TORRENS CATCHMENT WATER MANAGEMENT BOARD

in partnership with the

BOTANIC GARDENS OF ADELAIDE

Torrens Catchment Water Management Board

Government of South Australia | Department for Environment and Heritage

Investigation into the potential for Aquifer Storage and Recovery in the Botanic Gardens of Adelaide

- Stage 1

September 2005

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Australian Groundwater Technologies

Specialist Consulting Services

Aquifer Storage and Recovery
Groundwater recharge processes
Wastewater reuse
Remediation and contamination of groundwater
Short courses for industry and community education

Level 1, 50 Greenhill Road
Wayville
SA 5034

Ms Marion Santich
Manager, Urban Water
Torrens Catchment Water Management Boards
5 Greenhill Road
Wayville SA 5034

30th September 2005

Dear Marion,

Re.: Investigation into the potential for Aquifer Storage and Recovery in the Botanic Gardens – Stage 1

Please find enclosed two copies of a report describing the recent program to drill an ASR investigation well in the Botanic Gardens.

Stage 1 works comprised:

- project initialisation and field preparation (assess hydro-stratigraphy and site selection, services clearances, etc.);
- drilling, coring and construction of an ASR observation well;
- down-hole geophysical logging; and,
- reporting

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Please note that reference in this report is made to the Permit No. (PN 102084) as the Well Unit No. had not been issued for the Botanic Gardens bore at time of reporting. The Well Unit No. has subsequently been issued and is 6628-22152.

Kind regards

Eric Rooke
Principal Consultant
for and on behalf of Australian Groundwater Technologies Pty ltd

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1. STUDY OBJECTIVE AND PREAMBLE

The objective of this study is to assess the viability of aquifer storage and recovery (ASR) for Adelaide's Botanic Gardens, primarily by investigating the potential for the Adelaidean Basement fractured rock aquifer to bank and recover water.

Stage 1 of this study, reported herein, consisted of drilling an observation well in the Adelaide's Botanic Gardens as part of gaining an appreciation of the groundwater component of an ASR scheme.

As part of a water resource study of the Botanic Gardens (Ecological Engineering, 2003), AGT prepared a desk-top study of groundwater including ASR opportunities for irrigation supply[1].

Table 1 summarises this desk-top study.

Table 1 Summary of ASR Opportunities at Botanic Gardens

Aquifer	Hydrogeology	ASR potential
Quaternary (Q)	Thin, limited areal extent (sinuous lenses/channels); limited storage; shallow water-table	Injection and recovery rates of 3 L/s Bankable storage < 50 ML/year Recovery Efficiency (RE) > 75 %
Tertiary (T1)	Greater storage capacity than Q Expected yield 0.5-1.5 L/s Expected TDS = 1,300-3,800 mg/L SWL = 7 - 15 m	'well yields expected to be too low for a viable ASR scheme'
Adelaidean	Limited hydrogeological data (no wells drilled into bedrock at locality). Anticipated yields of 1 - 10+ L/s Anticipated TDS 1,500 - 2,500 mg/L	Most potential, (storage capacity & injection rate/well yield). RE lowest of the 3 aquifers. Salinity is unsuitable, unless shandied with mains water or stormwater

[1] This study estimated an irrigation demand of about 120 ML/year, with an average demand of 25 ML/month between December and March. (For 8 hour pumping cycles this equates to 30 L/s).

2. SCOPE OF WORK

The Scope of Work emanates from a variation issued on 25th October 2004 by the Torrens Catchment Water Management Board (TCWMB) as part of Stage 1 (essentially, drilling investigations) of the Adelaide Parklands investigation.

This scope of work is reproduced as follows:

- ◊ Drill an investigation hole to determine the underlying strata and prospects of intersected aquifers to be productive at the location. This will be achieved by mud drilling through the Tertiary sequence taking 1-metre samples to interception of the basement below the weathered zone. The hole shall then be cased and the basement diamond cored for a maximum of 50 metres with the core being appropriately logged. The hole is to be completed as a 100 mm diameter observation bore;
- ◊ Down-hole geophysics to be run on the upper and lower sections of the hole;
- ◊ Information to be collected and an assessment made as to the suitability of the site for ASR; and,
- ◊ Reporting of findings.

3. GEOLOGICAL AND HYDROGEOLOGICAL INTERPRETATION

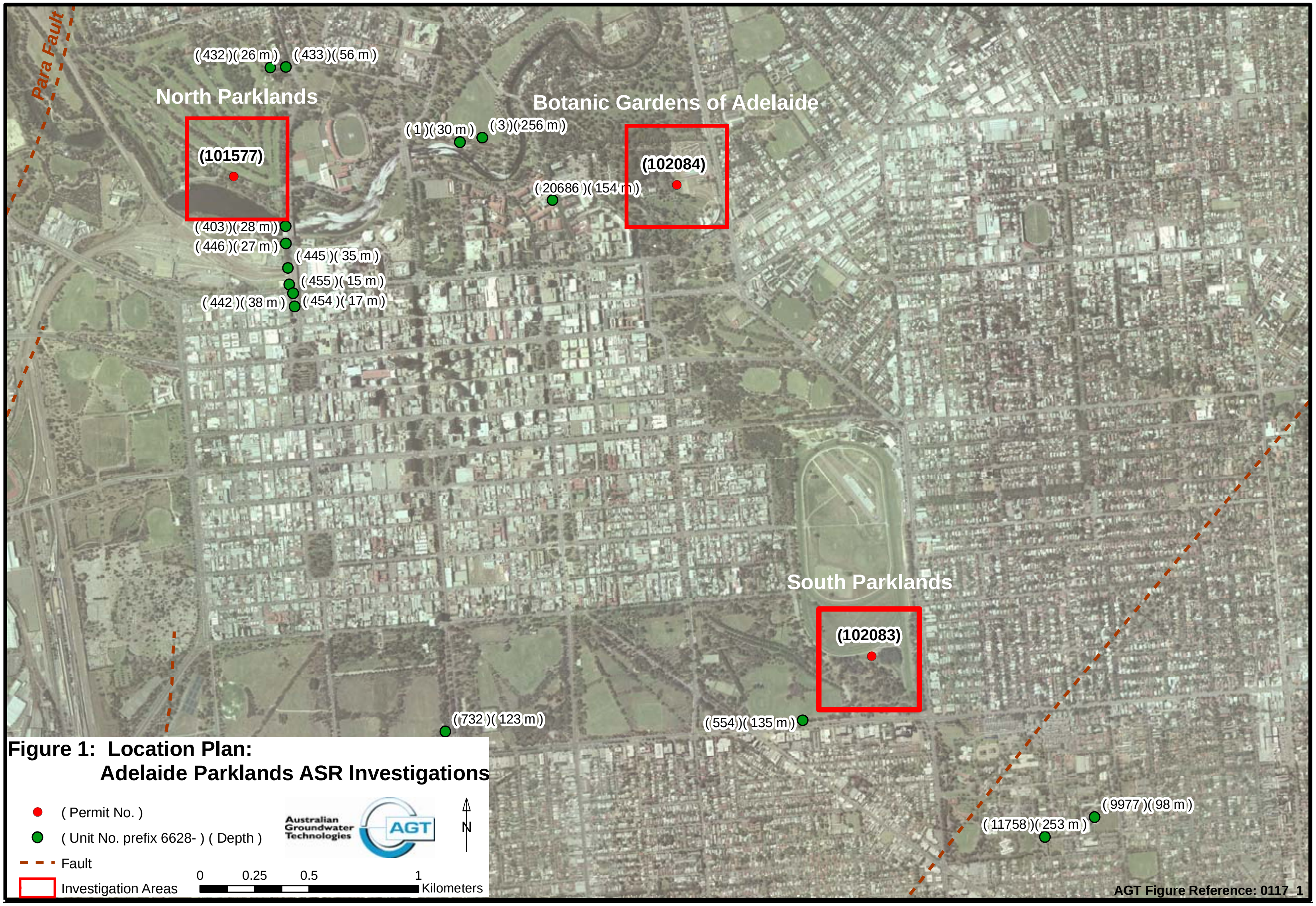
Little prior data was found to elucidate the bedrock hydrogeology of the Botanic Gardens.

All wells recorded from DWLBC's database are shallow (less than 20 m deep and, presumably, penetrate only the Quaternary). Some deeper drill-holes are situated in the vicinity but generally have inadequate associated data or none at all, apart from coordinates and total depths (Figure 1).

