Consolidated Volume of Reports on Groundwater Investigations at the LHSTC to May 2007

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ANSTO

PARSONS BRINCKERHOFF

Parsons Brinckerhoff Australia Pty Limited ACN 078 004 798 and
Parsons Brinckerhoff International (Australia) Pty Limited ACN 006
475 056 trading as Parsons Brinckerhoff ABN 84 797 323 433

Ernst & Young Centre,
Level 27, 680 George Street
Sydney NSW 2000
GPO Box 5394
Sydney NSW 2001
Australia
Telephone +61 2 9272 5100
Facsimile +61 2 9272 5101
Email sydney@pb.com.au

ABN 84 797 323 433
NCSI Certified Quality System ISO 9001

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Authors: Andrea Averkiou, Graham Hawkes, John Bradd, Emmy Hoffmann

Reviewer: ....John Ferris, John Ross, John Bradd

Approved by: ....Brian Rask

Signed: ....

Date: July 2007 ....

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1. Introduction

1.1 Background to this Integrated Volume

The purpose to this integrated volume is to consolidate all the data related to hydrogeology, groundwater monitoring network, geophysics, monitoring programs and sampling protocols undertaken at the Lucas Heights and Technology Centre (LHSTC) by PPK Environment & Infrastructure and Parsons Brinckerhoff since 2000. ANSTO undertake routine groundwater monitoring at the site and prepare annual reports for ARPANSA. Data from this routine monitoring has been included in this report by ANSTO.

This report is an amalgamation of five PPK/PB reports:

- Groundwater Monitoring and Management Program (PPK, 2000a);
- Groundwater Sampling Plan and Monitoring Protocols (PPK, 2000b);
- Supplementary Groundwater Investigation and Borehole Abandonment (PPK, 2001);
- Supplementary Drilling Program (PPK, 2002); and
- Replacement Monitoring Well MW11 and Piezometer Abandonment (PB, 2003).

The majority of site characterisation was undertaken in our first report (PPK, 2000a), in which a detailed baseline groundwater investigation was undertaken and the majority of the current groundwater monitoring network constructed. One of the primary aims of this investigation was to establish baseline groundwater conditions and to determine the nature of groundwater migrating from the site. To achieve this the following reporting and investigations were carried out; physical setting, geology and hydrogeology, resistivity imaging survey, down hole geophysics logging, data logger installation and groundwater flow calculations based on hydraulic conductivity data obtained from slug tests.

With the exception of (PPK, 2000b) which involved developing a groundwater sampling plan and monitoring protocol for the groundwater monitoring network, the remaining reports involved drilling replacement piezometers and abandoning old piezometers and geotechnical holes. The field investigations are summarised in *Table 1.1*.

Table 1.1: Summary of Work Undertaken

Report	Piezometers Constructed	Work Activities
PPK, 2000a	MW1s, MW1d, MW1 open, MW2s, MW2d, MW3s, MW3d, MW4s, MW4d, MW5, MW6s, MW6d, MW6 open, MW7s, MW7d	Drilling 15 piezometers to establish the groundwater monitoring network at LHSTC Resistivity imaging survey Down hole geophysical logging Field Hydraulic Conductivity tests Installation of data loggers to monitor groundwater levels
PPK, 2000b	-	Development of groundwater sampling plan and monitoring protocol for the groundwater monitoring network at LHSTC
PPK, 2001	MW8s, MW8d BH6, BH102, BH109, BH112	Drill MW8s, MW8d to replace MW4s and MW4d Convert 4 geotechnical bores (BH series) to piezometers Abandon 19 geotechnical holes and some monitoring wells in the Replacement Research Reactor/ John Holland EDI site (RRR/JHEDI)
PPK, 2002	MW9s, MW9d, MW10s, MW11, MW12, MW13, MW14, MW15s, MW15d	Construction of piezometers at the RRR/JHEDI site and at the LHSTC site. MW12 was cored from 13.5m – 50m
PB, 2003	MW11-2	Drill replacement piezometer for MW11, abandon MW11

2. Physical Setting

2.1 Site Layout

The Lucas Heights Science and Technology Centre (LHSTC) is located on the Woronora Plateau between the suburb of Barden Ridge and Heathcote Road at Lucas Heights, and is located on the southern side of New Illawarra Road. The large Lucas Heights waste facility operated by Waste Service NSW is situated approximately one kilometre north of the site. The closed Lucas Heights No.1 landfill is located two kilometres north-east of the site.

The LHSTC is approximately 50 hectares in area and there are a number of building clusters and precincts across the site. The general layout of the site is shown in *Figure 1* and the regional site setting is shown in *Figure 2*. ANSTO also owns a 1.6 kilometre buffer zone surrounding the whole site.

Sensitive areas that may contribute to groundwater contamination within the centre are the existing HIFAR facility and subsurface water bunker areas, Building 27 which houses the spent nuclear fuel rods, and to a much lesser extent, underground storage tank areas (USTs) associated with petrol/diesel storage and distribution.

The Replacement Research Reactor (RRR) itself is located west of the existing HIFAR on previously un-used land. In April 2007, the Open Pool Australian Light-water reactor (OPAL) was officially opened, so that the RRR is now called OPAL. The area on which OPAL and its associated infrastructure is built was, during construction, also known as the JHEDI site after the building construction consortium John Holland EDI. In this report, the RRR/JHEDI site refers to this portion of the larger LHSTC site.

Little Forest Burial Ground (LFBG) is an area on the Woronora Plateau, located approximately 1200m north-west of LHSTC between the suburb of Barden Ridge and Heathcote Road at Lucas Heights. Waste material from the Australian Atomic Energy Commission (now ANSTO) was disposed of by shallow burial at the LFBG in the 1960’s. A piezometer network is used to monitor groundwater at and around the site.

2.2 Topography and Drainage

The topography of the LHSTC site and the buffer zone consists of flat ridges dissected by headwater creeks that drain the site in all directions. Topographic contours are shown on *Figures 7 to 10*. The main drainage lines include Mill, Barden and Fire Creeks and the Woronora River, the former two being tributaries of the Georges River to the north. The LHSTC lies on the watershed divide between the Georges River and Woronora River catchments. Drainage of the site is mainly northwards to the Georges River catchment via Mill Creek or Bardens Creek respectively or eastwards/southwards towards the Woronora River. Minor tributaries draining the site into Melinga Molong Gully include “Strassman” and, “MDP” Creeks (unofficial names) and minor tributaries of Bardens Creek.

There is a groundwater baseflow component in some surface waters leaving the buffer zone, especially during dry low flow periods. Springs have been identified on the steeper slopes of the eastern and southern boundaries of the site feeding those tributary creeks that drain to the Woronora River.

2.3 Geology

The LHSTC is located on weathered and eroded Hawkesbury Sandstone of the Woronora Plateau. The Triassic Hawkesbury Sandstone is approximately 200 metres thick beneath the site and overlies interbedded sandstones and claystones of the Narrabeen Group and Permian Illawarra Coal Measures.

The Hawkesbury Sandstone generally consists of interbedded massive and current bedded layers with cross beds typically ranging from 1.5 to 3 metres thick and occasionally up to 15 metres thick. Relatively thin, laterally discontinuous shale and siltstone lenses occur throughout the Hawkesbury Sandstone.

Most of the sandstone units within the Hawkesbury Sandstone are composed of medium to coarse quartz sand grains cemented with silica, clay and iron oxides or carbonates to form massive sandstone. The Hawkesbury Sandstone dips at approximately 0.5 to two degrees to the north and is cross cut by joints up to 10 metres apart. The dip of these joints are typically vertical with some dipping at between 30 to 45 degrees.

A north–north-east to south–south-west oriented dolerite dyke occurs outside the western boundary of the LHSTC site and extends for up to five kilometres to the west. No extension of this dyke has been identified on the site or within the immediate western buffer zone area (Coffey, 1998).

2.4 Hydrogeology

2.4.1 Occurrence

Groundwater occurs in perched horizons within the weathered sandstone, and within deeper, poorly defined sandstone aquifers that occur across the Woronora Plateau. Prior to this drilling program, little information was available regarding water level depths and patterns, however decreasing heads in the sandstone were suspected, indicating vertical groundwater flow. Groundwater flow within the perched horizon is limited and is dominated by intergranular flow in the weathered sandstone. In contrast, groundwater flow within the deeper aquifers is along both primary features such as less well cemented zones within the sandstone and secondary structural features such as joints, shears, faults, and bedding plane partings. Bedding plane partings can form localised barriers which cause horizontal flow through porous sandstone. Some flow also occurs in sedimentary structures such as the more permeable cross bedded layers. A topographic influence is expected for both the perched groundwater and to a lesser extent the deeper aquifer zones.

The thickness of the weathered sandstone and sandy soil profile is highly variable across the site and may result in discontinuous perched groundwater zones. This is the direct result of jointing and cementation in the sandstone. Likewise the fracture pattern in the Hawkesbury Sandstone is highly variable. There is usually a high density of surface joints that are open and transmit groundwater. At depth, many of these joints are closed through iron oxide and clay deposition, and compressional stresses in the rock mass. Very few continuous deep vertical joints are thought to exist. No large faults, shears or other structure features exist in the area.

Inconclusive analysis of previous hydrogeological data from around the RRR/JHEDI site indicated groundwater flow in the upper perched aquifer in a south-westerly direction, while the deeper regional groundwater gradient appeared to flow in a north westerly direction (Coffey, 1998).

2.4.2 Recharge

Recharge of the Hawkesbury Sandstone is by direct infiltration of rainfall into the sandstone after rainfall collects in the weathered profile and the upper perched zone. Enhanced recharge may occur along open joints and fractures within any exposed sandstone or near sandstone outcrops. Groundwater discharge is known to occur on the valley sides via springs east of the site. Spring flows and creek baseflows derived from groundwater discharge areas have been noted previously. Numerous other spring areas are thought to exist in the lower valley areas east and south of the site.

2.4.3 Flow

There is significant variability in the occurrence and connection between shallow zones and deeper aquifers. A sketch that highlights groundwater flow and the likely relationship between aquifer zones, rainfall recharge and discharge areas is presented in *Figure 3*.

The relationship between groundwater flow in fractures and groundwater flow in the porous sections of the Hawkesbury Sandstone is uncertain. PB believe that groundwater flow in the main sedimentary structures and open fractures is the dominant process to be addressed, although pore water in the sandstone may also be important.

Shallow standing water levels in the sandstone aquifers are suspected near the centre of the ridgeline and plateau, with slightly deeper standing water levels around the perimeter of the LHSTC. Some differentiation between shallow and deep zones is expected. Rainfall recharge will accumulate in the upper weathered sandstone as perched groundwater. Some water will be lost to evapotranspiration while a proportion will recharge deeper aquifers. Some of this groundwater will discharge as springs while some will recharge even deeper aquifers. Ultimately all groundwater in the Hawkesbury Sandstone is thought to discharge to either the Woronora River or the Georges River.

2.4.4 Characteristics

The perched zone is unconfined and the deeper, more extensive aquifers are semi-confined with the water table generally reflecting a subdued reflection of the topographic surface. The shallow perched water table ranges in depth from one metre to seven metres below ground surface. The regional water table is typically deeper ranging in depth from two metres to 15 metres below ground surface (depending on topographic location). The groundwater in each aquifer can be characterised as sodium chloride, and is of good quality being less than 1000 mg/L total dissolved solids (TDS).

Groundwater piezometers at the Lucas Heights landfills operated by Waste Services NSW are known to be highly variable with some artesian flows in mid slope areas from aquifer zones at depth. It is not known whether aquifer systems at the LHSTC site have a regional relationship with the Hawkesbury Sandstone groundwater systems west of New Illawarra Road.

3. Investigations Prior to 2000

There has been limited drilling and investigation work on the LHSTC site (Chris Waring pers comm). A check of archival material and discussions with long term employees and contractors has not identified any useful groundwater investigations on site apart from recent studies for the EIS by Coffey Partners. However some investigations have occurred on adjoining lands and these are briefly described below. At this stage, none of the external data has been integrated with the LHSTC groundwater data to obtain a more regional appreciation of the groundwater flow characteristics.

3.1 Offsite

Department of Mineral Resources Exploration Bore

A number of deep coal exploration bores have been drilled on the Woronora Plateau. The closest borehole is Department of Mineral Resources Camden DDH86 located approximately 200 metres north of the LHSTC site which was drilled over a period of three months in 1965. The bore location is shown on *Figure 2*. The bore was fully cored to a total depth of 884.2 metres, intersecting Hawkesbury Sandstone, Gosford Formation, Bald Hill Claystone and Bulgo Sandstone. The bore is assumed to be plugged and abandoned.

DIPNR Database and Local Water Bore Data

A review of bores registered with the Department of Infrastructure, Planning and Natural Resources (DIPNR) shows there are only three bores within a 6.5 kilometres radius of the LHSTC. The closest bore (GW046782) is a groundwater test bore drilled in 1977 located approximately two kilometres to the north. The remaining two registered bores (GW072286 and GW010563) are located on the perimeter of the 6.5 kilometres search radius and are registered for stock, domestic and general purposes. Bore details are summarised in *Table 3.1*, with locations shown on *Figure 2* and full details in *Appendix A*.

Table 3.1: Private Bore Details in the Lucas Heights Area

Bore No.	Depth (m)	Aquifer Zones (m)	SWL (m)	Yield (L/s)	Use	Geology
GW010563	45.7	6 45.7	? 9.1	? 0.38	General	Sandstone, shale with ironstone and pyrite
GW046782	30	Unknown	?	?	Observation	0-7 Fill 7-19 Sandstone 19-30 Decomposed Shale
GW072286	5.5	?	?	?	Stock/Domestic?	Unknown

Source: DIPNR Groundwater Database

Lucas Heights #1 LandFill (Closed)

This is the closed landfill area located immediately north east of the existing operational landfill on the northern side of New Illawarra Rd. It is owned by Waste Services NSW and is the process of being developed for playing fields and other recreation uses. Numerous groundwater investigations have been carried out by staff and students from the University of NSW, and more recently by several consultants.

A large monitoring well installation program was completed in 1997 by Fluor Daniel GTI to establish multi-level leachate wells and single piezometers in the sandstone immediately below the landfill. Some 40 monitoring points were established to routinely monitor the leachate quality and the associated leachate impacts (if any) on shallow groundwater within the underlying shallow sandstone and deeper sandstone downgradient of the landfill.

