NATIONAL CENTRE FOR GROUNDWATER RESEARCH AND TRAINING

THE POTENTIAL IMPACT OF IRRIGATED AGRICULTURE ON GROUNDWATER QUALITY IN THE ROCKY HILL REGION, NORTHERN TERRITORY

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Cover Photo: View north from Rocky Hill. Courtesy of John Wischusen.

Executive Summary

Alice Springs' public water supply is currently largely sourced from the Roe Creek borefield, located approximately 15 km south-southwest of the town, in the north-eastern section of the Amadeus Basin. However, at current extraction rates, water levels at Roe Creek are expected to decline beyond economical pumping depths by approximately 2050. By this time, it is expected that much of Alice Springs' public water supply will be derived from a borefield within the Rocky Hill region. NT Portion 4704 was acquired by the Power and Water Corporation (PWC) for this purpose in 1996.

Undoolya Rocky Hill Agricultural Block (NT Portion 1476) is located immediately northeast of NT Portion 4704, and the two blocks share a common boundary. Fodder crops have been grown intermittently on the agricultural block under centre pivot irrigation since the 1970s, with intensification of irrigation since 2002 when grapes were planted in the southeast of the block. Currently, there are about 60 ha of irrigated vineyards at this site. Proposals have been developed for expansion of onions onto areas of Undoolya Pastoral Lease, immediately south of the current vineyard development, and a water licence to facilitate this development has been granted.

The development of irrigated agriculture will inevitably lead to increased rates of groundwater recharge, and there is potential for this recharge to impact groundwater quality. Because concentrations of chloride, nitrate and other salts are naturally high in arid zone soils of central Australia, irrigation drainage will leach these salts into the underlying groundwater. Proposed future pumping from a PWC borefield on NT Portion 4704 could potentially draw groundwater from beneath the irrigation areas into the water supply. Importantly, there is presently no evidence of contaminants derived from irrigation activities (either fertilisers, pesticides or herbicides) in the groundwater beneath the vineyard. This may be due to long travel times for water through the unsaturated zone.

Drainage rates beneath irrigated viticulture on the Undoolya Rocky Hill Agricultural Block have been estimated to be between 80 and 130 mm/y. This drainage water moves slowly down through the soil profile, pushing the pre-existing soil water ahead of it. After a period of time, this pre-existing soil water begins to recharge the underlying aquifer, which is at 50 – 55 m depth. Based on comparison of soil moisture profiles beneath the vineyards and adjacent native vegetation, and assuming that irrigation practices do not change, we estimate that this water will reach the aquifer within the next 5 - 10 years. When this occurs, leaching of salts that were originally stored within the unsaturated soil profiles into groundwater will result in salt fluxes of approximately 1.3 kg/m^2/y into the underlying aquifer. Multiplying by an approximate area under grapes of 0.6 km^2, gives 900 tonnes per year of salt. Assuming that irrigation at the site continues, then this salt flux will continue for

a period of 50 – 80 years, by which time the pre-existing soil water will have been completely flushed from the profile.

The flux of nitrate will also increase. The total mass of nitrate stored under native vegetation is 0.043 kg/m^2 NO_3-N. Movement of this water into the aquifer will therefore result in a nitrate flux of up to 0.7 g m^2/y NO_3-N over the next 50 – 80 years. However, this is unlikely to result in nitrate concentrations above safe drinking water levels.

Due to its slow movement through the unsaturated zone, the irrigation drainage water itself is not expected to reach the water table for 50 – 80 years. Once this occurs, the salt flux to groundwater will reduce to approximately 260 tonnes per year.