A hydrogeological section derived by Gerges (1999) suggests the following sequence, with inferred thicknesses, might be anticipated:

0 -15m:	Quaternary Hindmarsh Clay -clay with interbedded sand and gravels (Q aquifers)
15 – 30 m:	Blanche Point Marl – clay with chert, marl, limestone
30 – 35 m:	South Maslin Sands
35- 40 m:	Clinton Formation – lignite and clay
40– 90 m:	Weathered Adelaidean Basement – mostly clay and clay bound gravel
> 90 m:	Fresh Adelaidean Basement – slate, quartz, dolomite, phyllite

Australian Groundwater Technologies AGT



4. DRILLING INVESTIGATION

4.1 SITE LOCATION

The location of the investigation bore is depicted on Figure 2. It is sited approximately 50 m due south of the Bicentennial Conservatory adjacent to the east bank of First Creek. This site was pre-selected in conjunction with the TCWMB and Department for Environment and Heritage, Botanic Garden's Project Officer.

4.2 PRESCRIBED DRILLING PROGRAM

The drilling program was stipulated as follows:

- drill into the top of fresh bedrock to unknown depth (probably more than 120 m BGL) using the mud-rotary drilling technique;
- geophysically log (calliper, gamma, nuclear density, induction, and fluid temperature/fluid conductivity);
- cement 100 mm NB Class 12 PVC into the top of fresh bedrock;
- run HQ temporary casing;
- core the next 50 m maximum using NQ core barrel;
- withdraw HQ casing;
- geophysically log (calliper and acoustic televiewer); and,
- complete as an observation bore with a lockable surface cap.

4.3 AS CONSTRUCTED DRILLING COMPLETION

This investigation bore was drilled through a Quaternary and Tertiary sequence of sedimentary rocks into the Adelaidian Basement ('fractured rock') at the Botanic Gardens to a total depth (TD) of 186 m. Mud-rotary drilling was used to penetrate through the sedimentary rocks into the top of 'fresh' fractured rock at 118 m. The drill-hole was cased with 100 mm nominal diameter (NB) Class 9 PVC casing to 115 m, with the annulus cemented down to top of fractured rock. NQ hole size (76 mm NB) diamond coring was used to sample the fractured rock from 118.2 m to TD. TD was reached at 186.1 m thereby giving 67.9 m of core.

After consulting the client, due to promising signs of permeability at depth, coring exceeded the 50 m maximum specified. Despite encountering ongoing fractures at depth, coring was terminated due to (a) exceeding the specification (with consequent budgetary constraints) and, (b) problems in continuing drilling circulation.

The hole has been completed as an observation bore.

The mud drilled section of the hole was sampled and logged every metre. Soil/rock cuttings and cores have been archived in the PIRSA core library.

Appendix 1 details the schedule of drilling to complete this observation well.

Appendix 2 reproduces the well-site geologist's log of the drill cuttings obtained from the sedimentary rock sequence.

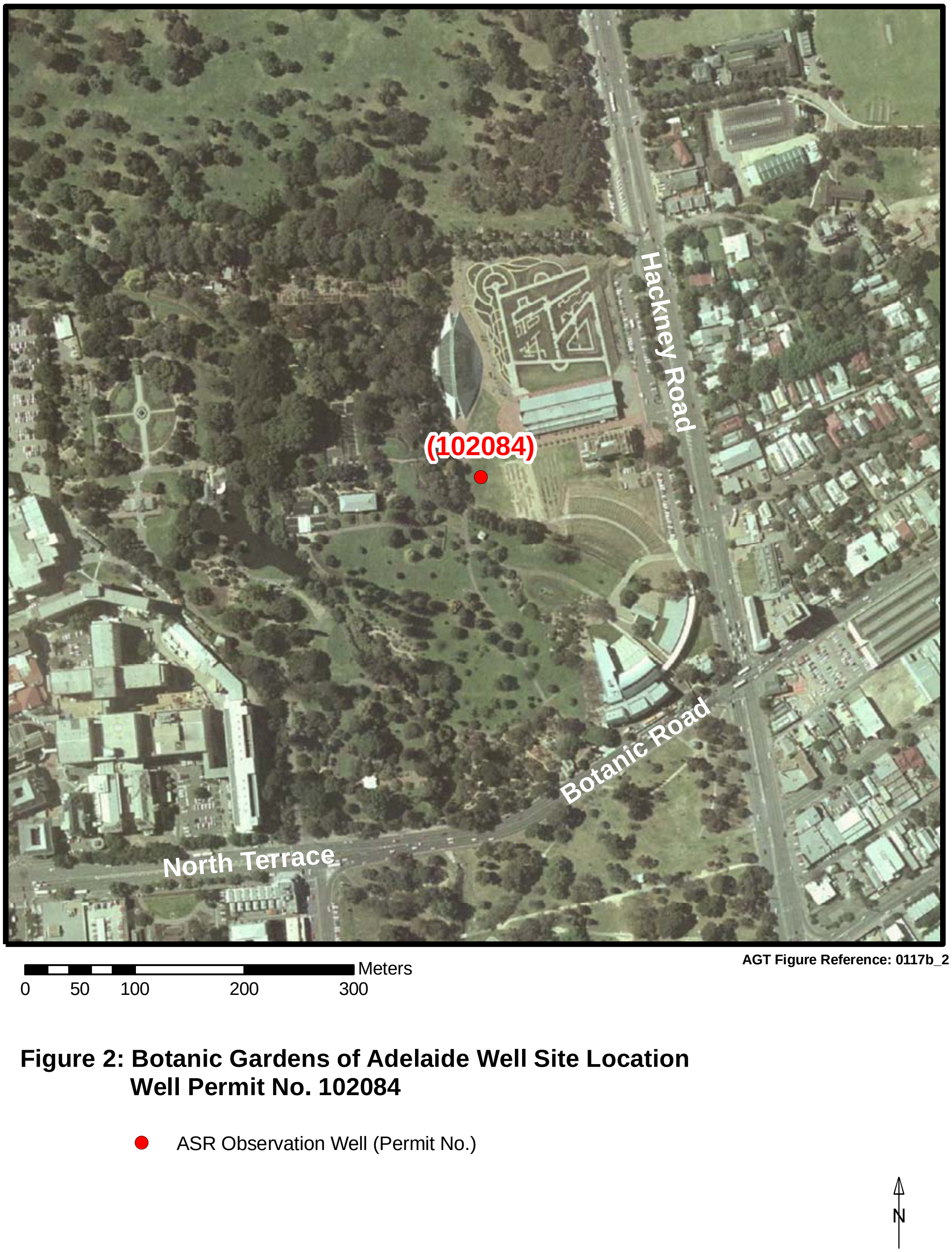
Appendix 3 presents a description of the core, logged and photographed (see Appendix 4) in the laboratory.

At the time of drilling and well completion, groundwater samples and yield estimates could not be taken due to the nature of the drilling. Subsequently, DWLBC, Groundwater Technical Services was engaged over a two day period (13th and 14th September 2005) to clear the bore of remnant drilling fluid, first by water-flush, then by airlift. Approximately 8.5 kL of water was airlifted at a rate of approximately 9 L/s until the water was essentially clear. The conductivity of the airlifted water measured between 2,970 and 3,010 ppm. Following cessation of airlifting, recovery back to SWL was measured for 1 hour. Water samples were collected and delivered to AWQC for analysis.

Water quality results and recovery measurements are appended (Appendix 5 and 6, respectively.

The laboratory measured groundwater TDS was 2,900 mg/L. Ions that are particularly concentrated in the groundwater are sodium (679 mg/L), Chloride (1,330 mg/L) and iron (2.07 mg/L). The native groundwater would be unsuitable for irrigation in terms of salinity and sodium hazards.

A transmissivity (T) value of 44 m^2/day was analysed from the recovery measurements.



AGT Figure Reference: 0117b_2

Figure 2: Botanic Gardens of Adelaide Well Site Location
Well Permit No. 102084

● ASR Observation Well (Permit No.)

4.4 INTERPRETATION

4.4.1 Sedimentary Rock Sequence

The hydro-stratigraphy interpreted from description of the drill cuttings obtained from the sedimentary rock sequence is presented in Table 2.

Table 2 Well PN 102084 – Sedimentary Rock Sequence – Hydro-stratigraphic Summary

Depth interval (m)	Formation	Hydrostratigraphic Unit	Hydrogeological Classification
0-15	Q/Pt Willunga	Q1/Q2	Semi-confined aquifer
15-21	Chinaman Gully	-	Aquiclude. Confining bed
21-24	Tandanya	T1/T2 (equivalent)	Aquiclude/aquitard
24-47	Blanche Point	-	Aquitard
47-48	Tortachilla	T3 (equivalent)	Confined aquifer
48-50	S. Maslin Sds.	T3 (equivalent)	Aquitard
50-60	S. Maslin Sds.	T3 (equivalent)	Confined aquifer
60-88	Clinton	-	Aquiclude (minor aquitards)
88-112	Saddleworth?	Weathered basement	Aquiclude
112-118	Saddleworth	MW basement	Aquifer?