Lucas Heights #2 Landfill (Operational)

Monitoring of groundwater conditions at a number of dedicated deep sites in the Hawkesbury Sandstone has been carried out by Waste Services NSW and their consultants in recent years. The closest bores that are part of this program are probably only one kilometre from the northern boundary of the site. None of this data has been obtained and integrated as part of this baseline study for the LHSTC investigation.

One of the initial hydrogeological investigations was undertaken two kilometres north-west of the LHSTC site (Douglas and Coffey, 1994). The local and regional groundwater regimes were investigated to assess groundwater flow directions and hydraulic conductivities within the Hawkesbury Sandstone. The report concluded groundwater flow was to the north but locally the groundwater gradient was strongly influenced by structural and topographic features. An isotopic testing program for tritium for dating purposes concluded the groundwater was older than 1950's and did not identify any irregularities. Calculated values of horizontal flow velocity varied between 0.034 m/day and 0.14 m/day. Extensive monitoring is being undertaken by Waste Services NSW.

Little Forest Burial Ground

Groundwater is monitored in 16 groundwater monitoring bores and two disposal trenches within the Little Forest Burial Ground (LFBG) and 4 bores to the north and east of the fenced area, which is located off-site between Mill Creek and Bardens Creek. The site is 1.5 kilometres north-west of the LHSTC site. This site was used to dispose of solid waste with low levels of radioactivity.

In 1996, ANSTO undertook a hydrological investigation based on a digital photogrammic method to assess remediation options associated with solid and liquid waste disposal in the Harrington Shale Quarry area (ANSTO, 1996). In this area, liquid and solid industrial waste was disposed in a disused shale quarry between 1969 and 1980. The report identified a number of remediation strategies to hydrogeologically isolate the site.

Dr Chris Waring from ANSTO has advised that DASCEM initiated a new investigation surrounding the LFBG in 2000. Work includes resistivity surveys, follow up drilling and a water sampling program. Up to 25 drill holes were drilled as part of the investigation program.

In 2002 PPK undertook a geophysical investigation and drilling program to further investigate the geology and geological structure, and to detect fracture zones in the bedrock surrounding the Little Forest Burial Ground (PPK, 2002a). The geophysical survey consisted of 2.7 kilometres of resistivity imaging and ground conductivity (EM34-3) surveying. On the basis of the geophysics two of the most-likely fracture anomalies were drilled and a shallow and deep piezometer installed at each site. The field program identified a shale lens but no fractures were detected within 100m of the LFBG disposal trenches.

Annual Environmental Monitoring Reports

Environmental monitoring of liquid effluent, surface water, seepage and atmospheric emissions are routinely conducted by ANSTO for its facilities at Lucas Heights (ANSTO, 1998). No systematic, routine groundwater monitoring occurred on the main LHSTC site prior to 2000. Annual environmental monitoring reports for the LHSTC have been issued since 1959.

Meteorological stations, creek water and sediment sampling sites are located off-site and on-site around the LHSTC.

3.2 Onsite

An initial groundwater investigation at the RRR/JHEDI site was undertaken by Coffey Partners International as part of the EIS suite of studies (Coffey, 1998). During this hydrogeological investigation and subsequent geotechnical investigation, 16 piezometers were constructed at 11 locations (*Figure 4*). Six packer tests were undertaken to assess the horizontal hydraulic conductivity. Localised transient perched aquifers and a deeper aquifer were identified with groundwater recharge between horizons being via interconnected sub-vertical joints and sub-horizontal bedding planes. During this program, a geophysical survey consisting of seismic refraction, resistivity soundings and magnetic profiles was undertaken. An inferred dolerite dyke was located 100 metres west of the RRR, trending north-north-east by a magnetometer survey.

Seismic Refraction

Seismic refraction profiling was undertaken to provide indications of significant variations in sediment densities, to map the bedrock profile and to identify any channel structures or significant fractures. The location of the three seismic lines is shown on *Figure 4.*

Three layers of differing seismic velocity were identified which were interpreted as representing soil and fill, extremely to moderately weathered sandstone and moderately weathered to fresh high strength sandstone.

Resistivity Soundings

Resistivity soundings were carried out to complement the seismic profiling since seismic profiling will not usually detect the top of the water table.

Three to four layers (S1 to S4) of differing resistivity were identified which generally decrease in resistivity with increasing depth. These layers were interpreted as representing dry soil and fill (S1), partially saturated soil, fill and weathered sandstone (S2 and S3) and saturated bedrock or conductive shale (S4).

Magnetic Profiles

Magnetometer profiling consisting of three profiles, was undertaken to identify if a dolerite dyke, identified approximately 400 metres north of the site and trending north-south towards the western edge of the RRR/JHEDI site, extended beneath the RRR/JHEDI site.

Line 3 was conducted over the known extent of the dyke located 400 metres north of the RRR/JHEDI site. A significant anomaly was detected consistent with a narrow dolerite dyke. Lines 1 and 2 located immediately north of the RRR/JHEDI site detected anomalous magnetic features. The feature seen at 140 metres on Line 2 is a possible extension of the dyke. Connecting these magnetic intercepts and from the fracture pattern in outcrop, a trend of 020 (NNE) is likely for the inferred dyke.

Environmental Impact Statement

The Environmental Impact Statement (EIS) for the RRR summarises the site hydrogeology and discusses the potential impact on groundwater quality and groundwater flow directions (PPK, 1998). It is essentially a summary of the Coffey, 1998 work. Volume 3 of the EIS (the EIS Supplement) addresses questions and issues raised following public consultation and display of the initial EIS. A number of groundwater issues are covered and reiterated in the supplement.

4. Groundwater Monitoring Network

There are two groundwater monitoring networks at the LHSTC, a network focused on the RRR/JHEDI site (now the OPAL site) located at the western corner of the LHSTC, and a regional network that is primarily monitoring groundwater around the perimeter of the LHSTC site.

The groundwater network at the RRR/JHEDI site was commenced in 1998 and has undergone a number of changes as the location of monitoring wells has been changed to accommodate the changing footprint of the RRR infrastructure. The location of monitoring wells and abandoned monitoring wells within the new RRR/JHEDI groundwater monitoring network in 1998 and following supplementary drilling programs in 2001 and 2002 are shown on *Figures 4 to 6*.

The regional groundwater monitoring network at LHSTC was commenced in 2000 and is shown on *Figure 7*. Monitoring wells have been added to the network in supplementary drilling programs in 2001, 2002 and 2003 as shown in *Figures 8 to 10* respectively.

4.1 Prior to 2000

Prior to 2000 no integrated groundwater monitoring program existed for the whole of the LHSTC site.

As part of the groundwater and geotechnical studies carried out for the Environmental Impact Statement for the RRR, a series of piezometers were constructed around the RRR/JHEDI site in the western corner of the LHSTC site in 1998. This groundwater network consisted of 16 piezometers, 11 intersecting shallow groundwater to 11 metres and the remaining five intersecting the deeper aquifer zones below 13 metres. Monitoring locations are shown on *Figure 4*.

Most of these piezometers were destroyed during the construction of the RRR. Only BH3 and BH3a remain from this network but replacement piezometers were constructed over the next few years.

4.2 Expanded Network in 2000

The LHSTC is located on a ridgeline where it is likely that groundwater flow is to the north, east and south. In 2000 an expanded monitoring network was constructed to ring the entire site and to target locations where monitoring was essential because of the adjoining activities, or the sites are close to established surface water sampling locations. Differentiation in vertical monitoring was also required at most sites to assess impacts in the shallow perched system and then the deeper aquifer system in the sandstone. The shallow perched system provides "early warning" of any site impacts before contaminants can reach the deeper aquifers. The distinction between the shallow perched system and the deeper aquifer is real at some sites and blurred elsewhere. From the available data, there was limited continuity of individual subsurface "aquifer" features. Trends were expected to extend more than tens of metres, or at most, a couple of hundred metres.

Two types of piezometers were designed by PPK; – Type 1 and Type 2. In summary Type 1 is cased with PVC whereas Type 2 is an open hole. These are described more fully in *Section 5.1.2*.

The rationale for locating the seven sites is to provide targeted locations and maximum coverage around the perimeter of the site. Bores were located thus:

- Site 1 is located off-site in the north western corner of the site along the western perimeter fence to provide additional monitoring close to the RRR and within the buffer zone (Note: Site 1 is now incorporated within the OPAL site fence). There are three piezometers at this location (shallow and deep Type 1 piezometers and a Type 2 piezometer). This is a key monitoring site;
- Site 2 is located off-site, north of the existing HIFAR reactor, in an adjacent grassed park within the buffer zone. A shallow and deep Type 1 piezometer are located at this site;
- Site 3 is located off-site, immediately north of the perimeter fence and road adjacent to Building 9 and beside a small drainage gully that flows to Bardens Creek. The location is up-gradient of Bardens Creek Weir, which is a surface water sampling location. A shallow and deep Type 1 piezometer are located at this site;
- Site 4 is located off-site on the eastern perimeter down gradient from Building 35C in an area of obvious shallow groundwater seepage. It is located below the LHSTC perimeter access track and within the buffer zone. A shallow and deep Type 1 piezometer are located at this site. There has subsequently been placement of sandstone rubble from the RRR/JHEDI site just to the south of these piezometers.
- Site 5 is located within the site behind Building 7 and down gradient from underground storage tanks and the fuel dispensing area. A shallow Type 1 piezometer is located at this site to assess whether any hydrocarbon contaminants are present in the shallow groundwater;
- Site 6 is located on-site, immediately down gradient from Building 27 where spent fuel rods are stored in stainless steel lined boreholes drilled into the sandstone bedrock. There are three piezometers at this location (shallow and deep Type 1 piezometers and a Type 2 piezometer). The location is up-gradient of the MDP Creek Weir sampling location and is a key monitoring location; and
- Site 7 is located off-site along the southern perimeter fence just beyond the perimeter access track. It is adjacent to Buildings 23C and 23D, and is down gradient from the HIFAR reactor. The location is also up-gradient of the surface water quality sampling location along Strassman Creek.

4.3 Changes in 2001

In 2001 the groundwater monitoring network at LHSTC was altered significantly. New piezometers were constructed around the RRR/JHEDI site to allow for background monitoring. Most existing piezometers in the RRR area and all open geotechnical holes were infilled with a cement/bentonite mix to ensure these holes did not act as conduits for potentially contaminated water into the Hawkesbury Sandstone. In total 16 geotechnical holes and three piezometers were abandoned during this program.

- Site 8 is located on the western side of the Environmental Radiochemistry Laboratory (Building 34) outside the perimeter fence and within the buffer zone. Two Type 1 (shallow and deep) piezometers are located at this site.

In addition at the RRR/JHEDI site four boreholes (BH6, BH102, BH109 and BH112) were converted to piezometers.

A number of piezometers (BH1, BH1a, BH2, BH2a, BH109) constructed in 1998 at RRR/JHEDI were abandoned because they were sited where buildings associated with the RRR were to be located. These piezometers were abandoned by removing the standpipes and infilling with a cement bentonite mixture (*Section 5.1.8*).

4.4 Changes in 2002

In 2002 nine piezometers were added to the groundwater monitoring network at seven sites. Three were located on the LHSTC site (MW11, MW13 and MW14) and the remaining six were located at the RRR/JHEDI site (MW9s, MW9d, MW10s, MW12, MW15s and MW15d).

The rationale for locating the seven sites is to provide sufficient coverage within LHSTC and maximum coverage within RRR/JHEDI. Bores were located thus:

- Site 9 is located in the south western part of the RRR/JHEDI site where two type 1 piezometers have been constructed. These piezometers (MW9s and MW9d) replace key piezometers BH1a and BH1;
- Site 10 is located adjacent to a stormwater detention point. The new piezometer MW10s together with BH102 form a nested pair that replaces BH2 and BH2a. Although BH102 was sampled in September and December 2002, it was subsequently buried by earthworks on the RRR/JHEDI site and could not be located during the next sampling round in March 2003. BH102 was located after construction activities in the area ceased, and sampling recommenced in August 2006;
- Site 11 is located outside Building 40 (next to the “Menzies Foundation Stone”) adjacent to HIFAR. No perched groundwater was intersected so only one Type 1 piezometer was constructed. This piezometer was completed with a road box flush with ground level. In 2003 this piezometer (MW11) was replaced with MW11-2 due to an obstruction in the initial piezometer that restricted groundwater sampling (PB, 2003);
- Site 12 is a Type 2 deep piezometer located next to the south western perimeter fence within RRR/JHEDI. It is a replacement for deep piezometer BH109 which was converted into a dedicated monitoring well in June 2001 and later abandoned in December 2001. MW12 was drilled using an air hammer to 13.4 metres, with the remaining depth to 50 metres cored using a HQ size core barrel. MW12 has a 160 millimetre diameter hole at surface and a 100 millimetre hole at depth. It contains a lockable 160 millimetre steel casing protector and cap protruding from a concrete plinth. The casing extends to two metres below ground level, and the remainder of the hole is uncased.

- Site 13 is located within the LHSTC on the grassed area outside Building 21 as an internal monitoring location. As at Site 11 no perched groundwater was intersected so only one Type 1 piezometer was constructed.
- Site 14 is located within the HIFAR complex of the LHSTC. One Type 1 piezometer was constructed outside Building 23d (GATRI facility) and is designed to monitor any water leakage from Building 23;
- Site 15 is located in the courtyard/drain area of the RRR where two piezometers were constructed. MW15s is located six metres from the edge of the pit dug for the reactor core, and MW15d is located 2.5 metres north of MW15s (PB, 2003).

4.5 Changes in 2003

In 2003 a replacement piezometer was drilled and constructed at Site 11, located outside Building 40 (next to the "Menzies Foundation Stone") adjacent to HIFAR as the previous piezometer (MW11) had partially collapsed. The initial piezometer was abandoned and backfilled with a cement bentonite slurry. The replacement piezometer (MW11-2) was constructed to the same specifications as the previous piezometer (Note that the bore log for this piezometer appears as MW14-2 in *Appendix B*).

5. Field Programs

5.1 Investigations

All field investigations were conducted in accordance to the Health and Safety Plans prepared by PPK/PB for all PPK/PB personnel and subcontractors to PB. Contractors were required to read and understand the PB prepared HASP. However, contractors were also responsible for formulating and monitoring their own health and safety program. PB ensured that all contractors working on the site were appropriately licensed for the activity that they were performing.

