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Installation of a Pilot Experimental Trench at the Little Forest Legacy Site

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IMPORTANT NOTE

This report is an outcome of the research study of the Little Forest Legacy Site, which is being led within ANSTO's Environmental Research Theme and is being implemented by ANSTO and external partners.

If significant new information is found, or revisions are required, a revised version may be issued.

This version issued: 6 July 2018

Summary

During 2017, a pilot experimental trench was constructed at the Little Forest Legacy Site (LFLS). The objective of installing this trench was to facilitate experimental field-work aimed at further characterising the site, in particular the hydrology of the excavated trenches and of the near-surface layers in which the trenches are located. The test trench is of similar depth to the waste disposal trenches at the legacy site (3 metres) and extends 6 m in length. However, unlike the disposal trenches, the experimental trench contains no waste materials of any kind. Instead, the trench contains a number of sampling points and other instrumentation, and is back filled with river gravel to provide a uniform composition and maintain structural stability. It is intended that the pilot trench will be followed by other trenches with specific experimental objectives. The purposes of this report are to discuss the background, rationale for, and implementation of the facility; to provide a detailed description of the pilot trench; and to compile information and photographs documenting the excavation process. Although some preliminary hydrological data and comparisons with the legacy trenches are presented, the scientific data will be fully discussed and interpreted in future scientific reports.

Acknowledgements

The research project at the LFLS is being implemented by personnel from the Australian Nuclear Science and Technology Organisation (ANSTO), in conjunction with various external partners. Valuable input from all participants in the project is acknowledged, and we appreciated the comments received on this document. We particularly thank the excavation team which comprised external contractors and personnel from ANSTO Asset Management and Services group. We also appreciate the work of the ANSTO radiochemistry group, who provided timely and valuable radiochemical analysis, and thank the analytical team for beryllium measurements. We thank the members of the Safety Assurance Committee (SAC) for their input and assessment of the safety submission and for provision of expert advice on safety aspects of the trench excavation.

Related reports

J. Twining, J. Harrison, M. Vine, N. Creighton, B. Neklapilova and E. Hoffmann (2009). Analytical Method Development for Tritium in Tree Transpirate from the Little Forest Burial Ground [ANSTO report NMESP/TN1].

T.E. Payne (2012). Background Report on the Little Forest Burial Ground Legacy Waste Site. [Report No. ANSTO/E-780].

S. Hankin (2013). Little Forest Burial Ground – Geology, Geophysics and Monitoring Wells [Report No. ANSTO/E-781].

T.E. Payne (2015). Little Forest Legacy Site – Summary of site history until the commencement of waste disposal in 1960. [Report No. ANSTO/E-782].

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LIST OF ABBREVIATIONS

AAEC	Australian Atomic Energy Commission
AHD	Australian height datum
ANSTO	Australian Nuclear Science and Technology Organisation
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
BOM	Bureau of Meteorology
DGPS	Differential global positioning system
EM	Electromagnetic
ERT	Electrical Resistivity Tomography
INL	Idaho National Laboratory
LFBG	Little Forest Burial Ground (the name of the LFLS at the time of operations, and in subsequent years until 2014)[1]
LFLS	Little Forest Legacy Site
PPE	Personal protective equipment
SAC	Safety Assurance Committee
SWL	Standing water level
TOC	Top of casing (sampling well)
USGS	United States Geological Survey

[1] Note that in this report the term “LFBG” is used when discussing burial operations, since these occurred when the site was a burial ground rather than a legacy site.

1. Introduction

From 1960 to 1968, the Australian Atomic Energy Commission (AAEC) disposed of radioactive waste, mostly derived from the operations of its Lucas Heights research facility, in trenches at the Little Forest Burial Ground (LFBG) on the southern periphery of Sydney. The waste disposals were in accordance with international practices applicable at that time for the disposal of low-level solid and liquid wastes. The materials disposed in the trenches included waste drums, chemicals, radioactive sources, disused equipment, laboratory trash and beryllium-contaminated items. The successor to the AAEC, the Australian Nuclear Science and Technology Organisation (ANSTO) controls and manages the site. Since the cessation of disposal operations, the AAEC/ANSTO has undertaken continuous care, maintenance, surveillance and monitoring activities at the site, now referred to as the Little Forest Legacy Site (LFLS).

For several years, a research project has been underway at LFLS with the intention of fully characterising the site and providing information relevant to future management and possible remediation decisions. The rationale and background of this project is described in a previous report (Payne, 2012). Several journal papers have also been published related to the project, including a general description of the "bathtub" effect which has led to some mobilisation of radioactivity at the site (Payne et al., 2013).

This document describes a pilot experimental trench which was constructed at the Little Forest Legacy Site (LFLS) during 2017 to facilitate field-work aimed at further characterising the site, including the hydrology of the near-surface layers and the excavated trenches. This pilot trench is of similar depth to the waste disposal trenches at the legacy site (3 metres) and extends 6 m in length, and is located to the south-west of the legacy trenches. A key objective of this report is to ensure that the experimental trench is fully described so that future measurements at the facility can be validly interpreted. This report also provides information on the rationale and construction of the trench facility. The present report, and its companion volumes, are intended to help ensure that information relevant to LFLS is brought together and preserved for the future.

2. Overview of status of LFLS research project

The LFLS has been monitored since the cessation of disposal operations in 1968 to the present day, with the results presented (together with monitoring results for other ANSTO facilities) in a series of reports (e.g. Hoffmann et al. (2008)). The regular environmental monitoring at LFLS has focused on the groundwater pathway, and has not detected any off-site radionuclide migration from the wastes buried at the site (other than a tritium plume in groundwater).

An ANSTO research project at LFLS has been in progress for several years, with the objective of assessing the status of LFLS and developing a more detailed understanding of the site (Payne, 2012). The project has undertaken detailed sampling and analysis of groundwater, surface soils and vegetation, and also completed soil coring, geophysical surveys and installation of groundwater sampling wells. ANSTO has partnered with external institutions within Australia and internationally (including several universities) to implement this research.

The current phase of the project was commenced after the licensing of the LFLS site by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) on 9th July 2015. One of the license conditions was that the licence holder (ANSTO) must provide a plan for management of the site, including options for the ultimate remediation of the site. In response to this condition, ANSTO initiated a project which will further characterise the site, including assessing the available in-situ remediation options, and comparing their effectiveness with the more costly exhumation of the site. Within this project, the work on the test trench facility was initiated. This facility was intended to support the in-field assessment of remediation options, facilitate detailed study of bath-tubbing phenomena and enable model parameterisation.

3. Rationale for experimental trenches

The outcomes from the research at LFLS have included journal papers on a range of topics including the mobility of tritium (Hughes et al., 2011), the groundwater geochemistry (Cendón et al., 2015) and possible mechanisms leading to the mobilisation of plutonium (Ikeda-Ohno et al., 2014). Some recent papers have identified the possible roles of micro-organisms (Vázquez-Campos et al., 2017) and co-disposed chemicals such as Tri-Butyl Phosphate (Rowling et al., 2017) in mobilising radionuclides at the site.

A qualitative description of the bathtub process was presented in Payne et al. (2013), who showed that the water level in the trench sampler (a sampling location within one of the legacy trenches) responded rapidly to rainfall and could rise to the surface during intense rainfall events (Figure 1). Because the trench water contains radionuclides such as Pu and Am, this has resulted in contamination of the shallow soil layers and ground surface with radionuclides. The key role of fluctuating geochemical conditions in mobilising radionuclides from the trenches has been recognised (Kinsela et al., 2016; Vázquez-Campos et al., 2017), but the hydrology of the site remains to be fully understood and parameterised. The proposed bathtub process can only be tested to a limited extent utilising the existing trenches and sampling boreholes. Experiments in the legacy trenches are complicated by their poorly characterised state, potential instability and the presence of hazardous wastes. Similarly, the inherent heterogeneity of the site (as in many other geological settings) means that borehole measurements are of limited value for hydrology measurements.

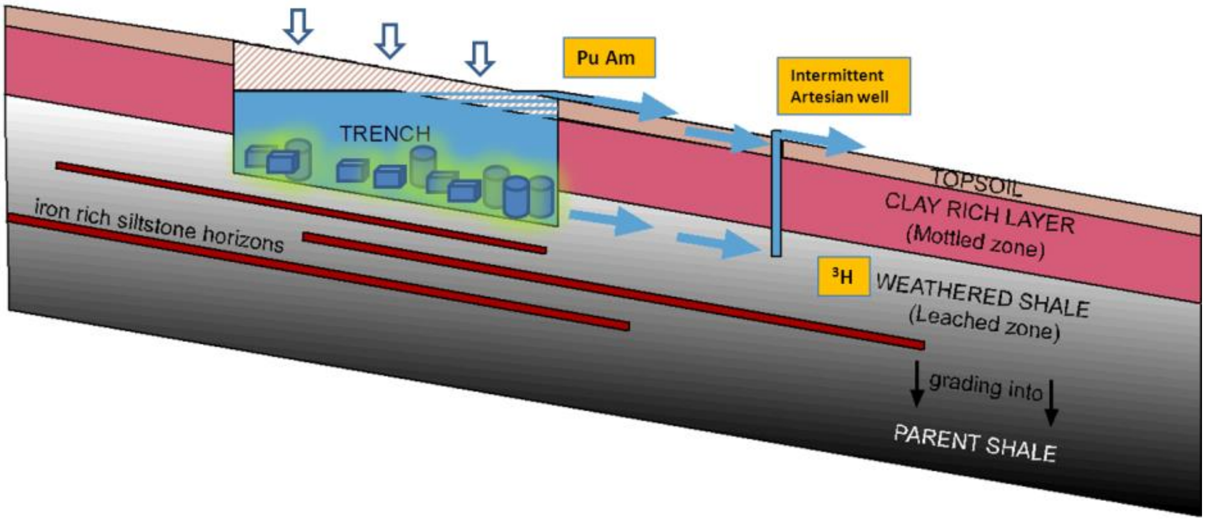

Figure 1. Conceptual model of "bathtub" effect in waste trench at LFLS as proposed in Payne et al. (2013). The main feature is water overflowing at the end of the trenches when the water level is high. Note that the slope of the trench is exaggerated.

Therefore, the construction of an experimental trench in the vicinity of the legacy trenches offers the potential for more comprehensive tests of the hydrology of the site, as well as an opportunity to collect intact profile samples and observe the lithology. The present report describes the installation of a pilot experimental trench, which contains a number of sampling points and other instrumentation, and has been back-filled with river gravel to provide a uniform composition and maintain structural stability. Further plans include hydrological studies and tracer tests involving the pilot trench as well as construction of further test trenches for engineering interventions, in-situ grouting tests, and detailed studies of in-trench chemical processes using simulated waste types.

4. Trench disposals at Little Forest

The LFBG trenches were filled sequentially from 1960 until the cessation of disposal operations in 1968 (Figure 2). The main trenched area contains trenches numbered from 1 to 77, and there were two additional trenches (S1 and S2) some distance to the south of the main trenched areas. These were filled in 1967 and 1968 respectively (Payne, 2012)[2]. Disposals in 1965 took place in the northern end of the eastern set of trenches (shown as 1965a) and the southern end of the western set (1965b). At the time when disposal operations started, a tractor with a back-hoe attachment was purchased by the AAEC to excavate the trenches (Figure 3a). The tractor was also used as a bulldozer for backfilling. A general description of the method normally adopted to fill the trenches suggests that a trench disposal operation would take around five days – including two days to excavate, a day to transfer the waste and two days to back-fill (Ellis, 1977).

The dimensions of the trenches have been typically reported (following Isaacs and Mears (1977)) as "nominally 25 m long, 0.6 m wide and 3 m deep and spaced 2.7 m apart". Given that these were regarded as "nominal" dimensions, there may have been some variation in width. Certainly, some trenches were much shorter than 25 m (see Figure 2). For example, Trenches 3 and 4 have a combined length of approximately 25 m, as do trenches 9-11, 12-15, and several other similar instances. The fence indicated near the eastern end of the trenches (Figure 2) has since been moved.

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[2]Based on disposal records, it is thought that trenches S1 and S2 were filled when other trenches were already being filled in the main trenched areas. See: "Estimates of Hazardous Waste Buried at the Little Forest Burial Ground" (AAEC, circa 1968).

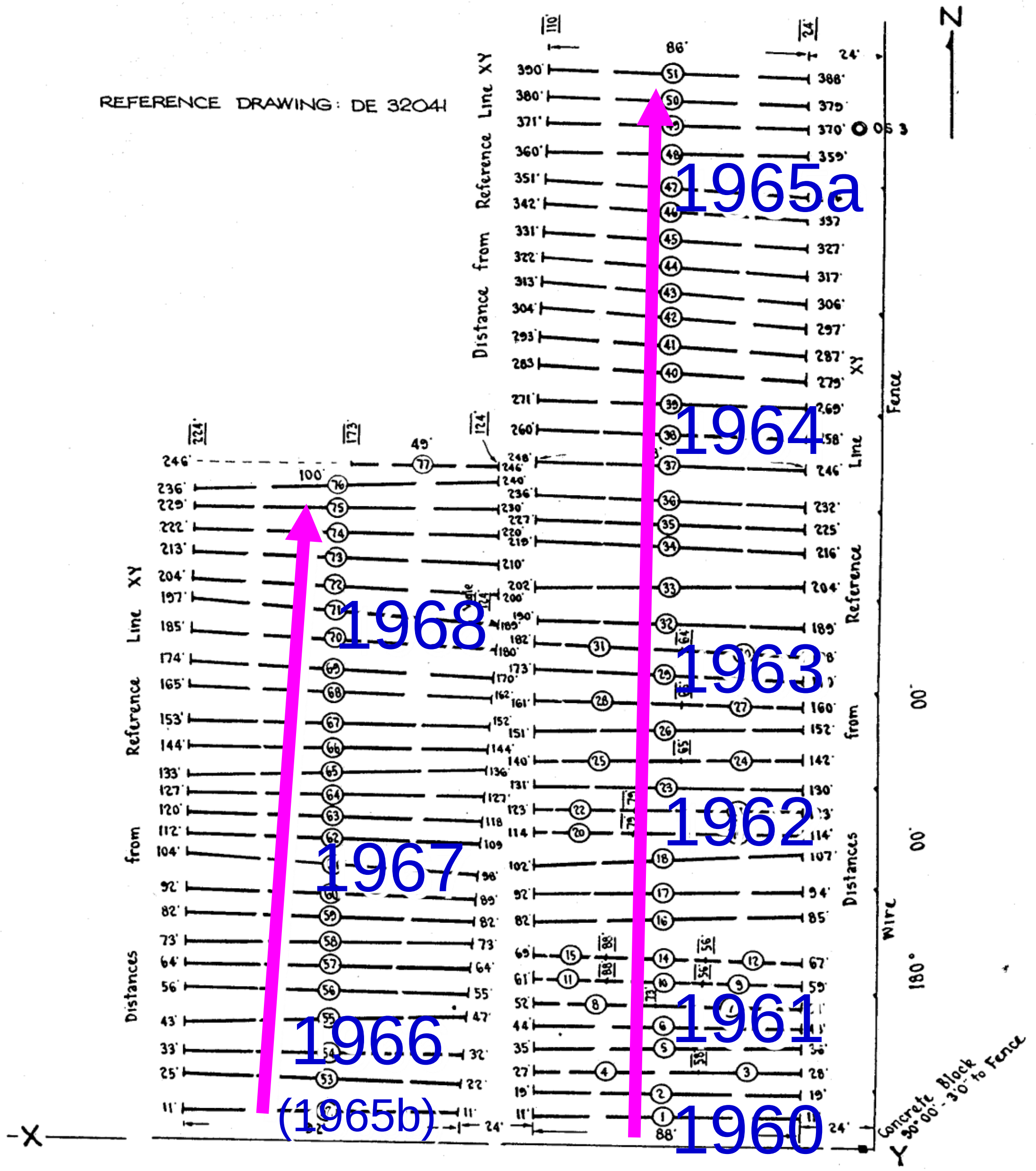

Figure 2. The sequence of filling the trenches at the LFBG from 1960 to 1968. Some trenches were much shorter than the nominal 25 m length, for example, trenches 3 and 4, and trenches 9 to 15. The significance of the breaks in the trenches indicated in the drawing is not known. Two additional trenches (S1 and S2) are not shown in this diagram. These were located to the south of the main trenched area. Lengths are given in the imperial unit (feet).

According to a contemporary source[3], some liquid waste was disposed in Trench 13, but this trench is absent from the trench diagram (Figure 2). Based on the same source, Trench 77 was partially dug when the direction to cease disposals was received and was filled with inactive waste during the clean-up of the site. Thus, the total number of known waste-filled trenches at the site comprises Trenches 1-76 (excluding 13), as well as S1 and S2.

The inventory of the trench contents was broadly described as waste drums, chemicals, radioactive sources, disused equipment, laboratory trash and beryllium-contaminated items. Some waste items can be seen in Figure 3b. An overview of the disposal records is given in previous reports (AAEC, 1985; Payne, 2012). A major effort is currently underway to evaluate the records of disposals at the site with the objective to estimate the contents of the individual trenches and the total inventory at the site, and the outcome of this survey will be presented in a future report[4].

Figure 3. Contemporary photographs of (a) trench excavation and (b) trench disposals. In (b) the presence of a significant amount of water is visible beyond the drums in the foreground [this is more obvious in the original print].

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[3] "Estimates of Hazardous Waste Buried at the Little Forest Burial Ground" (AAEC, circa 1968). This document is available as a digital spreadsheet.
[4] Note that this report will include the digital spreadsheet mentioned in the preceding footnote.

One of the main components of the disposed waste was 760 drums of sludge, contained in 200-litre steel drums (Ellis, 1977). Those which were stored on-site at LFBG in the 1960's were reportedly in poor condition and expected to fail (Bonhote, 1964). It is thought that these deteriorating drums were subsequently buried at the LFBG. Trench 41 (which was filled in 1964) received the greatest number (77) of sludge drums. Based on the typical dimensions of such drums (approximately 60 cm wide and 90 cm long), they would have occupied the full width of the trench, and would have needed to be stacked in layers to accommodate the number of drums reportedly disposed in Trench 41.

It appears that the close spacing of the trenches and the amount of material excavated resulted in considerable piles of soil accumulating near the trenches on the surface (Figure 4).

Figure 4. Photograph of soil being pushed into filled trench.

5. Previous trenching studies and related field work at LFLS

A significant number of boreholes have been drilled at Little Forest in a series of campaigns over several decades, as part of various site characterisation studies. The borehole network has been comprehensively summarised in Hankin (2012). However, it appears that the only previous trenching studies were in the late 1950's, prior to waste disposal operations. Archival documents suggest that the main reason for these excavations was to test the trenching machinery[5] and several back-hoes were demonstrated on the burial area[6].

The trenching allowed some observations to be made on the hydrology of the site, including field measurements undertaken in 1959 (Figure 5). Based on these observations, one AAEC scientist concluded that "as the water level rises after rain it is obvious that the trenches will fill with water that will become contaminated with leached out activity from the waste"[7]. Thus, the field trenching experiments raised some concerns about the performance of the (as yet) unconstructed trenches. The locations of some of the experimental features installed in 1959 (trenches and "test-holes") are still visible at the Little Forest site (Figure 6).

A number of field tracer studies have subsequently been attempted at Little Forest. Some examples are summarised in Table 1, demonstrating a range of different tracers, including a non-reactive salt, an organic dye and a radiotracer. The authors generally considered that the results of these tracer experiments were inconclusive and difficult to explain. In retrospect this may be partially attributed to the unsuitability of the study site to borehole tracer tests due to the clay-rich geology.

When compared to short-term tracer tests, the measurements of the tritium plume at Little Forest (Hughes et al., 2011) have been much more valuable in assessing the hydrology of the Little Forest site. This can be attributed to a number of factors, including the suitability of tritium as a conservative tracer of water movement, its

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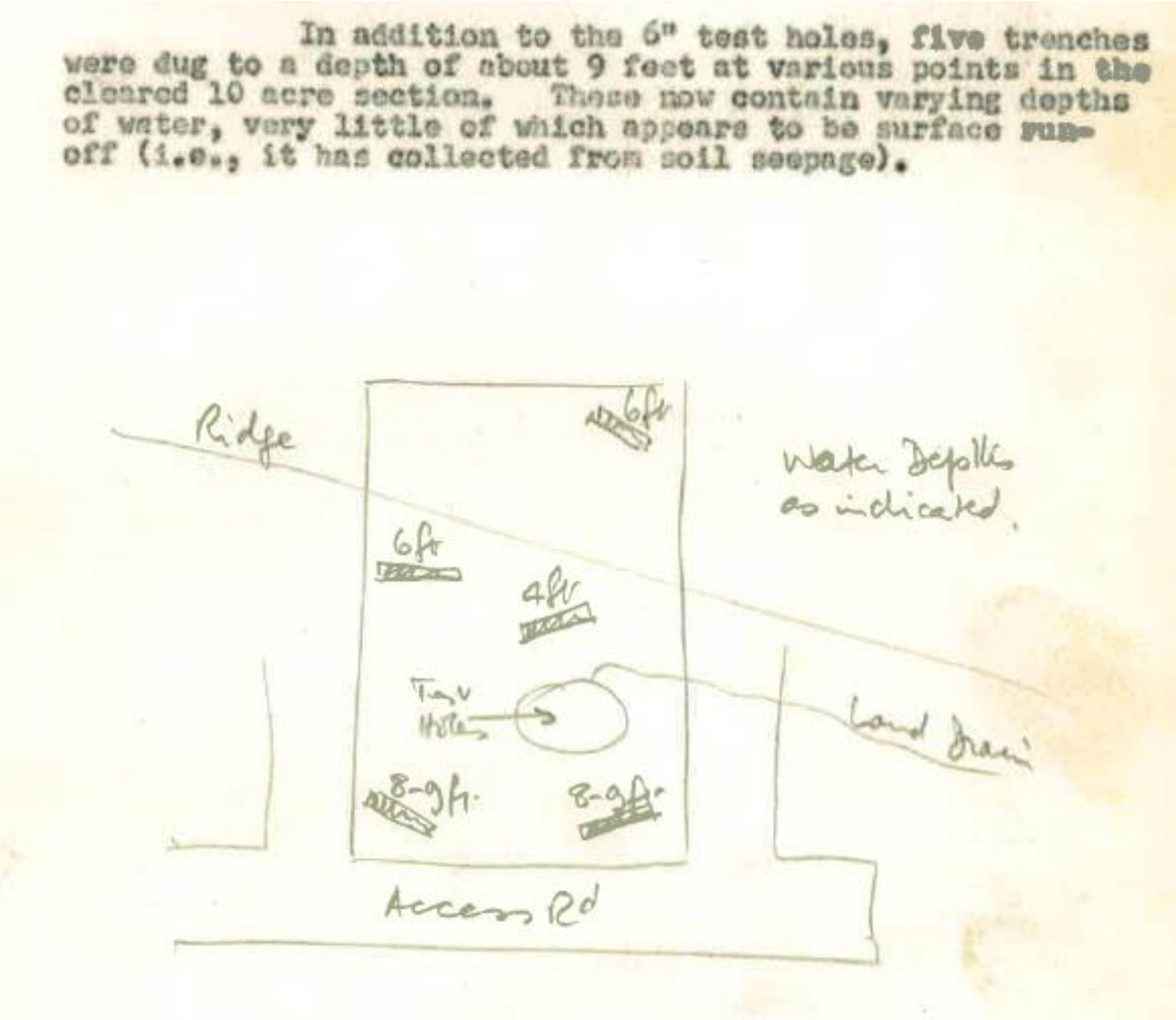
[5] Minute from E.D. Hespe to L.H. Keher, 10 February 1959.
[6] Minute from E.D. Hespe to L.H. Keher, 27 February 1959.
[7] Minute from R.B. Temple to the Effluent Committee Chairman, 5 March 1959.

relative longevity, the readily detected amounts of tritium found in the plume, and the extensive data-base of tritium measurements which has accumulated over the years since waste disposals. However, the tritium is distributed throughout the site and is also derived from other sites including Harrington's Quarry landfill. Therefore, tritium measurements generally do not provide specific information on individual trenches.