This report has not specifically examined drainage rates or unsaturated zone travel times under onions or other crops, or the effect of solute fluxes beneath irrigation on the water quality of the proposed Rocky Hill borefield. Under current conditions, due to the proximity of the irrigation bores and in the absence of any pumping from a PWC borefield on NT Portion 4704, most of the recharge from beneath the vineyard will be extracted by the irrigation bores. Simple calculations suggest that this might lead to an increase in total dissolved salt in pumping water of around 1300 mg/L, with potentially significant implications for vineyard management. However, it is likely that flow lines would change with the commencement of pumping from a PWC borefield on NT Portion 4704, or if the locations of irrigation bores were to change. In particular, groundwater beneath the agricultural block is likely to be within the capture zone of a PWC borefield proposed to be established on NT Portion 4704. However, groundwater which is derived from beneath the agricultural block will be diluted by groundwater from other areas, and so it is possible that salt fluxes beneath the irrigation areas may have little effect on concentrations of groundwater pumped by such a borefield. A groundwater model of the Roe Creek and Rocky Hill – Ooraminna region is currently being developed, and this groundwater model should be used to calculate groundwater travel times to the borefield and the extent to which groundwater from beneath irrigation areas are diluted by groundwater from other parts of the aquifer. Such simulations could use a range of hypothetical bore locations and pumping rates.

This report has also not specifically considered the consequences of future expansions of irrigation on the potential water quality of the production borefield. As a starting point, it is reasonable to assume that solute fluxes to groundwater will be similar to those beneath the current vineyard development. Thus, for example, if the area or volume of irrigation were to triple (in line with the recent increase in allocation), then it might be expected that the salt flux would also triple. If the groundwater model predicts that these solute fluxes are likely to have an adverse impact on the quality of groundwater sourced by the borefield, then additional studies to specifically examine drainage rates and travel times beneath other crops would be warranted.

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1. INTRODUCTION

Alice Springs' public water supply is largely sourced from the Roe Creek borefield, located approximately 15 km south-southwest of the town, in the north-eastern section of the Amadeus Basin. The borefield was commissioned in 1964, when the supply from the alluvial sediments beneath the town became inadequate. However, at current extraction rates, water levels at Roe Creek are expected to decline beyond economical pumping depths by approximately 2050, by which stage it is expected that much of Alice Springs' public water supply will be derived from a borefield within the Rocky Hill region (DLRM, 2016). Extensive hydrogeological investigations took place in the Rocky Hill region in the 1970s, and in 1996 NT Portion 4704 was acquired by the Power and Water Corporation (PWC) for the future borefield. Further detailed hydrogeological investigations in the area took place in 1998 – 2000 (Read and Paul, 2000, 2002).

Undoolya Station's freehold block, (NT Portion 1476; commonly known as the Undoolya Rocky Hill Agricultural Block), is a parcel of land excised from Undoolya Pastoral Lease. It is located immediately northeast of NT Portion 4704, and the blocks share a common boundary. Fodder crops have been grown intermittently on the block under centre pivot irrigation since the 1970s. The area of irrigation expanded significantly in 2002, when grapes were planted in the southeast of Undoolya Rocky Hill Agricultural Block. Currently, there are about 60 ha of irrigated vineyards at this site. In 2015, the NT Controller of Waters re-issued the 1 GL/y license for the grape block for a further ten years, along with an additional entitlement of 2.1 GL/y for horticultural development. Although the water table beneath the southern portion of Undoolya Rocky Hill Agricultural Block is relatively flat (Figure 1), future proposed pumping from a PWC borefield on NT Portion 4704 could potentially draw groundwater from beneath the irrigation areas into the water supply.

Groundwater recharge rates beneath irrigation areas are typically much higher than under native vegetation or dryland agriculture. Irrigation can result in increased leaching of salts that are naturally present in the soil under native vegetation, with consequent salinisation of underlying aquifers (Suarez, 1989; Cook and Telfer, 1992). Irrigation with groundwater can also lead to recycling of salts present in groundwater, leading to increases in salinity over time. Irrigation drainage can carry contaminants from applied fertilisers, herbicides and pesticides into underlying aquifers. There are numerous examples of groundwater degradation resulting from irrigation activities (Suarez, 1989; Bolger et al., 1999; DERM, 2012).