Field investigations were also undertaken in accordance with ANSTO's safety requirements. All PPK/PB field staff and subcontractors to PB undertook the ANSTO induction and obtained the appropriate security pass. All work associated with the remediation conformed at a minimum, to the requirements of the NSW Occupational Health and Safety Act.

5.1.1 Drilling Programs

Since 2000 PPK and PB have undertaken four drilling programs at the LHSTC, one for each year. The objectives of the drilling programs have been to drill and construct observation piezometers, investigate the sandstone stratigraphy, core sandstone to further investigate the sandstone stratigraphy and abandon geotechnical holes and no longer required piezometers.

In each case drilling has been undertaken by Macquarie Drilling using a Pioneer P160 drilling rig using the air-hammer drilling method. At one location (MW12) HQ coring was undertaken. Each drilling program was directed by a PPK or PB hydrogeologist. Previous drilling undertaken at the LHSTC in 1998 for the EIS was also undertaken by Macquarie Drilling.

The drilling programs were undertaken to investigate the weathered and solid sandstone stratigraphy, assess water bearing zones, aquifer permeabilities, and to provide groundwater monitoring coverage. Drilling was terminated in the deeper piezometers once the regional water table was intersected. Drilling of the shallow piezometers was terminated once the shallow perched zone was intersected. Lithological samples were collected at one metre intervals and the geology was logged on site during the drilling program. Borehole lithological logs are given in *Appendix B*.

5.1.2 Borehole Construction Details

Two piezometer types have been constructed at the LHSTC - Type 1 piezometers are constructed with 50 millimetres diameter, Class 12 PVC and screened opposite the selected aquifer zone. Type 2 piezometers are open holes within the Hawkesbury Sandstone drilled at a diameter of 120 millimetres. The design for Type 1 and Type 2 piezometers is shown schematically in *Figure 11*. At the dual piezometer sites, separate Type 1 piezometers were constructed about three metres apart. This monitoring well design complies with the ARMCANZ (1997) Specification for "Minimum Construction Requirements for Water Bores in Australia".

The monitoring network is designed to monitor groundwater within the upper perched aquifer and deeper aquifer at strategic locations within the site and at important boundary/buffer locations. Where perched groundwater was intersected dual Type 1 piezometers were installed to monitor groundwater in the shallow perched aquifer and deeper aquifer.

Type 1 Piezometers

At Type 1 dual piezometer sites, the deeper bore hole was constructed first to determine the stratigraphy and water bearing zones. The borehole was terminated once the regional watertable was intersected. The shallow bore hole was constructed beside the deep piezometer to the base of the weathered profile so that shallow perched groundwater could be monitored in a separate dedicated piezometer. Perched groundwater was not intersected art each site.

The upper 1 to 2 metres of each Type 1 piezometer was drilled at a diameter of 155 millimetres to seat temporary PVC casing in the weathered zone during drilling. The remainder of each hole was drilled at a diameter of 120 mm using a hammer bit.

Casing was installed in each borehole immediately after drilling had ceased. The lower three to nine metres of each monitoring piezometer was cased with 50 millimetres diameter, Class12 bell jointed, machine slotted, 0.4 millimetres aperture casing and completed with an end cap. All piezometers constructed since 2001 were constructed with Class 18 50 millimetres diameter screwed PVC casing. The borehole annulus was infilled with graded sand (1-2 millimetres diameter) to at least 0.5 metres above the screened section. A bentonite seal, at least 0.5 metres thick was placed on top of the graded sand to isolate surface water from the water-bearing zone. Each piezometer was completed with a lockable metal standpipe or roadbox set within a cement block.

Type 2 Piezometers

Type 2 piezometers were constructed to provide an open uncased hole to calibrate geophysical equipment. The upper two metres of each Type 2 piezometer was drilled at a diameter of 155 millimetres to accommodate permanent steel casing in the weathered zone. This was seated at about two metres into the top of the weathered sandstone to exclude the sandy surface soils and then cemented in place. The remainder of each hole was drilled at a diameter of 120 millimetres using a hammer bit. All cuttings were removed from the piezometer and each hole remains open in the Hawkesbury Sandstone sequence.

Piezometer construction details from all four drilling programs are summarised in *Table 5.1*. Standing water levels in *Table 5.1* were measured after each respective drilling program. Five piezometers from the BH series are also part of the groundwater monitoring network and are included in *Table 5.1* for completeness.

Table 5.1: Piezometer Construction Details

Piezometer	Drilled	Depth (m)	Screen Interval	Gravel Pack Interval (m)	Bentonite Seal	SWL
BH3	May 1998	24.0	21.3 – 24.0	18.0 – 19.0	1.0	15.60^^^^^
BH3a	May 1998	13.0	10.0 – 13.0	9.0 – 13.0	1.5	10.73^^^^^
BH6	May 1998	15.0	12.0 – 15.0	10.0 – 15.0	1.0	9.90^^^
BH102	Jun 2001+	21.0	17.9 – 20.9	13.6 – 20.9	1.5	2.73^^^
BH112	Jun 2001+	25.5	22.5 – 25.5	18.0 – 25.5	3.5	13.53^^^
MW1s	Feb 2000	12.5	0.5 – 12.5	0.2 – 12.5	0.2	6.36^
MW1d	Feb 2000	24.5	18.5 – 24.5	16.5 – 24.5	1.0	6.61^
MW1 open	Feb 2000	24.5	Open	-	-	6.55^
MW2s	Feb 2000	9.0	0.5 – 9.0	0.2 – 9.0	0.2	2.66^
MW2d	Feb 2000	27.5	15.6 – 21.6	14.2 – 27.6	1.2	2.15^
MW3s	Feb 2000	6.5	0.5 – 6.5	0.2 – 6.5	0.2	1.37^
MW3d	Feb 2000	24.5	18.5 – 24.5	17.6 – 24.5	0.9	0.59^
MW4s (Rep*)	Feb 2000	6.5	0.5 – 6.5	0.3 – 6.5	0.3	1.52^
MW4d (Rep*)	Feb 2000	24.5	18.5 – 24.5	18.0 – 24.5	1.0	2.54^
MW5	Feb 2000	9.5	0.5 – 9.5	0.3 – 9.5	0.3	2.58^
MW6s	Feb 2000	9.5	0.5 – 9.5	0.2 – 9.5	0.2	2.57^
MW6d	Feb 2000	24.5	18.5 – 24.5	17.8 – 24.5	0.7	6.24^
MW6 open	Feb 2000	25.5	open	-	-	3.71^
MW7s	Feb 2000	6.5	0.5 – 6.5	0.2 – 6.5	0.2	2.23^
MW7d	Feb 2000	21.5	15.5 – 21.5	20.0- 21.5	0.5	11.66^
MW8s	Jun 2001	6.5	0.5 – 6.5	0.3 – 6.5	0.3	6.36^^
MW8d	Jun 2001	30	24-30	23.0 – 30.0	1.0	22.61^^
BH6	Jun 2001	15	12.0 – 15.0	10.0 – 15.0	1.0	9.91^^^
BH102	Jun 2001	21	17.9 – 20.9	13.6 – 21.0	1.5	2.73^^^
BH109	Jun 2001	52	44.5 – 47.5	20.5 – 52.0	1.0	17.61^^^
BH112	Jun 2001	25.5	22.5 – 25.5	18.0 – 25.5	3.5	13.53^^^^
MW9s	Apr 2002	18.2	15.2 – 18.2	12.0 – 18.2	1.0	9.13^^^^
MW9d	Apr 2002	29.0	26.0 – 29.0	20.5 – 29.0	1.2	11.80^^^^
MW10s	Apr 2002	12.8	9.8 – 12.8	8.8 – 12.8	1.0	3.99^^^^
MW14	Apr 2002	27.8	21.8 – 27.8	20.0 – 27.8	1.8	11.97^^^^
MW12 open	Apr 2002	50.0	Open	-	-	9.30^^^^
MW13	Apr 2002	26.3	23.3 – 26.3	18.0 – 26.0	1.8	14.05^^^^
MW11 (Ab)	Apr 2002	30.6	18.6 – 30.6	16.0 – 30.6	1.8	7.27^^^^
MW15s	Jun 2002	12.3	9.3 – 12.3	8.0 – 12.3	1.0	4.18^^^^
MW15d	Jun 2002	20.0	16.5 – 19.5	13.5 – 20.0	1.2	13.82^^^^
MW11-2	Jun 2003	21.7	15.7 – 21.7	13.7 – 21.7	3.3	NM

Notes: + Boreholes drilled in 1999 but converted to piezometers in June 2001

*mbtoc = metres below top of casing ^ SWL measured 22 Feb 2000

SWL Standing Water Level ^^ SWL measured 18 Jun 2001

Rep* Borehole Replaced but not abandoned ^^^ SWL measured 15 Jun 2001

Ab Abandoned (June 2003) ^^^^ SWL measured Jun 2002

NM Not Measured ^^^^^ SWL measured 18 Jun 1998

5.1.3 Surveying

To determine groundwater flow directions, the location of most piezometers was surveyed to ISG Co-ordinates and Australian Height Datum. The location of the start and finish of each resistivity imaging section was also surveyed so that the survey can be repeated at exactly the same location in the future (if required). Surveying was carried out at the completion of the drilling programs by contract surveyors of EJ Garvin & Company. Details are provided in *Table 6.1*.

5.1.4 Falling Head Tests

Falling head tests were conducted in all thirteen of the Type 1 piezometers drilled in the 2000 drilling program to assess the hydraulic conductivity (permeability) of the Hawkesbury Sandstone water bearing zones at selected depths.

In each piezometer, the standing water level was measured and a pressure transducer installed. About 20 litres of water was poured into the monitoring piezometers and the declining water level measured by a data logger assembly connected to the pressure transducer at a one second interval. The results were analysed by the Bouwer and Rice method and are described in *Section 6.4*. Graphical plots and analyses are given in *Appendix C*.

5.1.5 Downhole Geophysics

Downhole geophysics was conducted on the monitoring wells constructed in the 2000 drilling program. The objective of the program was to obtain a baseline geophysical interpretation of the geology and water chemistry at all of the shallow and deep piezometers that make up the groundwater monitoring network. If future variations occur, these changes are most likely to be water quality changes as there can be no changes in the geological matrix.

Each of the 13 piezometers constructed in 2000 and four previously constructed piezometers (BH1, BH2, BH3 and BH4) were geophysically logged by Matt Baker of Groundwater Data Collection Services Pty Ltd over the period of 21 and 22 March 2000. The logging occurred during a week of very heavy rain in Sydney. The following four parameters were measured:

- Gamma (versus depth);
- Temperature (versus depth);
- Conductivity (versus depth); and
- Apparent conductivity (versus depth).

The objective of the downhole geophysical logs was to enhance the detail of the lithological logs, and to determine the vertical characteristics of the sandstone and groundwater profile prior to construction of the reactor. The gamma log is useful in detecting minor interbedded shale lenses within the Hawkesbury Sandstone. The conductivity and apparent conductivity logs are used to confirm the water inflow horizons and the water quality. The downhole geophysical log traces are shown in *Appendix E*.

5.1.6 Resistivity Imaging Survey

The objective of the resistivity imaging survey was primarily to provide subsurface structural information around the perimeter of the RRR/JHEDI site. This also provides a benchmark against which to assess future changes. A survey was also conducted down gradient from Building 27 where spent fuel rods are housed.

If future variations occur, these changes are most likely to be water quality changes as there can be no changes in the geological matrix.

The resistivity imaging survey was carried out along five transects by David O'Neill, Consulting Geophysicist over the period 25 to 27 March 2000.

The geophysical survey was conducted over five transect lines labelled L1 to L5 as shown on *Figure 12* with the total transect covering 1220 metres. Lines L1, L2, L4 and L5 surround the RRR, with an easterly extension past the HIFAR reactor along the northern perimeter fence, and L3 is located down gradient from Building 27. Lines L2 and L3 were split into sections L2a/L2b and L3a/L3b because the profiles curved. Detailed site descriptions, geophysical methodology and discussion are given in the geophysical report presented in *Appendix D*.

The geophysical survey used the resistivity imaging technique, a derivative of the traditional DC resistivity dipole-dipole electrical method. The purpose of the survey is to establish a reliable geophysical technique that is repeatable and can identify possible changes in groundwater such as water table fluctuations.

5.1.7 Data Logger Installation

In April 2000 automatic groundwater level dataloggers were installed in four piezometers (MW1s, MW1d, MW6s, and MW6d) to characterise the variation in rainfall recharge and associated water table fluctuations across the site. The two sites chosen are key sites with different topographic characteristics. Site 1 is located near the top of the ridge in the north west corner of the site while Site 6 is located in the MDP Creek catchment near Building 27.

The loggers are Dataflow single channel data recorders and 0-5 metre pressure sensor assemblies. Groundwater levels were measured on an hourly basis to detect any short term water table fluctuations and to complement manual groundwater level monitoring. These data loggers are completely enclosed in the borehole.

Manual groundwater level monitoring is recommended to be carried out on a three monthly basis by ANSTO staff. The automatic data loggers at the four locations should be down loaded at the same time for consistency. Full monitoring requirements together with download data and archival instructions are given in PPK, 2000a.

5.1.8 Abandonment Programs

Three borehole abandonment programs were conducted at LHSTC to remove unwanted piezometers and geotechnical boreholes so they do not provide a conduit for surface water and shallow groundwater to deeper aquifers within the Hawkesbury Sandstone. With the exception of MW11, located outside HIFAR all other abandoned boreholes were located at the RRR/JHEDI site. All boreholes were abandoned by pumping a Cement mix (10 percent bentonite and 90 percent Portland cement) into each hole, starting at the base and displacing all the water in each hole. Once the mixture started overtopping the borehole at the surface, the hose was slowly withdrawn, until the cement mixture stabilised at the top of the borehole. Grouting was also pumped into the annular space between the protectors and PVC casing. Each abandonment program was undertaken by Macquarie Drilling under the direction of a PPK/PB hydrogeologist.

Borehole abandonment programs were conducted in June 2001 (PPK, 2001), December 2001 (PPK, 2002a) and June 2003 (PB, 2002). Details of the borehole abandonment program are summarised in *Table 5.2*.