In addition to the 6" test holes, five trenches were dug to a depth of about 9 feet at various points in the cleared 10 acre section. These now contain varying depths of water, very little of which appears to be surface run-off (i.e., it has collected from soil seepage).

Figure 5. Some notes and a sketch drawing by Dr R.B. Temple showing trenches and test holes at LFBG in early 1959[8]. The trenches were 9 feet deep and became filled with "varying depths of water".

[8] Minute from R.B. Temple to the Effluent Committee Chairman, 5 March 1959.

Tracer	Description	Findings	Reference
^{198}Au	Within borehole tests at BH2 and BH10.	Direction of water movement was inconclusive and inconsistent with another ("float") technique.	Isaacs and Mears (1977), p7.
Nitrate	Unknown location ("control hole in burial ground") surrounded by monitoring holes at 2 m and 8 m distance.	Nitrate mostly moved by diffusion, but water velocity of around 2 mm per day was inferred.	Mumme (1974), p20; reporting experiments undertaken in 1959 -1960. Also discussed by Bradd (2003), p30.
Fluor-escein	Several test holes in the area shown in Figure 5. The central hole was 15 ft. deep. Three monitoring holes at 5 ft. distance.	Results were difficult to explain. Between the construction of the holes on 4 Feb 1959 and the 19 Feb, all the boreholes filled with water, but no fluorescein was detected in the monitoring holes.	Minute from E.D. Hespe to L.H. Keher, 10 Feb 1959. Minute from E.D. Hespe to L.H. Keher, 27 Feb 1959. Minute from R.B. Temple to the Effluent Committee Chairman, 5 March 1959.
Tritium	Long term monitoring of plume from waste trenches.	Provided valuable information on direction and characteristics of groundwater flow on a site-wide scale.	Hughes et al. (2011), reporting data from the years 1970 to 2010.

Table 1. Examples of tracer tests at Little Forest.

Figure 6. Apparent position of a trench excavated in 1959. This photograph was taken in May 2018 following a bushfire near the site which partially burned the fenced area. This is likely to be the location of the trench at the bottom right of Figure 5.

6. Similar experimental trench installations at other sites

Experimental trenches at legacy radioactive waste sites

There have been a number of experimental trench programs at overseas legacy radioactive waste disposal sites, particularly in the United States, such as the Maxey Flats site and Idaho National Laboratory site (PNL, 1981). The Maxey Flats waste disposal site was closed in 1977, following detections of plutonium and other radionuclides in the environs of the site. Similarly to LFLS, the site is located in weathered shale in a humid region, and this geology was implicated in water accumulation in the trenches and consequential water management problems (Toste et al., 1984). An experimental trench study was initiated at the site in 1979, in which several experimental trenches were dug near a waste burial trench. The experimental facility totalled 5 trenches of nearly 100 m total length, and of considerable depth (a large backhoe capable of 8 m depth was employed). Prior augering was undertaken to provide assurance that unrecorded waste would not be intercepted. The experimental trenches were filled with crushed rock and capped. Tracer experiments and measured radionuclide concentrations showed significant inter-trench migration rates (PNL, 1981). Further experiments aimed at determining the effectiveness of trench caps were undertaken.

The Idaho National Laboratory (INL) is a semi-arid site where wastes have been disposed, and a number of nearby experimental trenches have been constructed. A set of trenches was constructed in the 1980s to test in-situ grouting technologies. One test-trench (of dimensions 6.1. m x 2.1 m x 4.3 m deep) was filled with simulated (non-radioactive) waste, primarily randomly-dropped waste drums. The trench was then grouted and, after several weeks had elapsed, the test trench was destructively analysed. The results showed that although the grouting did stabilise the test trench and filled void spaces, the trench was not entirely filled with grout and the contents of waste drums were not encapsulated by the grout. Thus, the desired hydraulic isolation of the wastes was not achieved (Low and Clements, 1987). In another field experiment at INL, the “Cold Test Pit South” was constructed in 1988, for further tests of waste characterisation and retrieval technology. The experimental pit contained a simulated waste layer comprised of cardboard boxes, metals, concrete, drums, sludges, etc. A later study evaluated the bacterial community which had become established in this system after approximately 20 years had elapsed (Field et al., 2010).

Hydrological impacts of the INL trenches, in particular the effect of trenches on downwards water infiltration rates, have also been studied in test trenches at a nearby USGS site (Nimmo and Perkins, 2008). A summary of a number of the "Surrogate Buried Waste Test Pits" at the USGS site is given by INEEL (2002). The pits contain a variety of simulated wastes including randomly dropped drums, stacked drums, cardboard boxes, large objects, cement drums, plastic pipe, concrete blocks, wooden boxes, sludge, glass, paper, metals, HEPA filters, furniture, etc, with some cells geochemically marked using rare earth elements (Nd, Tb, Yb, Dy). One cell was used for testing cryogenic removal of soil and debris (following in-situ freezing with liquid nitrogen). Tests of in-situ grouting, using various types of cementitious grouts, as well as a paraffin-based mixture, were also undertaken.

Other examples of experimental trenches near waste facilities include:

- Barnwell (South Carolina, USA), a sandy coastal site, where experiments primarily involved hydrology studies, including tests of cover designs (McMahon and Dennehy, 1987).
- Los Alamos, (New Mexico, USA), a semi-arid site, where test trenches were constructed mainly for testing cover designs (McMahon and Dennehy, 1987).
- Beatty (Nevada, USA), a site in the Mohave Desert, which is one of the most arid areas in the USA. At this site, radioactive waste was disposed in large trenches up to 90 m wide and 15 m deep. A five-year experimental study investigated how the unsaturated flow system was altered by the installation of the waste disposal facility and the differences between water-fluxes through the trenches in vegetated and non-vegetated conditions. The experimental trenches were excavated cubes (edges approximately 4 m), and each trench contained 104 drums filled with soil to simulate wastes (Andraski, 1997).

This survey shows that a number of experimental trench facilities were constructed in the United States in the 1980's and 1990's, with a range of objectives. It is not known whether experimental trench work has been undertaken in other countries[9]. Some of the USA experiences, particularly the experiments with cover designs and simulated waste materials, are applicable to the test trench program at Little Forest. However, the available accounts of these field studies apply to a range of scenarios which differ from Little Forest in terms of geological setting, climate, waste disposal practices, and specific objectives. Furthermore, with some exceptions, accounts of the work are restricted to the "grey" literature, and the experiments are often reported in very site specific terms, thereby limiting the transferability of the conclusions.

A shallow trench facility at the Lucas Heights Landfill

A shallow (~60 cm) experimental infiltration trench facility was constructed at the nearby Lucas Heights Land Fill after the completion of an early stage of the disposal operations at that site (Srisuk, 1981). The aim of the research was to study the infiltration characteristics of the shallow surface layer above the disposed municipal waste. Due to the total removal of the natural geological layers across the entire landfill, the trench surroundings were entirely different to the pre-existing natural lithology. Furthermore, in this previous study, the experimental trench was located above the disposed wastes and various types of sandy loam soils were emplaced in these trenches. These considerations, together with the much shallower depth of the infiltration trenches and the entirely different objectives of the study, mean that this installation is dissimilar to the pilot trench described in the present report. However, the results obtained from this previous study are of relevance to some aspects of the ongoing work at LFLS.

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[9] A literature survey using various search terms did not uncover any other trenches constructed in relation to legacy radioactive waste sites, although there were a small number of examples of trench experiments undertaken in different contexts (including the Lucas Heights infiltration trench studies mentioned in this chapter). Other examples included field tests of rainwater harvesting trenches and municipal waste water disposal using infiltration trenches.

7. General considerations and planning for LFLS test trenches

General considerations

The proposed test trench facility was intended to facilitate an increased understanding of a number of issues, including:

- trench hydrology and the mechanisms by which the water levels in the trenches fluctuate
- the effects of the excavated trenches on the hydrology of the immediate surroundings and their impacts on one another, including when the trenches are saturated
- the processes of evolution of the waste materials leading to modifications of chemistry and physical form of these components
- the physical processes leading to trench subsidence
- the trench construction process and possible constraints faced during trenching operations in the disposal period (1960-1968)
- the proposed options for remediation – including engineered covers and in-situ grouting.

To achieve these objectives, several test trenches were foreshadowed (Figure 7). The primary concern of this report is the “Pilot” test trench, which was constructed in June 2017. This trench provides a reference scenario, for characterising the soil profiles and hydrology. The trench was filled with pebbles of known physical properties, thereby providing a relatively simple hydrological situation. No simulated waste was placed in this trench. However, some instrumentation was installed, including piezometers and perforated tubes for housing future experiments. As will be discussed, the excavation of the pilot trench provided valuable experience of constructing a field installation on this scale and allowed insights into the operational processes and constraints during the disposal period.

Several other experimental trenches were originally planned, including:

- A “Chemistry” Trench – a reference chemical evolution scenario (with simulated waste)
- A trench for testing different types of engineered covers
- Trenches for future experiments involving grouting.

A simulated waste comprising objects having a similar physical form or chemical composition to the disposed wastes (omitting hazardous substances) is expected to be emplaced in the “Chemistry” trench. This will enable the chemical evolution of wastes to be studied and may be useful for testing surface-deployed imaging techniques for locating buried objects. Further experimental trenches may be envisaged in the future. The remaining trenches will be constructed when information gained from the preliminary trench has been fully interpreted and reported (including the present report).

The selected site for the test trenches was up-gradient of, and at a minimum distance of 15 m from, the legacy trenches (to ensure the experimental trenches will not impact on any future remediation of the legacy trenches). The excavated dimensions of the Pilot Trench were ~3 m depth, ~ 6 m in length and ~ 1 m in width. The spacing between trenches is expected to be approximately 3 m, with a possible layout shown in Figure 7. This includes vacant trench spaces should further research be required. At the time of writing this report, only the Pilot Trench had been constructed. It should be noted that the positions, dimensions and layout of future trenches are likely to differ from the conceptual arrangement shown in Figure 7.

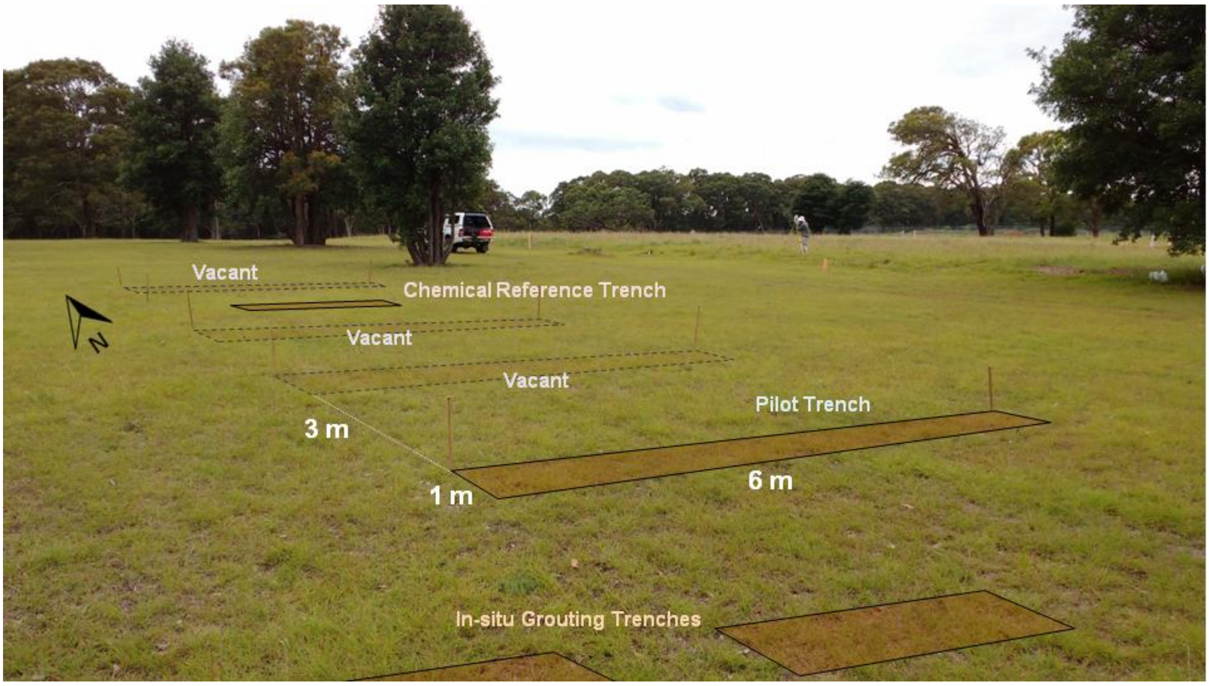

Figure 7. A proposed layout of the experimental trench facility at LFLS. The legacy trenches are located at the top of the photograph to the right of the vehicle. The excavation of the pilot trench is described in this report.

Sequence of excavation and construction activities

The main activities related to the pilot trench that were undertaken immediately before, and during, the trench excavation were the following (see also subsequent Sections of this report):

1. *Geophysical surveys*. These involved undertaking detailed electrical resistivity (primarily providing geological information) and electromagnetic (for buried metal) surveys at the proposed test trench site. These surveys were aimed at determining whether any legacy waste materials were present, or possible soil disturbances have occurred, that had not been recorded. Prior surveys of historical documents suggested that there has been no waste disposal at the proposed test trench location.
2. *Preparatory Coring*. Soil coring was undertaken using an auger-drill rig to facilitate soil and ground water sampling. This occurred around the perimeter of the proposed test trench site and in the locations of the proposed test

trenches. The aim of this task was to assess whether any contamination from the legacy trenches had moved in the direction of (or reached) the test trench location. Previous measurements over many years have suggested that contaminants (excluding tritium) have not significantly migrated westward from the legacy trenches. The samples were screened for gamma dose rate using a hand held device in the field as the core material was retrieved. This was followed by laboratory measurements of tritium, gross alpha, beta and gamma measurements as required, as well as tests for beryllium contamination. The excavation of the initial test trench was conditional on the results of the preliminary coring and groundwater sampling establishing that the area is free of contamination.

3. *Construction of piezometers*. Some of the preparatory auger boreholes were completed as water sampling and monitoring wells, and additional new piezometers were installed. These were intended to complement the boreholes already constructed at the LFLS site and enable monitoring of experiments in the test trenches.
4. *Test trench excavation*. The trench was excavated using an excavator equipped with various buckets and mechanical attachments appropriate to the geology encountered. Arrangements were made for installation of temporary shoring (known as a “trench box”) once a depth of 1.5 m below ground surface was exceeded. Staff members entering the trench were appropriately trained for working at heights and confined spaces, as is necessitated by Australian work-place law (see also Section 8 below). High resolution imaging of the trench walls was undertaken. Samples of various types of intact and fragmented cores were obtained at varying depths as the trenches were constructed. After safety clearance, samples were placed in sealed containers or bagged and retained for future laboratory experiments.
5. *Hydrology tests*. During construction, the extent of water ingress to the trench and the positions and behaviour of any water-bearing layers were noted. During trench installation the response of nearby piezometers was monitored and these data are discussed below (Section 15).
6. *Installation of monitoring equipment*. Various installations were placed within the test trenches, included experimental stations and sampling ports for ongoing monitoring purposes.

7. *Filling of trench void:* The pilot trench was filled using selected river-bed gravel (nominal size 2-4 cm, see Figure 32 and Table 6) which ensured a uniform composition and ensured structural stability.

Anticipated activities after construction

It is envisaged that various experiments will be undertaken within and around the test trenches. Hydrological experiments will assess the response of the trenches to natural and simulated water ingress (i.e. response to rainfall events). In addition, various experiments such as infiltrometer testing will be performed. Periodic samples will be obtained from the installed bore holes and multi-level samplers. Possible future experiments may involve adding non-radioactive tracer compounds (or possibly short lived radio-tracers). These may employ naturally occurring conservative tracers such as bromide, chloride, or other stable isotopes, as well as non-conservative tracers (possibly salts of rare earth elements) which could act as an analogue for any radiochemical ions. Experiments with organic tracers including dyes may be undertaken. Note that these post-construction experimental activities are outside the scope of this report.

8. Safety issues and documentation

A number of safety issues were considered in the safety assessment process and these are briefly discussed below. These have been documented here so as to facilitate the planning of similar future work. Further details were provided in the submission to the ANSTO Safety Assurance Committee (SAC), as discussed below.

Potential radiation and beryllium hazards:

Previous measurements had shown that the radiation hazard posed by soil and water samples outside the legacy trench area is negligible. Nevertheless, a safety assessment which entailed augering in the area between the legacy trenches and the proposed experimental trench area was undertaken prior to trench excavation. Samples of both water and soils were measured for gross alpha, beta and gamma activity in the laboratory. These samples were also measured for Beryllium contamination. Furthermore, a geophysical survey was also undertaken of the pilot trench area. The aim of these investigations was to establish that the proposed test trench area was free of contamination and buried objects.

As an additional precaution, the radiation levels in the excavated trench and in collected soil and water samples were screened during trench excavation using field radiation detection equipment (by Health Physics staff). Furthermore, potential exposures to particulate levels in the trench were minimised by wearing dust mask (class P2) protection and monitored continuously with on-person samplers.

Excavation Hazard Control

There are several main areas of risk associated with excavations as listed below:

- A person falling into an excavation: This includes both staff members who may be working along the trench edge or nearby, or unauthorised people (or animals) entering the Little Forest site. This hazard was controlled by the existing site fencing, specific inductions for all people working within the LFLS fenced area, a physical barrier > 2 m from all edges of the trench, as well as a guard rail at the trench edge, with fixed-point harnessing for those working within and above the open trench. In addition, the excavations were open for the minimal practical period and covered when the work-site was vacated.

- A person being trapped by the collapse of an excavation: Although the soil material is a strongly coherent clay and self-supporting, the depth of the trenches (> 1.5 m) necessitated the presence of a support structure whenever anyone was working within the trenches. Therefore an appropriately sized shoring box was emplaced and manoeuvred by the excavator / contractor. Access to the shoring box was via a ladder, with access restricted to personnel wearing fall restraint equipment.
- A person working in an excavation being struck by a falling object: Appropriate site management and personal protective equipment (PPE) enabled control of this hazard.
- Asphyxiation danger due to gas accumulation in the trench. Although considered unlikely, gas monitoring (O_2, CO_2, H_2S and combustible gases) was undertaken during excavations and portable ventilation equipment was kept on standby.

Other Aspects

Manual handling safety was also considered when manoeuvring heavy objects. Finally, the use of PPE when working in the trench was mandatory, including specific work clothes (e.g. high visibility vest) and steel-capped boots, hard hat, particulate mask and eye protection. Appropriate PPE (nitrile gloves, eye protection, P2 dust mask protection, field work clothing/boots, hearing protection – where necessary) was also worn during sampling activities. The availability of personnel with first-aid training and access to appropriate equipment was mandatory for the field work.

Safety submission process

The proposal for construction of the test trenches was prepared as a submission to the ANSTO Safety Assurance Committee (SAC). The SAC document number 2051 / 16 was submitted in November 2016 (part of this form is shown in Figure 8).

The submission was approved at the SAC meeting of 9 February 2017. As is customary for SAC, the safety aspects of the proposed work were examined in detail and a number of pre-conditions were required prior to the work being carried out. Following the approval by the SAC, the pre-requisites for the construction of the pilot trench were formally completed prior to trench excavation, including many of the issues mentioned above, such as:

- Prior augering and analysis, to demonstrate that the proposed area is free of radiological contamination and the presence of beryllium.
- Geophysical measurements of the site to identify any buried objects.
- Obtaining all the requisite safety equipment required for the potentially hazardous operations involved in constructing the trench and for personnel to enter the trench safely
- Training in working in confined spaces and/or at heights for some personnel.

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ansto **WHS Form**

Risk Management – Operation of SAC

Safety Assurance Committee Application Form

SAC No:	2051 / 16	Contact SAC manager for a number prior to submitting this form

Previous SAC No (if applicable):

Title:	Site characterisation and field studies at Little Forest Legacy Site, including installation of "Test Trenches"

Location of Proposed Operation	**Building No:**	Little Forest Legacy Site
	Room No:	

Figure 8. Safety submission form SAC 2051/16 covering installation of the test trenches

9. Geophysical and electromagnetic investigations

Electromagnetic survey (EM61 equipment)

Many of the objects buried at the LFBG were metallic. In particular, contemporary references indicate that steel sludge waste drums were buried (Ellis, 1977), and in some cases these were in a deteriorated condition prior to burial (Bonhote, 1964). Electromagnetic (EM) survey equipment is suitable for detecting buried metal objects, with the Geonics EM61 being designed primarily for detecting objects such as buried drums and storage tanks, as well as detecting utilities and delineating trench boundaries (Hoekstra, 1996).