Concerns have therefore been raised about the potential for irrigation developments on Undoolya Rocky Hill Agricultural Block and Undoolya Pastoral Lease to affect the quality of groundwater earmarked for Alice Springs future water supply. The current project was initiated in response to these concerns. It aims to:

- Assess evidence of soil or groundwater contamination in the vicinity of Undoolya Rocky Hill Agricultural Block

- Calculate timeframes for transport of irrigation leakage into underlying aquifers

- Assess possible future contaminant fluxes to groundwater beneath irrigation areas in the Rocky Hill area

The assessment has focussed on the vineyard within the Undoolya Rocky Hill Agricultural Block, as it constitutes the largest area of irrigated agriculture in the region.

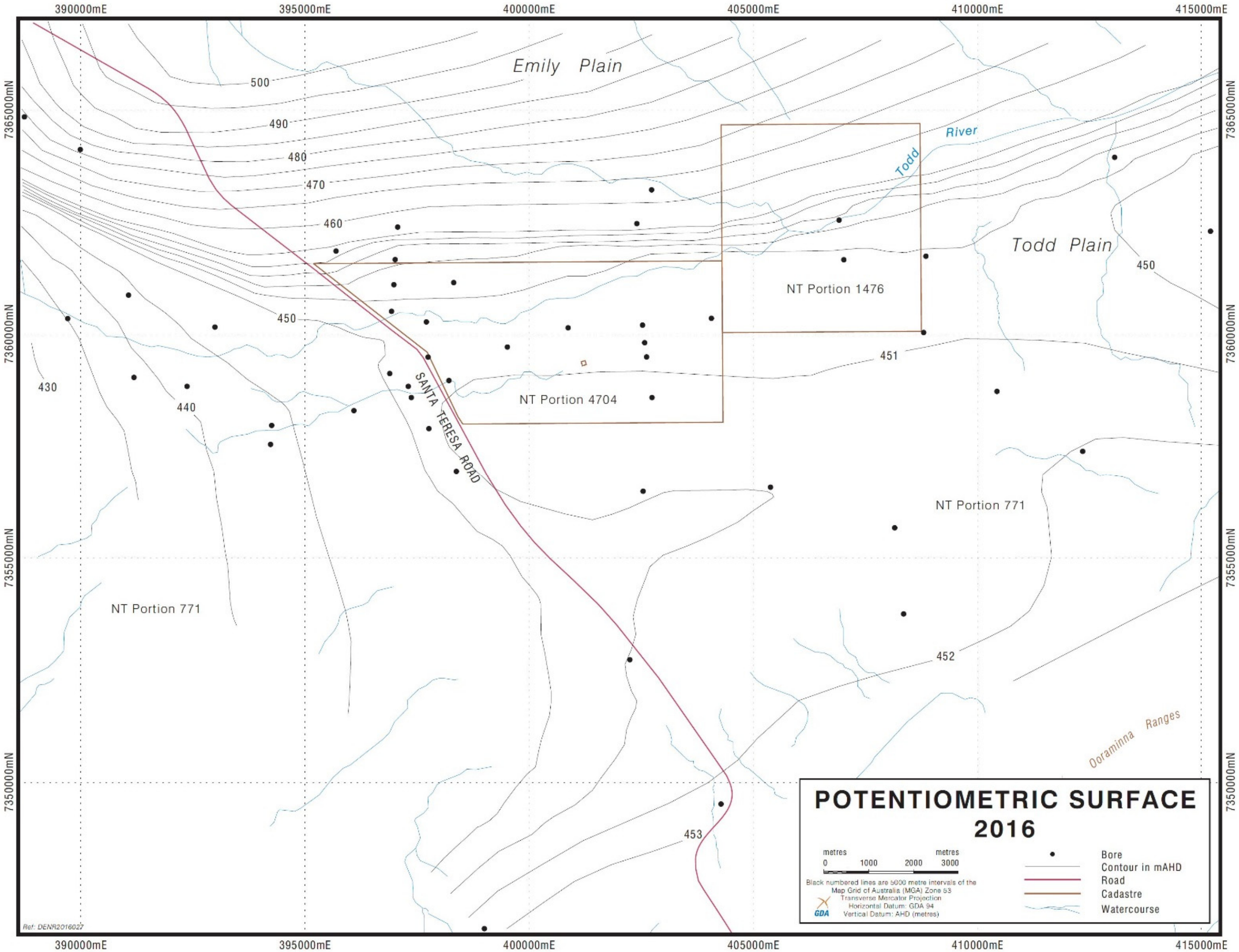

Figure 1. Potentiometric surface in the vicinity of the Undoolya Rocky Hill Agricultural Block (NT Portion 1476) and NT Portion 4704 - the proposed site of the Rocky Hill borefield.