Table 5.2: Borehole Abandonment Details

Borehole	Inclined declination/ Bearing (mag)	Diam. (mm)	Protector / Surface Casing +	Bore Depth (m)	Date Abandoned
BH1	Vertical	114^	P	45.00#	Dec 2001
BH1a	Vertical	114^	P	9.00	Dec 2001
BH2	Vertical	114^	P	27.00	Dec 2001
BH2a	Vertical	114^	P	13.00	Dec 2001
BH4	Vertical	114^	P	30.00	Jun 2001
BH4a	Vertical	114^	P	13.00	Jun 2001
BH4b	Vertical	114^	P	5.60	Jun 2001
BH5	Vertical	114^	P	28.60	Jun 2001
BH5a	Vertical	114^	P	12.20	Jun 2001
BH6	Vertical	125	SC	15.07	Rehabilitated
BH7	Vertical	125	P	15.13	Jun 2001
BH8	Vertical	125	PVC	15.06	Jun 2001
BH9	Vertical	125	PVC"	15.06	Jun 2001
BH10	Vertical	125	SC	15.08	Jun 2001
BH11	Vertical	125	SC	15.00	Jun 2001
BH101	Inc.60/232	96	SC	24.60	Jun 2001
BH102	Vertical	96	SC	20.90	Rehabilitated
BH103	Vertical	96	SC	24.12	Jun 2001
BH104	Inc.60/269	96	SC	25.60	Jun 2001
BH105	Vertical	96	SC	25.00	Jun 2001
BH106	Inc.60/135	96	SC	51.40	Jun 2001
BH107	Vertical	96	SC	51.60	Jun 2001
BH108	Vertical	96	SC	26.91	Jun 2001
BH109	Vertical	96	SC	51.14	Dec 2001

Borehole	Inclined declination/ Bearing (mag)	Diam. (mm)	Protector / Surface Casing +	Bore Depth (m)	Date Abandoned
BH110	Inc.60/305	96	SC	51.50	Jun 2001
BH111	Vertical	96	SC	26.96	Jun 2001
BH112	Vertical	96	SC	25.53	Rehabilitated
BH113	Vertical	96	SC	1.32	Could not locate
MW4s	Vertical	120	P	6.5	Replaced
MW4d	Vertical	120	P	30.0	Replaced
MW11	Vertical	120	P	30.6	Jun 2003

Notes:

+ Protector or Surface Casing (all nominal 100mm diameter). Protectors are steel, surface casing is PVC

* - all nominal 50mm

^ - 0 to 3m drilled at 159mm diameter

" – PVC has been snapped off at ground level

- BH1 50mm PVC to 24.7m, interval 24.7 to 45m backfilled

- - Could not locate

June 2001

In the June 2001 borehole abandonment program 19 boreholes were abandoned in the western portion of the LHSTC site (RRR/JHEDI). Of these 9 were geotechnical boreholes and the remaining 10 were piezometers likely to be destroyed during the construction of the research reactor. Borehole BH113 was to be abandoned but could not be located however this borehole was very shallow and would be completely excavated during the construction program.

Prior abandonment the depth of each borehole was measured to determine whether the drill rig was required to clean out any obstructions prior to backfilling. BH103 was the only borehole that appeared partially obstructed. It did not contain a monitoring tube so the drill rig lowered rods, and drilled out the obstruction (a collapsed clay zone) in the borehole prior to grouting.

Any protectors were removed, with most of them reused for the replacement and rehabilitated piezometers. The water in the boreholes was expelled prior to grouting with a manual bailer or generator pump. Once the majority of the water was removed, the cement-bentonite mix was injected into each hole. For those boreholes with monitoring tubes, grouting was also poured around the outside of the PVC if there was a void in the annulus between the PVC and the surface casing.

Although some settlement was expected at each site, the settlement in some of the bores exceeded five metres and the abandonment process had to be repeated at a number of sites. After all the bores were initially filled with grout, they were topped up to the surface again at the end of each day. The grout levels were measured on the 18th of June, when it was noted that of the 19 bores, six exceeded the expected settlement depth of three to five metres. This extra settlement is attributed to more fracturing and larger voids in the sandstone at these locations.

These boreholes were topped up again by Macquarie Drilling using the same bentonite/cement mixture and later measured on the 5th and 13th of July. After these additional two top ups, five of the six bores had grout levels which did not exceed five metres. BH106 required topping up again and was measured on the 27th of July. The top 8.5 metres of this borehole was filled with bentonite granules to provide a water tight seal. The water within the bore was bailed and about one metre of bentonite was poured into the borehole. Water was added, and then another metre of bentonite was poured into the borehole. This process was repeated until the granules reached the ground surface.

December 2001

In December 2001 five piezometers were abandoned at the RRR/JHEDI site. The piezometers abandoned were BH1, BH1A, BH2, BH2A and BH109 that are going to be lost because of the larger footprint for the replacement research reactor. BH1, BH1A, BH2, BH2A were constructed in 1998 during as part of the EIS studies. BH109 was geotechnical borehole that was converted into a dedicated monitoring piezometer during the June 2001 field program (PPK, 2001).

The initial borehole abandonment program was conducted on 20th December 2001 and grout levels were checked on 7th January 2002. No additional topping up of the cement-bentonite mix was required as all grout levels were above the 5m below ground level criteria.

June 2003

In June 2003 piezometer MW11 located outside Building 40 (next to the "Menzies Foundation Stone") adjacent to HIFAR was replaced as the piezometer had partially collapsed.

In abandoning the original MW11, Macquarie Drilling staff broke the concrete plinth around the older MW11 piezometer and removed the road box. It was possible to manually push the PVC further down the hole about half a metre, suggesting a rupture in the PVC at depth.

A 5 percent bentonite/cement grout mix was used for the abandonment work. Due to the shallow obstruction depth, this bentonite/cement mixture could be poured down the hole. The PVC was kept in the hole during abandonment to ensure the bentonite/cement mix reached the base of the hole. The bentonite/cement mix was filled to ground level.

5.1.9 Supplementary Drilling Programs

The initial monitoring groundwater monitoring network at the RRR/JHEDI site was constructed in 1998 in which 12 shallow piezometers and 5 deep piezometers were constructed (Coffey, 1998). In 2000 a groundwater monitoring network was established across the whole LHSTC site with 7 shallow, 6 deep and 2 uncased piezometers being constructed at strategic locations primarily around the perimeter of the site (PPK, 2000).

Since the construction of these two monitoring networks three supplementary drilling programs have been conducted to add further multi-level piezometers at strategic locations.

June 2001

In June 2001 a supplementary drilling program and borehole rehabilitation and abandonment program was conducted primarily at the RRR/JHEDI site although two piezometers were drilled near the laboratory facility located on the eastern boundary of LHSTC (PPK, 2001).

At the RRR/JHEDI site 19 boreholes were abandoned as outlined in *Section 5.1.8*. Four geotechnical boreholes (BH6, BH102, BH109 and BH112) were converted to dedicated monitoring wells. The rehabilitated piezometers were reamed and developed prior to the installation of screen and casing. BH6 was given a new monument, whereas the other three piezometers have recycled monuments at surface. Each piezometer was completed with surface casing, which was removed after the bores were developed and cleaned out to the full depth. The 50 millimetres screen and casing was inserted to conform to the Type 1 piezometer specification (PPK, 2000).

Piezometers MW4s and MW4d are located off-site on the eastern perimeter down gradient from Building 35C in an area of obvious groundwater seepage. This low-lying area has been built up by sandstone fill derived from the RRR/JHEDI site. The monitoring wells remain in place and have not been abandoned. Replacement piezometers (MW8s and MW8d) are located near the Environmental Radiochemistry Laboratory (Building 34) to provide background groundwater information for the LHSTC site. Piezometers MW8s and MW8d were drilled to depths of 6.5m and 30m respectively, contained a 6 m screen and screwed casing which conformed to the Type 1 piezometer specifications.

April 2002

In April 2002 nine piezometers were added to the groundwater monitoring network at seven sites. Three piezometers (MW11, MW13 and MW14) were located on the LHSTC site at strategic locations to provide additional coverage.

The remaining six piezometers (MW9s, MW9d, MW10s, MW12, MW15s and MW15d) are located at the RRR/JHEDI site to replace piezometers that were abandoned as they were located beneath the building footprint.

June 2003

In June 2003 a replacement piezometer was drilled and constructed for MW11 located outside Building 40 (next to the “Menzies Foundation Stone”) adjacent to HIFAR as the previous piezometer (MW11) had partially collapsed.

MW11 was initially drilled in April 2002 to a depth of 30.6 metres (PPK, 2002). ANSTO staff noted difficulties in lifting the Bennett pump during routine quarterly groundwater sampling. PB measured an obstruction at 12.8 metres. The depth of this blockage seems to correspond to a screwed casing join. This type of blockage is extremely unusual and the reason for the partial collapse is unknown, however may be related to the casing parting at the join.

After an initial inspection of the piezometer, it was considered impractical to try and rehabilitate MW11. In order to maintain the integrity of the piezometer network, abandonment of MW11 and drilling a replacement piezometer was undertaken. The new piezometer MW11-2 was drilled to a total depth of 21.7 metres with a six metres screen at the base (Note that the bore log for this piezometer appears as MW14-2 in *Appendix B*).

5.2 Groundwater Monitoring

5.2.1 Network and Frequency

A groundwater sampling plan and monitoring protocol were developed for the LHSTC site (PPK, 2000b – see *Appendix F*) and includes all monitoring phases from water level monitoring, purging, filtering, water sampling and sample preservation. The sampling plan and monitoring protocols were developed to satisfy the conditions of Environment Australia and reports are submitted annually to the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

The groundwater monitoring network consists of a series of deep and shallow piezometers at the RRR/JHEDI site (*Figure 6*) and a series of deep and shallow piezometers across the LHSTC (*Figure 10*). Since June 2003 the groundwater monitoring network across the whole LHSTC site consists of 26 MW series piezometers and 5 BH series piezometers as summarised in *Table 5.3*.

Table 5.3: Groundwater Monitoring Network 2003

Monitoring Network	Piezometers
MW series - Regional	MW1, MW1s, MW1d, MW2s, MW2d, MW3s, MW3d, MW4s, MW4d, MW5s, MW6, MW6s, MW6d, MW7s, MW7d, MW8s, MW8d, MW11-2, MW13, MW14
MW series - RRR/JHEDI	MW9s, MW9d, MW10s, MW12, MW15s, MW15d,
BH series - RRR/JHEDI	BH3, BH3a, BH6, BH102, BH112

The groundwater sampling plan consists of monitoring groundwater levels and hydrogeochemical sampling. Groundwater level monitoring is undertaken manually on a quarterly basis at all piezometers and continuously at four key piezometers installed with dataloggers. Groundwater sampling is required to undertake hydrogeochemical analyses. Sampling is undertaken quarterly to monitor field parameters and annually to collect samples for a comprehensive sampling suite for laboratory analysis. The groundwater sampling plan and sample frequency is given in *Table 5.4*.

As the groundwater monitoring network expanded, PPK/PB recommended that the additional monitoring wells be included in the annual sampling and quarterly monitoring program and in reports submitted to ARPANSA. This recommendation has been implemented by ANSTO.

The first groundwater sampling round was completed by ANSTO in November 2000. In order to collect as much data as possible prior to the construction of the RRR, two full rounds of monitoring (including the full suite of laboratory analyses) were completed in August and December, 2001. Note that quarterly measurement of water levels and field parameters did not commence until 2002, and problems with sampling equipment meant that only three of the four planned sampling rounds were completed that year. To date, the groundwaters have not been sampled or analysed for CFC's.

Table 5.4: LHSTC Groundwater Sampling Plan

Analytical Suite	Sampling Frequency	Parameters
Groundwater Levels	3 months	Manual monitoring and downloading dataloggers
Field Parameters	3 months	EC.* pH, Eh, Temperature
Major Ions	Annual	Na, K, Ca, Mg, Cl, SO_4, HCO_3, CO_3, TDS
Inorganic Nutrients	Annual	Total P, Oxidised Nitrogen, Total Kjeldahl Nitrogen, Ammonia (as NH_4-N)
Dissolved Metals	Annual	Fe, Mn, As, Cu, Pb, Zn, Cd, Cr, Ni, Hg, Se, Ar
Petroleum Hydrocarbons**	Annual	TPH (chainlength breakdown), BTEX (benzene, toluene, ethyl benzene, xylene)
Radioactivity	Annual	Gross Alpha, Gross Beta, Gamma emitters
Radioisotopes	Annual	Tritium
CFC***	2 Years	CFC

*EC – Electrical Conductivity

** Petroleum Hydrocarbons – only required for shallow piezometer (MW5s) in the vicinity of the USTs

*** CFC - Chlorofluorocarbon

Table 5.5 lists all of the groundwater monitoring programs that have been conducted by ANSTO up to and including May 2007. The data are presented in *Appendix J* (*Tables 7.1* to *7.41*). The data tables (*Appendix J*) include footnotes of any observations or unusual conditions which could affect the integrity of groundwater samples and subsequent analytical results.

5.2.2 Sampling Protocols

The sampling protocols developed in PPK, 2000b were adopted by ANSTO for the routine groundwater monitoring as far as practicable and incorporated into the ANSTO Quality System documentation. The ANSTO documentation (Purging Instructions, Sampling Instructions, and examples of chain-of-custody forms and field record sheets) are given in *Appendices G, H, and I*, respectively.