The EM61-MK2 (with 1 x 1m coil) used in this survey is a high sensitivity, high resolution, time-domain metal detector suitable for the detection of both ferrous and non-ferrous metal. The system can be pushed or pulled as a trailer, by a person or vehicle. Typical target response is a single, sharply defined peak, facilitating quick and accurate determination of location. Achievable depth of detection depends on several target characteristics, with the surface area and orientation of the target of particular importance.

The EM61 survey was undertaken during February 2017. The EM61 was hand-towed along parallel lines separated by approximately 1 metre (Figure 9). The data position was independently co-recorded using an Omnistar 9200-G2 DGPS.

The EM61 transmitter generates 150 electromagnetic pulses per second, and measures the secondary EM response from the ground during the off-time between pulses. The EM61 records 4 channels of data, representing receiver coil response in mV at 4 consecutive time intervals. The intention of the 4 channels is to allow discrimination between different types of targets based on the time-decay of the measured EM signal. Channel 1 (first time interval) is the most likely channel to contain a metal detection response from a wide variety of target types (in terms of both size and depth). The data from Channel 1 contained the greatest sensitivity in EM response, showing more detections in more areas, and were selected for plotting over aerial imagery without additional processing (GPS datum correction only). For this metal detection survey, no modelling has yet been attempted (this is beyond the scope of the present report).

The data were collected in seven blocks providing coverage of the following areas:

- Proposed test trench area
- Legacy trenches –western section (Trenches 52 to 77)
- Legacy trenches –eastern section (Trenches 1 to 51)
- S1 and S2 trenches, located to the south of the main trench area, (AAEC, 1985)
- Three of the early investigation trenches emplaced in 1959 (Figure 5).

Detections from objects visible at the surface, such as metal fences, cut fence-posts, bore monuments and concrete slabs can be accounted for in the data interpretation by correlation with the existing aerial imagery and prior survey coordinates.

The detection results from the test trench and legacy trench areas (Figure 10) showed that the area of the proposed test trenches was free of detections of buried metallic objects. The survey of the adjacent legacy trench area showed a correspondence with the locations of a large number of buried 44 gallon drums in the legacy trench area. A more thorough comparison of EM61 detections with the waste disposal records is being undertaken and will be reported as part of the current project.

Figure 9. EM61 survey equipment over proposed test trench area.

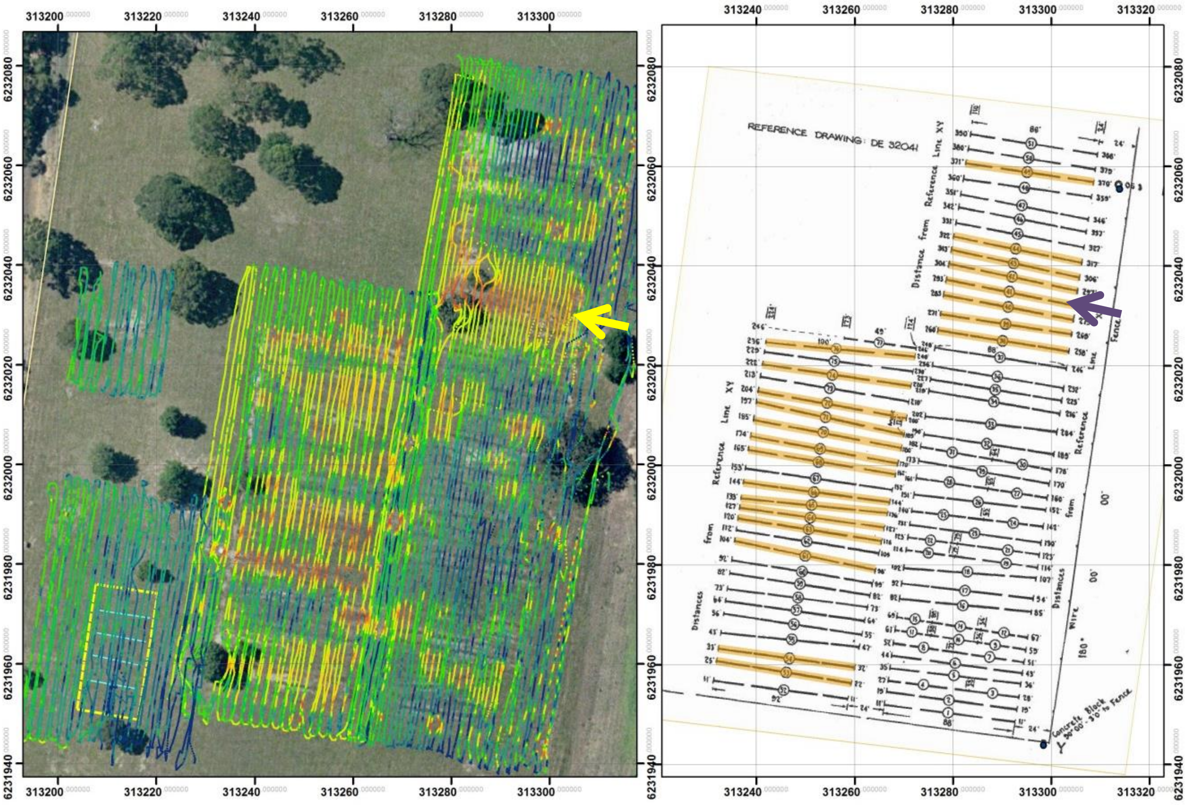

Figure 10. Correspondence of EM61 signal and position of waste drums as inferred from waste disposal records (trenches containing significant numbers of metal drums are indicated in orange in the RHS panel). Note the lack of detections in proposed test trench area (lower left of Figure). A strong signal (arrowed) is apparent in the vicinity of trench 41, known to contain a large number of drums (top right). The small test area in the top left of the figure recorded over a subsidence feature showed no detections.

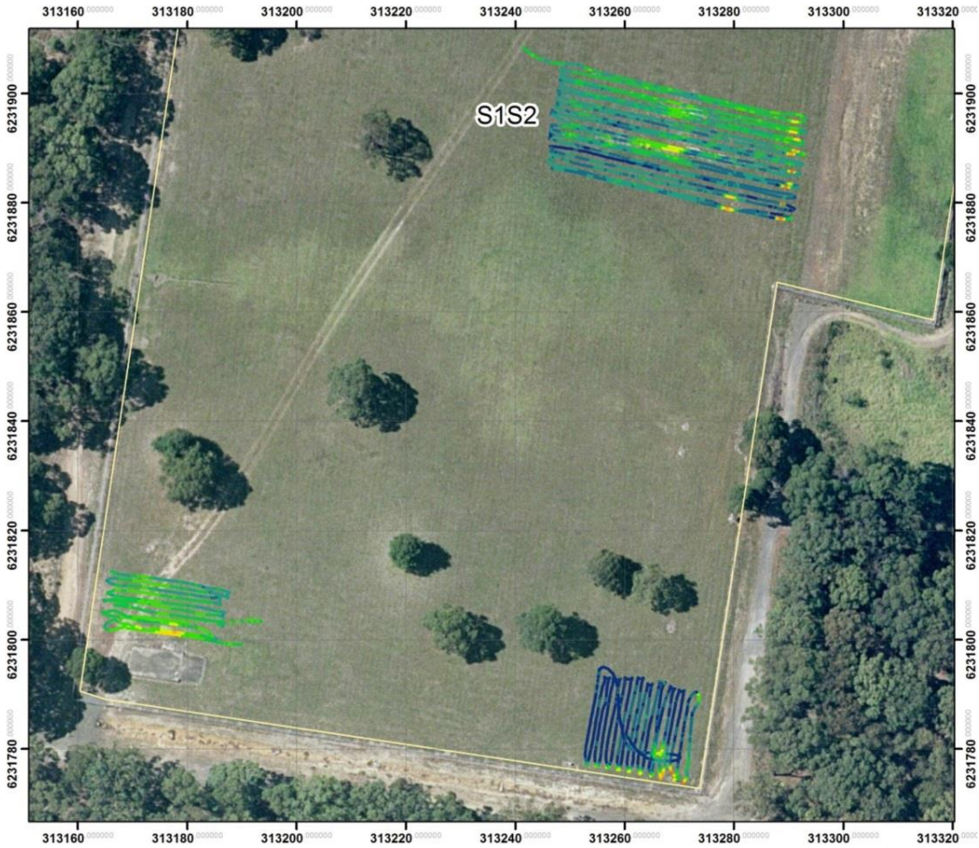

Figure 11. EM61 data for the S1 and S2 trenches and two other locations in the southern part of the LFLS fenced area.

The EM61 data recorded over the S1 and S2 trenches (to the south of the main trench areas) showed small amplitude, low frequency detections near the centre of both trenches, suggesting possible deep burial of one or a small number of drums (Figure 11). The S1and S2 data also shows surface metal features arising from the nearby well MB13, and old fence posts cut at ground level (these are aligned with the former continuous north-south fence-line, which was moved further east away from the trenches). The small test area undertaken over a subsidence feature in the south-west of the fenced area contained no detections aside from the influence of the adjacent concrete slab. The test area in the south-east of the fenced area over another subsidence feature showed a medium-amplitude medium-frequency detection, suggesting a metal object much smaller than a drum buried at shallow depth. This test site also showed surface metal features corresponding to the cyclone boundary fence and sign posts (Figure 11).

Fine scale electrical resistivity tomography

A closely spaced electrical resistivity tomography (ERT) survey was undertaken over both the legacy trench area as well as the pilot trench area in early June 2017, shortly before the excavation of the pilot trench[10]. Resistivity measurements are made by inducing an electrical current into the earth through two current electrodes and measuring the resulting voltage difference at two potential electrodes. Knowing the current and voltage values, an apparent resistivity value can be calculated. The investigation depth is related to the spacing between electrodes, with greater depths reached by increasing the electrode spacing[11]. The purpose of the ERT investigation was to contribute to understanding of legacy trench contents, distribution and variability by imaging the electrical resistivity of features related to the:

1. Depth of trench,
2. Thickness of backfill capping cover,
3. Water levels,
4. Position of drums, voids or other large resistive items.

As an additional objective, the resistivity equipment was also used to record pre-excavation conditions over the locations of the experimental trenches. The locations of the ERT survey lines chosen for the work are shown in Figure 12.

Resistivity profiles were collected using a Syscal Pro 72 electrode array and internal switching boards which selects the electrodes automatically, resulting in rapid resistivity imaging. All lines used a 72 electrode array with 0.4 m electrode spacing, resulting in a total profile length of 34.25 m and a maximum exploration depth of approximately 7 m (at the central third of the array only).

An initial test line was collected at both survey areas using both Dipole-Dipole and Schlumberger Array configurations. Following an onsite preliminary assessment of the data quality from each array type, Dipole-Dipole array was selected as being marginally superior and was used for the completion of both surveys. Location

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[10] This work was implemented by Stuart Hankin following discussions with colleagues from University of Strathclyde.
[11] ERT data acquisition and 2D data processing was contracted to GBG Australia Pty Ltd (Report No GBGA2054).

information for the start and end of each profile was recorded using an Omnistar 9200-G2 DGPS.

At the legacy trench site, three trenches of varying apparent composition were selected for resistivity surveying, largely based on interpretation of the EM61 data. Trench 5 was selected for its apparent low metal content, trench 61 was selected for its apparent high metal content, and trench 58 was selected as it is the host trench for the in-trench water sampler installed in 2011. Centre-lines were marked out for each of the three trenches using the GPS located EM61 results and also aerial imagery. The middle of the marked line for trenches 5 and 61 was located at the centre of the trench, accepting that the base of the trench may not be imaged at the extreme ends of the lines. The middle of the line for Trench 58 was marked offset to the east of the trench centre to ensure that data would not be truncated in depth at the trench sampler location (which is near the end of the trench).

Along each marked line, eight parallel profiles separated by a distance of 15 cm were undertaken using the resistivity equipment (Figure 13). The intention of acquiring resistivity data in such closely spaced profiles and small electrode separations was to allow for future specialist 3-dimensonal processing and interpretation of each set of 8 profiles as a single block model. At the experimental trench site, a single profile was collected aligned with each of the five proposed test trench locations.

Each recorded data line was subsequently processed using proprietary software Res2DInv to produce profiles of apparent resistivity (ohm.m). Resistivity profiles for the three legacy trenches (example shown in Figure 14) were broadly similar and have been interpreted with a three layer model.

1. Interpreted capping layer (approx. 250 mm – 400 mm),
2. Area of localised low resistivity (approx. 1 -3 m depth),
3. Interpreted host material.

Figure 12. Close-spaced resistivity survey lines showing the legacy trench area (red) and the proposed experimental test trench areas (green).

Figure 13. Close spaced array used for resistivity measurements

Most of the changes in the profiles are quite sharp, supporting the three-layer model. The capping layer can be seen as a thin, higher resistivity surface feature. This is above a broader deeper low resistivity feature, which starts at approximately 1 m depth and is approximately 2 m deep x 22 m long. This feature was seen across all legacy trench profiles.

The data reveals some areas of lower resistivity values with depth (below 4m) possibly indicating higher quantities of moisture. Small scale anomalous objects are seen within the data which may represent buried scrap, pipe or cable. Some areas of extreme low resistivity within the legacy trench areas indicate possible voiding or the presence of hollow objects such as barrels. Areas of high resistivity at depth may indicate scrap or fill.

The proposed experimental trench area (Figure 15) provided straightforward signals representative of native soils and clays and was interpreted as an undisturbed area.[12]

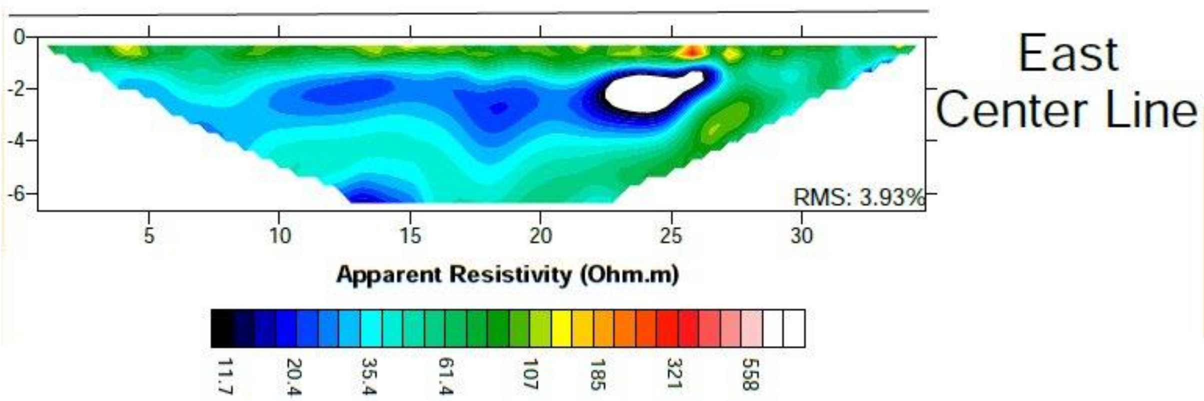


Figure 14. Example of a legacy trench image (parallel to trench) from closely spaced resistivity measurements.

[12] Further details of the ERT survey and its interpretation are contained in GBG Australia Report GBGA2054 (this report will be archived with other project documents and can be obtained from the lead author of the present report).

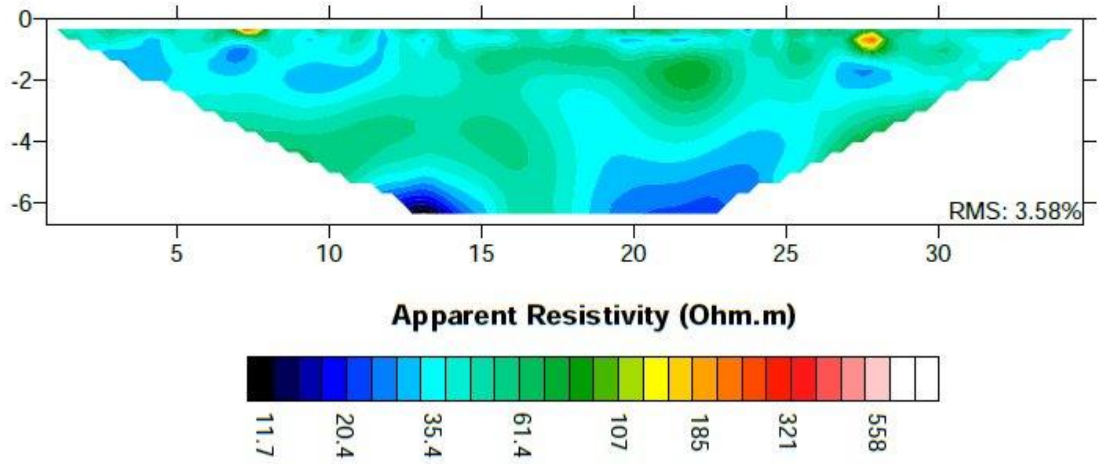


Figure 15. Example of an image across the proposed pilot trench area.

Larger scale resistivity

A number of larger scale resistivity traverses have been undertaken to delineate some of the larger scale features of the site. In contrast to the fine-scale resistivity described above, these primarily elucidate features at greater depths than the proposed test trenches, such as the contact between the shale and the sandstone layers. For this reason, these results are less applicable to the construction of the shallow experimental trenches but provide context for interpreting the results of field experiments with the trenches (for more detail of the large scale resistivity work, refer to Appendix 1).

Figure 16 shows the results for three transects in the vicinity of the test trench area[13]. The figure shows the thickness of the shale lens as well as its contact with underlying Hawkesbury sandstone materials, with results validated by existing bore lithological records.

[13] Locations of the transects are shown in Appendix 1 (Figure 64).

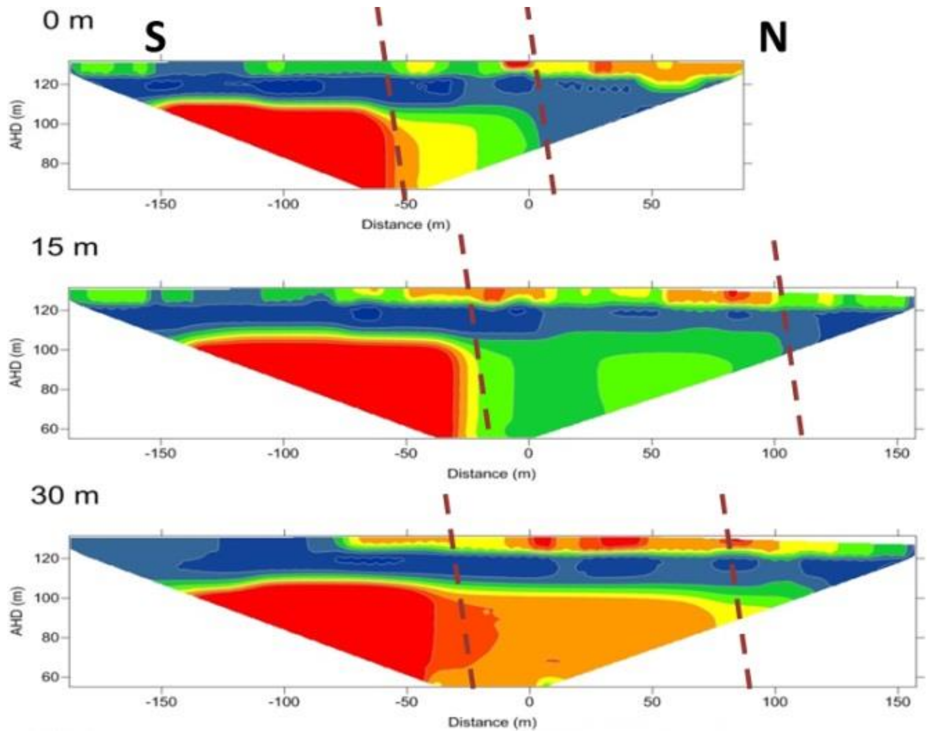


Figure 16. Examples of larger scale resistivity traverses for three N-S lines across the proposed test trench area (indicated as 0m, 15 m and 30m on Figure 64)

10. Preliminary coring (augering)

The preliminary augering exercise was undertaken on March 31st, 2017. The auger holes were in two locations (see Section 11 and Figure 21). The northerly one closest to the legacy trenches is auger hole TT01. The more southerly one is TT02, which later became part of the line of piezometers along the northern side of the pilot trench. Note that the locations of all piezometers within and in the proximity of the trench are shown in Figure 21 and Figure 23 (below).

Observations summarised below were made of the geology of the material as the samples came to the surface. Qualitatively the sequence was similar to previously reported (as shown in Figure 17).

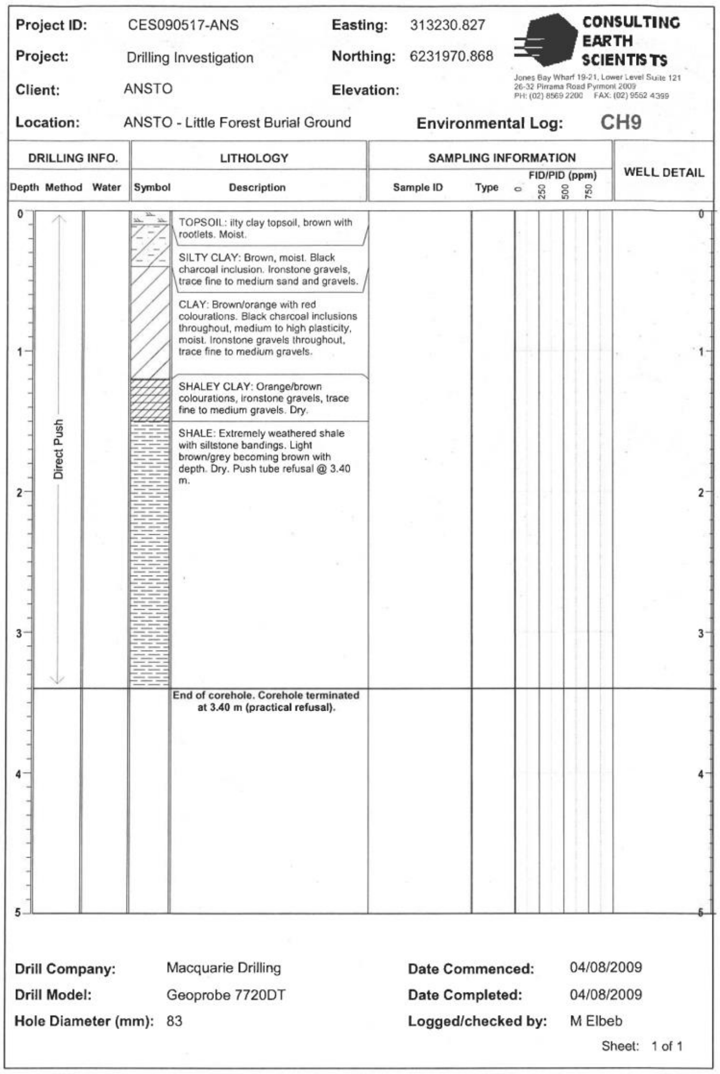


Figure 17. Geological log of CH9 near pilot trench (Hankin, 2012) .