2. BACKGROUND

2.1 Theory of Soil Infiltration and Recharge

Soil water movement following an increase in deep infiltration has been extensively studied in mallee areas of South Australia, Victoria and New South Wales (Allison and Hughes, 1983; Allison et al., 1990; Jolly et al., 1989; Cook et al., 1989, 1997). In these areas, soils are predominantly sandy and have relatively high hydraulic conductivities, and the increase in infiltration resulted from clearance of native vegetation and the development of dryland agriculture (mostly wheat in rotation with perennial pastures for sheep grazing). Similar processes occur when the increase in infiltration occurs in response to development of irrigation.

Water that is surplus to plant requirements and which is not lost to evaporation, will move down through the soil profile. Under conditions of piston flow, this infiltrating water will push the pre-existing soil water ahead of it. This creates a pressure front, which moves down the profile in advance of the infiltrating water (Figure 2). A simple mass balance shows that the change in soil moisture storage above the pressure front must be equal to the volume of infiltrating water:

$$\int_0^{z_{pf}} \Delta\theta(z)\, dz = \int_0^{z_{if}} \theta(z)\, dz \qquad (1)$$

where z_{pf} denotes the depth of the pressure front, z_{if} is the depth of the infiltrating front, θ is the volumetric soil water content, $\Delta\theta$ is the change in volumetric soil water content, and z is depth below the land surface.

The drainage rate can be calculated by summing the volume of water stored within the profile to the depth of the infiltration front, and dividing by the time since the change in land use:

$$D = t^{-1} \int_0^{z_{if}} \theta(z)\, dz \qquad (2)$$

where t is the time since the change in land use. However, this relies on identification of the depth of infiltrating water. This may be possible from water chemistry (or salinity), if this infiltrating water has a different composition to the water that was previously stored within the soil profile. Drainage can also be estimated from the change in water content above the pressure front:

$$D = t^{-1} \int_0^{z_{pf}} \Delta\theta \, dz \qquad (3)$$

where $\Delta\theta$ is the change (increase) in water content following the development of irrigation.

In some cases, the drainage rate can also be estimated from a salt mass balance. Under steady state conditions, the salt flux in infiltrating water must be equal to the salt flux in precipitation and in applied irrigation water