The Quaternary aquifer might produce superficial amounts of groundwater from shallow wells or spear-point wells, but would be unsuitable for ASR[2].

The only other aquifer of any hydrogeological significance is part of the South Maslin Sands, T3 aquifer (10 m thick). This may yield a reasonable supply of groundwater with good well construction and well development techniques. However it would be problematic for ASR due to its carbonaceous, silty matrix[3].

4.4.2 Fractured Rock Sequence

The summary driller's log Appendix 1 indicates water loss intervals that are indicative of the potential yield.

It is difficult to judge whether drilling fluid losses into the formation are cumulative or not owing to the drilling methodology. The yield appeared to decrease from 2 L/s

[2] Too shallow for injection without potential surface environmental impact and, seemingly, of limited areal extent and unpredictable grading (i.e. generally poorly-sorted).
[3] In addition the silt fraction, the lignitic particles would tend to align on injection/recovery leading to clogging

then stabilize below about 137 m at 1.2 – 1.7 L/s as hole was made. This decrease in yield is probably an artifact of increasing mud-weight and viscosity as mud was added to maintain circulation; hence the possible plugging of water-bearing fractures above. It is probable, however, that the yield is underestimated and is, in part, cumulative.

Apart from intervals 132.7 - 132.8 m and 183.83 – 186.0 m, zones of lost core (no core return) appear to comprise of rock-breaks rather than genuine voids or open joints/fractures (refer Table 3).

A water loss of maximum 2 L/s was estimated (by means of water loss whilst circulating through the mud-pits). This is considered to be an under-estimate due to the inherent difficulty of estimating water circulation in a dynamic situation, combined with the inhibition of circulation by the accumulation of cuttings in the hole and viscosity agents added to assist lifting of cuttings (refer Section 6 for synopsis)

5. GEOPHYSICAL LOGGING

Geophysical logging was not undertaken in the open hole prior to casing because the sedimentary formations showed little aquifer potential. Instead logging of the hole was conducted post-casing and drilled TD.

Logging was carried out on 8th March 2005 by Geophysical Technical Services, DWLBC. The spontaneous potential (SP), single point resistivity (SPR), and density sondes were re-run on 17th May 2005 after poor results at the first attempt whence the former two may have been influenced by excessive drilling mud left in the hole, and the latter one by malfunction.

The important sections of the logs are graphed in Appendix 7.

A short glossary of the geophysical techniques employed is provided as Appendix 8.

The major features of hydrogeological interest are discussed under Section 5.1.

5.1 INTERPRETATION

5.1.1 Calliper

- ◊ Rugose zone between base of 100 mm NB permanent casing at 115 m and 118 m which, although an artefact of drilling completion to this depth (6” bit) rather than a geological feature per se does substantiate the driller’s record (Appendix 1) of variable hard-bands and fractures.

- ◊ Very fine, constant chatter throughout total depth of NQ cored hole indicating ‘bedding laminae’ and, potentially, uniform lithology with no major fractures/joints/voids detected. Slight, progressive apparent reduction in hole size with depth is probably due to hole being drilled somewhat out of vertical.

5.1.2 Natural Gamma

- ◊ Lower counts toward base of Quaternary / T1 (aquifer?).
- ◊ Low counts between 49 and 60 m marking T3 aquifer (geologist’s log indicates interval 50-60 m).
- ◊ Shift in gamma towards greater counts in transition zone into highly weathered bedrock (at approximately 80 m) owing to clays (coincident with Clinton/weathered Clinton formation on geologist’s log).

5.1.3 Spontaneous Potential

- ◊ A positive deflection in the SP log occured as the sonde just exited bottom of casing at 115 m.

- ◊ Other positive ‘kicks’ occur at 154 m and at 157 m and just below 180 m.

5.1.4 Single Point Resistivity

◊ Coincident with the SP reaction at 115 m is a low SPR response that may indicate a zone of saline groundwater to about 118 m (gravelly bedrock logged by geologist).

◊ Coincident with the SP reaction at 154 m and at 157 m is a zone of slightly lower resistivity.

◊ Coincident with the SP reaction just below 180 m is left ‘kick’ (lower resistivity) in the SPR.

5.1.5 Neutron

◊ The neutron log detected the SWL at approximately 3 m bgl (March, 2005)[4].

◊ Coincident with SP and SPR reactions is a decrease in the neutron log count indicating potentially a zone of high porosity from bottom of casing to 118 m.

◊ Coincident with SP and SPR reactions is subdued decreases in the neutron log count at 154 m and at 157 m and a stronger reaction just below 180 m.

◊ A zone of slightly lower neutron counts between 162 and 168 m may reflect moisture content in porous veins and laminae (refer geologist’s log, Appendix 3) rather than greater permeability per se.

5.1.6 Density

◊ The density log hardly reacts; therefore is of little diagnostic use[5].

5.1.7 Acoustic Scanner Log

Geoscience (2005) has produced independently a report that interprets in great detail results of the acoustic scanning logging run by DWLBC.

Logging took place between 107.7 m and 184.7 m; i.e. was mostly confined to the NQ section of the hole.

Below is a précis of that information of import to the groundwater resource potential.

Many minor fractures are recorded (Appendix G, Geoscience, 2005) however geological logging of the core has indicated that the vast majority of these are hydrogeologically insignificant.

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[4] The rest of the log through the cased section appears to indicate signal attenuation.
[5] Its signal may have been attenuated by drilling mud left in the hole.

6. INTEGRATION AND INTERPRETATION OF DRILLING/LOGGING DATA

Table 3 presents a 'matrix' of where significant fractures interpreted by the acoustic scanner processing tallies with those geologically logged for the cored section of the hole, and recorded by the driller/site geologist.

Of these 'matching fracture zones' the ones considered potentially groundwater-bearing are, approximately, the intervals:

- 114[1] – 118.2[2] m;
- 118.2 – 119.1 m;
- 132.4; 132.7 - 132.8 (and, possibly, 138.2 m);
- 155.4 – 156.2;
- 180.1 – 180.7; and,
- 183.8 (possibly to EOH).

It is considered that most of the groundwater was encountered in the zones 114 – 119 m, 155 – 156 m, and 180 – 181 and at 183 m (to TD?).

The general lithology of the core indicates a predominantly metamorphosed, indurated siltstone/mudstone with 'cleavage-like' fractures and laminated rock fabric (rather than joints).

The bore was airlifted at rate of approximately 9 L/s of groundwater salinity 2,900 mg/L with most of the supply probably emanating from the weathered zone between114 and 118 m. The aquifer's transmissivity (T) value (over the open section) is 44 m^2/day. This indicates a productive fractured rock aquifer in terms of yield.

[1] 114 – 115 m cased off.
[2] The permeability within this interval is due to a combination of weathered rock and fractures.

Table 3 Significant Fractures interpreted from Acoustic Scanning Logging versus Geological Logging (NQ core hole only)

Acoustic scanner (depth m bgl)	Comment	Geological Log (depth interval m bgl)	Comments	Drillers Log (depth interval m bgl)	Comments
118.3 - 119.13	Either “sedimentary fabric” or “minor fracture”	118.2 – 119.1	Broken and sheared	117 - 118	“Hard interbeds & possible fractures”
132.45	“Sub-major fracture”	132.4; 132.7 - 132.8	Latter no core returned	131.4; 132.9	“Significant water loss from pits” (2 L/s)
-	-	138.2	Mineralised fracture	137.4	“Significant water loss from pits”
143.54	“Minor Fracture”	-	-	142.4; 143.5	“potential fractures”
146	“Minor Fracture”	-	-	145.9	“potential fractures” (1.7 L/s)
154.75; 154.91	“Minor Fracture; Fracture?”	-	-	154.8 – 155.2	“vertical fractures”
155.59	“Sub-major fracture”	155.4 – 156.2	Shatter zones, iron-stained joints	155.5 – 156.2	“vertical fractures; significant water loss”
157.63	“Sub-major fracture”	157.6	-	156.7 – 156.9; 157.4	“potential fracture zones’ (1.7 L/s)