Key issues outlined in the sampling protocols are:

- Equipment required;
- Preparation;
- Groundwater Purging;
- Measuring Field Parameters;
- Sampling for Laboratory Analysis;
- Documentation; and
- Quality Assurance and Quality Control

Table 5.5: LHSTC Groundwater Monitoring Rounds to May 2007

Nominal Month of Campaign	**Monitoring Period** start of purging to end of sampling	**Results Tables** (1)	**Measurements** Water Levels	Field Parameters	Full Suite of Laboratory Analysis
Nov 2000	20 Nov -11 Dec	7.2 to 7.4	✓	✓	✓
Aug 2001	20 Jun - 15 Aug	7.5 to 7.7	✓	✓	✓
Dec 2001	26 Nov - 6 Dec	7.8 to 7.10	✓	✓	✓
May 2002	29 May - 20 Jun	7.11	✓	✓	-
Sep 2002	19 Aug - 26 Sep	7.12 to 7.14	✓	✓	✓
Dec 2002	5 Dec - 14 Jan	7.15	✓	✓	-
Mar 2003	14 Mar - 27 Mar	7.16	✓	✓	-
Jun 2003	17 Jun - 24 Jun	7.17	✓	✓	-
Aug 2003	5 Aug - 12 Aug	7.18 to 7.20	✓	✓	✓
Dec 2003	8 Dec - 9 Jan	7.21	✓	✓	-
Mar 2004	16 Mar - 23 Mar	7.22	✓	✓	-
May 2004	19 May - 31 May	7.23	✓	✓	-
Aug 2004	26 Aug - 8 Sep	7.24 to 7.26	✓	✓	✓
Dec 2004	3 Dec – 9 Dec	7.27	✓	✓	-
Feb 2005	15 Feb – 22 Feb	7.28	✓	✓	-
May 2005	9 May – 15 May	7.29	✓	✓	-
Aug 2005	15 Aug – 2 Sep	7.30	✓	✓	-
Nov 2005	21 Nov – 23 Nov	7.31 to 7.33	✓	✓	✓
Feb 2006	23 Feb – 2 Mar	7.34	✓	✓	-
May 2006	22 May – 24 May	7.35	✓	✓	-
Aug 2006	29 Aug – 1 Sep	7.36 to 7.38	✓	✓	✓
Nov 2006	23 Nov – 6 Dec	7.39	✓	✓	-
Feb 2007	22 Feb – 26 Feb	7.40	✓	✓	-
May 2007	21 May – 23 May	7.41	✓	✓	-

1. Annual laboratory analyses schedule includes hydrocarbons for monitoring well MW5s. All results are given in Table 7.1.

A summary of the sampling procedures is provided below along with any relevant observations made by sampling teams during monitoring rounds.

Sampling Procedures

The groundwater monitoring bores were not sampled in any particular order, although to minimise time spent on the RRR/JHEDI construction site the bores in that area were usually all purged and sampled within a day or two of each other.

During purging and sampling, observations concerning the condition of monitoring bores and their surrounding area were noted in the field data sheets (*Appendix I*). Any factors which could affect the integrity of groundwater samples were also recorded and these observations appear as footnotes in the data tables (*Appendix J*).

Table 5.5 indicates the duration of each monitoring campaign completed, from the first bore purged to the last sample collected. The purging and subsequent sampling dates for all monitoring rounds are given in the relevant field parameter data tables (*Appendix J*).

Groundwater Levels

At each bore, prior to purging, the depth to water level was measured from the top of the PVC casing to the nearest 0.01m using an electronic dipper probe with sound signal. This undisturbed water level was recorded as the Standing Water Level (SWL) in metres Below Top of Casing (mBTOC) on the field data sheet. Water levels were also measured just before sampling and used to calculate the volume of water available for sampling. The mBTOC values were later converted into heights under the Australian Height Datum system (mAHD) and are reported as such in *Appendix J.*

After measuring at each bore the water level probe and tape were washed with distilled water to prevent cross contamination between sites.

Purging Procedures

Prior to sampling, all bores were purged using the submersible air-driven Bennett pump and/or a two-stage electric pump, or via the more rapid air-lift method, as detailed in the purging instructions (*Appendix G*). There is no air to fluid contact within the Bennett pump. The purpose of purging is to remove all stagnant water from the piezometer, ensuring that the sample taken is representative of the groundwater in the stratum of interest. The volume of water that must be removed in order to obtain a representative sample depends on the method of purging and hydrogeological conditions.

In accordance with PPK's recommendation (PPK 2002) the air-lift method will be used to purge the wells approximately every two years in order to remove any sediments that naturally accumulate at the bottom of the piezometers. This purging method was employed in the June and August 2003 campaigns. Apart from these two campaigns in 2003, all other purging and sampling was carried out by either pumping or bailing (using disposable hand-bailers if problems arose with the pumping equipment). The use of pumps that are either battery-powered or run on compressed air avoids the need for petrol generators which generate fumes that could otherwise contaminate the bores.

Most of the LHSTC piezometers are low-yield, in which case purging to dryness is considered adequate. In all monitoring rounds completed at the LHSTC, purging was carried out until the well was essentially 'empty,' or up to three bore casing volumes of water were removed. Note that there is always a small amount of water remaining in the bottom of the wells, regardless of which purging technique is used. Any wells that were dry or contained insufficient water to sample were recorded in the data tables as ND – not determined.

Until December 2002 the sampling pump was lowered to within two metres of the base of the well before purging commenced. From March 2003, the pump was placed near the top of the water column at the start of the purging process, then gradually lowered to within two metres of the well's base. The method was changed to ensure that the entire standing water column was removed before inflow of fresh groundwater into the screened section of the bore casing. From 2005, the four-stage 12-volt pump was used for purging and sampling whenever possible in preference over the Bennett pump, due to its lightweight construction (reducing manual handling risks) and more efficient flow rate.

Prior to 2004 the volume of water removed during purging was not recorded, but the wells were purged until they were effectively empty. Since 2003 the purged water has been collected in a 10-litre bucket and the total volume recorded. The purged water is discarded onto the ground several metres away from, and down slope of, the bores.

From 2004 groundwater samples were collected as soon as possible after purging, *ie* on the following day or when a sufficient volume of water had recovered to allow sampling. Prior to this, the practice was to purge all of the wells before proceeding to the sampling phase (usually a week later) sometimes resulted in delays of up to 10 days from purging a well until it was sampled.

Field Parameter Measurements

ANSTO used the same YeoKal water quality field probe to take all of the field parameter measurements (pH, temperature, turbidity, electrical conductivity, oxidation/reduction potential). The YeoKal field probe was calibrated against freshly prepared known standards according to the manufacturer's instructions prior to each sampling campaign.

During the inaugural sampling round (Nov. 2000), field parameters were measured in-situ down most wells unless otherwise noted. In subsequent sampling rounds, the groundwater was pumped into a bucket for measurement. For the March and June 2003 sampling campaigns, field parameter measurements were taken on three separate aliquots. Parameters were recorded after the pH had effectively stabilised,. From mid-2003, the YeoKal probe was placed in a flow-through cell so that fresh sample was continuously available. The field data for each piezometer was stored in the Yeokal's memory and downloaded upon return to the laboratory, then printed and pasted into the field record data sheets. Data reported in *Appendix J* are the averages of 3 to 5 stable readings.

Sample Collection and Preservation

Table 5.6 lists the sample containers and preservation requirements given by PPK, 2000 for the annual laboratory sampling round and any changes from these in practise. Samples were drawn from the wells using the Bennett pump unless otherwise noted on the field data sheets, where the sampling depths are also recorded (*Appendix J*). The HDPE sample bottles were thoroughly rinsed with the sample prior to filling (apart from the inorganic nutrients bottles which were pre-acidified with sulphuric acid up to and including the Aug. 2003 campaign).

The first bottles to be filled were the tritium, cations, anions and inorganic nutrients samples. Samples for dissolved metals and radionuclide analyses were filtered in the field. This was done by filling a clean bucket with the groundwater then using a plastic hand-pump to filter the sample through a high-capacity *Waterra* 0.45 micron cartridge filter. The August, 2001 samples were filtered using a hand pump that contained some chrome-plated mild steel, but at all other times samples were filtered using an inert plastic pump.

Table 5.6: Groundwater Sample Preservation and Storage

Analytical Suite	Sample Container	Specified Preservation (PPK, 2000)	Implemented Preservation

Major Ions	2 L HDPE[(1)]	Refrigerate to 4^0C	As specified
Inorganic Nutrients	1 L amber glass	H_2SO_4 , Refrigerate to 4^0C	As specified until Aug. 2003. Then sampled in 1L HDPE and frozen.
Dissolved Metals	250 mL HDPE	Filter to 0.45 μm, acidify with HNO_3 and refrigerate to 4^0C	As specified
Petroleum Hydrocarbons	1 L amber glass; 2 x 40 mL glass septum vials	Refrigerate to 4^0C; acidify with HCl and refrigerate to 4^0C	As specified
Radioactivity	5 L HDPE	Filter to 0.45 μm, Refrigerate to 4^0C	Filtered to 0.45 μm and acidified with HNO_3
Tritium	1 L HDPE	Filter to 0.45 μm, Refrigerate to 4^0C	Not required since analysis involves distillation

1. HDPE – high density polyethylene.

In the field, all samples were placed in chilled eskies immediately after collection. Upon return to the Environmental Monitoring laboratory, the cations and dissolved metals samples were acidified with nitric acid and placed in refrigerated storage. Radionuclide and tritium samples do not require refrigeration. From August, 2003 preservation for nutrients samples involved freezing them upon return to the laboratory, as specified by the NATA-accredited laboratory that performed the analysis.

Samples were assigned unique laboratory identification numbers and chain-of-custody documentation was completed and accompanied all samples upon transfer to the relevant laboratory for analysis. Nutrients & hydrocarbon samples were transported by courier in chilled eskies to external laboratories, usually on the day following collection.

Field Duplicates and Equipment Wash blanks

A field duplicate is a split sample collected at the time of sampling and it is analysed for the same suite of analytes as the original sample. Two field duplicates were collected per annual sampling round (ie for laboratory analysis of groundwater). Comparison of analytical results of original and field duplicate samples provides an assessment of the precision of field sampling and analytical procedures.

Field equipment or ‘wash’ blanks were taken at the conclusion of each annual monitoring round by pumping and collecting reverse-osmosis water through the rinsed sampling equipment (pump & hose). Wash blanks analysed to date have shown no evidence of cross-contamination, confirming the adequacy and effectiveness of the cleaning procedures.

Laboratory Analytical Procedures

All chemical and radiological analyses of groundwater samples were undertaken by ANSTO, with the exception of inorganic nutrients (Sydney Analytical Laboratories, then from Sept. 2002, Sydney Water) and petroleum hydrocarbons (Labmark Pty Ltd). Refer to *Appendix L* for a summary of the analytical methods.

6. Investigation Results

6.1 Drilling Program

Drilling using the air hammer method typically intersected a shallow soil profile consisting of a silty clayey sand derived from weathered sandstone. The soil profile is underlain by a moderately weathered sandstone grading into solid sandstone at depth. The intersected sandstone is typically medium grained, siliceous and interbedded with minor shale lenses. The sandstone within the upper profile is interbedded with yellow brown goethitic clay, red-brown haematitic clay and pale grey kaolinitic clay, becoming increasingly kaolinitic with depth. There is a variable lateritic profile developed across the site.

Shallow groundwater was intersected within the upper 10 metres of the profile and typically within the upper 5 metres of the weathered sandstone profile, although this was difficult to detect at some sites because of the small seepages. At site MW5, adjacent to the USTs, the hole was thought to be dry as groundwater was not initially intersected. However the site was completed as a piezometer and made water over the following 24 hours.

Typically, deeper groundwater was intersected at depths between 15 and 25 metres, and then rose under pressure, suggesting the deeper aquifers are partially confined. At each dual piezometer site, the groundwater yield varied significantly between the perched zone and the deeper aquifer.

For instance, at Site 7 during the construction of the shallow piezometer, a moderate yield of 0.5 L/sec was intersected at a depth between two to three metres. Also associated with this groundwater inflow was a hydrogen sulphide odour. In contrast, no such horizon was intersected during the construction of the deeper piezometer, less than three metres away. Similarly at Site 1, a moderate groundwater yield of 0.5 L/sec was intersected in the open borehole at a depth interval of 11-12 metres but was not intersected in MW1s or MW1d. This suggests that near surface groundwater flow occurs predominantly along fractures or joints, and boreholes can only ever be expected to monitor a limited number of fracture systems within the rock mass.

Perched groundwater was not always intersected at the LHSTC. At Sites 11 and 14 shallow groundwater was not intersected and consequently only one deep piezometer was constructed at these sites. At Site 12 the Hawkesbury Sandstone was cored from 13.5 metres to 50 metres. Core samples are archived with the ANSTO Environment Division in building 21.

6.2 Geological Profile

The drilling program provided some variable fracture and water inflow results as described in *Section 6.1*. However when comparing the geological profiles across the site there is little geological variability. PPK/PB have reproduced a number of cross sections around the RRR/JHEDI site that show the geological profile in detail. The location of these profiles is shown on *Figure 13*. Section A-A and B-B has been reproduced from Coffey Partners, 1998 (as *Figure 14*) while Section C-C is a new, across gradient profile (see *Figure 15*).

Cross Section A-A is north-south through Coffey boreholes BH10, BH5, BH8 and BH6. Topsoil and sandy clay overly medium strength and high strength sandstone. Minor shale occurs in BH8 at 4 to 4.5 metres depth.

Cross Section B-B is north-west - south-east through Coffey boreholes BH11, BH9, BH1, BH7 and BH6. Topsoil and clayey sand/sandy clay overly medium strength and high strength sandstone. Minor shale occurs in BH1 in the top 25 metres, but there is much more shale at depth - shale lense intervals were 5 to 5.75 metres, 29 to 30 metres, 36 to 40 metres and 43 to 45 metres.

Cross Section C-C is west-east through boreholes MW1, BH11, BH2 and BH10 at the northern end of the RRR/JHEDI site. No shale lenses were intersected in the geological profile to 25 metres in this part of the site.

6.3 Surveying

Survey results are given in *Table 6.1* along with hydraulic conductivity results for the new monitoring piezometers. Survey sites were surveyed to ISG co-ordinates and levelled to the Australian Height Datum (AHD).