$$c_i I + c_p P = c_D D \qquad (4)$$

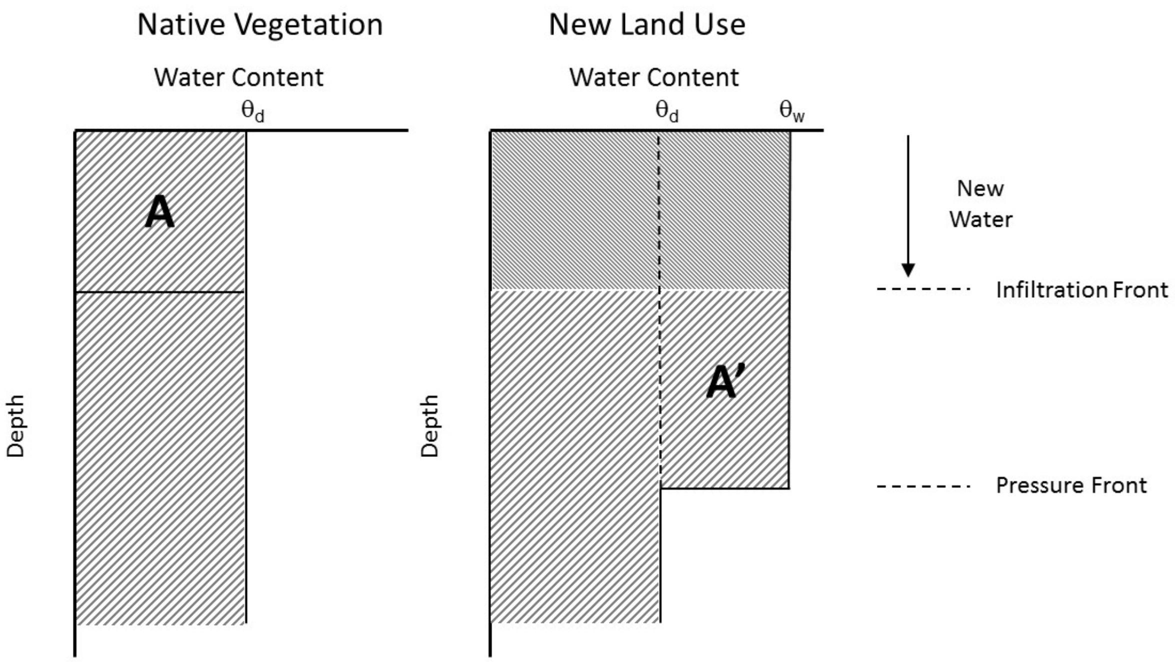

Figure 2. Water content of the soil under native vegetation and following a change in land use, showing the movement of the pressure front in advance of the solute front in soil following land use change.

where I is the irrigation rate, P is the precipitation rate, D is the drainage rate, c_i and c_P are the salt concentrations in irrigation water and precipitation, respectively, and c_D is the salt concentration in drainage water.

In most cases, $c_P P$ is negligible, so that this can be rewritten as

$$c_i I \approx c_D D \tag{5}$$

or

$$\frac{D}{I} = \frac{c_i}{c_D} \tag{6}$$

The ratio D/I is sometimes referred to as the leaching fraction. Where the salt content of irrigation water is high, then a high leaching fraction is required to prevent salt build-up in the crop root zone. The drainage rate can therefore be estimated from the salt concentration below the root zone, if I and c_i are known. Most usually, chloride is used for this purpose rather than salinity or total dissolved salts (TDS), because the chloride ion is not involved in most soil reactions and is not a significant component of most fertilisers.

Until the pressure front reaches the water table, groundwater recharge to the water table continues at the same rate as it did prior to the change in land use. Once the pressure front reaches the water table, the recharge rate increases and becomes equal to the drainage rate. In a uniform soil profile, the time lag for the pressure front to reach the water table is

$$t_p = \frac{z_{wt}(\theta_w - \theta_d)}{D} \tag{7}$$

where z_{wt} is the water table depth, θ_w is the mean volumetric soil water content above the pressure front, θ_d is the mean water content below the pressure front, and D is the drainage rate (Figure 2). (Strictly speaking, θ_w is the mean volumetric soil water content that will occur under irrigation once the pressure front reaches the water table, and θ_d is the mean water content of the soil profile before the change in land use. These will be equal to the mean volumetric soil water contents above and below the pressure front, respectively, only in the case of a uniform soil profile. Equations for non-uniform soil profiles are provided in Appendix 1.)

The time lag for the water that has infiltrated since the change in land use to reach the water table will be greater, and is given by

$$t_i = \frac{z_{wt}\theta_w}{D} \tag{8}$$

The infiltration front, which is the boundary between the water which was in the soil profile prior to the change in land use, and the water which has infiltrated since the change in land use, has previously been termed the solute front, because this boundary can often be distinguished by a change in concentration of solutes in soil water (Jolly et al., 1989). The position of the pressure front in a soil profile is most easily measured by matric potential, estimated using the filter paper technique (Greacen et al., 1987). Matric potential, which is always a negative number, is a measure of how much energy is required to remove water from the soil, and is measured in units of pressure (e.g., kPa).

It should be noted that the above model assumes that soil water movement occurs by piston flow. Piston flow is the uniform downward movement of water, whereby the infiltrating water displaces existing soil water without bypassing it. It should be distinguished from preferential flow, which includes movement along preferred pathways, such as fractures and root channels. If preferential flow occurs, then some fraction of infiltrating water will reach the water table earlier than the above calculations suggest. Also, if very low permeability layers occur within the profile, then this can impede the downward movement of water and lead to the development of perched aquifers. The presence of such low permeability layers will increase travel times.

