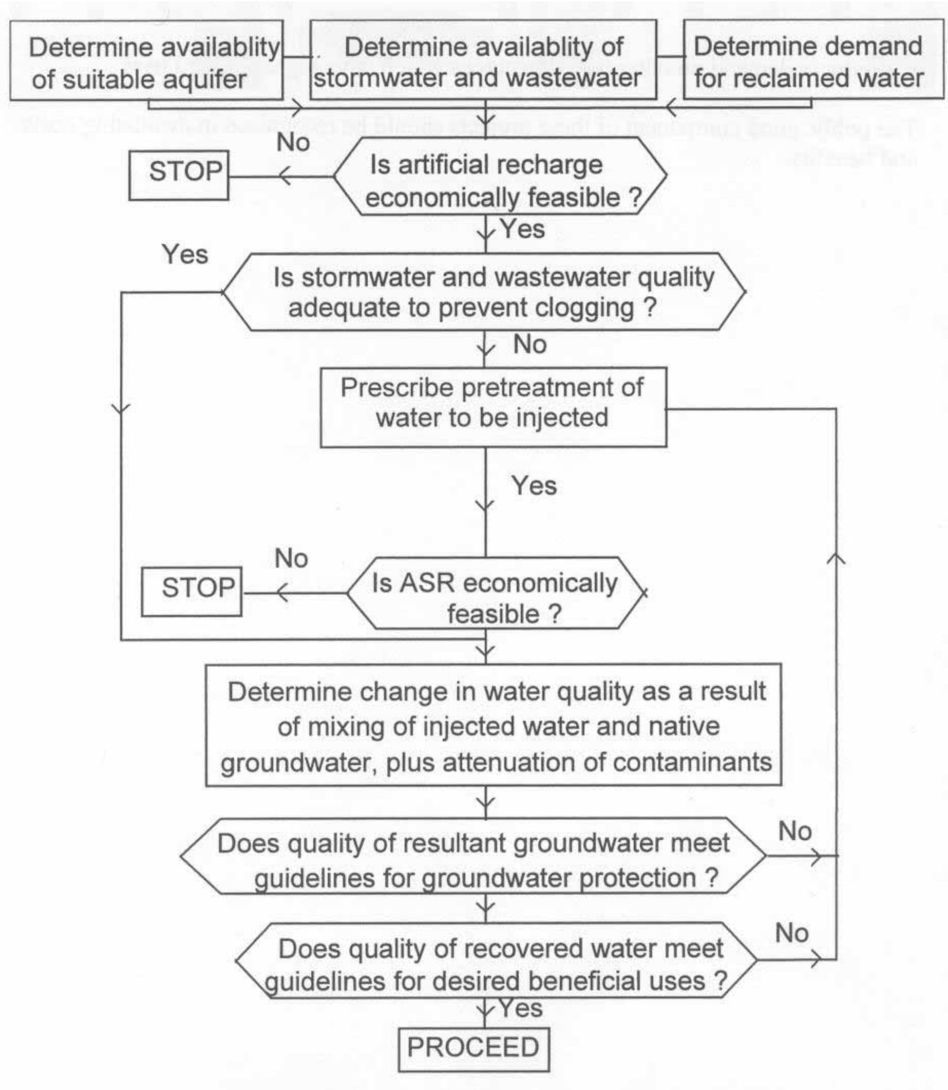


B. Longitudinal section

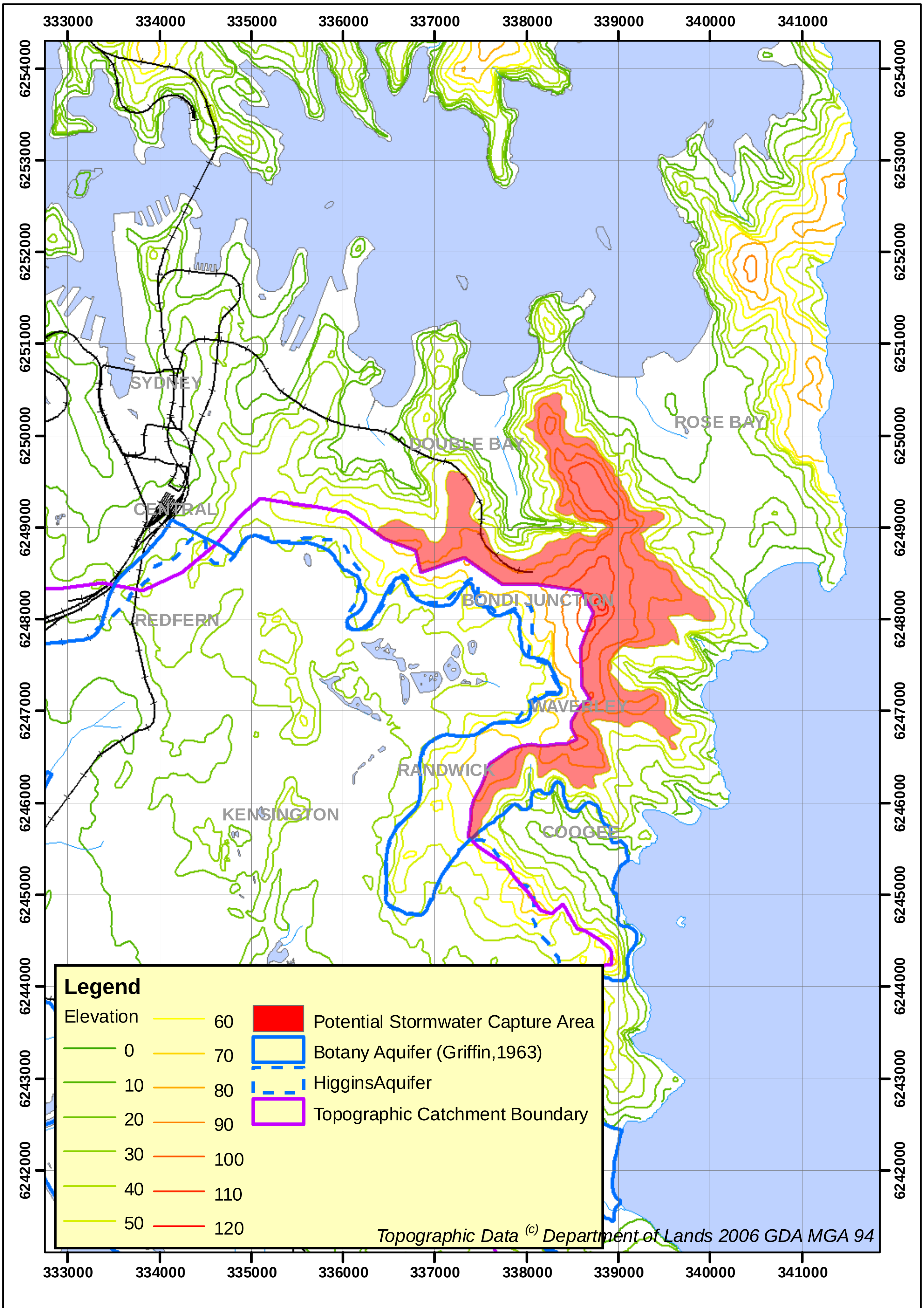


Source: Acworth and Jankowski (1993)

WRL Report No. 2006/33	HYDROCHEMICAL ZONES IN THE BOTANY AQUIFER	Figure 15 03117-file