Table 6.1: Survey and Hydraulic Conductivity Results

Piezometer	Co-Ordinates		RL^		
	Easting	Northing	RL Top of PVC Casing	Hydraulic Conductivity m/sec	Stickup magl^^
MW1s	297867.84	1230769.63	157.555	1.28×10^{-7}	0.80
MW1d	297865.49	1230766.70	157.71	3.89×10^{-7}	0.76
MW1 open	297865.49	1230766.44	156.64^{x}	#	0.84^{+}
MW2s	298116.52	1230959.26	145.43	4.55×10^{-8}	0.78
MW2d	298114.67	1230959.08	145.445	2.32×10^{-8}	0.75
MW3s	298551.05	1231041.69	130.515	5.28×10^{-8}	0.74
MW3d	298551.53	1231043.65	130.535	2.33×10^{-9}	0.76
MW4s	298983.74	1231005.02	128.73	8.21×10^{-10}	0.71
MW4d	298982.50	1231002.99	128.78	8.99×10^{-8}	0.70
MW5s	298833.43	1230959.68	138.92	2.50×10^{-9}	-0.10
MW6s	298755.49	1230540.73	131.51	7.83×10^{-8}	0.81

Piezometer	Co-Ordinates		RL^		
	Easting	Northing	RL Top of PVC Casing	Hydraulic Conductivity m/sec	Stickup magl^^
MW6d	298756.07	1230542.85	131.63	3.73×10^{-10}	0.80
MW6 open	298754.79	1230538.60	130.54^{x}	#	0.86^{+}
MW7s	298202.08	1230500.20	147.89	5.83×10^{-8}	-0.10
MW7d	298202.35	1230497.94	148.415	3.07×10^{-8}	0.62
MW8s	NS	NS	NS	#	
MW8d	NS	NS	NS	#	
MW9s	297850.27	1230655.31	156.67	#	0.79
MW9d	297852.02	1230654.37	156.51	#	0.58
MW10s	297966.41	1230763.4	154.47	#	0.71
MW14	298133.15	1230653.49	156.15	#	
MW12	297852.79	1230624.02	155.24	#	
MW13	298476.34	1230581.42	153.51	#	
MW11-2	298155.94	123059.22	155.92	#	-0.10
MW15s	NS	NS	NS	#	
MW15d	NS	NS	NS	#	

Note:

^ metres Australian Height Datum. ^^ magl metres above ground level

* mbToC metres below Top of Casing NS Not Surveyed

hydraulic conductivity tests not undertaken + Extra casing added June 2000

x Steel casing stickup 0.2 metres in February 2000 NS Not Surveyed

6.4 Hydraulic Conductivity

Towards the end of the 2000 field program falling head tests were carried out to assess the hydraulic conductivity (K) of the monitored horizons. The results represent a maximum horizontal hydraulic conductivity value since the screens were placed opposite the interval of maximum groundwater inflow via water bearing fractures, bedding planes and laminations. Results analysed by the Bouwer and Rice method (Bouwer and Rice, 1976) are given in *Table 6.1* and plotted analyses given in *Appendix C*. Hydraulic conductivity statistics from the perched zone and regional, deeper rock aquifers are summarised in *Table 6.2*. Falling head tests have not been carried out on additional piezometers added to the groundwater monitoring network since 2000.

Table 6.2: Hydraulic Conductivity Statistics

	Perched Zone	Deeper Aquifer
number of results	7	6
minimum K (m/sec)	8.21×10^{-10}	3.73×10^{-10}
maximum K (m/sec)	1.28×10^{-7}	3.89×10^{-7}
mean K (m/sec)	5.23×10^{-8}	8.93×10^{-8}

The results in *Table 6.2* indicate the range of hydraulic conductivity values measured within the perched zone and deeper aquifers are similar, the mean values being 5.23×10^{-8} m/sec and 8.93×10^{-8} m/sec respectively. These results are consistent with published values of hydraulic conductivity (Domenico and Schwartz, 1990) for sandstone and indicate low water transmitting characteristics.

Even though the permeability of the perched zone and deeper aquifer are similar, there is limited connection between the zones because of the variable fracture patterns. The sandstone strata between the two horizons is inferred to be low permeability. There is expected to be a large range in vertical hydraulic conductivities.

6.5 Groundwater Flow

Groundwater flow within the sandstone is via primary (intergranular) and secondary (fracture) pathways. Groundwater flow occurs in both primary and secondary structural features such as joints, fractures, fissures and along bedding planes, providing preferred groundwater pathways. Shale lenses within the sandstone are likely to inhibit vertical groundwater movement, potentially causing locally perched aquifers.

The relationship between groundwater flow in fractures and groundwater flow in the porous sections of the Hawkesbury Sandstone is uncertain. PB believe that groundwater flow in the main sedimentary structures and open fractures is the dominant process to be addressed, although pore water in the sandstone may also be important at localised sites.

From the PPK/PB investigations, it is apparent that both the water table and the deeper piezometric surface is typically a subdued reflection of the surface topography and the groundwater flow path generally mirrors surface drainage.

The following discussions about groundwater level variation, regional groundwater flow and travel times and local groundwater flow around the RRR/JHEDI site is based on results from the February and July 2000 field programs.

6.5.1 Groundwater Level Variations

Analysis of the static water level data for the Type 1 piezometers (*Tables 6.1* and *6.3*) in 2000 shows some interesting trends across the site. Similar water levels in shallow and deep piezometers were not recorded at any of the sites. At four of the sites (MW1s/d, MW4s/d, MW6s/d, MW7s/d), the deeper piezometer had deeper water levels than the shallow zone indicating the potential for vertical recharge. Also these sites (except MW1s/d) were located near the steep Woronora Valley, suggesting that the deeper zone was discharging to springs lower in the valley.

At sites MW2s/d and MW3s/d, the water levels in the deeper piezometers were higher than the water levels in the shallow perched zone, suggesting that the deeper zone is partially confined and is not discharging to nearby springs. This agrees with their setting in the flat ridge area along the northern boundary of the LHSTC site. Limited vertical recharge is also expected at these sites.

The degree to which the deep aquifer is confined and the degree of vertical recharge varies site to site. The confined conditions at each site and the vertical recharge rates can only be assessed with time series monitoring data and in-situ velocity measurements.

Not surprisingly, the open Type 2 piezometer at site MW6 had a composite water level between the water levels observed in the adjacent Type 1 piezometers. At site MW1, the open Type 2 piezometer had a slightly deeper water level than the adjacent Type 1 piezometers. This may be attributed to the large fracture zone encountered at the MW1 (open) site.

Groundwater levels were previously measured in the perched zone and deep aquifer in the monitoring bore network at the RRR/JHEDI site (Coffey, 1998). These studies concluded the water table of the perched aquifer ranged between 6.02 metres to 10.73 metres below the ground surface with an apparent flow direction to the west and south-west. Conversely the deeper aquifer varied in depth from 12.4 metres to 19.7 metres below the ground surface with an apparent flow direction towards the north-west. These single direction flows suggested by Coffey, 1998, are now considered unreliable.

6.5.2 Regional Groundwater Flow and Travel Times

Standing water levels were measured in each piezometer once steady state conditions had been reached after drilling (22 February 2000). Reduced groundwater levels relative to “m AHD” have been calculated for each piezometer and are given in *Table 6.1*. These reduced groundwater levels have been plotted and groundwater level contours constructed. Insufficient piezometers are present to determine precise contours so the contours have been manipulated to reflect topographical influences. The water table contours have been calculated for the years 2000 to 2004 for the shallow perched zone and are presented on *Figures 16 to 16d* respectively. Similarly potentiometric maps calculated for the deep aquifer for the years 2000 to 2004 are presented on *Figures 17 to 17d* respectively.

For the ridgeline occupied by LHSTC, the groundwater flow within the shallow zone and deep aquifers is a subdued reflection of the surface topography with groundwater flowing to the north, south and east away from the topographically high areas.

Under present flow conditions, some coarse travel times can be estimated within the rock aquifer assuming an effective porosity (ϕ) of between one percent and five percent. For instance, the water table between MW5s and MW4s falls ten metres over 120 metres giving a hydraulic gradient (i) of 0.083. The hydraulic conductivity (K) of the shallow aquifer at MW4s was measured at 8.21×10^{-10} metres per second or 7.09×10^{-5} metres per day. The linear (or true) velocity is therefore calculated by the following equation:

$V=Ki/\phi$ - Equation 6.5

Thus $V = (7.09\times10^{-5} \times 0.083 /0.01) \times 365 = 0.21$ m/year; for $\phi = 1\%$

$V = (7.09\times10^{-5} \times 0.083 /0.05) \times 365 = 0.04$ m/year; for $\phi = 5\%$

These are extremely low flow velocities. However with preferred pathways through the Hawkesbury Sandstone in less well cemented zones in the sandstone, bedding plane partings and near surface fractures, higher flow rates can be expected in some areas. More field investigations are required to obtain better estimates of permeability and groundwater flow velocity.

With higher heads, and a large range of permeability (K) values, flow velocities could be significantly higher in some areas and at different times. *PPK strongly recommended the insitu monitoring of flow velocities directly in the open piezometers at MW1 and MW6, across a range of rainfall conditions.*

Using equation 6.5, hydraulic conductivity values from *Table 6.1*, a porosity of five percent and the inferred hydraulic gradients in February 2000, some notional shallow and deep groundwater velocities can be calculated. These range between 0.04 metres per year and 3.85 metres per year for the shallow zone, and between 0.02 metres per year and 7.36 metres per year for the deeper zone. These true velocities have been annotated on *Figures 16 and 17*.

6.5.3 Local Groundwater Flows around the Replacement Research Reactor

A more detailed analysis of the groundwater flow conditions around the RRR/JHEDI site was carried out using water level data collected on 14 July 2000. These water levels and reduced levels are shown in *Table 6.3*, and the water table and the potentiometric contours for the July 2000 monitoring event are shown on *Figures 18 and 19* respectively.

The groundwater contours and flow directions are similar to the regional site data obtained in February 2000.

Table 6.3: Water Level Data Around RRR/JHEDI Site

	RL^	SWL(1) (22-2-2000)		SWL(2) (14-7-2000)	
Piezometer	**RL Top of PVC Casing**	**mbToC**	**mAHD^**	**mbToC**	**mAHD^**
MW1s	157.555	6.36	150.395	7.78	149.775
MW1d	157.71	6.61	150.34	8.25	149.46
MW2s	145.43	2.66	141.99	3.34	142.09
MW2d	145.445	2.15	142.545	2.65	142.795
MW7s	147.89	2.23	145.66	2.27	145.62
MW7d	148.415	11.66	136.045	12.58	135.835
BH1a	157.34*	-	-	8.28	148.52
BH1	157.4*	-	-	14.79	142.61
BH2a	154.94*	-	-	5.13	149.81
BH2	154.94*	-	-	9.43	145.51
BH3a	156.78*	-	-	10.2	146.58
BH3	156.83*	-	-	13.62	143.21
BH4a	156.32*	-	-	6.43	149.89
BH4	156.32*	-	-	12.09	144.89

Note:

^ metres Australian Height Datum.

SWL(1) - Standing Water Level (22/2/00)

SWL(2) - Standing Water Level (14/7/00)

* Approximated from Site Topography

6.6 Downhole Geophysics

Downhole geophysics logs were conducted on the newly constructed monitoring wells following the February 2000 field program. Results for all downhole gamma logs and conductivity logs are given in *Appendix E*. The location of holes used for the downhole geophysics are shown in *Figure 12*.

Every new piezometer (shallow, deep and open) and the older BH series boreholes that are to be retained in this monitoring network were logged using a Century Geophysics Ultralite downhole logging unit. The gamma traces are indicated by the red traces and the temperature by the pale blue trace alongside the gamma trace. Opposite these traces, the conductivity (pale blue) and apparent conductivity traces (dark blue) are plotted.

Groundwater Data Collection Services Pty Ltd (GDCS) provided the following explanatory notes for the downhole logs:

- the logs plotted represent about half the data set collected, each piezometer was logged both with the tool descending the hole and with the tool ascending collecting values at five millimetres intervals. Each log was compared to the other to check for repeatability before logging the next hole.
- the logs plotted are provided in two forms. A single page plot for each piezometer and a merged plot showing all piezometers of the same number at each station.
- the logs plotted represent five measured parameters; Depth, Gamma, Temperature, Conductivity and Apparent Conductivity. Of the conductivity logs, the Apparent Conductivity is mostly used as it is temperature compensated;
- the vertical axis of each conductivity log is at (-10) due to the highly resistive nature of the formation at Lucas Heights and the presence of cultural interference when calibrating the tool as some of the apparent conductivity values recorded were less than zero. As the logs were repeatable even at values less than zero they are still useful as a benchmark to monitor changes;
- all logs are plotted at the same scale with exception of BH2-deep;
- 1 MMHO/M = 1mS/m on the conductivity plots; and
- each depth value is relative to the natural surface at each piezometer. The merged plot may seem out of alignment with each log within it. In most cases this is due to slight variations in the natural surface at each piezometer within each nest.

Gamma

The gamma log count increases with increasing clay content or shale. There is a number of gamma ‘peaks’ when looking at the plots of the deeper Type 1 piezometers. These ‘peaks’ are evident at most sites; although shale lenses were only recorded in the drilling logs at sites MW2 and MW6. High gamma counts recorded in MW2d at 18 metres and MW6d at 22-24.5 metres are consistent with shale being recorded in the stratigraphic log. The gamma logs are considered the most accurate representation of clay and shale in the sequence. At all sites (apart from more distinctive shale layers in MW2, MW6, BH2 and BH4), the peaks in the gamma logs represent either very thin shaley bands or increased clay content in the sandstone matrix.

A gamma geophysical section through the RRR/JHEDI site is presented in *Figure 21.* The geological profile is given in Figure 20 with the location of the section shown on *Figure 12*. The section identifies shale lenses (?) in BH2 and BH4 (again consistent with the borehole logs in BH4 but not in BH2). These shale lenses do not extend along the orientation of the section confirming the shale horizons are discontinuous. All the responses in all the boreholes are considered to be natural geological responses.

Temperature

The temperature of the groundwater profile at each location was remarkably constant. No fluctuations were evident with the insitu groundwater temperature, which was generally around 15.5°C.

Conductivity

Both the conductivity and apparent conductivity logs generally increase with depth in all boreholes although the increases are relatively minor. Large conductivity inflections were measured in MW2d (14.5m), MW6d (17.0m) and BH2 (22m). The reason for these peaks is uncertain although they may relate to more saline water perched on top of the shale lenses immediately below.

Other trends cannot be determined at this stage without other repeat runs or other independent data. Because of variable permeabilities and flow velocities some variation in groundwater conductivities is also to be expected within the profile. A conductivity geophysical section through the RRR/JHEDI site is presented in *Figure 22*.

In general, the conductivity profiles indicate very low salinity water in both pore spaces and the sandstone aquifer zones which is very typical of all Hawkesbury Sandstone environments.

All the responses in all the boreholes are considered to be natural geological and hydrogeological responses.

6.7 Resistivity Imaging Survey

Consulting Geophysicist, David O'Neill, completed the resistivity imaging investigation in March 2000. Five resistivity imaging sections were completed; four surrounding the RRR/JHEDI site and one down-gradient of Building 27. The location of the profiles is shown on *Figure 12*. Summary details are given below in *Table 6.4*. The resistivity report, dated 3 May 2000 is presented in *Appendix D.*

Table 6.4: Resistivity Survey Line Summary

Line	Segments	Location	Length (m)
1		North of RRR and HIFAR	275
2	2a	SW of RRR	135
	2b	West of RRR	205
3	3a	East of Building 27	95
	3b	SE of Building 27	100
4		East of RRR	275
5		South of RRR	135

Apparent resistivity pseudo sections and interpreted resistivity sections in colour have been prepared for each transect and are presented in *Appendix D*. The relatively high resistivities measured across the site are consistent with the sandstone geology.