Drainage rates beneath native vegetation in arid regions are usually very low (< 5 mm/y; Allison et al., 1990; Kurtzman and Scanlon 2011). Recharge rates beneath irrigated areas in arid and semi-arid regions will be a function of soil type and crop type, rainfall and climate, the volume of applied water and frequency of application. Published values range from 10 – 500 mm/y (Scanlon et al., 2006; Jiménez-Martínez et al., 2010), with Scanlon et al. (2006) reporting an average value of approximately 5% of water applied (precipitation plus irrigation).

In South Australia, Jolly et al. (1989) estimated that it would take about 90 years for the infiltration front to reach the water table at 60 m depth following clearing of native vegetation for dryland agriculture, and 200 years for the infiltration front to reach the water table. However, these time delays are strongly influenced by the drainage rate.

2.2 Irrigation Development at Rocky Hill

The Undoolya Rocky Hill Agricultural Block (NT Portion 1476) was excised from Undoolya Pastoral Lease in the 1970s. Lucerne was grown under centre pivot irrigation in the northern part of the block in the 1970s and 1980s, but later curtailed because of lucerne aphid (Tucker et al., 1999). Since 2013, onions have been grown under centre pivot irrigation in the same area (Figure 3).

In 2002, grapes were planted in the southeast of the Undoolya Rocky Hill Agricultural Block. The area of vineyards progressively increased until 2012, and currently, there are about 60 ha of irrigated vineyards at this site, arranged in five blocks, each of approximately 12 ha. (The two most easterly blocks were planted in 2002, followed by the third block and part of the fourth block in 2004, with the fifth block established in 2012.) Small areas of other crops have also been grown immediately north of the vineyards since 2012.

Groundwater for irrigation of onions is extracted from bore RN 10669, while vineyard irrigation water is mostly sourced from RN 17035 and RN 17817 (Figure 3). Groundwater use from these bores has been metered since September 2004. Irrigation volumes have progressively increased over time as the area of planting has increased. Since 2012/2013, the annual groundwater use for irrigation of the vineyard (and the small area of cropping immediately north of the vineyard) has averaged 630 ML. Based on an irrigation area of 60 ha, this represents an irrigation rate of approximately 1000 mm/y. Groundwater extraction for irrigation of onions has averaged 320 ML/y since 2012/2013.

In 2014, an application to clear pastoral land for onion development on nearby Undoolya Pastoral Lease was submitted, and in 2015, the NT Controller of Waters re-issued the 1 GL/y license for the grape block for a further ten years, along with an additional entitlement of 2.1 GL/y for agricultural development on Undoolya Pastoral Lease.