For example, TT01 comprised the following:

- 0 - 20 cm. Topsoil
- 20 – 100 cm. Red-clay (some tree-roots)
- 100 – 150 cm. Grey, powdery, very dry, crumbly
- 150 – 240 cm. Continued dry and powdery, crumbly light grey.
- 170 cm. A grey gravelly layer and chips of shale
- 240 cm. A very hard layer, mottled grey and with iron mottling
- 250 – 300 cm. More grey-brown material, quite dry (water was added to advance the auger).
- At the base of the hole, samples were relatively dry and dark-brown in colour.

Similarly, TT02 involved:

- 10 - 20 cm. Topsoil.
- 20 – 90 cm. Red clay.
- 90 – 120 cm. Mottled grey clay (more apparent in TT02 than TT01).
- 120 – 170 cm. Weathered shale, crumbly, grey and more resistant to the auger. At 1.6 m it was noted as being dry and dusty. At this depth samples were predominantly chips of dry weathered shale.
- 170 – 180 cm. A harder gravelly layer.
- 190 – 200 cm. A yellow tinged section, possibly coloured by iron oxides.
- 200 cm to the base of the hole was harder material. However, because of difficulties in advancing the auger, water was added. This made observations of water-bearing layers difficult.

The quality of these in-field observations is limited by the mixing and disaggregation during the augering process. Therefore, the observations in the excavated trench are more useful in this regard (see Section 13 below). Samples were taken at various depths in both holes as the auger descended. Field measurements detected no radiation signal.

Figure 18. (a) Preliminary augering to ascertain absence of local contamination. Note the puff of dust (LHS). This shows how dry the shaly-clay layer is, despite several weeks of prior rainy weather. (b) Sampling from auger. External gamma screening on all samples revealed no contamination above background

Following completion of the drilling, both holes were finished off as piezometer sampling points (see Figure 19). After the holes had filled with water (a few days later), samples were taken for tritium analysis. As has been previously discussed, (Hughes et al., 2011) the legacy trenches are a source of tritium to the Little Forest groundwater, so this testing was intended to ascertain whether tritium was present at this location.

The results for the auger holes indicated no detectable tritium (Table 2), indicating that transport of tritium in groundwater from the legacy trenches is not significant. Water samples were also measured for gross alpha and beta, which were below measureable levels. Gamma analysis of soil samples revealed no detectable gamma activity (Table 3). Analysis of water samples obtained from the piezometers installed in the auger holes the following week similarly showed no detectable gamma-emitting radionuclides.

sample date	TT01 Bq/L	TT02 Bq/L
4/04/2017	<6	<6
6/04/2017	<6	<6

Table 2. Tritium results for water collected from TT01 and TT02 auger holes.

Radionuclide	Activity (Bq/kg)
^{234}Th	< 2.1
^{234m}Pa	< 7.2
^{230}Th	< 15
^{214}Pb	< 0.2
^{214}Bi	< 0.3
^{210}Pb	< 2.8
^{228}Ac	< 0.4
^{228}Th	< 13
^{224}Ra	< 1.6
^{212}Pb	< 0.1
^{212}Bi	< 1.0
^{208}Tl	< 0.9
^{235}U	< 0.7
^{227}Th	< 0.3
^{40}K	< 3.4
^{241}Am	< 0.2
^{137}Cs	< 0.1
^{60}Co	< 0.1

Table 3. Gamma analysis of bulk soil samples from the trench horizons in TT02. Results for samples from TT01 were similar.

Figure 19. (a) Pre-constructed piezometer, note the slotted section and spacers to keep it central in the hole. (b) Installation of sand-pack around slotted section. For more details, see Figure 25.

Elemental analysis of the soil samples obtained from the augering and subjected to acidic, microwave digestions (Table 4) showed that the trace element content of the samples (and the content of stable forms of selected waste radionuclides shown in Table 3) were typical of global averages for shales (based on comparisons with data in Krauskopf (1983)). In particular, the beryllium levels were not elevated in soils relative to global averages. Measurements of beryllium in groundwater indicated that all samples were below detection limits (0.1 µg/L). A similar analysis based on individual samples from specific depths (and using the more recent reference data of McLennan (2001) reinforces the above findings (Figure 20).

In conclusion, analysis of water and soil samples in the vicinity of the proposed pilot trench area revealed no levels of beryllium or any radionuclide which could be associated with any releases from the nearby trenches.

	Be	Co	Sr	Cd	Cs	Pb	Th	U
	µg/kg	µg/kg	mg/kg	µg/kg	µg/kg	µg/kg	µg/kg	µg/kg
TTA01, 0-1m	1410	2413	180	<130	7493	26636	12384	2402
TTA01, 1-2m	1450	5943	158	<110	8087	26973	12110	2201
TTA01, 2-3m	1700	5333	199	<70	8979	36626	13318	2623
TTA02, 0-1m	1320	3436	177	<60	9828	22572	12845	1903
TTA02, 1-2m	1390	2880	168	<60	8847	21110	10505	1436
TTA02, 2-3m	1550	1784	164	<70	9402	34581	10841	1547
Average (µg/kg)	**1470**	**3632**	**174**	**--**	**8773**	**28083**	**12001**	**2019**
Composition as percentage of global average shale value	49%	18%	44%	--	125%	140%	100%	58%

Table 4. Comparison of measurements for selected trace elements with global average shale values (from Krauskopf (1983)). Beryllium, cobalt and strontium are significantly below the global average shale. Other elements are within a factor of two of the average.

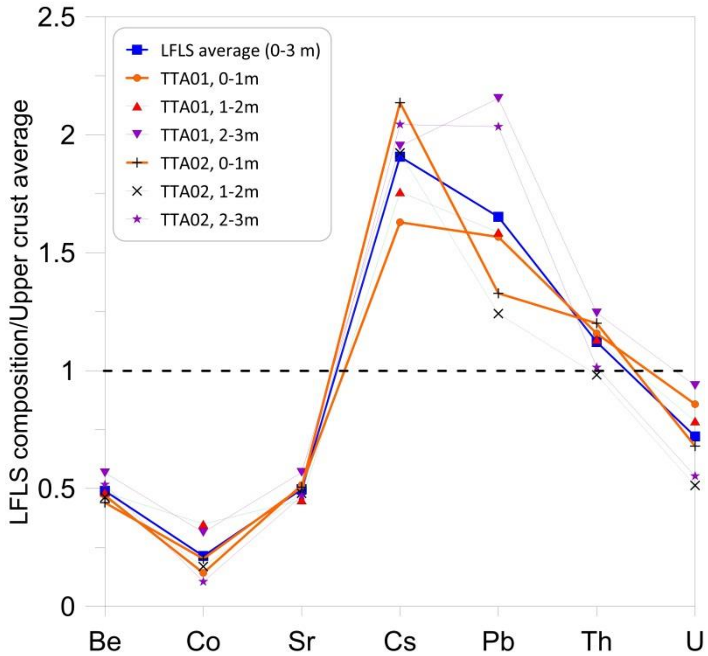


Figure 20. Relative enrichment or depletion between concentrations in LFLS trench samples (0-3 m) and average upper crust compositions (McLennan, 2001) . The dashed horizontal line separates those elements that are enriched at LFLS, compared to Upper crust average compositions (Cs, Pb, Th) from those that are depleted (Be, Co, Sr, U).

11. Installation of piezometer network

Drilling of further holes prior to excavation of the pilot trench was undertaken on May 23rd, 2017 so that a more thorough hydrological characterisation of the area (including "slug tests") could be undertaken prior to pilot trench installation. The locations of the installed piezometers in relation to the Pilot Trench are shown in Figure 21 (TT01 to TT07). The drilling procedure (Figure 22) was exactly the same as described for previous auger holes (TT01 and TT02), however, the main objective was simply the installation of the auger holes rather than assessing the presence of contamination. Figure 23 and Figure 24 show the cross sectional layout of the six piezometers immediately surrounding the pilot trench. These consisted of a line to the north of the pilot trench (TT02-TT04) and a set of piezometers (TT05-TT07) at different depths to the south. The layout is shown in plan-view in Figure 21. More details of piezometer construction are shown in Figure 25 and Table 5.

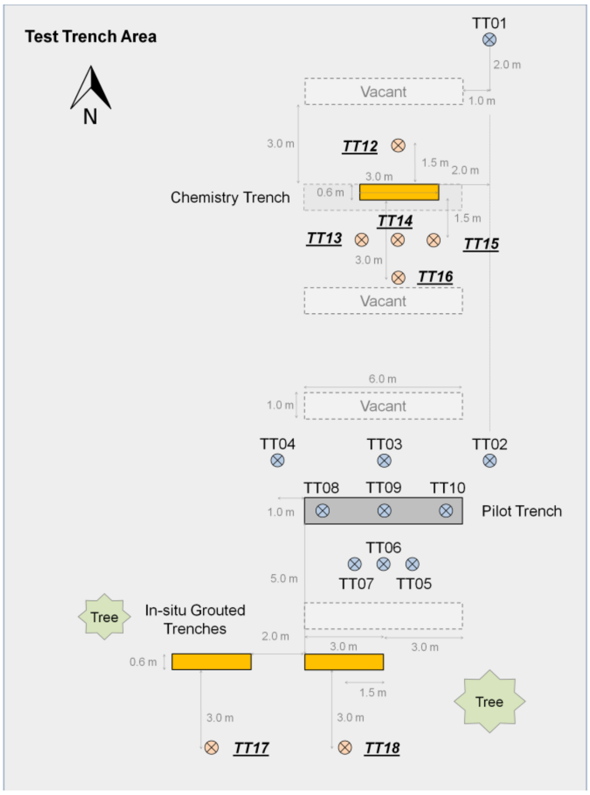


Figure 21. Conceptual design of the proposed multi-trench installation. Note that the positions of future trenches and auger holes (shown in orange) are yet to be finalised. However, the figure does depict the accurate position of the pilot trench and piezometers TT01 to TT07.

Figure 22. (a). Augering for installation of piezometers 15 (b) Completed layout of new piezometers looking south-easterly (25/05/17).

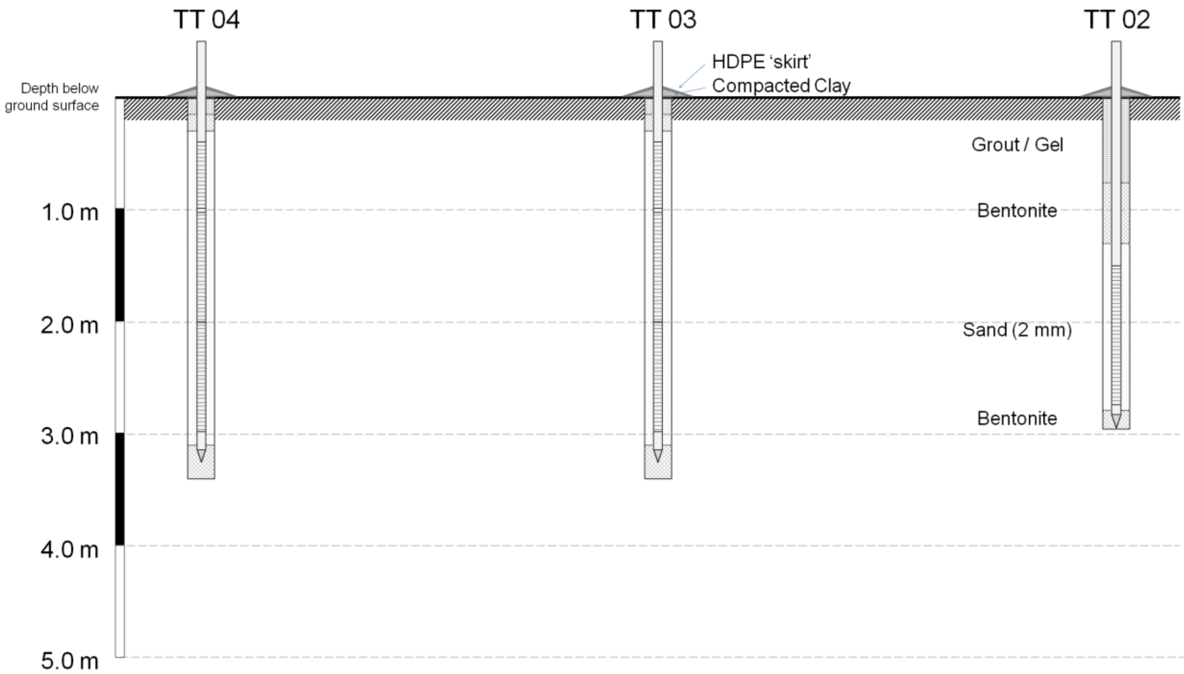


Figure 23. Line of piezometers located to the north of the pilot trench, comprising TT02 (installed during the augering exercise) and two other piezometers (TT03 and TT04).

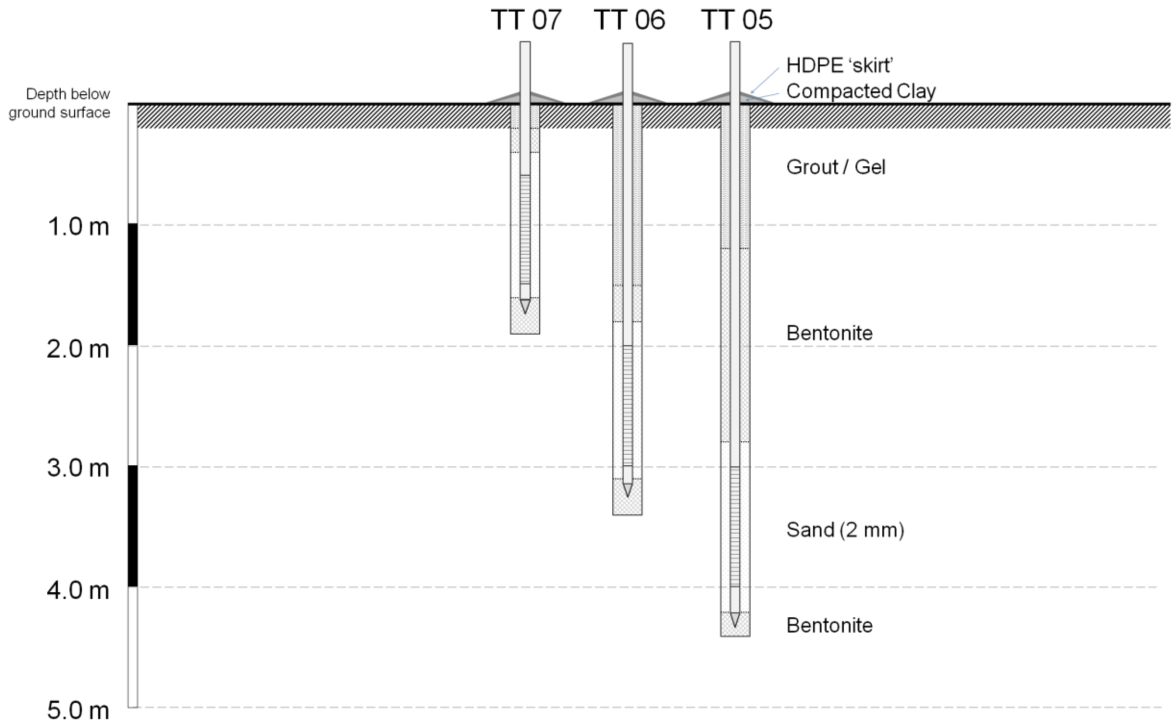


Figure 24. Nested piezometer set located to the south of the pilot trench, comprising piezometers TT05 (~4.4 m), TT06 (~3.4 m) and TT07 (~1.9 m).

ID Name	Type	Depth (m)	Screened interval (m)	Location
TT01	Piezometers installed via auger	2.95	1.5 - 2.75	Between legacy trenches and pilot trench
TT02		2.95	1.5 - 2.75	In a line north and parallel to pilot trench.
TT03		3.4	0.5 - 2.9	
TT04		3.4	0.5 - 2.9	
TT05		4.4	3.0 - 4.0	South line parallel to pilot trench
TT06		3.4	2.0 - 3.0	
TT07		1.9	0.58 - 1.5	

Table 5. Details of all piezometers and sampling points installed prior to the excavation of the pilot trench. Note: Four additional piezometers of similar diameter were included within the Pilot trench (TT08 to TT11) – see Figure 49, Figure 50 and Table 8.

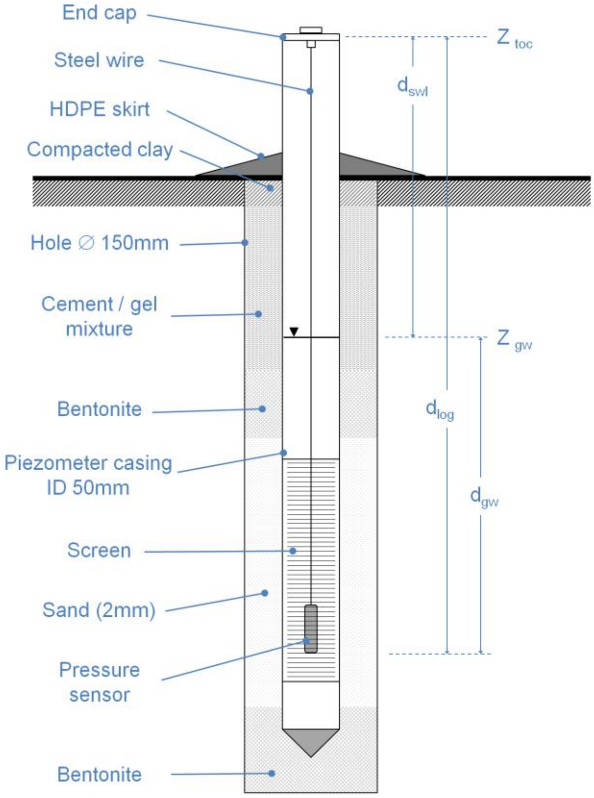


Figure 25. Construction details of representative piezometer. [Note: Z_{toc} - standing water level measurement reference point, d_{log} - pressure logger measurement point depth relative to Z_{toc}, d_{swl} – depth to standing water level measurement relative to Z_{toc}]. The installed well caps were of a sealable type which excluded atmospheric interaction. However experience suggests that these types of boreholes do not necessarily remain sealed from the atmosphere, hence in future work appropriate corrections will be made to the data using a calibrated barometric logger located in an adjacent well. Further details of the piezometer measurements, terminology and data analysis are given in Appendix 2.

12. Excavation of Pilot trench

Sequence of excavation

The pilot trench was excavated over a period of 4 days, Monday 26th June until Thursday 29th June, 2017. Firstly, the area of the trench was marked out between the previously installed piezometers (Figure 26a) and excavation commenced using a 0.9 m wide excavation bucket to carefully remove the surface/vegetation layer (Figure 26b).

The approximate progress of the trench excavation depth after each day is shown schematically in Figure 27. On day 1, the process commenced, progressively exposing horizontal and vertical faces, and obtaining intact cores from these depths using pre-manufactured metal tubes (see also Figure 37).

The progress of trench construction is documented in Figure 26 to Figure 31. Please refer to these figures and captions for brief explanations. Note that the shoring boxes seen in many of the figures were part of the safety requirements for this operation (as discussed in Section 8 of this report). After installation of in-trench sampling ports and piezometers, the trench was filled with river gravel to provide a uniform composition and maintain structural stability (Figure 32 to Figure 34). The properties of this material are summarised in Table 6.

Figure 26. (a) Marking out the area for the pilot trench. (b) commencement of excavation (Monday 26th June).

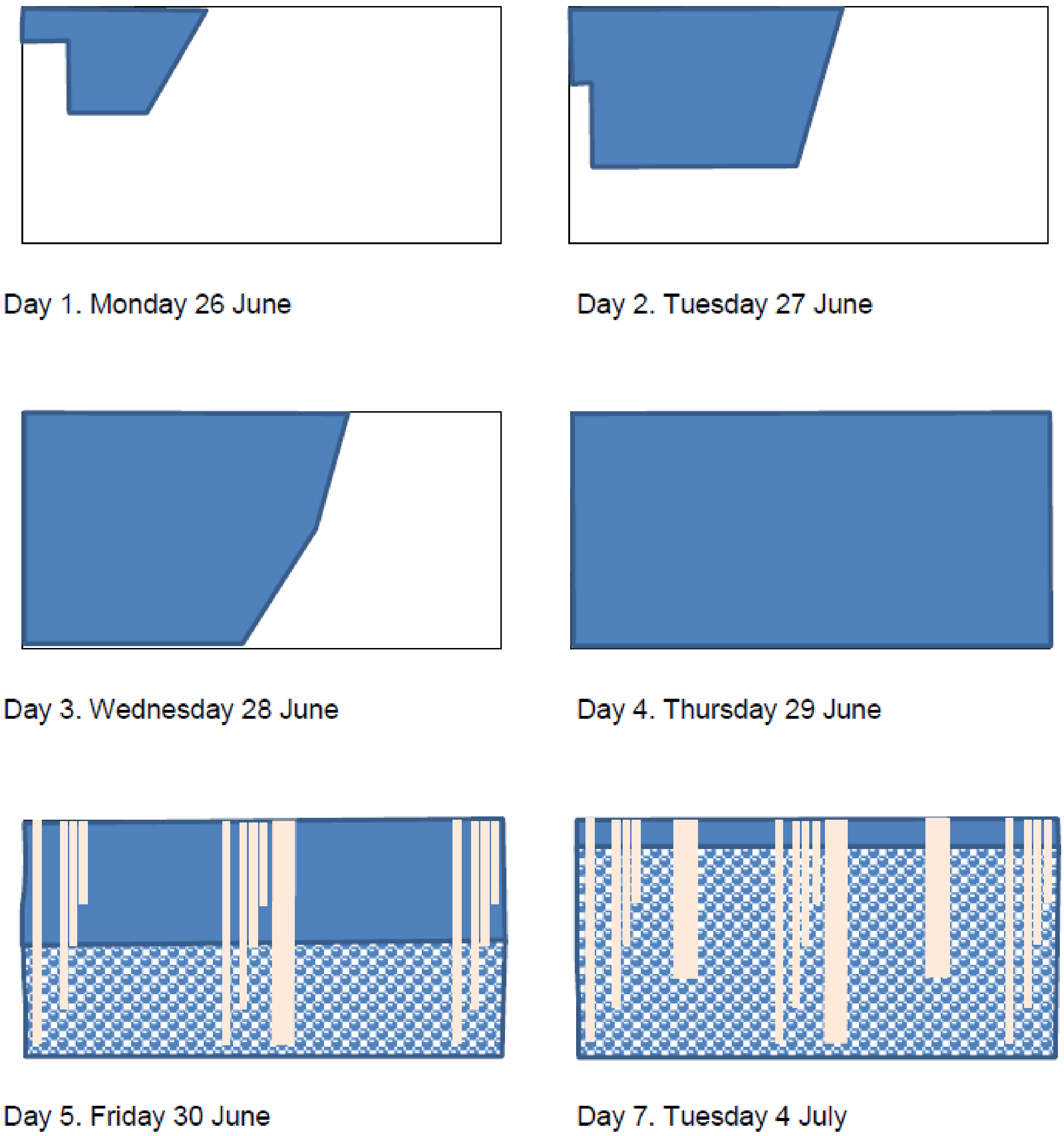


Figure 27. Schematic of daily progress on trench installation (section from west to east). Sections in blue correspond to excavated material and blue hatching to gravel infill (added on Friday 30th June and Tuesday 4th July). The last two panels show installed piezometers.