Acoustic scanner (depth m bgl)	Comment	Geological Log (depth interval m bgl)	Comments	Drillers Log (depth interval m bgl)	Comments
158.13	"Sub-major fracture"	158.0	Brittle fracture?	158.0	Brittle fracture?
166.77	"Fracture?"	-	-	166.8	"potential fracture"
179.4	"Minor fracture"	-	-	179.4	"potential fracture"
180.19	"Major fracture"	180.15 – 180.65	Very broken; two joint sets	180.15 – 180.65	Very broken; two joint sets
180.34; 180.53; 180.62	"Sub-major fracture"	180.15 – 180.65	As above	180.15 – 180.65	As above
183.83	"Sub-major fracture"	183.83 – 186.0	No core returned	183.83 – 186.0	No core returned

7. CONCLUSIONS

7.1 SEDIMENTARY ROCK SEQUENCE

- The Quaternary aquifer may be suitable for supplementary supplies for irrigation and, possibly, for smalls-scale ASR development. Previous experience of wells completed within the same aquifer in the vicinity suggests sustainable pumping yields of about 3 L/s.
- In developing ASR within the Quaternary aquifer a careful assessment would be required to assess potential interaction with the surficial environment.
- The potential exists for a relatively low permeability aquifer in the North Maslin Sands (NMS) between approximately 50 and 60 m bgl.
- The NMS aquifer could not be easily exploited for ASR due to its lithology.
- With careful well completion and development (as dedicated extraction wells) the NMS aquifer might yield exploitable quantities of groundwater of unknown salinity.

7.2 FRACTURED ROCK SEQUENCE

- The fractured rock is a predominantly metamorphosed, indurated siltstone/mudstone with ‘cleavage-like’ fractures and laminated rock fabric (rather than joints).
- The fractured rock sequence has many thin, sometimes isolated and re-healed fractures; the latter two types exhibiting little permeability.
- A zone of *weathered* fractured rock grading to fractured rock (fractured rock permeability enhanced by seemingly clay-free weathered rock) occurs between 114 m and 119 m. This interval may constitute the most productive zone.
- The main *fracture* zones in order of permeability (consequently, groundwater-bearing capacity) potential occur between 180 m and 181 m, 155 m and 156 m, and 183 m (possibly to TD).
- The bore was airlifted at rate of approximately 9 L/s of groundwater salinity 2,900 mg/L with most of the supply probably emanating from the weathered zone between114 and 118 m.
- The aquifer’s transmissivity (T) value (over the open section) is 44 m2/day. This indicates a productive fractured rock aquifer in terms of yield.

◊ Severe clogging during the ASR cycle by suspended solids and nutrients may be problematic due to the thinness of the fractures[8]. To combat this potential clogging, membrane (nano-) filtration as part of tertiary treatment of the source injectant water would almost certainly be necessary.

7.3 RECOVERY CAPABILITY

There is potential for recovering 45-50 ML/a of injected water based on the measured airlift yield and assuming a recover efficiency of 75 %. This would be suitable for irrigating an oval of, say, 4 ha area given a 3 months irrigation season. Recovery efficiencies are very unpredictable in fractured rock aquifers and this estimate is a best guess only. Aquifer testing, as recommended in Section 8, is a prerequisite to confirm this estimate.

8 This should be investigated as part of any Stage 2 investigations.

8. RECOMMENDATIONS

The recommendations below only pertain to the groundwater part of the ASR scheme; they do not address hydrological yield of source water.

The key issues to progress the development of a potential ASR scheme for the Botanic Gardens of Adelaide (BG) site are:

- ◊ anticipated long-term recharge (harvesting) and injection rate, long-term annual recharge volume, and long-term annual recovery rate (flow and volume including the recover efficiency, RE);
- ◊ assessment of the likely salinity of recovered volumes dependent on salinity of the groundwater and assumed salinities of the source water (cf the RE);
- ◊ environmental risks associated with injection, banking and recovery of water at the site; and,
- ◊ recommendations for further studies and investigations to satisfy all information and EPA requirements pertaining to establishing a successful ASR scheme at the BG site.

Cognisant of these issues the following recommendations are made:

- ◊ the Board and DEH should instigate negotiations with the EPA to assist in gaining a trial ASR licence[9] for the BG site;
- ◊ after negotiation with the Board and EPA, and at the behest of EPA, drill (a) dedicated monitoring bore(s) (MB), say, from 20 m-50 m distant from PN 102084. Structural analysis indicates that at least one monitoring bore should be sited N of PN 102084 and possibly another ESE (to intersect the 'sedimentary fabric' assuming this is hydraulically conductive)[10].
- ◊ test pumping[11] PN 102084 is recommended as follows:
    - o a 24 hour well test with four steps at 100 minutes duration; at rates of 2, 4, 6 and 9 L/s (the last step extended) followed by a 24 hour recovery test. Well performance parameters (including well efficiency) analysed from this test should determine anticipated long-term yield and dictate progress to injection testing.

9 Especially related to compliance requirements re. ASR of the Environment Protection (Water Quality) Policy 2003 (EPPWQ). (Within Adelaide metropolitan area, the EPA will licence an ASR project as a 'prescribed activity of environmental significance' if discharge of stormwater to the aquifer occurs from a catchment area of more than one hectare or, if the stormwater as been significantly chemically treated).

10 assuming local groundwater flow-path follows the structural azimuth and dip

11 Injection and recovery testing shall begin subject to successfully gaining a trial ASR licence from the EPA.

- o drawdown in MB(s) should be recorded, too during test pumping

◊ Injection testing of PN 102084 using mains water[12] for 5 - 7 days at a rate dictated by the results of the test pumping;

- o impress in MB(s) should be recorded, too during injection

◊ 5-7 days recovery (‘pump-out’), or until the groundwater salinity returns to its ambient (native) TDS

- o drawdown in MB(s) should be recorded, too during pump-out

Both pumped and pump-out tests [including MB(s)] should be monitored manually in addition to monitoring by data-loggers. The monitoring of the ASR test bore, PN 102084 should incorporate in-line water quality testing for pH, temperature, Electrical Conductivity and Dissolved Oxygen. The mains water’s TDS and temperature would be verified prior to injection testing.

During this well testing program, there is an opportunity to carry out groundwater flow tracing to inform and conceptualise the local hydrogeological regime. It is recommended (initially anyway) that simple techniques such as groundwater temperature monitoring, fluorescin dye and/or salt-slug techniques are employed[13]. Packers could be deployed both in PN 102084 and the MB(s) (with possible pumping of MB and observation of PN 102084, too) to determine flow paths and fracture contributions.

Given the fracture detail revealed from the Stage 1 investigation, and after analysis of the testing program, (anisotropic) groundwater numerical modelling (GWM) should be employed to attempt to:

◊ predict the shape of the injectant plume; and,

◊ simulate recovery and test recovery scenarios including the recovery efficiency[14].

GWM might employ an analytical spreadsheet basis or Modflow-MT3D (PMWIN).

12 Aerated through a holding tank per EPA requirement to purge free chlorine prior to injection

13 Rather than environmental in-situ tracer such as Cl36 or CFCs

14 for a threshold salinity of recovered volume dependent upon mixing with the salinity of native groundwater and assumed salinities of the source water

9. REFERENCES

Ecological Engineering, 2003. Adelaide Botanic Gardens – Waterways Study, May 2003.

Geosciences, 2005. Acoustic Scanner logging – Interpretation Report and Job Summary BH: PN102084 for the PTCWMB, March 2005.

Gerges, N.Z., (1999). The Geology and Hydrogeology of the Adelaide Metropolitan Area. Flinders University of S.A. PhD Thesis.