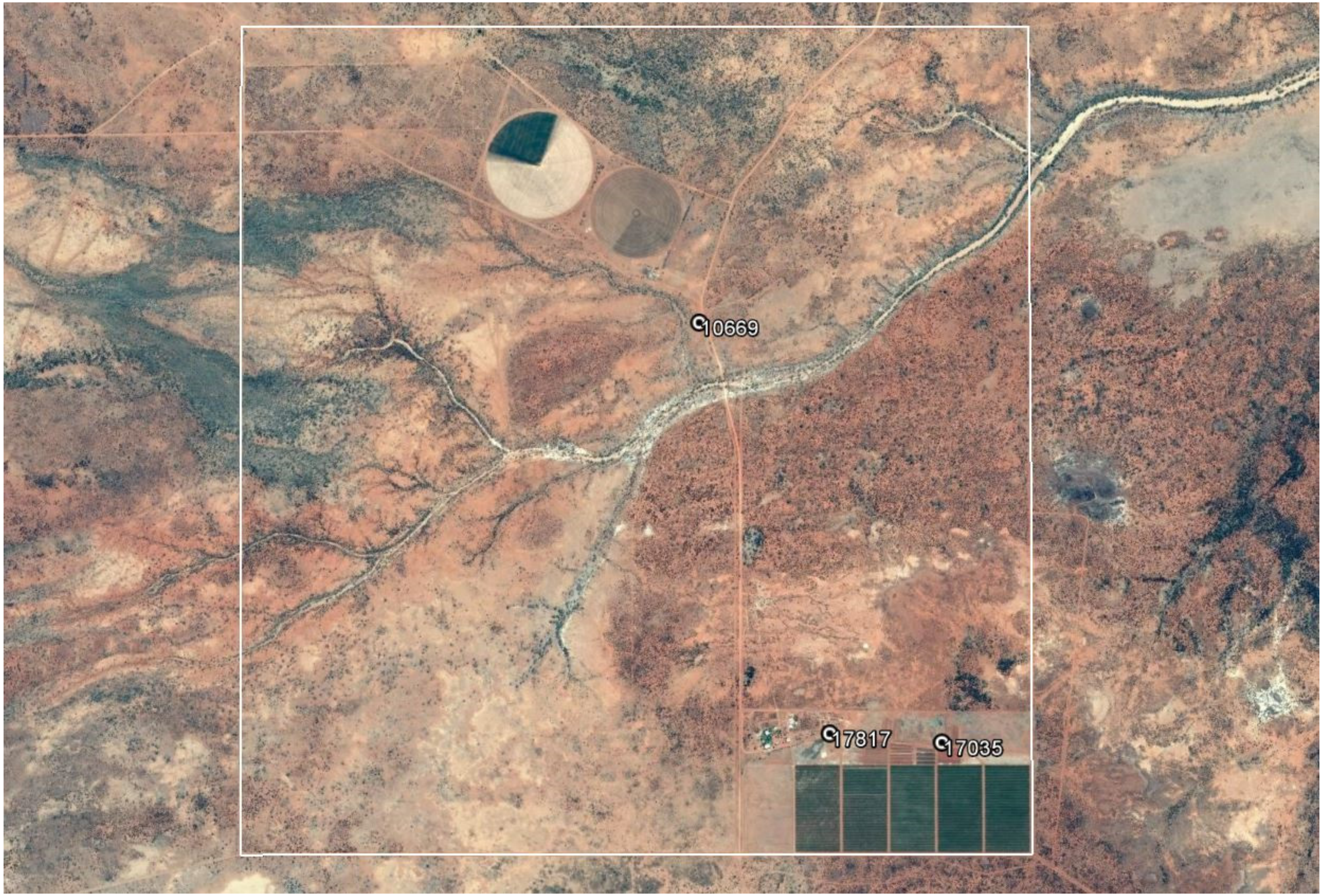

Figure 3. Undoolya Rocky Hill Agricultural Block, showing onion crops in north and vineyard development in the southeast.

3. METHODS

The investigation involved soil water analysis on cored holes beneath the vineyard and under nearby native vegetation, and groundwater chemical analysis on samples obtained from the water table at these sites.

3.1 Drilling and Soil Sampling

The Water Resources Division of the NT Department of Environment and Natural Resources (DENR) Ingersoll Rand TH75 top drive drilling rig rotary air cored four investigation holes at the Rocky Hill grape block in July and August, 2016. As the project relied on water content and geochemical analysis of core samples, there was concern about possible contamination of samples from drilling fluids. For this reason, core was cut using compressed air as the only hole clearing fluid. For comparative purposes, a shallow core hole was also drilled with mud (RN 19188) nearby to an air cored hole (RN 19187).

Bores RN 19190 and RN 19191 were drilled within the vineyard. RN 19191 was located between the two most easterly plots, which were established in 2002. RN 19190 was located between plots established in 2002 and 2004. Native vegetation sites RN 19187 and RN 19379 were located south-west of the vineyard. RN 19188 was located adjacent to RN 19187.

Core was collected in a 3m long, 127 mm outside diameter, double core barrel. After each 3 metres of coring, the core barrel was pulled from the hole and laid out on a table. The recovered core was then pushed out of the core barrel into a section of PVC pipe using compressed air against a rubber plunger at the top of the core barrel.