Figure 28. Progress of the trench early on Tuesday 27th June.

Figure 29. (a) First installation of a trench shoring box in the partially excavated trench (Tuesday 27th June, 3 pm). (b) Photograph of trench with shoring box removed (Wed 28th June, 1 pm).

Figure 30. (a) Installation of a shoring box in the completed trench (Thursday afternoon, 29th June). (b) In-situ inspections of completed trench within shoring box (Friday 30th June, 10 a.m.).

Figure 31. (a) Installation of the sampling tubes and in-trench piezometers (Friday, 30th June, 2 pm). (b) Removal of shoring boxes (Friday 30th June, 3 pm). The removal of the shoring boxes was a delicate operation, with special care being taken to avoid disturbing installed piezometers.

Figure 32. (a) River gravel used to fill the pilot trench. The pebbles were nominally in the range 2 cm to 4 cm in size. (b) Commencement of filling of the trench (Friday 30th June, 3:30 pm). On Friday the trench was filled to within 1.5 m of the ground surface, at which point it no longer met the definition of a confined space.

Figure 33. (a) The removal of some PVC pipes which had protected the piezometers when the stones were being emplaced. (b) Final filling of the trench on Tuesday 4th July. Prior to this time, two additional large diameter sampling experimental tubes (XP1 and XP3) were installed to a depth of ~2 m. See also Figure 50.

Figure 34. (a) Final state of the trench after filling with pebbles to within approximately 300 mm of ground surface (b) After installation of plywood to protect the side walls of the trench. Following extensive discussion it was decided not to cover the pebbles with a soil layer as this would have introduced a flux of particles into the pebbles which would have progressively affected hydraulic properties. The option remains to install a soil cover at a later date if desired.

Bulk porosity (void space in filled trench)	41.36%
Particle density of pebbles	2.646 tonnes / cubic metre
Bulk density of dry gravel filled trench	1.552 tonnes / cubic metre

Table 6. Properties of the river gravel (pebbles) used to fill the trench

13. Soil profiles and photographs during excavation

A large number of photographs and samples were obtained during excavation. This section mainly presents photographic evidence to assist the reader in interpreting the work undertaken and the geologic materials encountered. The details in the photographs are elucidated in the captions.

The top 1.25 m of a soil profile from the trench is shown in Figure 35. Qualitatively the profile is similar to that previously observed in nearby locations (Figure 17). This photograph also shows some metal tubes inserted for the purpose of obtaining intact samples. A view of the excavation of the trench is shown in Figure 36. Some of the obtained samples are shown in more detail in Figure 37 and Figure 38.

Examples of geological samples obtained are shown in Figure 39 to Figure 43. Of particular importance to note is the presence of tree roots in many samples from 2.5 m or greater depth (Figure 42). This is considered to be of significance because of the potential for tree roots to penetrate the waste trenches (at comparable depth) as well as the possibility of forming preferential pathways through some of the less permeable layers. Tree roots were encountered alive, dead and decomposed, and also burnt (i.e. charcoal). This results in enhanced macro-porosity and permeability around the tree roots. In one case the channels formed by a former-tree root were simply tested by pouring water through them, thereby demonstrating significant possibility to act as water conduits.

The material from the trench was put aside for later use (Figure 44) with the topsoil stored separately. Note that more detailed geological and soil-profile information has been presented in previous reports (e.g. Hankin (2012)) and these profiles will be discussed in upcoming reports and papers.

Photographs taken within the trench after the completion of the trench were particularly useful. These showed some of the positions of water ingress to the trench near to the base of the trench (Figure 45 to Figure 47) and the clear differentiation with the drier shallower layers (Figure 48).

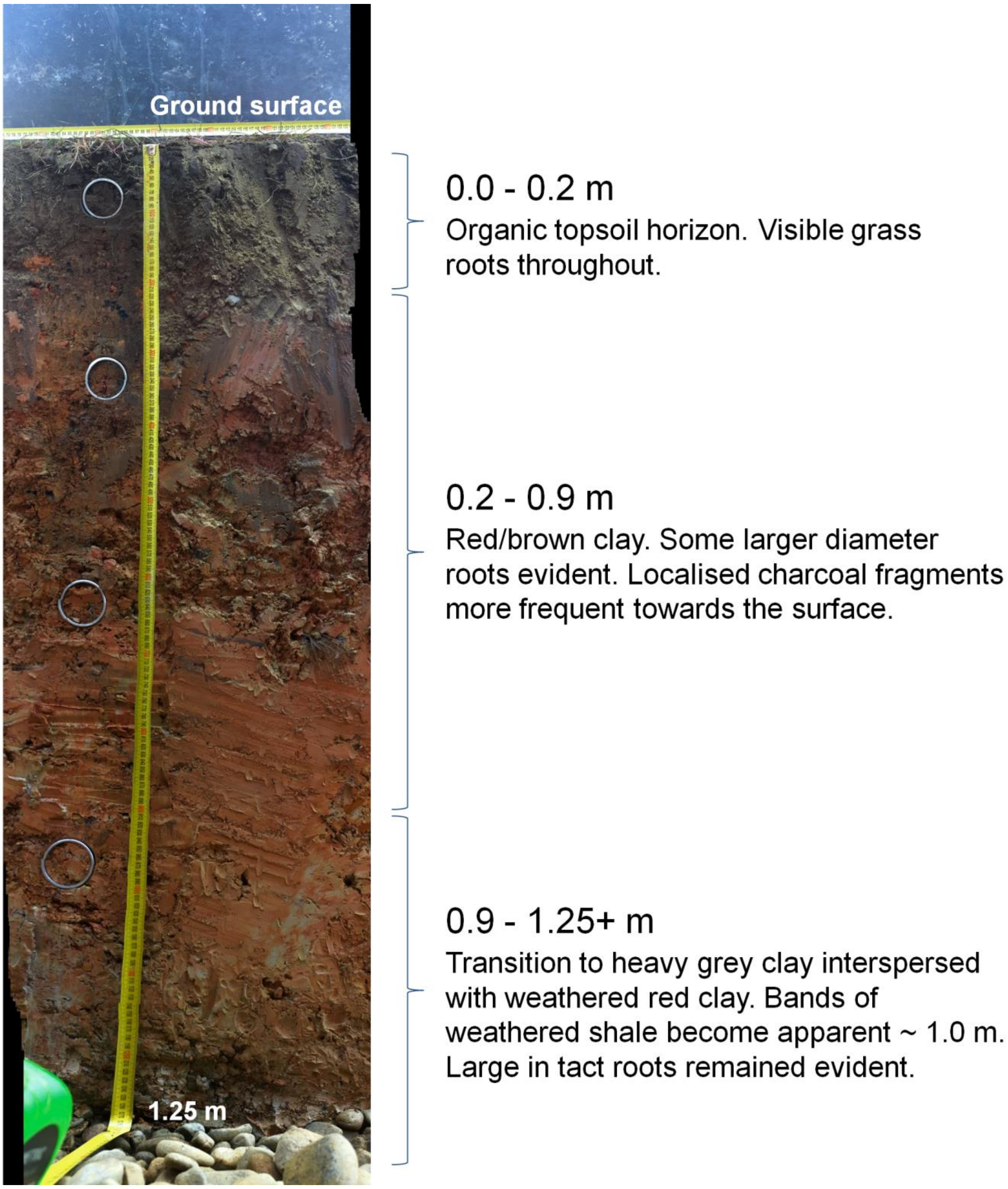


Figure 35. Photograph of soil profile in the pilot trench.

Figure 36. Southern Wall of Pilot Trench.

Figure 37. Photograph of sampler for intact materials for both (a) vertical cores (b) horizontal cores. Intact cores could only be obtained by this method for depths to ~1.1 m below ground level. Beyond this depth, the less-weathered shale materials fractured when trying to insert the steel corers.

Figure 38. Example of intact core obtained from the red clay layer.

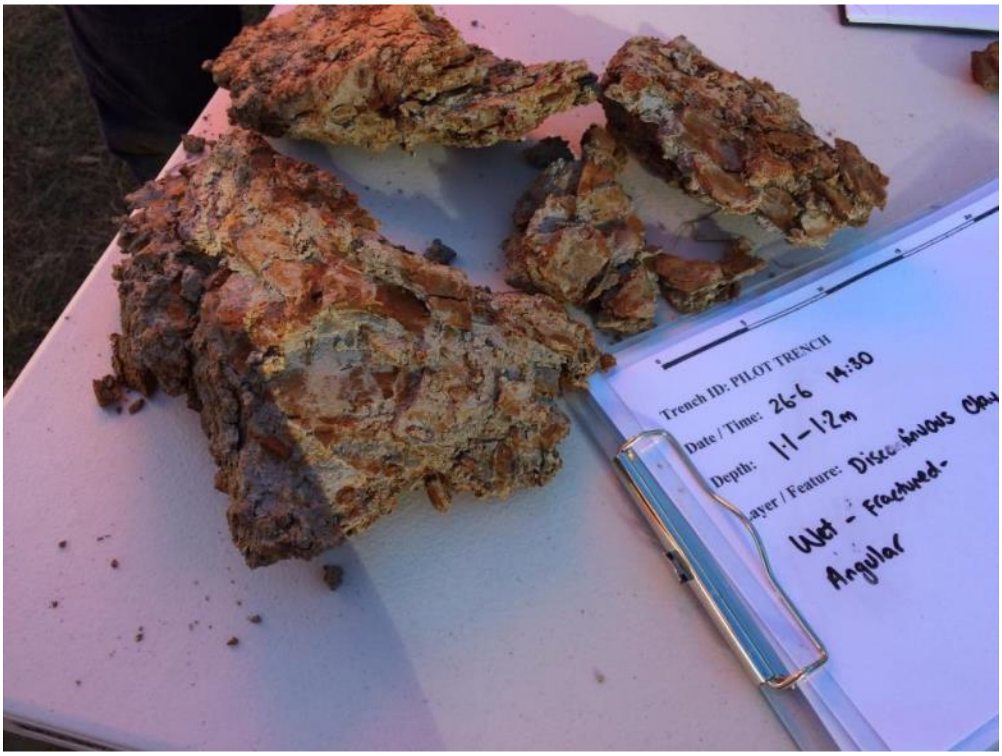


Figure 39. Weathered mottled clay fragments obtained from 1.1-1.2 m depth highlighting the transition through the partially weathered shale layer. The weathered shale showed weaknesses along horizontal bedding planes. Some of the fractures along bedding planes were noticeably wet, suggesting a pathway for the lateral movement of water.

Figure 40. Photographs of a sample from the partially weathered shale layer (~ 1.1 m below ground level) which contained tree roots.

Figure 41. Examples of less weathered samples (a) from 2.0 – 2.2.m and (b) from 2.5 to 2.7 m.

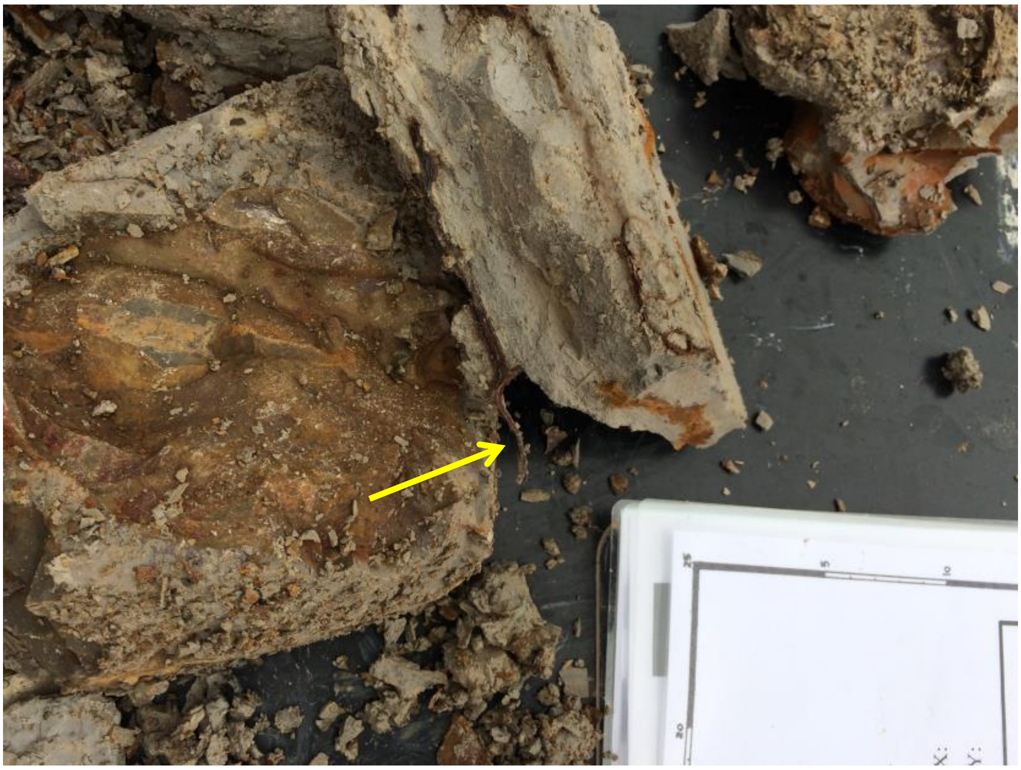


Figure 42. Photograph of a sample from around 2.6 m containing a root in the centre of the image.

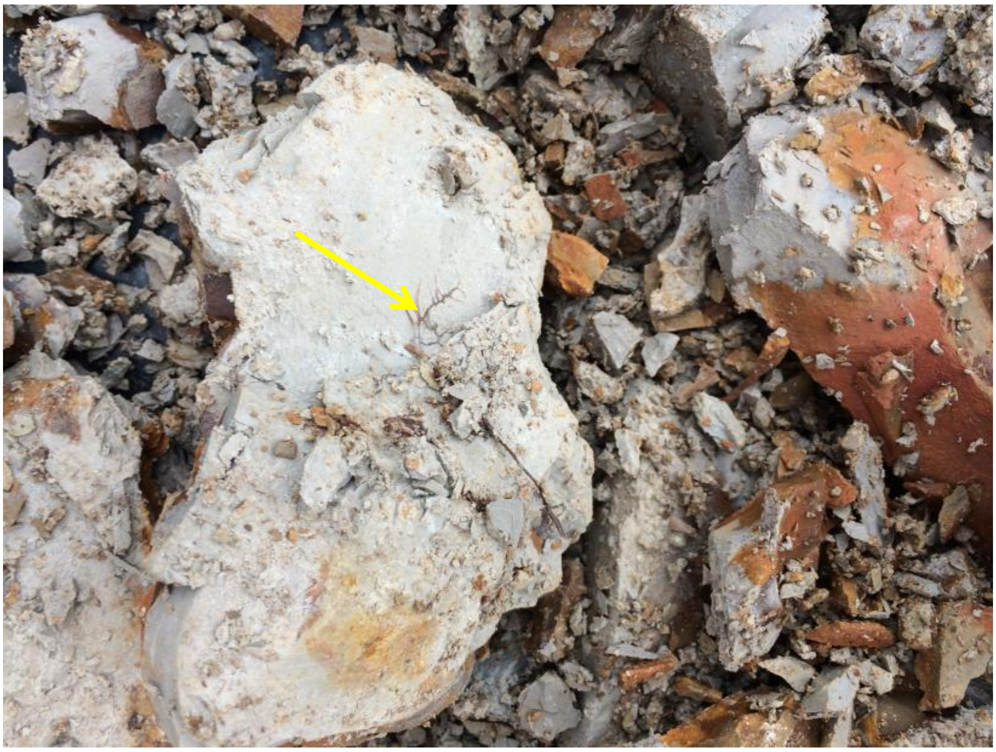


Figure 43. Another example of a relatively unweathered sample containing a root. Towards the right of the image, iron staining along fracture planes indicates a potential water flow path.

Figure 44. The piles containing material removed from the trench during the excavation, showing differences in coloration of materials from various depths.

Figure 45. (a) Water accumulated in the base of the completed trench, southern side, western end (video still). Note the position of the measuring tape, with its end resting on the trench base. (b) Clear evidence of water entering the trench approximately 35 cm above the base at the western end (video still, depth ~2.65 m).

Figure 46. Video stills from southern face of the trench, near the eastern end. Note that the upper image overlaps the lower image (the arrows show a common feature in the two photographs, which is possibly a scrape from the excavator). Both images were taken at approximately the same depth (2.8 m). There is clear evidence of water ingress at this depth (for example, in the circled area in the upper image).

Figure 47. Video still of the base of the trench (southern trench face, western end). Note that the trench sides appear to be more weathered but less fractured at the western end and the nature of the connectivity appears different from that shown in Figure 46.

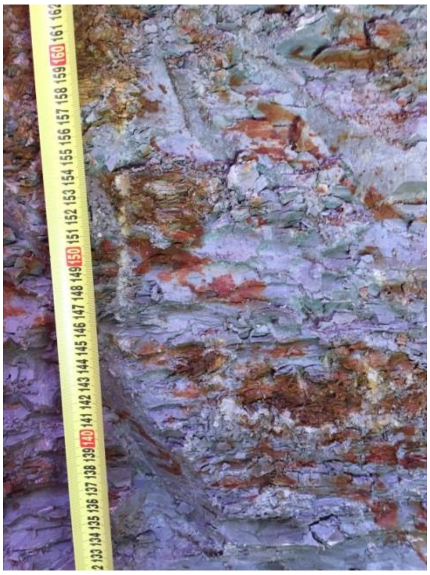


Figure 48. A photograph of drier weathered shale around 1.5 m below the surface (eastern end). This is believed to be above the layer where most water enters the trench.

14. Final layout of Pilot Trench

The final trench plan is shown in Figure 49. The sampling ports included;

- Large diameter perforated pipes for future experiments (XP series)
- Piezometers made of PVC slotted in specific intervals (TT series)
- Nested sets of piezometers (NP series)
- Multi-level geochemical sampling tubes (MGS series).

The depth of the trench was very uniform along its length, with a slight inclination reflecting the surface topography (Table 1). A full list of all piezometers, sampling points and future experimental locations is given in Table 8 along with their reference identification numbers.

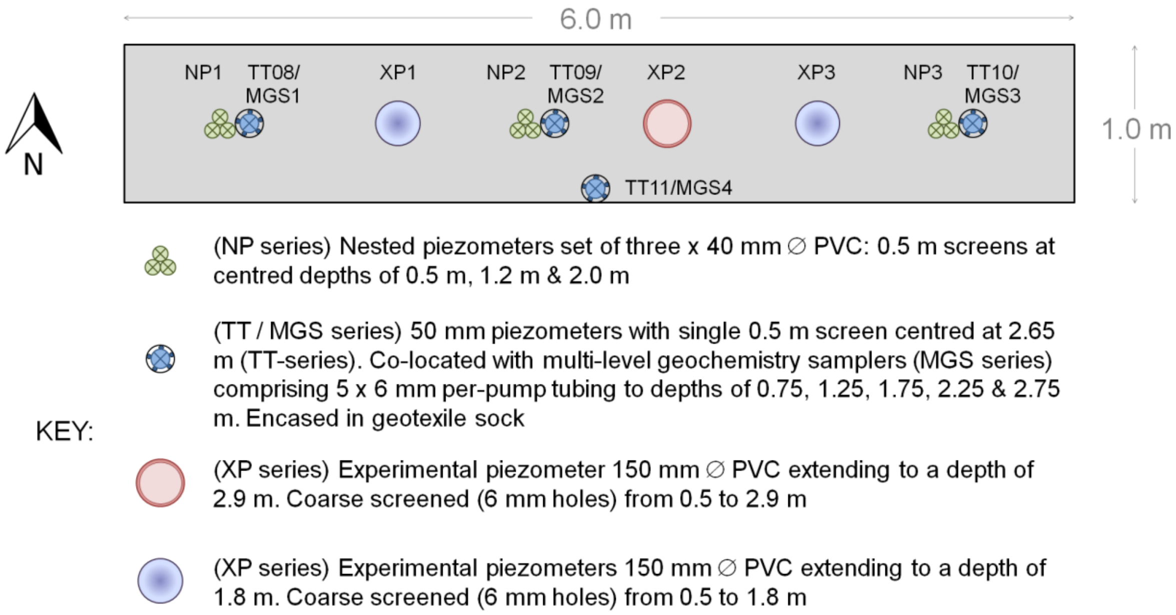


Figure 49. Plan-view of the pilot trench as constructed. Note that this diagram is not to scale and the indicated positions are approximate.