APPENDIX 1

SUMMARY DRILLER'S LOG

PN102084 – Summary of Driller's Log

Coordinates: GDA 94 Zone 54 281895E 6133460N

Driller: Underdale Drillers, Drilling Solutions
Drill method summary: Rotary mud with TH60 rig to 118 m
Cased and pressure cemented to 115 m
Diamond cored with MK5 rig to 186.15 m
Hole geophysically logged to 185.3 m

Date	Depth (m)	Description
22/02/05		Drilling activities at 102084 commence Bridge reinforced for truck access and mud pits prepared Underdale TH60 Rig on site
23/02/05	0 – 45 45 – 113 113 – 115	Rotary mud drilling commences using a 7" blade bit Changed to 6.5" blade bit *Drilling 'got firm' at around 107 m* Fitted 6" rock roller bit *Penetration rate of ~ 3 m/hr* *Bit refused at 115 m*
24/02/05	115 – 116 116 – 118 118	Drill head hammering at 116 m *Hard interbeds and possible fractures 117 m – 118 m* *Penetration rate of < 4 m/hr* Maximum drilled depth of upper hole reached Hole cased to 115 m using 100 mm PVC Hole was pressure cemented using: 50 x 20 kg bags cement, 1225 L water and 50 kg bentonite DWLBC Drilling inspector present during pressure cementing Cement was not observed to reach the top of the anulus
25/02/05		Underdale TH60 Rig departs site
28/02/05	118 – 118.9	Drilling Solutions MK5 Rig on site Diamond coring commences Cement plug encountered at 112.4 m *Grout and lignite evident in retrieved core (connected fractures)* Starting to drill fresh ground at ~ 118.4 m
1/03/05	118.9 – 120 120 – 122.7 122.7 – 126.4 126.4 – 129.4 129.4 – 141.4	*Significant water loss with no circulation to clear cuttings from hole* Aus-Plug (hydrated crystals) added to control water loss and re-establish circulation *Penetration rate ~ 5.7 m/hr through broken ground* *Hard rock encountered at ~ 124.4 m, circulation lost* *Hard rock encountered at ~ 125.4 m* *Penetration rate ~ 4.2 m/hr* *Water loss ~ 1.65 L/s* *Penetration rate 7 – 8 m/hr* *Potential fracture zone ~ 129.1 m* *Penetration rate ~ 7.2 m/hr*

		Significant water loss from pits at ~ 131.4 m, 132.9 m, 137.4 m *Water loss ~ 1.8 – 2 L/s*
2/03/05	141.4 – 142.3 142.3 – 147.4 147.4 – 150.4 150.4 – 156.4 156.4 – 157.4 157.4 – 161	1,000 L water tank brought on site to supplement water supply to pits *Potential fracture zones at ~ 142.4 m, 143.5 m, 145.9 m, 147.6 m, 148.2 m, 149.4 m and 150 m* *Water loss ~ 1.58 L/s* *Penetration rate ~ 7.2 m/hr* *Resistant layer at ~148.2 m* Driller having difficulties maintaining drill rotation, possibly due to accumulation of cuttings in hole Bio-Vis drilling mud added to pits *Penetration rate ~ 5.2 m/hr* *Vertical fractures at ~ 154.8 – 155.2 m and at 155.5 – 156.2 m* *Significant water loss was observed, coincident with drilling through these fracture zones* Driller having difficulties maintaining drill rotation Bio-Vis drilling mud added to pits *Potential fractures zones at ~ 156.7 – 156.9 m and 157.4 m* *Water loss ~ 1.65 L/s* Liqui-Pol viscosifier added Drill rods cavitating *Penetration rate ~ 3.6 m/hr* Drill head failure
3/03/05	161 – 170.9	Liqui-Pol viscosifier added *Water loss ~ 1.4 L/s (cuttings potentially blocking fractures)* *Potential fracture zones at 161.3 m, 166.8 m and 170.2 – 170.5 m* *Penetration rate ~ 5 m/hr* Drill rotation problems
4/04/05		No Drilling
7/03/05	170.9 – 180.1 180.1 – 180.6	*Potential fracture zones ~ 173.4 – 173.6 m, 174.8 – 175.1 m, 175.4 – 175.6 m, 176.3 m, 179.4 m* *Penetration rate ~ 1 m/hr* Drill rotation problems Drill head hammering ~ 178.1 m Poor or absent water returns *Penetration rate ~ 2 m/hr* *Water loss ~ 1.25 L/s* Liqui-Pol viscosifier and CR-650 added directly into casing and washed down with hose New drill head fitted
8/03/05	180.6 – 186.15	Penetration rate ~ 3 m/hr *Potential fracture zone at ~ 185.8 m*

	186.15	*Water loss ~ 1.69 L/s* Bottom of Hole Hole cleaned by driller using a core catcher in preparation for geophysical logging Hole successfully geophysical logged to a depth of 185.3 m Drilling Solutions MK5 rig departs site Drilling operations concluded Underdale Drillers to clean site

APPENDIX 2

GEOLOGICAL LOG OF CUTTINGS – PN 102084

Drilled Depth (m)		Lithology		Description	Formation	Aquifer
From	To	Major	Minor			
0	1	n/a	n/a	Undifferentiated sand, silt and gravel	**Recent**	
1	2	Sand	Clay	Dark brown sandy clay	**Quaternary Alluvium**	**Cb**[15]
2	3	Sand	Clay	Orange brown sandy clay		
3	4	Sand	Clay	Brown sandy clay		
4	5	Clay	Sand	Orange brown medium to coarse sandy clay		**Q1 / Q2**
5	7	Clay	Sand	Orange brown clay, some fine sand		
7	8	Sand	Clay	Light brown sandy clay, some light grey silt		
8	9	Sand	Gravel	Light brown medium sand and coarse angular quartz gravel		
9	10	Sand	Gravel	Yellow brown medium sand and angular to rounded coarse quartz gravel		
10	12	Sand	n/a	Yellow fine sand, some nodules of grey brown fine sand		
12	13	Sand	n/a	Light grey fine sand	**Port Willunga Fm. Sand Unit**	**T1** Equivalent
13	14	Sand	n/a	Yellow and grey fine sand		
14	15	Sand	Silt	Light grey fine sand and yellow brown silty fine sand		
15	20	Clay	Silt	Dark grey silty, lignitic clay	**Chinaman Gully Fm.- Tandanya Sand**	
20	21	Clay	Silt	Dark grey to black silty clay		
21	22	Sand	n/a	Black carbonaceous fine sand		**T2** Equivalent
22	24	Sand	n/a	Dark grey to black carbonaceous fine silty sand		
24	27	Siltstone-Sand-Marl	Silt	Grey brown highly carbonaceous fine sand, marl, (note: acid reaction below this depth).	**Blanche Point Formation- Gull Rock Member - Tortachilla Limestone**	**Cb**
27	45	Siltstone-Sand-Marl	Silt	Grey carbonaceous marl, fine sand and silt. Glauconitic		
45	46	Siltstone-Sand-Marl	Shells	Brown grey carbonaceous medium sand, shells. Glauconitic		
46	47	Siltstone-Sand-Marl	Shells	Dark brown carbonaceous fine to medium sand, shells. Glauconitic		
47	48	Sand-Limestone	Shells	Dark brown carbonaceous medium sand, shells Highly glauconitic limestone.		**T3** Equivalent

[15] Cb = confining bed

48	49	Silt	n/a	Dark brown/grey carbonaceous silt and fine to medium sand, shells	**South Maslin Sands**	**T3** Equivalent
49	50	Silt	Sand, Shells	Dark grey black fine sand, shells		
50	52	Sand	Silt, Shells	Dark grey/black highly carbonaceous fine silty sand, shells, some angular quartzite chips		
52	57	Sand	Silt, Shells, Gravel	Dark grey/black highly carbonaceous fine silty sand, shells, some angular quartz chips and some rounded medium quartzite gravel		
57	58	Sand	Shells	Dark grey/black highly carbonaceous fine sand, shells, some angular red quartzite chips		
58	59	Sand	Gravel	Dark grey/black highly carbonaceous fine sand, with some medium rounded quartzite gravel and some angular quartzite chips		
59	60	Sand	Silt/ Gravel	Dark grey/black silty fine sand, with some well rounded medium to large quartzite and sandstone gravel		
60	61	Sand	Silt	Black lignitic fine silty sand	**Clinton Formation**	**Cb**
61	63	Lignite	n/a	Black lignite (note: no acid reaction below this depth)		
63	64	Clay	n/a	Stiff grey brown clay		
64	65	Clay	Sand	Light grey/brown sandy clay		
65	66	Clay	Sand	Grey stiff clay, fine to medium sand		
66	67	Clay	n/a	Very stiff grey clay		
67	68	Clay	n/a	Very stiff light grey clay		
68	69	Clay	Lignite	Very stiff light grey clay, some lignite		
69	71	Lignite	n/a	Black lignite		
71	72	Clay	Lignite	Light grey very stiff clay, some lignite		
72	74	Sand	Clay, Lignite	Grey fine to medium sand and lignite, some stiff light grey clay nodules		Minor **T3**
74	75	Clay	Silt/ Lignite	Grey silty clay, some lignite		**Cb**
75	76	Clay	Silt/ Lignite	Grey silty clay and lignite		
76	77	Silt	Clay/ Sand/ Lignite	Black silty clay and sand		
77	78	Clay	Silt/ Sand/ Lignite	Black lignitic silty clay, some fine sand		