Plots of the results of the survey for each survey line are presented in *Figures 3 to 9* in *Appendix D*. Each of these figures consists of three diagrams:

1. **Traditional apparent resistivity 'pseudo-sections'** represent the actual survey 'data'. The contoured parameter is apparent resistivity, the horizontal axis represents the ground surface and the vertical axis represents a 'pseudo' depth.

   The apparent resistivity pseudo-section provides an unbiased representation of the data and is a useful means of comparing changes in subsurface conditions over time.

2. **Interpreted resistivity sections (local colour spectrum)** represent the interpreted subsurface 'true' resistivity. The interpretation process involves the technique of inversion of the field data using a finite-difference-based forward modelling approach. This technique produces an interpreted subsurface resistivity distribution that entails some ambiguity ('electrical equivalence').

   Sections in this category use a non-linear colour distribution for representing the interpreted resistivities. The colour 'stretch' is chosen to spread the colour range over the entire range of resistivities for a given survey line so as to emphasise variations as much as possible.

3. **Interpreted resistivity sections (global colour spectrum)** are identical to the 'Type 2' sections except that the same (non-linear colour distribution) is used for all sections so as to facilitate the comparison of interpreted sections from line to line.

The results presented *in Figures 3 to 9* of *Appendix D* show that high resistivities occur across the entire survey area, consistent with the prevailing geology and observed surface conditions. However, there are some elements of some lines that are worthy of some comment:

Line 1 (Figure 3 in Appendix D)

This line is located at the northern boundary of the RRR/JHEDI site. Its distance north of the grounded metal boundary fence combines with the resistive surface conditions to ensure that interference effects are likely to be minimal.

Three zones of possible fracturing within the sandstone are identified. The interpretation of the location and orientation of these zones is mostly based on the sections presented in the diagram. The zones are characterised by relatively low resistivities that arise through increased weathering of the sandstone and increased water content. Of the three zones identified, the western-most zone (chainage 65-75 metres approximately) is the most prominent and is considered to be the most likely. The two zones to the east are associated with only weak resistivity anomalies and, should they be fracture-related, these fractures are likely to be minor.

Piezometers MW1 and MW2 are too remote from the section to provide any correlation.

Line 2 (Figures 4 and 5 in Appendix D)

This line is located at the western boundary of the RRR/JHEDI site. It is located nominally 10 metres west of the grounded metal boundary fence, and a little closer at the southern end. The resistive surface conditions limit the likelihood of interference effects from the fence.

Line 2A shows no evidence of fracturing.

Line 2B suggests a relatively consistent distribution of weathered sandstone. A weak, low resistivity anomaly is identified (chainage 75 - 85 m approximately) as a possible fracture zone.

The open fracture zone detected in MW1 open (chainage 160 m) is not obvious on this section.

Line 4 (Figure 8 in Appendix D)

This line is located at the eastern boundary of the RRR/JHEDI site, a few metres west of the grounded metal boundary fence. The resistive surface conditions limit the likelihood of interference effects from the fence.

A well-defined low resistivity zone (chainage 65-80 m) is identified as being possibly fracture-related.

Piezometer BH4 is located approximately at chainage 140 metres in an area of no obvious features.

Line 5 (Figure 9 in Appendix D)

This line is located in the southern part of the RRR/JHEDI site, beginning about 25 metres west of the north-south border fence on the western side and ending a few metres from the eastern border fence.

A possible fracture zone near the western extent of the line is identified. There are no monitoring piezometers in this area.

Line 3 (Figures 6 and 7 in Appendix D)

Line 3, south of the wastewater tank in the south-eastern part of the LHSTC site, is far from ideally located. The line consists of two segments (A and B) necessitated by the presence of a steep gully preventing the locating of a straight survey line.

High resistivities occur at the southern and northern ends of the line in response to poorly compacted ‘fill’ material and topographic highs giving rise to relatively low ground saturation. The northerly dipping low resistivity zone in the southern part of Line 3A is not believed to be fracture-related.

The closest monitoring piezometer is MW6 inside the site boundary at about 70 metres chainage along Line 3A.

Summary

In summary the loose sandy soils and broken sandstone at the surface are non-ideal survey conditions for this technique, although a consistent pattern of topsoil overlying weathered sandstone with fresher sandstone at depth with occasional shale lenses was achieved.

Some low resistivity zones along Sections 1, 2B, 4 and 5 have been identified as possible indicators of fracturing within the sandstone unit. These may be substantial preferred pathways for groundwater flow in the sandstone and should be investigated further. The exact locations of these low resistivity zones are (chainage from start of line).

- Line 1 (1A-1 to 1A-2) - 60 - 75 m
  - 145 - 155 m
  - 215 - 225 m
- Line 2B (2A-1 to 2A-2) - 75 - 85 m
- Line 4 (4A-1 to 4A-2) - 65 - 80 m
- Line 5 (5A-1 to 5A-2) - 10 - 20 m

Further investigation of these anomalies is required before any detailed interpretation of the geology, fracture zones and groundwater attributes can be given.

6.8 Data Logger Installation

Automatic groundwater level monitoring commenced in August 2000 to complement manual groundwater level measurements carried out by ANSTO on an approximate three monthly basis. Four Dataflow pressure transducer and data logger assemblies were installed in piezometers MW1s, MW1d, MW6s and MW6d, recording water levels on a two hourly basis to detect long and short term water table fluctuations in the shallow and deep aquifers. These data loggers are completely enclosed in locked boreholes with the keys being held by ANSTO staff.

Down loading the data loggers and data manipulation is to be undertaken by ANSTO in accordance with the protocol described in (PPK, 2000a).

7. Monitoring Programs

Groundwater quality parameters are measured quarterly and all other parameters are typically monitored annually as outlined in *Table 7.0*. Groundwater quality parameters, inorganics and radioactivity and chemistry (dissolved metals, anions and cations) have been monitored between November 2000 and May 2007 and are presented in *Tables 7.1* to *7.41* in *Appendix J*.

Table 7.0: Groundwater Program Monitoring Events

Monitoring Event	Field Parameters	Inorganics and Radioactivity	Chemistry*
Nov 2000	x	X	x
Aug 2001	x	X	x
Dec 2001	x	X	x
May 2002	x		
Sep 2002	x	X	x
Dec 2002	x		
Mar 2003	x		
Jun 2003	x		
Aug 2003	x	X	x
Dec 2003	x		
Mar 2004	x		
May 2004	x		
Aug 2004	x	X	x
Dec 2004	x		
Feb 2005	x		
May 2005	x		
Aug 2005	x		
Nov 2005	x	X	x
Feb 2006	x		
May 2006	x		
Aug 2006	x	X	x
Nov 2006	x		
Feb 2007	x		
May 2007	x		

* Chemistry includes dissolved metals, anions and cations

Quarterly temporal data for electrical conductivity and standing water levels, as well as annual data for tritium, Gross Alpha, Gross Beta and Gamma-emitters are presented in

Appendix K in *Tables K1 to K6* respectively. Groundwater quality at the LHSTC is typical of a sandstone aquifer, tending to be acidic and with generally low salinity (indicated by electrical conductivity, EC).

The temporal variations for tritium, electrical conductivity and standing water levels are presented in *Figures K1 to K3* respectively. Hydrogeochemical trends in the groundwaters beneath the LHSTC are discussed more fully in *Section 8.2.*

8. Integrated Conclusions

8.1 Investigations

Parsons Brinckerhoff (PB) have completed an integrated volume consolidating all the data relating to hydrogeology, groundwater monitoring network, geophysics, monitoring programs and sampling protocols undertaken at the Lucas Heights and Technology Centre (LHSTC) by PPK Environment & Infrastructure and PB since 2000. Routine groundwater sampling undertaken by ANSTO has also been included in this report. In this consolidated report no data reinterpretation has been undertaken. This integrated volume is an amalgamation of the following five PPK/PB reports:

- Groundwater Monitoring and Management Program (PPK, 2000a);
- Groundwater Sampling Plan and Monitoring Protocols (PPK, 2000b);
- Supplementary Groundwater Investigation and Borehole Abandonment (PPK, 2001);
- Supplementary Drilling Program (PPK, 2002); and
- Replacement Monitoring Well MW11 and Piezometer Abandonment (PB, 2003).

The following outcomes and conclusions have been drawn from this study and the previous studies:

- The boundary (regional) groundwater monitoring network consists of:
  - 7 shallow piezometers;
  - 9 deep piezometers; and
  - 2 deep open boreholes for specialist downhole geophysics, permeability and velocity flow studies.
- The RRR/JHEDI groundwater monitoring consists of:
  - 4 shallow piezometers;
  - 6 deep piezometers; and
  - 1 deep open boreholes for specialist downhole geophysics, permeability and velocity flow studies.
- During the supplementary drilling programs 19 piezometers and geotechnical holes were abandoned at the RRR/JHEDI site and one piezometers was abandoned within the regional groundwater monitoring network;
  - A groundwater monitoring plan has been established (PPK, 2000b)
- downhole geophysical logs (gamma and conductivity) in each new piezometer and four older boreholes that have been retained for the monitoring program; and
- resistivity imaging sections totalling 1220 m for 5 lines surrounding the RRR/JHEDI site and the spent fuel rod repository.
- groundwater occurs within a two aquifer system (an upper perched zone and lower aquifer), although deeper aquifers are also suspected;

- connection or definition of the two aquifers is variable across the site;
- groundwater flow within the shallow and deep aquifers beneath the LHSTC is a subdued reflection of the surface topography with groundwater flowing to the north, south and east away from the topographically high area;
- at most individual locations (especially those on the southern and eastern boundaries of the LHSTC), the deeper aquifer levels are lower than the perched zone suggesting this lower zone is draining to springs lower in the valley, or deeper aquifers;
- there is potential for water in the shallow perched zone to percolate into the deeper sandstone profile except at Sites 2 and 3 on the northern boundary where the deeper water levels are higher than the perched water table;
- permeability testing and groundwater flow analysis suggests that the weathered zone and rock permeabilities are very low and have associated low flows and velocities;
- the range of hydraulic conductivity values measured within the perched zone and deeper rock aquifer are similar; the mean values being 5.23 x 10^{-8} m/sec and 8.93 x 10^{-8} m/sec respectively;
- inferred true groundwater velocities range from 0.02 metres per year to 7.36 metres per year;
- baseline geological and hydrogeological conditions were confirmed by the downhole geophysics and a resistivity imaging survey;
- high gamma counts recorded in MW2d at 18m and MW6d at 22-24.5m were consistent with shale being recorded in the stratigraphic log. Large conductivity inflections measured in MW2d (14.5m) and MW6d (17.0m) suggest more saline groundwater perched on top of the shale lenses;
- a number of anomalies were detailed in the resistivity imaging survey that may represent fracture zones. Two of these are located near the RRR site; and
- four Dataflow pressure transducer and data logger assemblies were installed in piezometers MW1s, MW1d, MW6s and MW6d, recording water levels on a two hourly basis to detect long and short term water table fluctuations in the shallow and deep aquifers.

8.2 Monitoring

Groundwater monitoring at LHSTC within the current piezometer network has been undertaken since 2000. The parameters being monitored are outlined in *Table 8.1*.

Table 8.1: Groundwater Monitoring Parameters

Sampling Suite		Parameters
Field Parameters		standing water level, electrical conductivity (EC), pH, oxidation reduction potential (Eh), temperature, turbidity
Inorganics		Total nitrogen, ammonia, oxidised nitrogen, total Kjeldahl nitrogen, total phosphorus
Radioactivity		Gross Alpha, Gross Beta, Tritium, K-40, Am-241, Cs-137, Co-60
Chemistry	Metals	Cr, Mn, Ni, Cu, Zn, As, Se, Cd, Hg, Pb, Fe
	Cations	Ca, K, Mg, Na
	Anions	Cl, SO_4, HCO_3 (as $CaCO_3$), CO_3, TDS

* Chemistry includes Metals, Anions and Cations

Monitoring the groundwater field parameters and chemistry at LHSTC since November 2000 has highlighted the nature of the local aquifer systems. Groundwater flow is primarily dependent on topographic features. The groundwater level beneath the ground surface at any one place and time is a sub-surface representation of the land surface. Groundwater quality is typical of a sandstone aquifer, tending to be acidic and with generally low salinity. The Eh, which indicates the oxidation-reduction potential of shallow groundwaters, generally shows oxygenated waters, although a negative Eh and/or an H_2S odour has been reported occasionally in more than 50% of piezometers. Three shallow piezometers (MW1s, MW4s and MW7s) have shown evidence of anoxia on at least 30% of sampling occasions.

The LHSTC groundwaters are predominantly sodium-chloride-sulfate type waters, consistent with a primary influence from marine aerosol input. Piezometers monitoring groundwater to the north and north east (ie. MW2s,d, MW3s,d, MW4s,d, & MW5s) show a predominance of magnesium with some calcium and bicarbonate type waters. This could reflect a more calcite rich source, possibly from the cementing material of the sandstone in this area. Shallow piezometer MW4s has shown consistently higher pH, EC and somewhat elevated Ca, Mg, SO_4, and HCO_3 concentrations. This piezometer is located in a natural drainage line below a chlorinated swimming pool, and the chemistry of surface waters and shallow groundwater from this area has been influenced by the leakage of treated water from the pool. Note that EC values recorded in September 2002 (*Figure K2*) are overestimated, due to incorrect selection of the EC scale (i.e. data were recorded in mS/cm instead of uS/cm). Low EC values recorded in Dec 2000, Dec 2002, March and June 2003, and in Aug 2004 coincided with periods of higher rainfall.