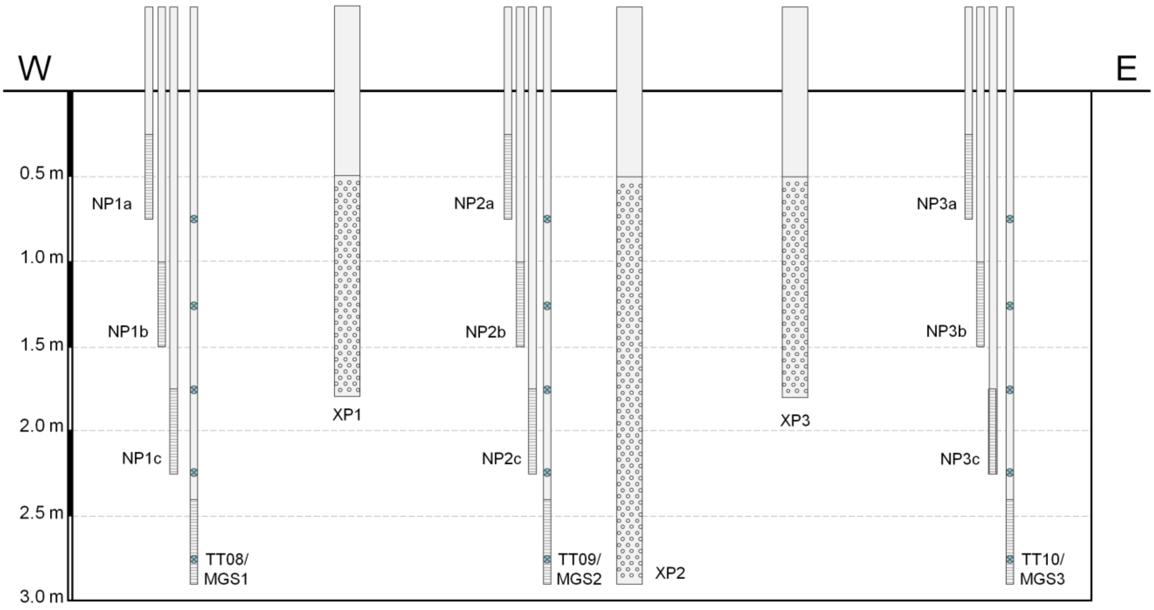


Figure 50. Side view of the pilot trench showing locations of all in-trench piezometers and sampling points (excluding MGS4 and TT11). Note that this diagram is not to scale and the indicated positions are approximate.

The pilot trench as constructed was almost a rectangular prism (dimensions 6.259 m (L) x 0.944 m (W) and depth 3.02 m), with very slight longitudinal and transverse slopes reflecting the topography. The base therefore had a slight slope, with the trench edge at the eastern end approximately 200 mm below the western end (the transverse slope is approximately 20 mm). The depth was determined by a laser device and direct tape measurements, which were in agreement except at the eastern end where there was a shallow pool of accumulated water. The dimensions in Table 7 reflect the depth to base of trench along the centreline and, where water was present, the approximate depth of water.

Distance along centreline from western end	0.65 m	1.43 m	2.68 m	3.54 m	4.64 m	5.93 m
Depth to trench base (m)	3.02	3.03	3.03	3.02	3.02	3.02
Water depth at time of observation (mm)	0	0	0	20	50	80

Table 7. Depth of trench measured along centreline and water depths.

ID Name	Type	Depth (m)	Screened interval (m)	Location
Large experimental ports in pilot trench [1P] along mid-line				
XP1-1P	150 mm coarse screened PVC pipe	1.8	0.5 – 1.8	West end
XP2-1P		2.9	0.5 – 2.9	Centre
XP3-1P		1.8	0.5 – 1.8	East end
Piezometers of similar construction to TT01 to TT07 (on trench mid-line)				
TT08	50 mm PVC screened from 2.4 to 2.9 m	2.9	2.4 – 2.9	West end (co-located with MGS-1)
TT09		2.9	2.4 – 2.9	Centre (co-located with MGS-2)
TT10		2.9	2.4 – 2.9	East end (co-located with MGS-3)
Piezometer of similar construction to TT01 to TT07 (on southern side of trench (see Figure 49)				
TT11	50 mm PVC	2.9	2.4 – 2.9	Centre, south side (co-located with MGS-4)
Nested piezometers in pilot trench along mid-line				
NP1a-1P	40 mm PVC	0.75	0.25-0.75	West end
NP1b-1P		1.45	0.95-1.45	
NP1c-1P		2.25	1.75-2.25	
NP2a-1P	40 mm PVC	0.75	0.25-0.75	Centre
NP2b-1P		1.45	0.95-1.45	
NP2c-1P		2.25	1.75-2.25	
NP3a-1P	40 mm PVC	0.75	0.25-0.75	East end
NP3b-1P		1.45	0.95-1.45	
NP3c-1P		2.25	1.75-2.25	
Note: The screened intervals in the MGS samplers provide similar sampling points to the NP series at greater depths of 2.4 to 2.9 metres.				
Multi-level geochemistry (MGS) samplers (co-located with 50 mm PVC piezometers)				
MGS1-1P	Tubing at depths of 0.75, 1.25, 1.75,2.25 and 2.75 m (supported by 50 mm PVC tubes).	2.9	Various sample depths – see note	West on mid-line (co-located with TT08)
MGS2-1P		2.9		Centre on mid-line (co-located with TT09)
MGS3-1P		2.9		East on mid-line (co-located with TT10)
MGS4-1P		2.9		Centre on south face (co-located with TT11)
When referring to individual sample points in the MGS piezometers, an additional indication of the depth interval will be required. For example, MGS1(0.75m); MGS1(1.25m), MGS1(1.75m), MGS1(2.25m) and MGS1(2.75m).				

Table 8. Details of all sampling points installed within the pilot trench. Note that the designation "-1P" (in the ID after the hyphen) for each sampling port identifies the point as experimental trench 1 (Pilot trench). Other trenches will be designated similarly. It is suggested that the part of the ID name after the hyphen can be omitted in all cases where there is no ambiguity about which trench is being discussed.

15. Hydrological measurements during and following trench excavation

This chapter provides a qualitative overview of the impact of the construction on the test trench on the water levels in surrounding piezometers. The following chapter examines the obtained data in more detail and correlates the hydrological measurements to the near-surface lithology of the site.

Overview of measurement methods

As discussed in detail in Section 11, a total of 7 piezometers (TT01 to TT07) were installed prior to the excavation of the pilot trench[14]. The location of the piezometers is shown in Figure 21. Automated water level loggers (known as "Hobo" loggers) were installed in each of these piezometers.

Aquifer tests

The possibility of slug tests of the installed piezometers was investigated. Preliminary investigation found that some piezometers were screened above the water table and/or were not air tight. Therefore, air pressurised slug tests were not performed on the monitoring piezometers. An alternative approach using Lugeon tests was implemented.

All test trench piezometers (TT01 to TT07) were subject to Lugeon tests on 14th June 2016, in which each piezometer was filled to, or just above, ground surface with town water. Prior to this hydraulic testing the loggers were programmed to temporarily collect data at a higher frequency to provide information on the propagation of pressure pulses through the system.

Observations during test trench construction

The controlled excavation of the test trench provides a comprehensive test of the aquifer and aquitard properties surrounding the test trench. The major observations include:

[14] Four similar piezometers (TT08 to TT11) were also installed within the pilot trench. These were subsequently used for hydrologic tests involving incremental additions of water to the pilot trench. These experiments are not described in the present report.

- Small amounts of water seepage into the trench from clay layers (Figure 51)
- A greater amount of water seepage occurred from the weathered shale below the clay layers (Figure 52 to Figure 55)
- The walls of the trench were visibly wetter on northern side, which reflects the inferred hydraulic gradient at the site
- Plant roots were observed across the entire depth range (see e.g. Figure 42)
- Examination of a soil profile from within the excavated trench (Figure 35). Note that the photographs were supplemented by video-recordings which have been preserved for future examination (some stills from these recordings are included in the present report).

Main features of piezometer water level response Pilot trench construction

As noted above, the prior installation of the surrounding piezometers meant that the excavation of the Pilot Trench provided a unique opportunity to study the response of the hydrologic system to the excavation of the pilot trench.

The raw data from this exercise were very informative (Figure 56). The data should be interpreted taking into account:

1. The positions of the piezometers (Figure 21)
2. The depths of the screened sections in the piezometers (Table 5)
3. The geological layering and transitions (Figure 36).
4. The daily progress of excavations (Figure 27).

The water levels in all piezometers slowly declined in the period prior to the trench excavation, due to lack of rainfall after the earlier Lugeon tests. On the first day of excavation (Monday 26th June), during which a depth of ~1.2 m at the western end of the trench was reached, there was very little response of any piezometer. A very small loading response was recorded within the shallow TT07 piezometer and a very small unloading response was recorded within the deeper piezometers TT02 and TT06. This may be associated with movement of heavy vehicles and equipment about the piezometers, opening and closing of the well caps or adjustments to the data loggers themselves.

The more substantial excavation to a depth of ~2 m on the following day (27th June) elicited a strong response from both of the deeper down-gradient boreholes (TT05 and TT06), and also from the two north-westerly (up-gradient) piezometers (TT03 and TT04). Further excavation on 28th June (to ~ 3 m in the western end of the pilot trench) caused another sharp response in TT06, and an increased rate of decline in TT03, TT04 and TT05. The more easterly piezometer in this set (TT02) only responded when the excavation of the eastern end of the trench was completed on the 29th June.

A key feature of the data which is immediately apparent is the evidence of good connectivity between the pilot trench and the surrounding piezometers (except at shallow depths). This means there is potential for water flow in these layers. This should not be interpreted as meaning that flow of water in these layers is rapid (the tritium data shows the flow rate is only a few metres per year), but it does show the potential for rainfall into the trenches to flow outwards from the trench at depth (as well as inwards). This connectivity may contribute to the extent of the tritium plume at the site (Hughes et al., 2011) as well as the observation that boreholes in the trenched area can show artesian properties after intense rainfall (see the discussion in (Payne et al., 2013), particularly Figure S4 in the supplementary information to that paper, also shown in Figure 57). However, the limited response of borehole TT02 to the excavation of the western end of the trench (and its response to the excavation of the eastern end - see Figure 56) reveals an important additional feature of the hydrology of the site. The strong apparent connectivity of TT02 with the eastern end of the trench but lack of initial response to the excavation of the western end suggests that the connectivity within the lower shale layer is clearly not uniform[15]. One implication of this observation is that the trenches, as well as forming windows between the surface layers and the (partially) confined layers below, may also act as conduits for lateral flow of water.

Therefore, the surrounding piezometers showed clear responses to the excavation of the pilot trench, which could be linked both to their position (Figure 21) and depth (with respect to the geologic layering), as well as to the excavation of specific depths

[15] Another possible explanation for this observation is that there is a delay (~2 days) in the response of TT02 to the construction of the western end of the trench. This possibility cannot be excluded based on the current data, but seems less likely based on subsequent irrigation tests.

of the pilot trench. Thus, the comparison with Figure 27 is particularly instructive. The preceding discussion is based on a qualitative interpretation of the raw data presented in Figure 56.

Figure 51 (a) Photographs of a small amount of seepage observed from shallow layers (b) View of southern edge of trench after initial excavation (to ~1.2 m).

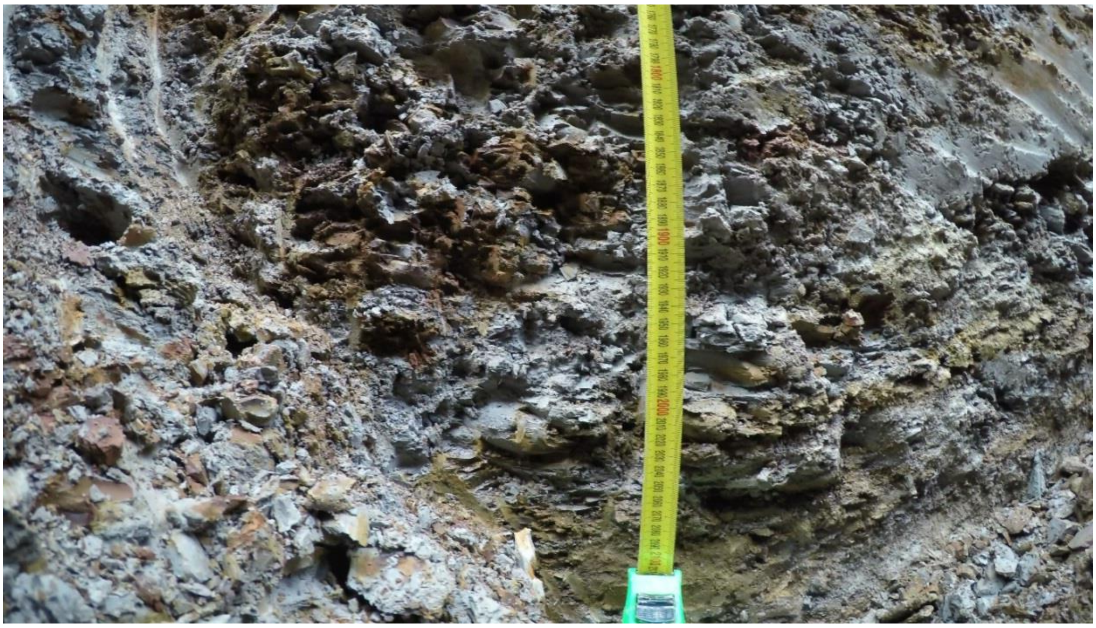


Figure 52. Weathered shale layer (~1.7-2.0 m) immediately above a seepage accumulation zone (northern face of trench).

Figure 53. Dr Cath Hughes inspecting seepage into Pilot Trench below the hard shale / siltstone layer at 2.15m depth

Figure 54. Seepage into Pilot Trench below the hard shale/siltstone layer at ~2.15m depth

Figure 55. Water accumulating in the trench from the wetter layers observed at depth. The colour gradation in the layers shows a transition from (red) clay to (grey) weathered shale. The boundary occurs between ~0.9 and ~1.1 m.

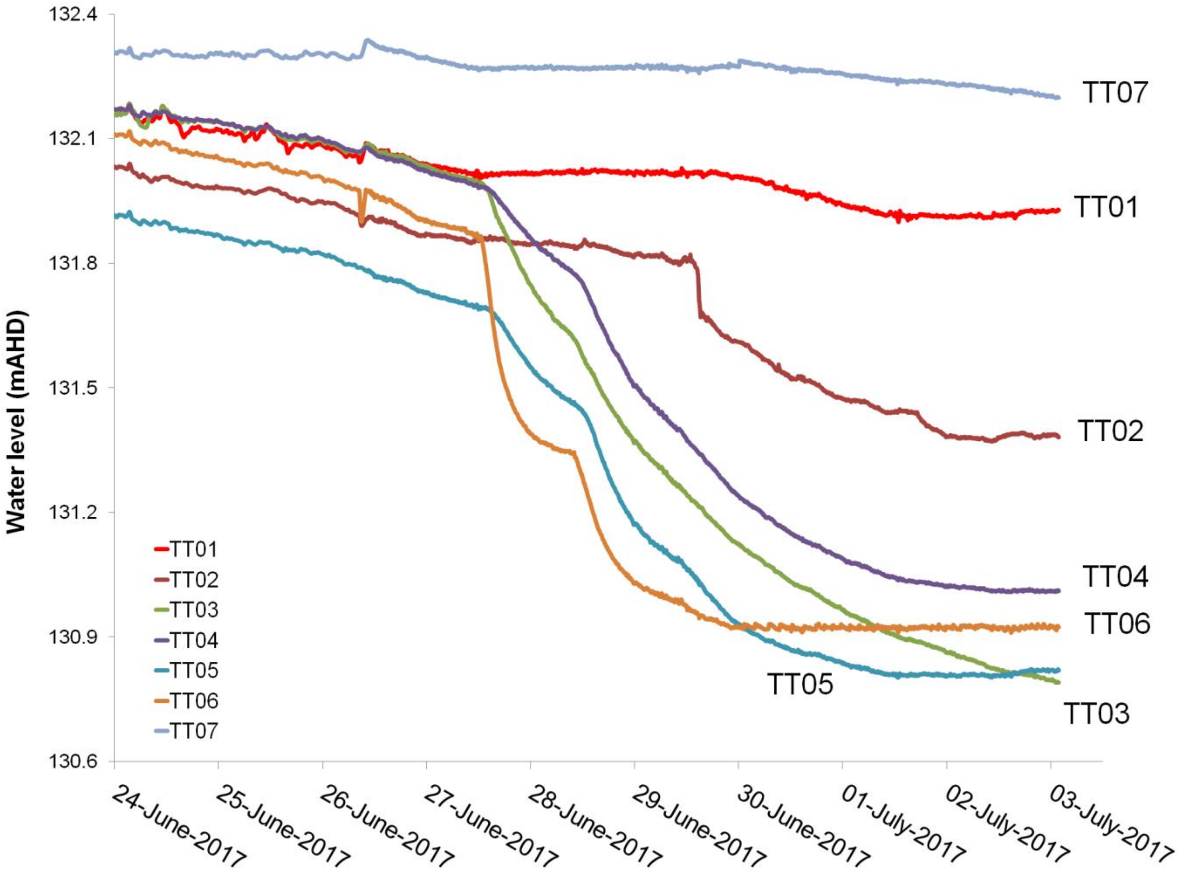


Figure 56. Hydrographic response to excavation. The daily progress of the trench is shown on Figure 27, with clear hydrographic responses to each additional excavation step. The four up-gradient piezometers are TT01 (some distance away), TT02, TT03, and TT04 (all ~3m depth arranged E to W). The other measurement points (TT05, TT06, and TT07) are the nested set on the down-gradient side (4.4, 3.4 and 1.9 m depth respectively, as depicted in Figure 24). TTT02 responds later to the excavation of the eastern end of trench on 29th June (Figure 27). The lack of hydrologic response of the down-gradient shallow piezometer (TT07) is noticeable. Note that the high water level in this borehole is due to the addition of water during Lugeon testing (see Figure 58).

Figure 57. Borehole OS3 after extreme rainfall event showing artesian behaviour (9 March, 2012).

16. Preliminary quantitative interpretation of piezometer data: prior to, during and after pilot trench construction

Groundwater level and rainfall observations for the test trench field campaign are reproduced in Figure 58. Observations are presented from 25th May 2017 to 3rd July 2017. This period commenced approximately one week prior to the augering and construction of the test trench monitoring piezometers. It extends to the completion of test trench excavation. Note that the water-level traces from the pilot-trench construction period appear towards the right of Figure 58. (The same data appeared on Figure 56). The following sections and accompanying figures expand the various sections of this time period, including initial seepage into piezometers, response to a rain event (7-11 June), Lugeon tests (15th June), and finally a preliminary interpretation of the piezometer responses during the construction of the test trench.

Seepage of groundwater into the newly constructed piezometers between 2nd and 6th June

The water levels in the piezometers following their construction are shown in Figure 58 (note there was a delay between construction and the commencement of water-level monitoring, so there is only a few days of data prior to the first rainfall event). The asymptotic response of the groundwater levels following construction of all piezometers provides evidence of a water table within the weathered and fractured shale on hard shale at approximately 2 m depth (131.25 m AHD).

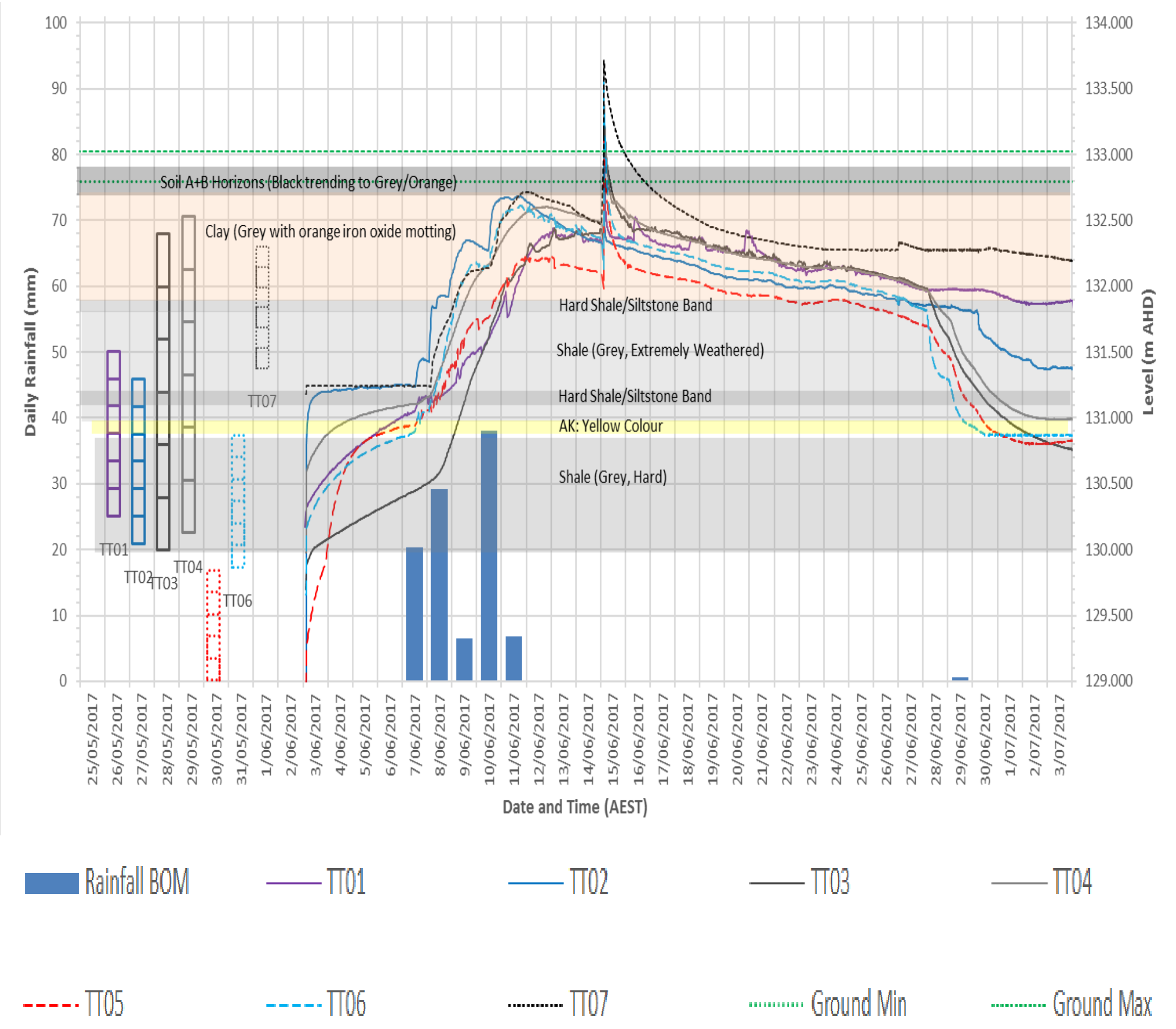


Figure 58. Piezometer Water Level Responses (from Piezometer Construction, during Lugeon Testing and Pilot-Trench Construction). The screen depths for each borehole are shown at the left side of the figure. Note the effect of rainfall from 7th to 11th June.