78	80	Clay	Pyrite	Off white very stiff clay, some disseminated pyrite	**Weathered Clinton Formation**	**Cb**
80	86	Clay	Pyrite	Off white very stiff clay (note: slight acid reaction below this depth)		
86	88	Clay	Pyrite	Off white very stiff clay, some disseminated pyrite, some light brown clay nodules, some lignite		
88	89	Clay	Gravel/ Pyrite	Light grey clay with some disseminated pyrite, some fine rounded quartz gravel (note: strong acid reaction below this depth)	**Weathered Bedrock**	**Cb**
89	90	Clay	Gravel/ Pyrite/ Silt	Light grey silty clay with some disseminated pyrite, some fine to medium rounded quartz gravel		
90	93	Clay	Silt/ Gravel/ Pyrite	Grey silty clay, some disseminated pyrite, some fine to medium rounded milky quartz gravel		
93	96	Clay	Silt/ Gravel/ Pyrite	Light grey and light orange silty clay, some disseminated pyrite, some fine to medium rounded quartz gravel		
96	98	Clay	Silt/ Pyrite	Light grey and orange silty clay, some disseminated pyrite		
98	99	Clay	Silt/ Pyrite	Light grey and orange and light yellow silty clay, some disseminated pyrite		
99	100	Clay	Silt/ Gravel/ Pyrite	Light yellow and light orange and light grey silty clay, some disseminated pyrite and some fine to medium quartz gravel		
100	106	Clay	Silt/ Gravel/ Pyrite	Light grey and light orange and light yellow silty clay, some disseminated pyrite, some fine to medium angular chert, and quartz gravel		
106	111	Clay	Silt/ Gravel	Light grey silty clay with angular fragments of quartz		
111	112	Silt	Gravel	Grey silt and metasediment, some angular quartz and quartzite and feldspar gravel		
112	114	Silt	Gravel	Grey silt and metasediment, some angular fine to medium quartz gravel	**Moderately Weathered Bedrock - Saddleworth Fm.**	**Cb**
114	118	Gravel	n/a	Grey metasediment and angular medium quartz gravel		**Pc**

APPENDIX 3

GEOLOGICAL LOG OF CORE – PN 102084

Tray	Depth Interval (m BGL)	Colour[16]		Degree of Weathering[17]	Fracture Spacing (mm)	Approx. Fracture Dip (^{0})	Fracture Zone[18] (m BGL)	Fracture Aperture (mm)	Other features	Rock Type
		Dry	Wet							
1	118.2-119.3	N7	5B5/1 N4	MW	50-100	45-60	118.2-119.1	2-6	Broken, chlorite, talc, pyritised fracture surfaces. Meta-siltstone is sheared	DOLOSTONE & Meta-SILTSTONE
1	119.3-119.85	N7	5B5/1 N4	SW	100	45	-	0-2	Dolostone phase contains ‘xenoliths’. Disseminated pyrite. Poorly developed foliation parallel to fracture planes	Meta-SILTSTONE Secondary DOLOSTONE
1	119.85-120.75	N7	5B5/1 N4	SW	100	45	-	0-2	Dolostone subsumed. Xenocrysts – N8/9 colour. Limonite weathered surfaces 45^0 to fracture planes. Talc slickensides on some fractures planes.	Meta-SILTSTONE & ‘MARBLE’
1	120.75-121.2	N7	5B5/1 N4	SW	100	45	-	0-2	Pyritised foliation becomes sub-vertical. Specks of carbonaceous material/biotite?	As above
1	121.2-123.55	N7	5B5/1 N4	SW	50-200	45	-	0-2	As above	As above
2	123.55-128.8	N7	5B5/1 N4	SW-Fr	100-500	60-75	-	0-2	As above. Fresher and more massive than preceding. Occasional dolomite veins; orthogonal dip to factures. Occasional limonite staining.	As above
3	128.8-134.2	N7	5B5/1 N4	SW-Fr	100-500	60-75	132.4	0-2	As above. Orthogonal infilled, healed veins of white, banded calcite	As above No core returned 132.7-132.8

[16] Colour codes accords with Geological Society of America Munsell colour chart. N2 = greyish-black; N3 = dk grey; N4 = medium dark grey; N5 = medium grey; N6 = medium light grey; N7 = light grey; N8 = v. light grey; N9 = white; 5B 5/1 = medium blue-grey; 10R 6/6 = moderate reddish-brown.
[17] Degree of weathering terms accords with AIMM. Fr = Fresh; SW = Slightly weathered.
[18] i.e. discrete open fractures that might be groundwater transmissive.

Tray	Depth Interval (m BGL)	Colour		Degree of Weathering	Fracture Spacing (mm)	Approx. Fracture Dip (^{0})	Fracture Zone (m BGL)	Fracture Aperture (mm)	Other features	Rock Type
		Dry	Wet							
4	134.2-139.7	N7	5B5/1 N4	SW-Fr	100-400	50	138.2?	0-2	Copper mineralisation on fractures. 'shatter' zone 138.4-138.5	As above
5	139.7-145.05	N7	5B5/1 N4	SW	100-400	45-55	-	0-2	Slightly more iron-stained than preceding. Zones of marble veins < 300 mm with 'xenoliths'. Foliation dips steeper than fracture planes.	As above
6	145.05-150.4	N7	5B5/1 N4	SW	100-400	45-55	149.4; 150	0-2	As above	As above
7	150.4-156.4	N7	5B5/1 N4	SW	50-400	45-55	155.4-156.2	0-2; 2-6 @ 155.4-156.25	Orthogonal fracture set at 70^0 dip starts. Pyrite-stained fracture planes; heavy iron-stained joints. 'Shatter' zones 155.4-156.0 & at 156.25 with 40^0 foliation dip	As above
8	156.4-162.2	N7	5B5/1 N4	SW-Fr	50-400	45-55	156.6; 158.0; 161.3	0-2	Slate intraclasts, brecciated/mylonitised structural fabric. Foliation @ 50^0 with conjugate fractures @ 30^0 Brittle fractures & core loss caused by barrel rotation?	As above. Below 157.5 becoming a MARBLE; below 161.5 changes to meta-SILTSTONE/MUDSTONE. No core returned 159.13-159.23
9	162.2-168.0	N7 & N3	5B5/1 N4	SW-Fr	100-400	55-60	166.8	0-2	Many calcite 'stringer' vein; conjugate set @ 80^0. Occasional void spaces in veins & smaller 'xenoliths' than above. Foliation @ 35^0 heavily Pyritised meta-shale. Fissile zone 164.8-165.1 with heavy iron sulphide and calcite-staining on laminae. Ghost-veining below 167.3	meta-SILTSTONE/MUDSTONE & meta-SHALE No core returned 162.35-162.55
10	168.0-174.21	N7 & N3	5B5/1 N4	SW-Fr	100-400	55-60		0-2	As above. Veining prominent again below 168.2. Coarse-grained marble texture 169.75-169.85. More weathered 169.9-171.2 – 'greenstone' like. 10R6/6 on fracture planes; calcite veins absent below 169.9. Core loss caused by barrel rotation?	As above. No core returned 169.9-170; 171-171.1; & @ 174

11	174.21-180.15	N7 & N3	5B5/1 N4	SW-Fr	100-400 reducing to 20-100	55-60		0-2	As per interval 169.9-171.2 but slightly less weathered. Below 175.6 becomes v. fissile with brittle cleavage @ 40^0. Fracture intervals reduce below 179.95.	As above.
12	180.15-186.0 EOH	N7 & N3	5B5/1 N4		20-600	55-60	180.15-180.65?	0-6?	As above 180.15-180.65 – v. broken with 2 conjugate joint sets. Iron-stained and slightly more weathered 182.9-183.55	As above. No core returned 183.55-186.0

APPENDIX 4

PHOTOGRAPHS OF CORE – PN 102084

Permit 102084, 'Tray 1', 118.2-123.55 m

Permit 102084, ‘Tray 2’, 123.55-128.8 m

Permit 102084, ‘Tray 3’, 128.8-134.2 m

Permit 102084, ‘Tray 4’, 134.2-139.7 m

Permit 102084, 'Tray 5', 139.7-145.05 m

Permit 102084, ‘Tray 6’, 145.05-150.4 m

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Permit 102084, 'Tray 7', 150.4-156.4 m