The gross alpha and gross beta activities in filtered samples of the LHSTC groundwater have remained well below the levels prescribed for Class C surface waters in New South Wales (PEOA, 1997) and were also below the more restrictive screening level of 0.5 Bq/L for Australian drinking waters (NHMRC and NRMMC 2004). This comparison is only indicative since these are groundwaters and not surface waters. Gamma-emitting radionculides, specifically americium-241, caesium-137 and cobalt-60 have not been detected in filtered groundwater samples. A study of sediment taken from representative LHSTC piezometers (BH3, MW1s, MW1d, MW3d, MW5s, MW6s, MW7d, MW8d and MW14) also showed no detectable non-natural gamma-emitters. Any small detection of radioactivity has been attributed to natural background radioactive levels. Background radioactivity is generally associated with natural radioactive emitters, in particular potassium-40, uranium-238 and thorium-232. Potassium-40 (^{40}K) and uranium-238 (^{238}U)

are commonly associated with the clay fractions of the sediments, while thorium-232 is associated with the heavy mineral monazite found in the sand fraction of sediments.

Tritium concentrations have been consistently well below drinking water reference levels, reflecting a predominance of groundwater greater than 30 years old. The World Health Organisation (WHO) reference level for tritium activity in drinking water is 7,800 Bq/L. Shallower piezometers generally display higher tritium concentrations than deeper piezometers, as is typical of aquifers with a vertical downward hydraulic gradient. Tritium concentration in LHSTC groundwater samples ranges from less than the detection limit (without electrolysis) to a maximum of 611 Bq/L, with a median of 11 Bq/L. Tritium concentrations found in the shallow piezometers are similar to or less than the LHSTC surface water background with many of the deeper piezometers reporting levels less than detection limits without electrolytic concentration.

Tritium from local rainwater in the vicinity of LHSTC since the HIFAR reactor was commissioned has typically migrated only as far as the shallow piezometers - generally less than 10 metres vertically. The background tritium concentration in Sydney rainfall is approximately 27 Bq/L. Concentrations of tritium in LHSTC groundwater exceeding 27 Bq/L are assumed to be due to a local contribution from HIFAR. Values less than 27 Bq/L may include a variable mixture with water greater than 45 yrs old, which contains no tritium. An approximate maximum vertical flow rate of less than 0.35 m/yr is estimated based on the tritium data presented to date.

In conclusion, the monitoring of groundwater since 2000 at LHSTC has revealed there is no impact on the health of the community. ANSTO will continue to monitor the LHSTC groundwater to ensure that this current status continues.

9. References

Bouwer H and Rice RC (1976) – A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells, Water Resources Research 12(3), pp 423-428.

Coffey Partners, 1998) "Replacement Reactor Site. Lucas Heights Hydrogeological and Hydrochemical Study" Report G459/1-AG dated August 1998.

Domenico and Schwartz (1990) – Physical and Chemical Hydrogeology. John Wiley & Sons, 824p.

DJ Douglas & Partners Pty Ltd and Coffey Partners Pty Ltd (1994); Report on Hydrogeology and Groundwater Monitoring, Lucas Heights Waste Depot, Vol 1, dated May.

NHMRC and NRMMC, 2004 "Australian Drinking Water Guidelines 6" National Health and Medical Research Council & Natural Resource Management Ministerial Council. Australian Government Publishing Service, Canberra.

PEOA, 1997 "Protection of the Environment Operations Act 1997". Government Gazette, NSW Government Printery, Sydney.

PPK, 1998 "Replacement Nuclear Research Reactor. Draft EIS and Supplement (Volumes 1, 2 and 3).

PPK, 2000a "Groundwater Monitoring and Management Program – Lucas Heights Science and Technology Centre" Pr_1452 dated August 2000

PPK, 2000b " Groundwater Sampling Plan and Monitoring Protocols - Lucas Heights Science and Technology Centre" Pr_1419 dated July 2000

PPK, 2001 "Supplementary Groundwater Investigation and Borehole Abandonment – Final Report Lucas Heights Science and Technology Centre" Lt_2190 dated August 2001

PPK, 2002 "Supplementary Drilling Program - Lucas Heights Science and Technology Centre" Lt_2532 dated June 2002

PPK, 2002a "Borehole Abandonment Program – Lucas Heights Science and Technology Centre" Lt_ANSTO dated January 2002

PPK, 2002b "Geophysics and Drilling Program – Little Forest Burial Ground. Australian Nuclear Science and Technology Organisation." Pr_2553 dated August 2002

PB, 2003 "Replacement Monitoring Well MW14 and Piezometer Abandonment - Lucas Heights Science and Technology Centre" Lt_2862 dated June 2003

Figures

Appendix A

Private Bore Details

Appendix B

Borehole Logs

Appendix C

Falling Head Test Data and Interpretations

Appendix D

Geophysical Resistivity Imaging Report

Appendix E

Downhole Geophysical Logs

Appendix F

PPK Groundwater Sampling Protocols

Appendix G

ANSTO Groundwater Purging Instructions (Air-lift and Pump Methods)

Appendix H

ANSTO Groundwater Sampling Instructions

Appendix I

Examples of ANSTO field data sheets and chain-of-custody forms

Appendix J

Results of ANSTO's Annual and Quarterly Groundwater Monitoring: Tables 7.1 to 7.41

Appendix J Tables 7.1 to 7.41

Appendix K

Results of ANSTO's Temporal Chemical Parameters

Appendix K Tables K1 to K6

Figures K1 to K4

Appendix L

Summary of ANSTO’s Analytical Methods and Detection Limits

Table L1 ANSTO Laboratory Analysis Methods and Detection Limits

ALYSIS	LABORATORY	METHOD AND INSTRUMENT	DETECTION LIMITS
rganic rients	Sydney Analytical Laboratories (SAL)	APHA Standard methods of Water & Wastewater Analysis 20th Ed. 4500BE Total Phosphorus 4500F Oxidized Nitrogen 4500BC Total Kjeldahl Nitrogen 4500D Ammonia	0.1 mg/L 0.1 mg/L 0.4 mg/L 0.1 mg/L
	Australian Water Technologies Pty Ltd (AWT)	Ammonia NH3-N low-level Oxidized Nitrogen NOx-N low-level Soluble Reactive Phosphorus Total Phosphorus Total Kjeldahl Nitrogen low-level	0.01 mg/L 0.01 mg/L 0.002 mg/L 0.002 mg/L 0.10 mg/L
lrocarbons	Labmark, NATA No. 13542	• Monocyclic Aromatic Hydrocarbons (MAH's): Benzene, Toluene, Ethyl benzene, Xylene (BTEX) - direct P&T injection. Analysis by P&T GC/PID confirm. Column FID, Ref. USEPA 8020. • P&T C_6-C_9: Volatile Total Petroleum Hydrocarbons (TPH) analysis by P&T GC/FID. • Fractions C_{10}-C_{36} by TPH extraction with dichloromethane. Analysis by GC/FID.	Benzene 1 ug/L Toluene 1 ug/L Ethyl benzene 3 ug/L Total Xylene 3 ug/L TPH: C_6-C_9 50 ug/L; C_{10}-C_{14} : 100 ug/L C_{15}-C_{28} : 500 ug/L C_{29}-C_{36} : 500 ug/L
emistry nple prep.	ANSTO - Environmental Chemistry	Sample digestion: (Water by Block Digester) - ANSTO method VEC-I-9-01-021	N/A
als	ANSTO - Environmental Chemistry	ICP-AES: ANSTO method VEC-I-9-03-002; and ICP-MS: ANSTO method VEC-I-9-03-007	
ons	ANSTO - Environmental Chemistry	Ion Chromatography - ANSTO method VEC-9-03-004	
al solved ds (TDS)	ANSTO - Environmental Chemistry	APHA method 2540C	
alinity	ANSTO - Environmental Chemistry	ANSTO method VEC-I-9-02-010.	
um	ANSTO - Environmental Chemistry	Tritium - distillation followed by liquid scintillation counting.	4 Bq/L
ss na/beta	ANSTO-Environmental Monitoring	ANSTO method ENV-I-041-008 based on ISO standards 9696 & 9697(1996). Canberra and Protean gas proportional counters.	Gross alpha & beta : 0.01 Bq/L
mma tters	ANSTO-Environmental monitoring	ANSTO method ENV-I-041-003. Three litres of sample concentrated to 50 mL then set in agar gel & counted for 23 hours on low-background, High Purity Germanium (HPGe) Gamma detection systems.	Varies for each sample and radionuclide. Any less-than values quoted are the minimum detectable activity, calculated at the 95% confidence level.

ANALYSIS METHODS PERFORMED BY ANSTO

Alkalinity

The bicarbonate ion content was determined by titration of 50mL of each sample against standardised hydrochloric acid. The endpoint of the titration is pH 4.6 for high range samples and pH 4.3 for low range samples, measured by a pH meter.

The ANSTO instruction for this analysis is VEC-I-9-02-009, which is based on the American Public Health Association (APHA) method 2320.

Elemental Analysis

Samples were prepared by digesting 20mL of each sample in a block digester at 98oC for 3 hours after the addition of nitric and hydrochloric acids.

The ANSTO instruction for this sample preparation is ENV-I-035-021.

The process continues via the construction of standard curves from the signal outputs of a range of NIST traceable single element, high purity standards run on either a Varian ICP-AES or an Agilent ICP-MS.

Determination of specific elemental concentrations in the digested samples was achieved by comparison of the sample solution signal output to the standard curves, from one of the instruments. The choice of instrument is dependent on each instrument’s capabilities and element concentration.

The quantification limit for each element is the lowest concentration standard, on the standard curve that generates a distinguishable signal output.

The ANSTO procedures for these analyses are ENV-I-035-026 and ENV-I-035-027, which are based on the USEPA methods No. 200.7 & 200.8.

Ion Chromatography

Unacidified samples were filtered through 0.2µm membranes. A series of standards were prepared from NIST traceable single anion, high purity standards for chloride and sulfate by serial dilution with deionised water. Standards and samples were injected into a Dionex 4500I ion chromatograph and eluted through an AS14 column using carbonate eluents. Analyte response was measured using suppressed conductivity. Standards curves were prepared by plotting standard concentration against instrument response. Determination of specific anion concentrations was achieved by comparison of the sample signal output to the standard curves.

The quantification limit for each anion is the lowest concentration standard, on the standard curve that generates a distinguishable signal output.

The procedure for this analysis is based on APHA method 4110.

Total Dissolved Solids (TDS)

Between 100 and 200mL of each sample was filtered through a Whatman GF/F (0.7µm) glass fibre filter. The filtrate was transferred to a pre-weighed beaker and heated to dryness in an air oven, until a constant mass was obtained. The beaker was re-weighed and TDS calculated.

The ANSTO procedure for this analysis is ENV-I-035-012, based on the American Public Health Association (APHA) method 2540C.

Tritium (H-3)

Samples were prepared by distilling 50 mL. Standards were prepared by diluting aliquots of NIST SRM4926E, certified reference material for 3H, with "tritium-dead" water. Blanks were prepared from dead water. A 10 ± 0.05 g aliquot of each sample, standards and blanks was weighed into 20 mL scintillation vials and 11 mL of scintillant added (Instagel Plus). Samples and standards were counted for 20 minutes, repeated over 15 cycles, a total of 300 minutes for each vial. Tritium concentrations in the samples were determined by comparison of sample net counts against standard net counts. Minimum detectable activity was determined from blank total counts.

Gross alpha/beta activity

Gross alpha and beta activity was determined via ANSTO method ENV-I-041-008, based on the thick-source method ISO standards 9696 & 9697(1996). Samples were prepared by evaporating 1-2 litres down to 50 mL, sulphated using 1 mL conc. sulphuric acid and taken to dryness on a hotplate. The sample residue was then ignited in a muffle furnace at 350 degrees celsius overnight, or until constant mass was achieved. Sample residues of 100 mg, dispersed upon stainless steel planchettes were counted for 400 minutes on a Protean or Canberra 2400 gas proportional counter. Standards and blanks were included with samples. Standard sources of Americium-241 and K-40 were used to calibrate the system for alpha and beta activities, respectively. Counting decision limits as per Gilmore & Hemingway were used to assess the net counts and calculate the minimum detectable activities at 95% confidence.

Gamma Spectrometry

Sample preparation:

Filtered, acidified groundwater samples were prepared by evaporation, with a volume of approximately 3 litres reduced to 50 mL. The sample was then adjusted to lie between 3-4 pH units, heated and set with approx. 2.0 g powdered agar in a 65mm diameter petri dish. The petri dish was sealed using silicone and allowed to cure overnight.

Counting:

Sample gamma spectra were acquired over a counting period of 23 hours. Background spectra for each gamma detector were also acquired for 23 hours using a blank (distilled water and agar). Secular equilibrium of the naturally-occurring U/Th decay series was not necessarily established in any sample at the time of counting.

Calculations:

Sample spectra were assessed for any peaks, whether natural or anthropogenic in origin, including Co-60, Cs-137 and Am-241. All peaks were identified and compared with the same region on the blank's spectrum. Radionuclides with a net peak area greater than that of the blank were considered further. The peak data (gross & net area in counts with error) for the sample and blank spectra were entered onto an Excel spreadsheet. The peak areas in both the blank and sample spectra were assessed for significance above their own background (Compton) continuum, using the concept of a Critical Limit. The critical limit is calculated as 2.33 times the uncertainty of the peak background estimation.

Reporting Results:

The critical limit is used to assess the statistical validity of a calculated net count. When we are 95% confident that the sample net peak area is statistically significant (i.e. above the critical limit), a result with its associated uncertainty is quoted. The uncertainty includes the errors due to peak area calculation, background subtraction, efficiency calibration, sample volume, and gamma-ray abundance data. If the sample net peak area is NOT statistically significant (i.e. less than the critical limit) the activity must be declared "not detected" and an upper limit or "less than" level calculated. This statistical upper limit is converted to an activity and reported as "less than" the activity that we are 95% confident of detecting, i.e. the minimum detectable activity. It is important to appreciate that both the critical and the upper limit are a posteriori estimates based upon actual measured counts.

Further information may be found in Gilmore & Hemingway, Practical Gamma Ray Spectrometry, 1995, ch 5, published by John Wiley & Sons.

A limit of detection may, of course, be calculated for any radionuclide, based upon the counts in the sample and background spectra. Slight variations in sample composition and background spectra on different detectors will also give rise to varying detection limits. The agar used contains small amounts of natural radioactivity such as K-40 and some U-238 and Th-232 series progeny. Any peaks ascribed to natural activity in the sample spectra were not processed further, unless at least 50 counts greater than the blank spectrum. For any radionuclide present at low count rates, where there is a peak on the blank's spectrum, the overall uncertainty of the result will be high (> 50%) due to the peaked background correction.