Response to a rainfall event

Rapidly increasing groundwater levels were recorded in response to rainfall between 7th and 11th June, followed by a gradual decline over 3 days (Figure 59). The groundwater level responses to rainfall can be analysed quantitatively with various methods to determine hydrogeological properties and / or relationships between parameters. Noticeable features of the data are the stepped responses to rainfall of some piezometers (eg TT02) that are screened in the hard grey shale layer. These may reflect the presence of recharge zones across the site allowing water to enter this layer. The deepest sampling point (TT05) shows the most muted response to rainfall and in general responds differently to the other boreholes.

Lugeon tests

Sharp increases in groundwater levels were observed on 14th June 2017 (of approximately 1 m) in response to the Lugeon tests (described above), followed by a decline in water levels until 26th June (Figure 60). The groundwater level responded to near-simultaneous Lugeon testing generated artesian pressures in all piezometers, which provided evidence of pressure responses moving between piezometers within a very short period of time. For example, groundwater level decline rates at:

- TT06 appear to be arrested within 3 minutes of testing TT07
- TT05 appear to be arrested within 6 minutes and start rising within 7 minutes of testing TT06
- TT04 appear to be arrested within 1 minute and start rising within 2 minutes of testing at TT03

There are some delayed peaks in the piezometric levels in TT01 (located some 15 m distant from the other auger holes). This piezometer recorded a number pressure pulses with amplitudes of up to 0.16m in the days after the Lugeon test. The shapes of the pressure pulses appear to be ‘muted’ versions of Lugeon test response at the piezometers closest to the pilot trench. For example, pressure pulses were recorded on 15th, 17th and 19th June approximately 1.2, 3.4 and 5.6 days after the Lugeon test (Figure 60). Given the absence of rainfall, the most likely explanation for these measurements is a pressurisation response from the Lugeon test travelling away from the test piezometers at different speeds through the different geological layers.

The TT07 piezometer exhibited a slow draining response indicative of a perched water table on low permeability materials. Based upon the geological logs recorded at TT02, this could be the hard shale or siltstone layers encountered at approximately 1m and 1.7m depth.

Response of water levels in surrounding piezometers to the construction of the test trench

Declines in groundwater level occurred from 26th June 2017 to 3rd July 2017 due to groundwater seepage into the constructed test trench (Figure 61).

1. There was very little response of any of the piezometers to the initial excavation of about 1.5 m at the western end of the pilot trench on 26 June 2017.
2. Groundwater levels at TT06 began to decline rapidly at midday 27th June 2017, when the depth of excavation reached approximately 2 m (Figure 27). It is possible that the excavator broke through competent layers at approximately 131.2m to 132.4m AHD (1.6m to 1.8m depth) around midday resulting in a loss of confinement at TT06 and drainage of water from the vicinity of TT06 into the trench. A loss of confinement at TT06 would be consistent with the field observations that the lower layers of weathered shale appeared saturated from below.
3. A few hours later on 27th June 2017 at 14:30, groundwater levels in TT03, TT04 and TT05 begin to decline asymptotically towards 131.25 m AHD which corresponds to the inferred base of weathering at 1.5 - 2 m depth. In general, this response, and the absence of a response at TT07 and TT02, could be explained by the test trench intercepting a south-easterly groundwater flow path. Thus TT06 and TT05 would respond first, being located down-gradient of the test-trench and closest to a discharge point, followed by TT04 and TT03 up-gradient of the test-trench and closer to points of groundwater recharge. The declining response at TT05 is most interesting as this well is screened below the depth of test trench excavation. If it is assumed that the sand 'gravel' pack is placed as per Figure 25 and the bentonite seal is competent, this response could be explained possibly either by a loss of confinement at TT05 and the upwards seepage of water into the test trench (possibly via the

TT06 piezometer), or a dipping south easterly flow path between TT04 / TT03 and TT06 / TT05 that cuts through the hard siltstone layers between approximately 1.5m and 2.0m depth down to 3.0m to 4.0m depth. This might be explained by vertical defects such as fractures or root holes, both of which were observed to some extent during test-trench construction (Section 13).

4. On the 28th June 2017 at 10:00 groundwater levels in TT06 declined again when the excavation depth reached ~3 m (Figure 27) in the western end, followed approximately 1 hour later by TT03, TT04 and TT05.
5. On 29th June 2017 at 14:45, after the excavation depth reached ~3 m in the eastern half of the test trench (Figure 27), there was a small sudden drop in groundwater pressure at TT02 followed immediately by an increase in the rate of pressure decline in all monitoring piezometers. This suggests connectivity between the eastern end of the trench and TT02. Quantitative analysis of the lag times for this pressure effect to be observed at other nearby piezometers could provide further estimates of the relationships between key aquifer properties (e.g. hydraulic conductivity and storage).
6. Minimum groundwater levels were observed at all piezometers between 1st and 3rd July 2017 and subsequently began to recover, except for the TT03 piezometer which continued to decline. If it is assumed that survey levels and estimated logger depths for TT03 and other piezometers are accurate, this observation could be explained by:
    - TT03 intercepting a permeable zone which drains water below the base of the test trench; and
    - There is a natural groundwater flow-path to the north-west away from the middle of the test trench.

Increases in water levels in the test trench and eventual stabilisation of groundwater levels would be expected to occur in the piezometers about the test trench. Furthermore, various hydrological experiments involving adding water to the pilot trench were undertaken in the period following construction of the test trench. The hydrological data for this subsequent period (and experiments) are not presented in the present report.

These observations are of particular relevance for future groundwater flow and transport modelling of the site. The data suggest that predictive models for LFLS should explicitly represent the presence of hard shale / siltstone layers that: (a) support perched aquifers in clay and weathered shale, and (b) pressurise (confine) the groundwater in deeper layers, and account for the effect of the adjacent Harrington's quarry site. Analysis and modelling of the data will provide further understanding of groundwater flow and may provide measurements or constraints on the range of aquifer properties that can be used for site scale modelling.

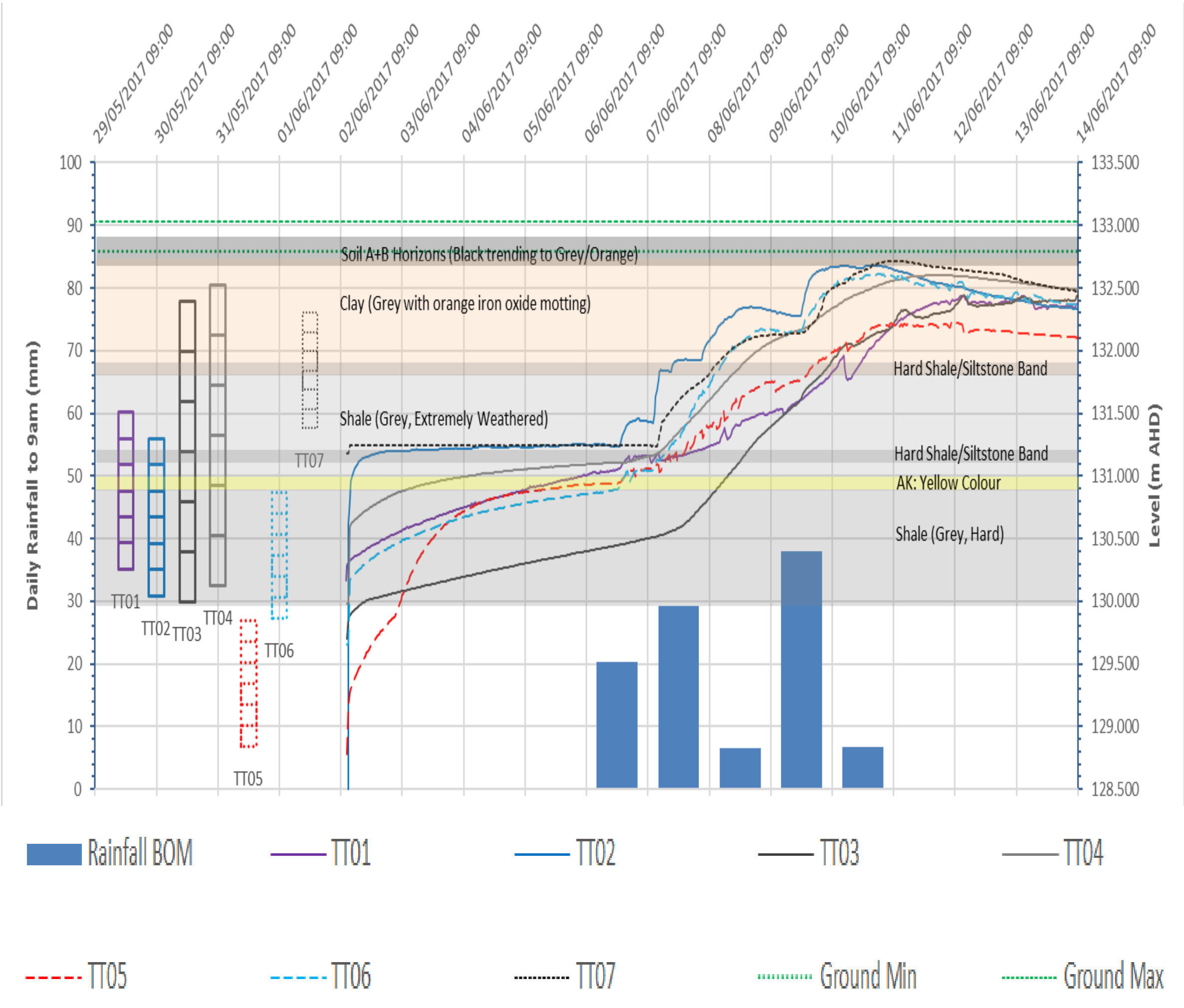


Figure 59. Piezometer responses following augering and well construction (2nd June 2017 to 14th June 2017). The screen depths for each borehole are shown at the left side of the figure.

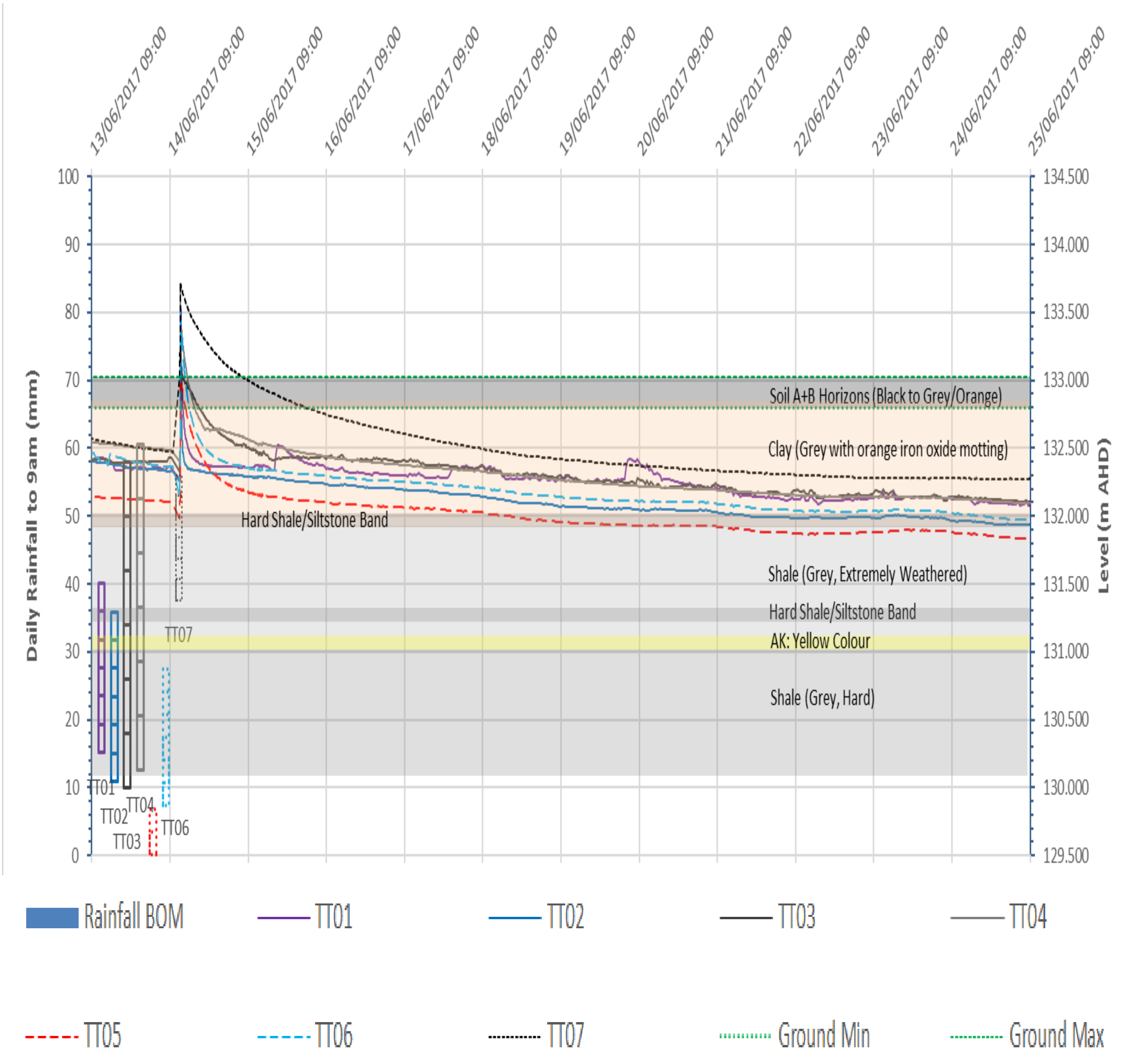


Figure 60. Piezometer responses to Lugeon testing prior to Pilot Trench construction (14th June 2017 to 25th June 2017).

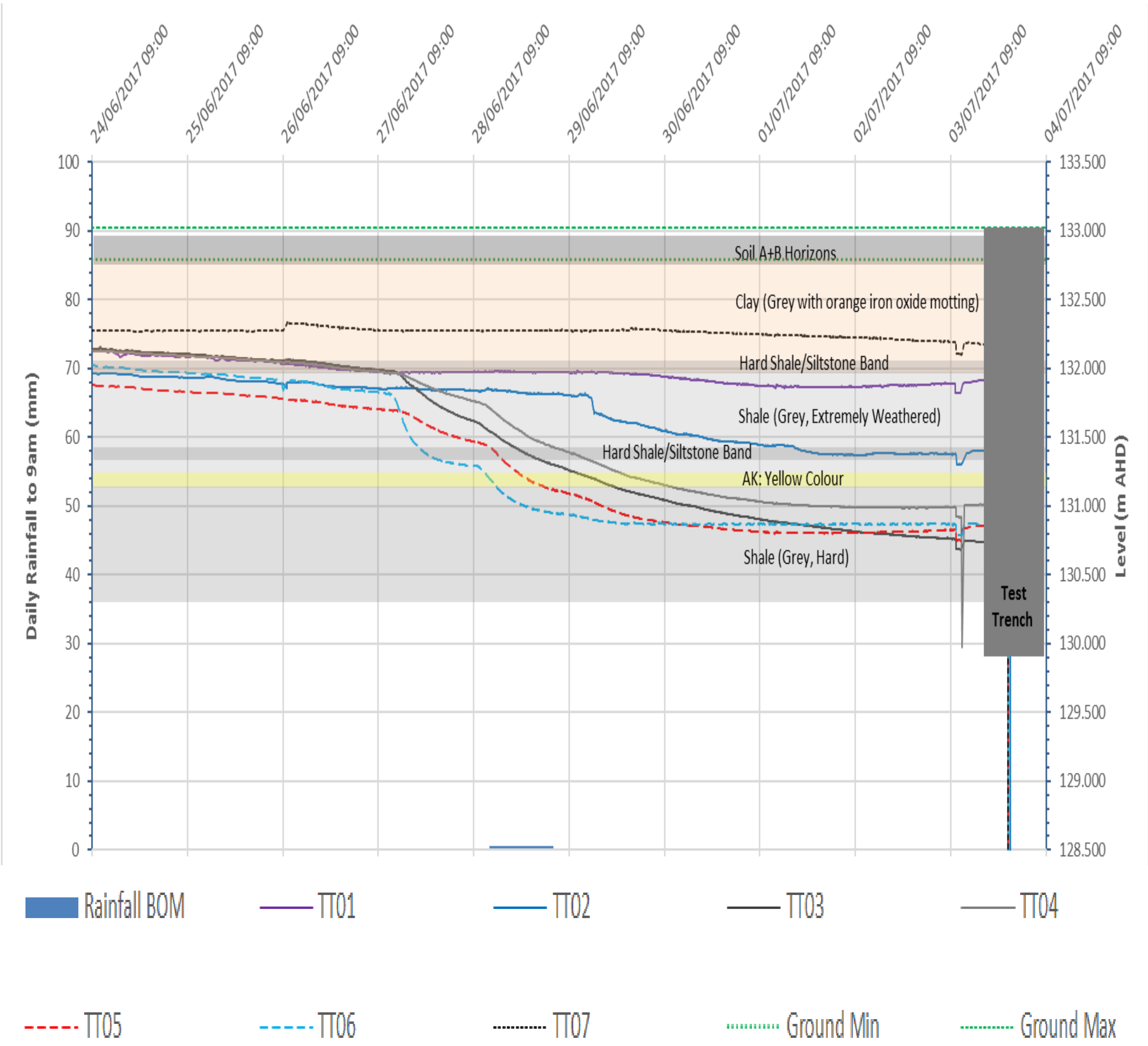


Figure 61. Nearby piezometer responses to Pilot Trench construction (25th June 2017 to 4th July 2017). Note that this is a more detailed interpretation of the data also shown in Figure 56.

17. Comparison of constructed trench with legacy trenches

Figure 62. Comparison of photographs of (a) excavation of historic trenches and (b) of the pilot trench.

Although our equipment was somewhat different from what was used during the disposal operations, we were able to make some comparisons, which were assisted by considering contemporary and historic photographs (Figure 62). The accuracy with which the modern equipment could excavate the pilot trench, and the storage of spoil in a separate location resulted in a very neatly defined trench (Figure 62b). As noted above, very exact dimensions were obtained which were very similar to the nominal dimensions described in the various available historical reports. However, the experience suggested that the legacy trenches may well have not conformed closely to the nominal specifications in all cases.

It is also possible that the stepped appearance of the trench base shown in Figure 62(a) may have resulted in a trench which differed somewhat from the pilot trench which conformed almost exactly to a rectangular prism. Unfortunately it is not possible to know whether the photograph in Figure 62(a) represents the final trench, or whether additional excavations occurred to make it more in conformance with a rectangular prism (similar to the pilot trench construction). It is noted that the steps (if present) would have affected the amount of materials emplaced and possibly the mode of emplacement.

Figure 63. Contemporary photographs covering of disposal trenches. Note the amount of fill materials on the ground surface

The resistance of the deeper, more intact shale layers to our trenching equipment was considerable and it is arguable whether the 1960's operations would have penetrated deep into the shale if it was encountered. Furthermore, the amount of spoil generated (Figure 44), should be compared with Figure 62(a) and photographs in Figure 63. It should be taken into account that we constructed a single trench 6 m long, whereas the legacy trenches comprised over 70 trenches of nominal lengths of 25 m. This consideration (together with the photographic evidence) verifies the presence of large amounts of unconsolidated materials around the disposal trenches, which would have affected the trenching process[16]. In modelling the site, allowance may need to be made for the effect of all these extracted soils on the shallow above-trench layers. Modelling may also need to account for the more crumbly nature of the historical trench edges compared to our modern trench, where the spoil was removed from the vicinity, resulting in a very clean cut (Figure 62b).

[16] These considerations may provide more insights into the possible reasons why trenches S1 and S2 were located some distance away from the main trenched area. It is known (from the disposal records) that trenches S1 and S2 were probably open at the same time as some trenches in the main trench area. It may well have been easier to construct trenches simultaneously at separate locations from each other to prevent additional spoil affecting excavation of adjacent trenches.

18. Summary of trench installation process and lessons learned

The construction of the pilot trench has been a valuable exercise, from a number of different viewpoints.

Firstly, the research team gained practical experience relevant to excavating a trench. This will be useful in constructing the other experimental trenches. The entire planning process, including addressing the safety aspects, required considerable attention, because there were significant hazards associated with the work and it was necessary to demonstrate adherence to safety standards. The logistics of installing and removing the shoring boxes, obtaining samples, emplacing the sampling and monitoring points into the trench, were quite complex. In particular, the delicate operation to fill the trench with gravel and remove the shoring boxes without damaging the installed equipment required careful planning and considerable skill in implementation by the contractors.

Secondly, numerous soil samples (including intact samples), data, photographs and information were obtained during excavation. The information gained included observations of the near-surface layers, the characteristics of water entering the trench, and the presence of roots throughout the profile (e.g. Figure 42). The channels formed by the roots provide a significant potential for water movement.

Thirdly, a unique set of insights into the surrounding hydrology was obtained from the piezometric data. It was extremely advantageous to install the surrounding piezometers prior to the excavation of the pilot trench, and study their hydrologic response during excavations. The water level data in the nearby boreholes and the response to trench excavation facilitated study of the characteristics of the near surface layers. Field observations of the ingress of water through the clean cut faces of the trench provided insights on the direction of water movement. In general, a large amount of information was obtained which would have been difficult to derive solely from borehole measurements. It is expected that much more information will be obtained in the future, and this is expected to be particularly valuable for modelling purposes. The connectivity between the different layers, and the apparent increase in lateral connectivity caused by trench excavation, would be difficult to simulate with a smaller scale field installation.