Permit 102084, ‘Tray 8’, 156.4-162.2 m

Permit 102084, 'Tray 9', 162.2-168.0 m

Permit 102084, 'Tray 10', 168.0-174.21 m

Permit 102084, 'Tray 11', 174.21-180.15 m

Permit 102084, 'Tray 12', 180.15-186.0 m EOH

APPENDIX 5

WATER QUALITY RESULTS – PN 102084

Parameter	Units	Guideline Values		Botanical Gardens (PN 102084)
		Freshwater Aquatic Ecosystems	Potable	
General				
BOD	mg/L	10		
Chlorine	mg/L	0.003	5	
Conductivity	µS/cm			4,870
DO	mg/L			
pH	pH Units	6.5-9	6.5-8.5	7.7
Phenols	mg/L	0.05		
Redox Potential	mV			
Suspended Solids	mg/L	20	10	
Temperature	°C			
Dissolved Solids (by Calculation)	mg/L			2,900
Total Dissolved Solids (by EC)	mg/L			2,700
TOC		15		
Turbidity	NTU	20	5	
Major ions				
Calcium	mg/L			175
Magnesium	mg/L			160
Potassium	mg/L			28.8
Sodium	mg/L		180	679
Bicarbonate	mg/L			390
Chloride	mg/L		250	1,330
Fluoride	mg/L		1.5	0.29
Sulphate	mg/L		500	314
Nutrients				
Ammonia as N	mg/L	0.5		0.667
Filt Reactive Phosphorus as P	mg/L			0.007
Nitrate as N	mg/L			0.000
Nitrite as N				<0.005
Nitrate + Nitrite as N	mg/L		11	<0.005
Nitrate + Nitrite as NO_3	mg/L			<0.02
Phosphorus - Total as P	mg/L	0.5		0.155
Silica - Reactive	mg/L			17
Total Nitrogen	mg/L	5		
TKN as Nitrogen	mg/L			1.21

PARAMETER	UNITS	GUIDELINE VALUES		BOTANICAL GARDENS (PN 102084)
		FRESHWATER AQUATIC ECOSYSTEMS	*POTABLE*	
Metals				
Aluminium - total	mg/L			0.624
Antimony - total	mg/L	0.03	0.003	
Arsenic - total	mg/L	0.05	0.007	<0.001
Barium - total	mg/L		0.7	
Beryllium - total	mg/L	0.004		
Boron	mg/L		0.3	<0.040
Cadmium - total	mg/L	0.002	0.002	<0.0005
Chromium (VI)	mg/L	0.001	0.05	
Chromium - total	mg/L			<0.003
Cobalt - total	mg/L			
Copper - total	mg/L	0.01	2	0.003
Iron - total	mg/L	1	0.3	2.07
Lead - total	mg/L	0.005	0.01	0.0008
Manganese - total	mg/L		0.5	0.0564
Mercury - total	mg/L	0.0001	0.001	
Molybdenum - total	mg/L		0.05	
Nickel - total	mg/L	0.15	0.02	<0.0005
Selenium - total	mg/L	0.005	0.01	
Silver - total	mg/L	0.0001	0.1	
Thallium - total	mg/L	0.004		
Vanadium - total	mg/L			
Zinc - total	mg/L	0.05	3	0.006
Derived Data				
Alkalinity as CaCO3	mg/L			320
Ion Balance	%			1.68
Langlier Index	-			0.84
Sodium Adsorption Ratio	-			8.92
Total Hardness as $CaCo_3$	mg/L			1096

APPENDIX 6

RECOVERY MEASUREMENTS – PN 102084

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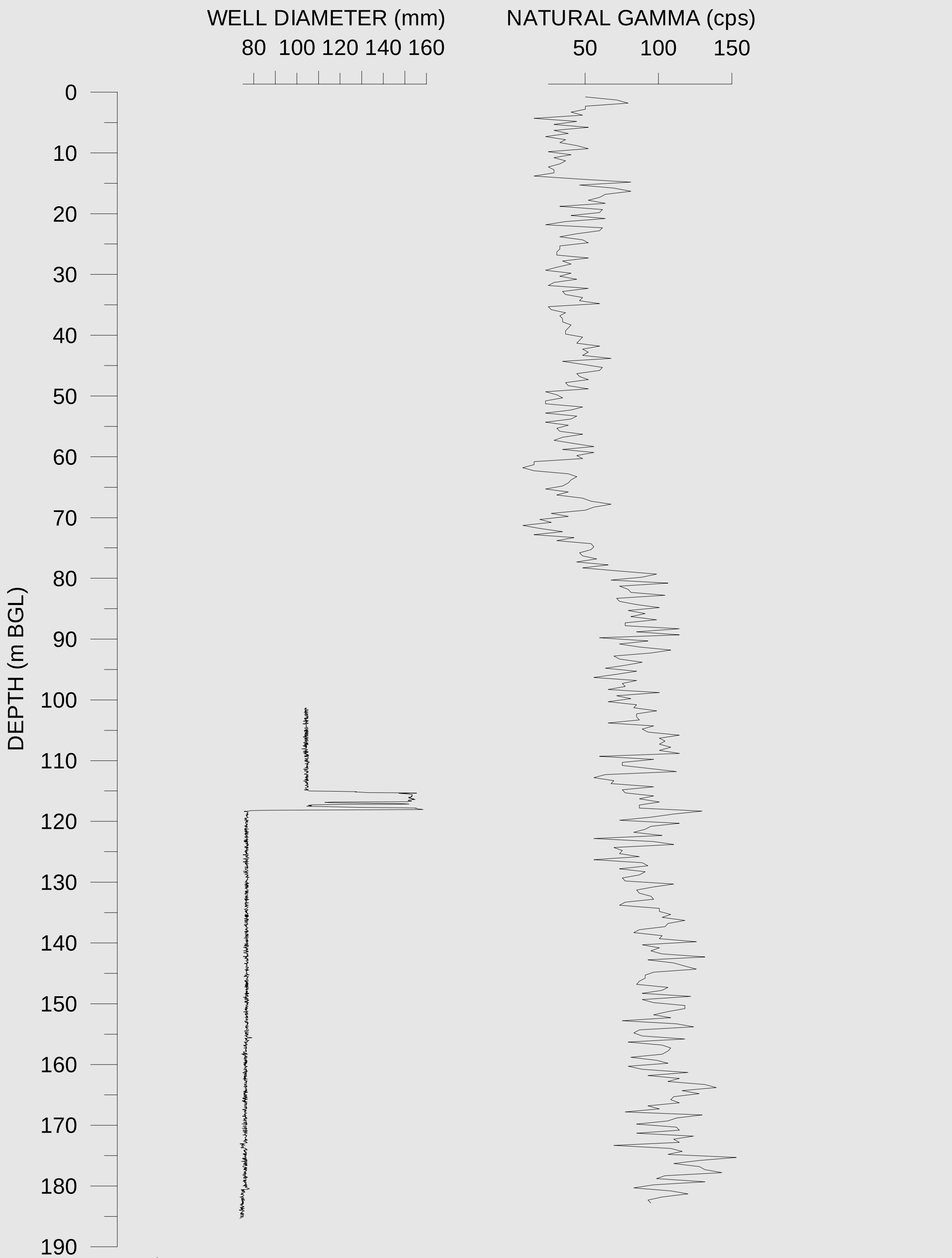
				Job No:	0117d		
				Sheet	1	of	1
Recovery after airlifting - drawdown recording sheet							
Client:	T CWMB			Recorded by:		IS	
Principal:				Checked:			
Project:	Parklands ASR			Measuring / Reference Point (RP):		Top of Headworks	
Location:	Botanical Gardens			Height of RP Above TOC:		~ 1.055	
Pumping Bore:	BG1			Pump Make & Model:			
Observation Bore (if applicable):	n/a			Pump Inlet Setting:		Hose set to ~ 63 m	
Pre Test Standing Water Level:	3.4			Discharge Measurement Method:		Filling 2,800L tank over 5 min	
Distance from Pumping Bore (m):	n/a			Pumping Test Start Date & Time:		14th September 2005 11.50 hrs	

Min		Sec	Elapsed Time (mins)	Water Level / Pressure (TO Headworks) (mbRP / kPa)	Corrected Water Level / Pressure (TOC) (mbRP / kPa	Drawdown (m)	Airlift Yield (L/s)	Notes	pH	temp	EC
	:		0 (pre-test)				9.4	Removal of headworks			
2	:	29	2.5	3.810	2.705	-0.695					
2	:	54	2.9	3.300	2.195	-1.205		SWL equipment malfunction			
6	:	53	6.9	4.580	3.475	0.075					
7	:	5	7.1	4.500	3.395	-0.005					
7	:	39	7.7	4.540	3.435	0.035					
9	:	20	9.3	4.535	3.430	0.030					
10	:	35	10.6	4.530	3.425	0.025					
11	:	50	11.8	4.525	3.420	0.020					
12	:	45	12.8	4.528	3.423	0.023					
14	:	0	14.0	4.527	3.422	0.022					
15	:	25	15.4	4.525	3.420	0.020					
16	:	0	16.0	4.524	3.419	0.019					
18	:	0	18.0	4.522	3.417	0.017					
20	:	0	20.0	4.520	3.415	0.015					
22	:	0	22.0	4.518	3.413	0.013					
25	:	0	25.0	4.514	3.409	0.009					
30	:	0	30.0	4.510	3.405	0.005					
35	:	0	35.0	4.510	3.405	0.005					
40	:	0	40.0	4.510	3.405	0.005					
45	:	0	45.0	4.508	3.403	0.003					
50	:	0	50.0	4.506	3.401	0.001					
55	:	0	55.0	4.505	3.400	0.000					
60	:	0	60.0	4.505	3.400	0.000					