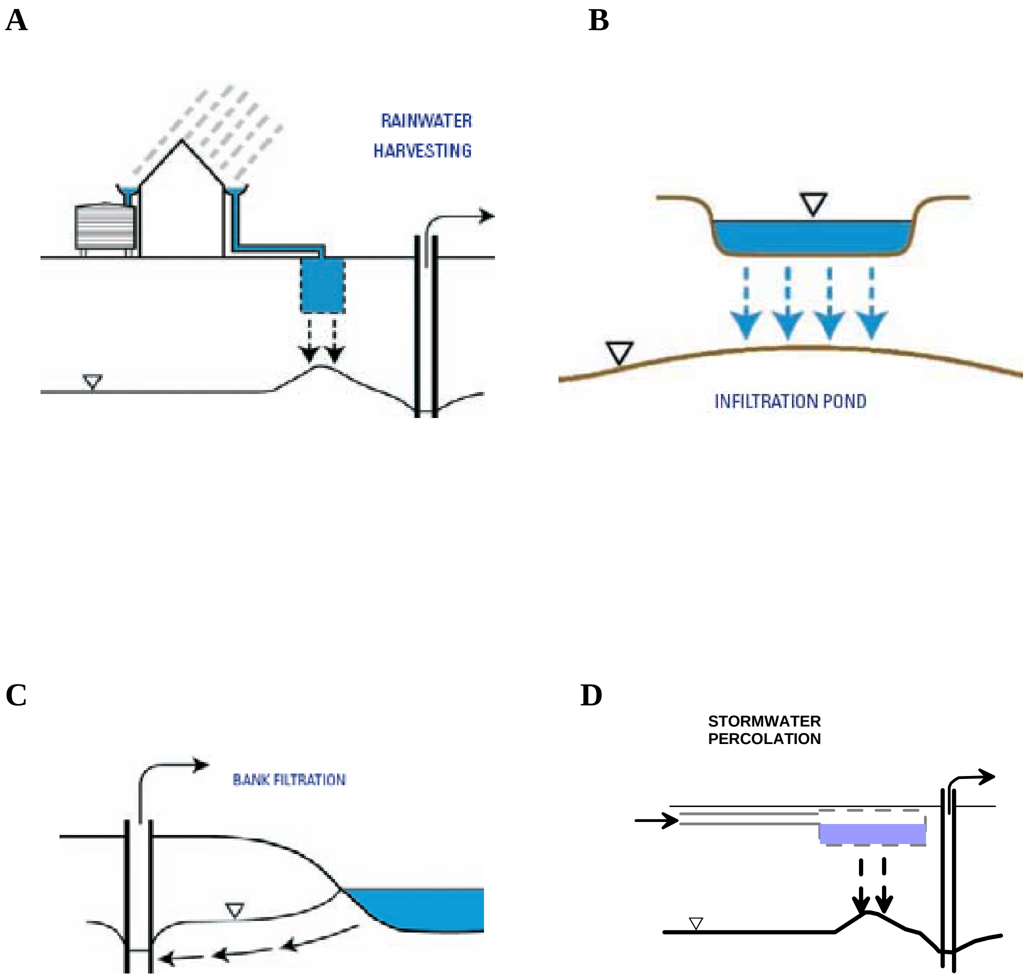


Source: Dillon and Pavelic, 1996



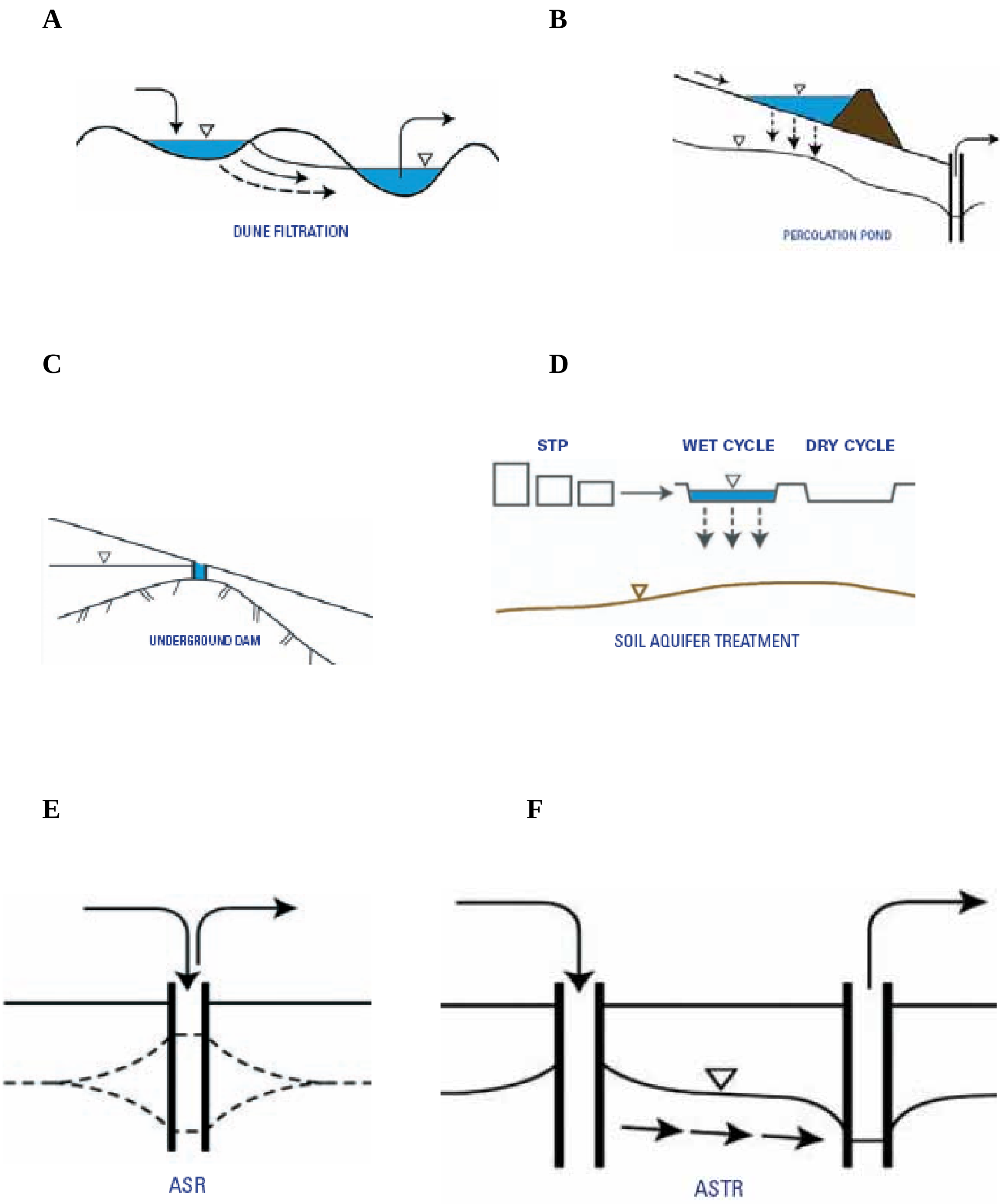
WRL Report No. 2006/33	POTENTIAL STORMWATER CAPTURE AREAS (> 60 M AHD)	Figure 17

insert filename



Source: Dillon (2005), Gale and Dillon (2006)

WRL Report No. 2006/33	CURRENT TYPES OF AQUIFER RECHARGE IN THE BOTANY AQUIFER	Figure 18 03117-file



Source: Dillon (2005), Gale and Dillon (2006)

WRL Report No. 2006/33	POTENTIAL TYPES OF MANAGED AQUIFER RECHARGE IN THE BOTANY AQUIFER	Figure 19 03117-file

Appendix A

Review of Groundwater Modelling in the Botany Aquifer

Groundwater modelling is the best method we have for estimating the components of the water balance for the whole aquifer, and for examining "what if" scenarios. It is vital for exploring borefield design, borefield capacity, and impacts from infrastructure works. The modelling process involves three major steps: conceptualisation, calibration and prediction.

To date, all computer models of the Botany Sandbeds have been restricted to the northern lobe of the Botany Basin, to the north of Botany Bay. The first attempt at computer modelling was made by Merrick and Barratt (1981) on a mainframe computer at UNSW. This was a very coarse single-layer finite difference model that was soon improved upon by Ghassemi (1984) using finite elements. Both models had a conceptualisation inadequacy, as the role of Alexandra Canal as a groundwater discharge zone was overlooked. A more detailed finite element model (using AQUIFEM-1 software) was built by Merrick and Blair (Merrick, 1994) during 1985-1987 at the Department of Water Resources. This model, apart from local refinements in resolution and better boundary definition, is essentially the same as the whole-of-basin model still in use today (see Figure 12). It was converted from PDP-11 hardware to an IBM personal computer in 1989.

The whole-of-basin model (Merrick, 1994) has the advantage of natural boundary conditions and variable spatial scale (due to finite element design), and has been used on all of the major infrastructure projects in the Botany Basin – (1) The Third Runway (Knight et al., 1990); (2) the Airport Link railway (Merrick, 1997, 1998a); (3) the Eastern Distributor (Merrick and Jewell, 2003); and (4) Port Botany Expansion (Merrick, 1998b; Merrick and Knight, 2003). Its weaknesses are that it simulates one layer only, has coarse grid size in many areas, cannot be upgraded for solute transport, and relies on proprietary pre-processing and post-processing software.