Fourthly, the construction exercise enabled many insights to be gained into the operations which took place in the 1960s (see Section 17). However, the operational procedures we employed caused much less disturbance of the trench surroundings, in part because the excavated soil was removed (Figure 44). We infer that the more disturbed trench environs and the presence of piles of soil on both sides of the legacy trenches (Figure 62a and Figure 63) would have the potential to cause more instability of the trench sides compared to the pilot trench. This, together with the extended filling periods, and the close proximity of multiple trenches, should be accounted for in assessing the legacy trenches. It seems likely that the cover layer above the legacy trenches is partly comprised from left-over fill and the presence of this material may contribute to the behaviour of the near surface layers.

Finally, the trench comprises a unique platform for conducting future field experiments. As discussed in Section 7, various experiments will be undertaken within and around the test trenches. Hydrological experiments will assess the response of the trenches to natural and simulated water ingress (i.e. response to rainfall events). In addition, various experiments, such as infiltrometer testing will be performed. Samples will be obtained periodically from the installed bore holes and multi-level samplers. Possible future experiments may involve adding non-radioactive tracer compounds (or possibly short lived radio-tracers). Naturally occurring conservative tracers such as bromide, chloride, or other stable isotopes, as well as non-conservative compounds (e.g. rare earth elements) which could act as an analogue for any radiochemical ions, or experiments with organic tracers including dyes may be envisaged. While the full experimental value of the trench is yet to be exploited it is clearly a useful facility for both LFLS-focused and more general hydrological research.

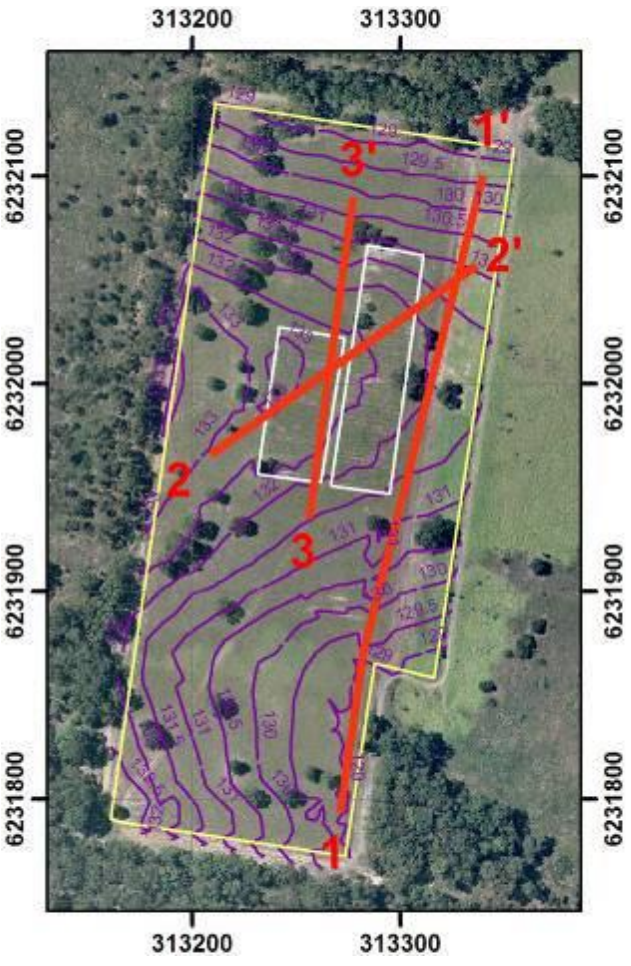
In conclusion, we expect that the accumulated experience will be helpful in the construction of the future experimental trenches for proposed experimental activities involving studies of chemical evolution with simulated waste, tests of engineered covers and experiments field involving grouting. Thus, the excavation of the pilot trench has laid a valuable foundation for future activities.

19. Appendices

APPENDIX 1

Recent large scale electrical resistivity studies of the Little Forest Legacy Site[17]

A preliminary electrical resistivity survey of the LFLS site was undertaken in 2011 with three lines completed and the results were previously reported (Cendón et al., 2015; Hankin, 2012). The transects used in this work are shown in Figure 64. The results (Figure 65) identified the thickness of the shale lens as well as its contact with underlying Hawkesbury sandstone materials, with results validated by existing bore lithological records.



[17] The valuable contribution of Mr Ander Guinea (Federation University, Australia) to this aspect of the work is gratefully acknowledged.

Figure 64. Location of transects within the LFLS site.

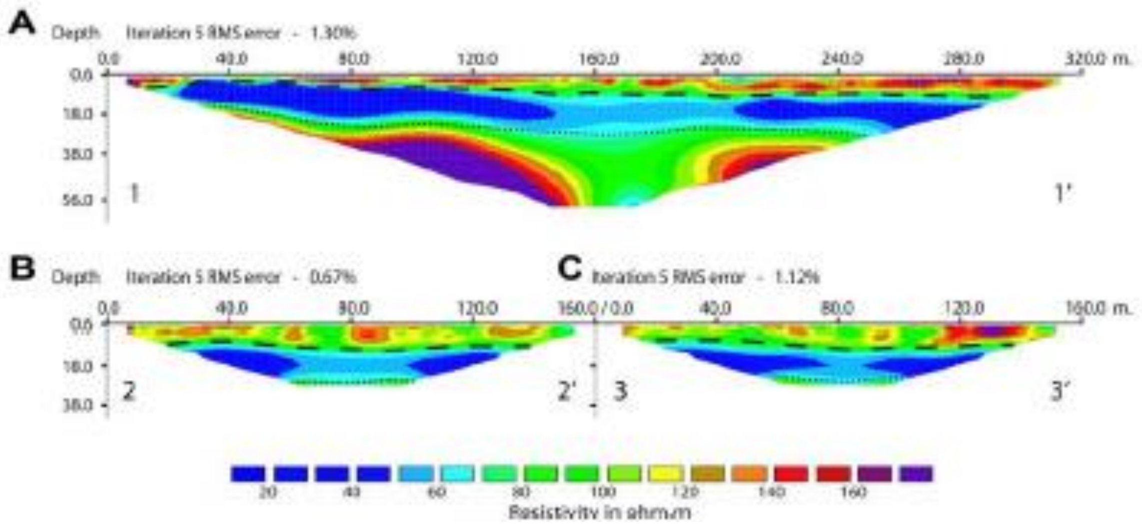


Figure 65. Electrical resistivity profiles oriented following the numeric legend in the transects (See Figure 64). High resistivity materials close to the surface (green to purple in colour) represent the soil and top weathered shale. The low resistivity colours (blues) represent the shale lens. Higher resistivity materials below the shale represent the sandstone (from (Hankin, 2012)).

Prior to installation of the pilot experimental trench a more intensive resistivity study was designed to cover the entirety of the LFLS site (including adjacent land areas) with the objectives being:

a) map the extent, thickness and dip of the shale lens across the site
b) establish depths to contact between shale and surrounding Hawkesbury sandstone
c) investigate potential heterogeneities in the underlying sandstone
d) inform potential future deeper drilling
e) to understand paths of groundwater flow in the Hawkesbury sandstone below the LFLS and
f) provide a robust 3D framework of the main lithologies that can be exported to hydrogeological models.

A total of 13 resistivity profiles were carried out in July 2016 (Figure 66) using a SAS 4000 Terrameter with an ABEM Lund system (Dahlin, 1996). The Wenner-Schlumberger electrode array was selected due to the lateral continuity of the layers (Szalai et al., 2009) with apparent resistivity data inverted with the software RES2DINV (Loke and Barker, 1996).

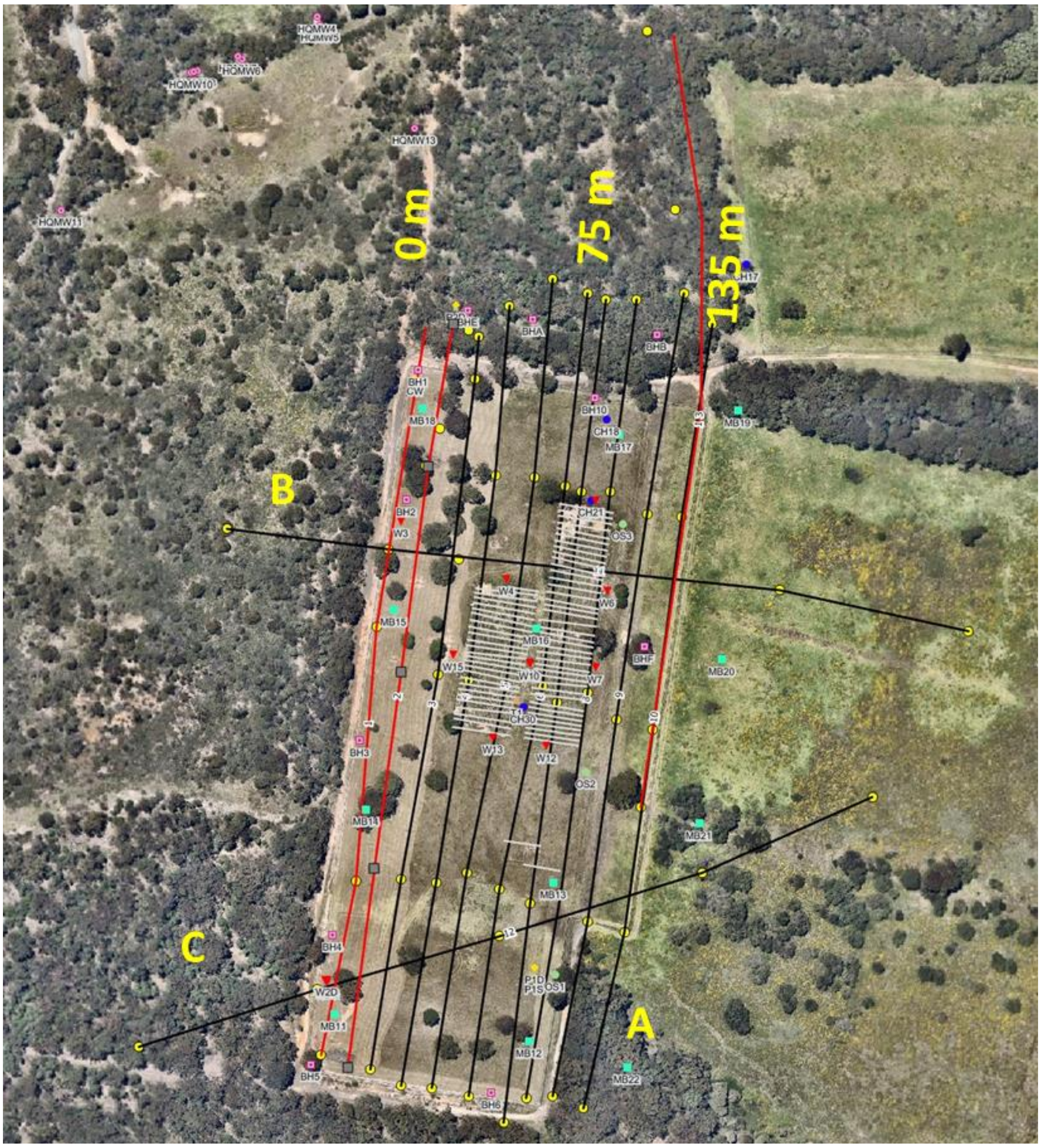


Figure 66. Coverage of the 13 ER lines recorded in the 2016 survey. Yellow dots correspond to coordinates recorded along the arrays with GPS. Lines are spaced every 15 m, starting from the west boundary of the site. Line A in red is an extension to the north, while lines B and C are quasi or perpendicular to main lines with their western side in Harrington's Quarry (B) or in undisturbed landscape (C). Both B and C lines extend to different portions of the night soil area to the east.

Four cables with 16 electrodes each (64 in total) were connected to the main unit in sets of two. The procedure was to take a resistivity profile, then move a portion of the cable array, redeploying cables further along the same direction and then taking a new profile. This allowed the sections to be extended beyond the 350 m of LFLS fenced area. All sections were obtained using the Wenner-Schlumberger array with 5 m spacing between electrodes. The maximum depth of the investigation (~60 m) was in the centre of the transects, roughly coinciding with the position of the trenches, decreasing towards the edge of the array.

Ten lines extended S-N and were spaced approximately 15 m from each other starting from the western boundary (0 m) and finishing on the eastern boundary (135 m, see Figure 66). Additional lines (A, B and C) were taken to explore contacts beyond the fence area and to study the potential effect of other land uses (i.e.: Harrington’s Quarry). Note that some of the profiles crossed the proposed test trench area.

The thickness and shape of the shale lens is represented in the ER sections by low resistivity materials (blue colours). This thickness is influenced by the local lows and elevated sections of the Hawkesbury sandstone base. The shale has a similar thickness below the trenches almost across the whole fenced area except to the SE of the site where it pinches out, with the Hawkesbury sandstone outcropping outside the fence area along the drainage line (known as Turtle Creek). To the north of the LFLS site the shale thickness appears to increase with a sandstone raise to the NE of the LFLS seemingly separating two portions of the shale lens. No stratigraphic control exists to the NE to reinforce this later interpretation.

Step like features are observed in the underlying sandstone, spaced every 30 to 60 m (i.e.: line 135 m). Widely-spaced sub-vertical to vertical joint sets (fractures without any offset) and lineaments are common within the Hawkesbury sandstone and prominent along the coastline (Mauger et al., 1984; Norman, 1996). Predominant directions for these features are NNE, parallel to the coast, as well as W-E roughly perpendicularly. Resistivity sections show continuity of the sandstone features in most S-N profiles as well as in the E-W section (Figure 67), suggesting these lineaments are continuous across the LFLS.

The sandstone to the south of the site shows higher resistivity as seen in all N-S sections and in section C. To the north and roughly coinciding with the position of Harrington’s Quarry, sandstone has lower resistivity.

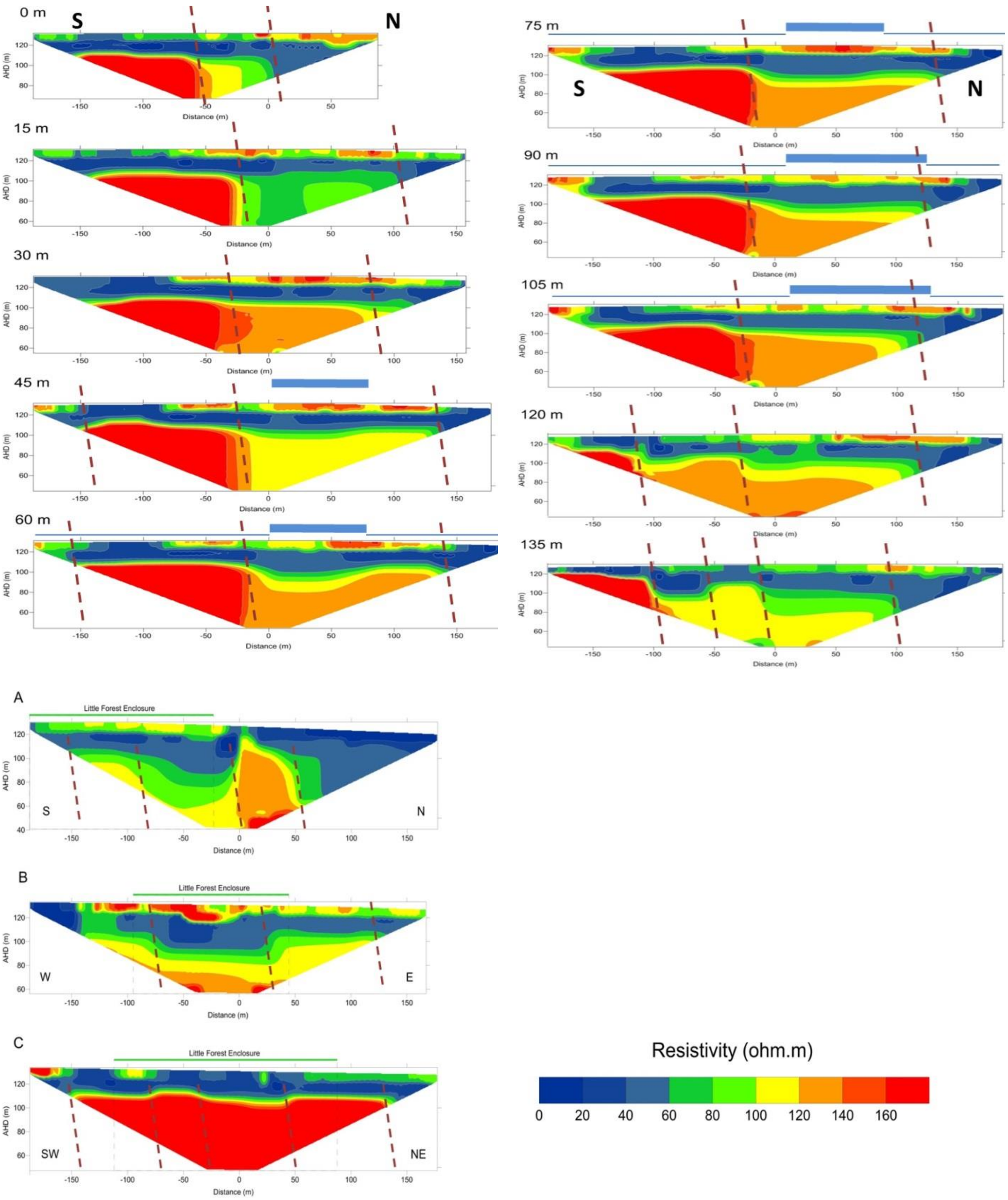


Figure 67. Topography compensated resistivity profiles for all lines. The positions of the lines are shown in Figure 66. All S-N trending lines are depicted with the north to the right hand side of the section. The W-E and SW-NE sections are depicted with the eastern side to the right hand side. The resistivity legend is the same for all figures. The extension of the trench area (blue bars) and the LFLS boundary (enclosure) have been depicted as a reference in appropriate sections. Vertical dashed lines correspond to interpretation of potential lineaments in the Hawkesbury sandstone.

APPENDIX 2

Details of piezometer measurements and data analysis

A2.1 Hobo logger deployment and data collection

Automated Hobo Loggers (U20L-04 Series) were deployed at known depths in monitoring piezometers TT01 to TT07 to record groundwater levels and temperatures. The U20L-04 sensor can record sustained water level depths of up to 4 metres and temperatures in the range of -20 C to 50 C.

The pressure (level) resolution and accuracy specifications of the U20L-04 Series Hobo Pressure Loggers are ± 0.014 kPa (1.4 mm) and ± 0.043 kPa (4.2mm), respectively, i.e. approximately 0.1% and 0.3% of Full Scale (FS), respectively. With accurate water level measurement, known water density, accurate barometric pressure compensation and a stable temperature environment (> 20 minutes since temperature change) the loggers are typically accurate to ± 0.1% FS (4 mm). When exposed to rapid thermal changes the sensor is only accurate to approximately 0.5% FS (20 mm).

The resolution and accuracy of the temperature sensor is ±0.10 C and ±0.44 C, respectively, with a drift of approximately ±0.10 C per year. The 90% response time of the sensor is typically 10 minutes. The instrument clock is accurate to ± 1 minute per month (± 12 minutes per year) and has a nominal five-year battery life.

Measurements of the Hobo loggers were supplemented by manual measurements using dip-meters. Standing water level measurements (SWL) were obtained on 26th June 2017 around 9:00 a.m. and again on 3rd July 2017 around midday.

A2.2 Water Table Calculation Method

Water table elevations in metres Australian Height Datum (m AHD) were calculated from the data loggers by the following two step approach:

1. Barometric pressure and water density corrections: Raw logger data were processed to calculate a water depth over each pressure sensor using the pressure and temperature data recorded by the sensors;

2. Datum adjustments: Datum adjustments incorporating available Top of Casing (TOC) survey and standing water level measurement data to obtain an estimate of the elevation of each logger in m AHD.

The following sub-sections describe this approach in more detail.

Barometric Pressure Correction

The depth of water above each pressure sensor ($d_{gw,t}$) was determined from the raw pressure and temperature logger measurements as follows:

$$\boldsymbol{d_{gw}} = \frac{(\boldsymbol{P_{gw}} - \boldsymbol{P_{atm}})\ \boldsymbol{x}\ \mathbf{1000}}{\boldsymbol{p}\ \boldsymbol{x}\ \boldsymbol{g}}$$

Where:

- ***P_{gw}***: The measurements of absolute pressure in groundwater as obtained from the data loggers deployed in each monitoring well
- ***P_{atm}***: The measurements of atmospheric pressure obtained at the weather station at the nearby ANSTO site, which contain a small, variable offset bias but smaller component of measurement error compared to the atmospheric pressure measurements obtained at LFLS
- ***p***: The groundwater fluid density, for which the ionic strength dependence was assumed to be negligible, allowing density to be estimated from measured temperature (T) using a standard relationship
- ***g***: the local acceleration due to gravity, assumed to be 9.8065 ms^{-2}.

Datum Shifts

After being converted to an equivalent water depth, the water pressures (in kPa) and temperatures (in C) recorded by the Hobo pressure sensors were converted to an estimated groundwater level, ***Z_{gw}***, in m AHD as follows:

$$Z_{gw} = Z_{toc} - \frac{\left(\sum_1^n d_{swl,calibration}\right)}{n} - \frac{\left(\sum_1^n d_{gw,calibration}\right)}{n} + d_{gw,t}$$

Where:

- Z_{toc}: The top of casing survey elevation for each monitoring piezometer in m AHD.
- $d_{swl,\ calibration}$: The depth to groundwater below top of casing as measured on set dates and times when the data loggers were in the monitoring piezometer and recording data.
- $d_{gw,\ calibration}$: The depth of groundwater in the monitoring piezometer above the height of the data logger on set dates and times when calibration SWL measurements were obtained.
- $d_{gw,t}$: The time series of groundwater level depth above the data logger as determined

Therefore, the depth / elevation of each instrument (d_{logger}) in each well was determined relative to the surveyed standing water level measurement reference elevation, Z_{toc} by subtracting the average of the sum of the corresponding depth to standing water level measurements (d_{swl}) and recorded groundwater depths above the pressure sensors (d_{gw}) within each of the monitoring wells from the Z_{toc} value determined during elevation survey at times when the pressure sensor was in the monitoring piezometer and recording. To provide an analysis and reduction of error these estimates of logger depth were additionally cross checked against summation of the following measurements:

1. Length of the steel wire attached to the hobo pressure sensor;
2. Distance between the lip of piezometer end cap and steel wire attachment point; and
3. Distance between top of instrument and pressure sensing membrane.

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