APPENDIX 7

GEOPHYSICAL LOGS – PN 102084



Date	Jun-05	GROUNDWATER CONSULTING SERVICES Patawalonga & Torrens Catchment Water Management Boards INVESTIGATION INTO THE POTENTIAL FOR AQUIFER STORAGE AND RECOVERY IN THE BOTANIC GARDENS - STAGE 1 **GEOPHYSICAL LOG - WELL PERMIT 102084 (caliper, natural gamma)**	**FIGURE A.5.1**
Scale			
Drawn	ERR		Job: N0117b
Approved			

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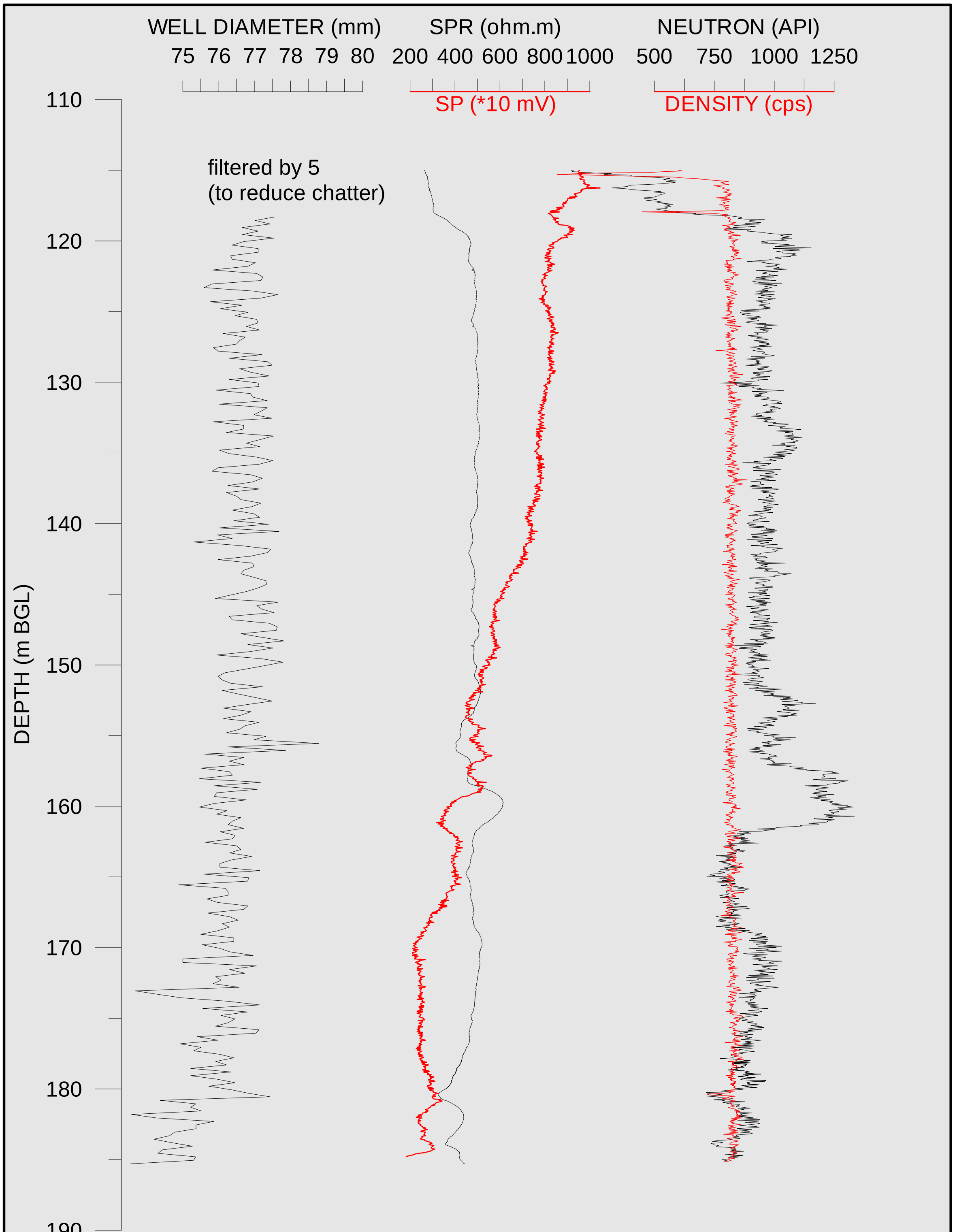

Australian Groundwater Technologies	Date	Jun-05	GROUNDWATER CONSULTING SERVICES Patawalonga & Torrens Catchment Water Management Boards INVESTIGATION INTO THE POTENTIAL FOR AQUIFER STORAGE AND RECOVERY IN THE BOTANIC GARDENS - STAGE 1	**FIGURE A.5.2**
	Scale			
	Drawn	ERR	**GEOPHYSICAL LOG - WELL PERMIT 102084** **(exploded view below permanent casing)**	
	Approved			Job: N0117b

APPENDIX 8

GLOSSARY

DIAMOND DRILLING AND CORE RECOVERY

INDUCTION LOG

A log recorded in uncased boreholes which involves the use of electromagnetic induction principles for the measurement of formation conductivity or resistivity. The induction logging tool has advantages for use in nonconductive borehole fluids (air. oil gas) where other electrical resistivity logging tools cannot be easily used or should not be used. The induction log is widely used in electrically conductive drilling muds where it works well provided the formations are not too resistive and borehole effects are known and not too great (i.e., mud not too saline and hole diameter not too large).

Practical induction sondes include an array of several transmitter and receiver coils designed to provide focusing and deep investigation and to minimize borehole and adjacent-formation effects. A high-frequency alternating current, constant in magnitude, is passed through the transmitter coils. The resulting alternating magnetic field induces currents in the formation which flow in circular ground-loop paths coaxial with the sonde. Those ground-loop currents generate their own magnetic fields which induce in the receiver coils signals which at low conductivities are essentially proportional to formation conductivity. At high conductivities, the reading may be affected by skin effect. Receiver-coil signals produced by direct coupling with the transmitter coil are balanced out by the measuring circuits.

Induction tools can be run separately or can be combined with other devices to run combination services. Integrated tools, combining in one tool the devices necessary to perform different resistivity-measuring operations, are commonly used in the well-logging industry. Examples of such tools are the induction device with a deep depth of investigation in combination with: another induction device having a shallower depth of investigation, invaded zone investigative devices (e.g., short normal device, short laterolog or guard log, or Spherically Focused Logging device), long lateral, and SP.

NEUTRON LOG

A log of a response primarily related to hydrogen concentration but also affected by mineralogy and borehole effects. The neutron log does not distinguish between the hydrogen in the pore fluids (i.e., water, oil, gas), in water of crystallization, or water bound to solid surfaces. In clean oil-filled or water-filled formations the apparent porosity reading ot the neutron log reflects the amount of liquid-filled pore volume. Used with other porosity information. the neutron log is useful to ascertain the presence of gas and determine mineralogy and shaliness.

The tool contains a continuously emitting neutron source and either a neutron- (n-n tool) or a gamma-ray detector (n-g tool). High energy neutrons from the source are slowed down by collisions with atomic nuclei. The hydrogen atoms are by far the most effective in the slowing down process because their mass is nearly equal to that of the neutron. Thus, the distribution of the neutrons at the time of detection is primarily determined by the hydrogen concentration. Depending on the tool type, detection is made of either (1) thermal neutrons; (2) gamma rays, generated when thermal neutrons are captured by thermal-neutron absorbers in the formation (primarily chlorine); or (3) epithermal neutrons (neutrons having energies higher than thermal).

Neutron curves are scaled in API units or in terms of apparent porosity. The neutron log can be recorded in open or cased liquid-filled well bores. There is a maximum hole size limitation in empty holes for running tools in which the detector does not contact the formation wall. See also sidewall neutron log and compensated neutron log.