The earliest model by Merrick and Barratt (1981) was based on a total recharge of 40 ML/day (15 GL/year), with 3.4 ML/day being discharged to Botany Bay and Cooks River. This was in contrast to a very early physical section model by Nettleton and Hall (1964) that claimed 110 ML/day outflow to the bay. During the drought in the early 1980s, groundwater usage was believed to be about 50 ML/day. For a storage estimate of 200 GL, Merrick and Barratt (1981) inferred a storage-to-pumpage ratio of 11 years.

In 1992, this whole-of-basin model was coupled with an economic optimisation model for conjunctive water management of both mains water and groundwater subject to economic, environmental and supply constraints (Davies and Merrick, 1994).

There have been many smaller models built for specific purposes, all set up from scratch, most of which are documented in confidential reports. Figure 12 shows the extents of a few other models in the Botany area, two by UTS and two by URS.

The UTS analytical model (Merrick, 2003) using HotSpots software allows dense bore networks, simulates two layers and has an in-built optimisation module. However, it cannot accommodate spatial variability or drains, does not handle the bay boundary properly, and cannot be extended to solute transport. This model investigated a containment line of 10 bores spaced 30 metres apart around the south-western corner of Southlands adjacent to the Botany Industrial Park to capture the Orica contaminant plume (see Figure 12).

The URS Stage 2 model (Woodward-Clyde, 1996) using MODFLOW and MT3D software simulates three layers (see Figure 12). Its main shortcoming is the cell size range from 100 metres to 200 metres, which is too coarse for investigating pump-and-treat bore networks and for accurate solute transport modelling. The URS Stage 3 model using MODFLOW and MT3DMS software has more accurate solute transport modelling due to the cell size range from 20 metres to 100 metres (see Figure 12). Discretisation near Southlands is suitably fine, but elsewhere the model cells are relatively coarse. The main problem with this model is its limited spatial extent, and its reliance on artificial boundary conditions which might overly constrain the simulation results.

In 2004, a model covering the south-eastern part of the aquifer (north of the bay) was initiated by Orica in order to design an effective pump-and-treat network and an associated groundwater treatment plant. The model extent, shown in Figure 12, was designed to include the entire Lachlan Lakes system, the full extent of the proposed Port Botany expansion, and extension to the east towards the ocean where boundary conditions have been problematic in earlier models. The cell sizes of the new model vary from 10 metres to 100 metres. The model was calibrated against steady-state groundwater contours and measured vertical hydraulic gradients between the upper and lower aquifers.

This MODFLOW model was coupled with OPTIMAQ optimisation software to give optimal bore locations and pumping rates across five layers (Merrick, 2004) in order to achieve hydraulic containment of a swathe of contaminant plumes. Layers 2, 3 and 4 were essentially subdivisions of a single hydraulic layer based on chemical differentiation and the need to screen dewatering bores at different depths across the main transmissive zone.

After operational data became available from interception pumping along Foreshore Road, the model was re-calibrated and improved by Laase (2005). Again, calibration was restricted to steady-state. Informative particle track simulation and capture zone analysis was done at this time.

Way Forward

Overall, the groundwater model situation can be summarised in the following points:

- The best current model in the basin is the Orica model that has five layers but covers only the south-eastern portion
- The only whole-of-basin model is dated, has insufficient vertical detail, and runs with non-standard software
- Transient calibration (more accurate than steady-state) has not been done since 1989 when the whole-of-basin model was calibrated on the 1980-1988 dataset
- No serious solute transport modelling has been attempted to date, except for a few local-scale proprietary contamination models.

There is a need for extension of the Orica model to natural boundaries to the north and to the west, with better vertical definition throughout. The extended model should undergo transient calibration. When this is done, the model will provide a platform for proper solute modelling (using MT3DMS), geochemical modelling (using PHT3D), and coupled optimisation (using OPTIMAQ).

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Appendix B

Presentation by UNSW-UTS Groundwater Expert Team

Appendix C

Presentation by Dr Noel Merrick (UTS)

Appendix D

Presentation by Professor Ian Acworth