The core was then immediately wrapped in plastic cling wrap, and moved to a shaded sampling area. Samples of core were collected in duplicate at approximately one metre intervals and stored in one litre glass jars with rubber gasket sealed metal lids. As the core obtained was usually comprised of competent sandstone the use of a hammer and chisel was required to break up the core to fit into the glass jars.

These jars, once filled and sealed, were stored in the shade. At the end of the coring project, one set of the duplicate glass jar samples were packed on a pallet and sent to Flinders University in Adelaide by road transport for analyses. Core samples were analysed for gravimetric water content, matric potential and chloride content. The remaining jars were retained in Alice Springs as a sample archive.

Figure 4. Locations of drill holes.

Table 1. Details of drilling.

Bore	Easting	Northing	Land Use	Total Depth (m)	Cored Intervals (m)	SWL (m BGL)	Screen Depth (m)
RN19187	407432	7359963	Native	57.0	0 - 57	50.9	NA
RN19188	407442	7359954	Native	48.3	6 - 27		NA
RN19189	407400	7359960	Native	57.0		51.3	49.9 – 55.2
RN19190	408215	7360118	Grapes	72.4	0 - 57	54.1	57.0 – 63.0
RN19191	408481	7360121	Grapes	66.0	0 - 63	55.4	59.0 – 63.0
RN19379	407020	7359489	Native	60.3	0 - 54	51.3	52.0 – 55.0

On three of the bores, separate samples were collected in 50mm clear plastic jars (also at approximately one metre intervals) for nitrate analysis. Again, pieces of competent sandstone core were broken up to fit into the plastic jars. Once collected, the plastic jars were left with the lids off to dry the sample. The plastic jars were then capped with screw top lids and transported to an air conditioned laboratory at the DENR depot in Alice Springs each evening after drilling. At the laboratory the jar lids were removed and the samples were placed in a large oven set at 40°C for at least 24 hours. The samples were then removed from the oven and capped with screw top lids and transported to Flinders University for analysis.

After completion of coring at each site, the hole was reamed with a 279 mm rock roller drilling bit to 5.7 m depth. Then 6 m of 219 mm steel casing was run into the hole (0.3 m casing above ground) and the annulus between the 279mm open hole and the 219mmm steel casing was filled with cement and water. Once the cement had set, the entire hole was reamed with a 200mm rock roller bit. A 100 mm diameter PVC casing was installed, slotted below the water table, and the PVC casing annulus was backfilled with 100mm gravel to above the depth of the slotted interval. A cement slurry was then used to seal the aquifer from the surface, and the annulus was backfilled with clean sand to a depth of about 6m. The upper 6 m was sealed with cement. RN 19187 could not be completed, and so an additional bore (RN 19189) was drilled for completion as a piezometer.

Bore locations are shown in Figure 4, and details of well screen depths and core sampling are given in Table 1. Further details are provided in Appendix 2.

3.2 Soil Analysis

In the Flinders University laboratory, the soil cores were further broken up with a hammer, and ground with a mortar and pestle. The gravimetric water content was measured by oven-drying a 30 – 50 mg subsample for 24 hours at 105°C. Results are expressed as grams of water per gram of oven-dry soil. For calculations requiring volumetric water content, a bulk density of 1.5 g cm^{-3} is assumed.

The matric potential of each sample was estimated using the filter paper method (Fawcett and Collis-George, 1967), as modified by Greacen et al. (1987). Three filter papers (Whatman No. 42, 5.5 cm diameter) were buried in the soil (which was packed down to ensure good contact with the filter paper), and allowed to equilibrate in a constant temperature room (at 18°C) for 7 days. After this time the filter papers were removed, brushed lightly to remove adhering soil particles, and their fractional water contents determined. Matric potential was then estimated using the calibration equations presented by Greacen et al. (1987). The value reported is the mean of the three replicates.

The chloride concentration in soil water was measured on the same sub-sample used for the gravimetric water content determination. Distilled water was added to the oven-dry sample to create a 1:5 soil water extract, which was shaken for 1 hour and then allowed to stand for

24 hours. The chloride concentration of the dilution extract was then determined colorimetrically utilising mercuric thiocyanate by Flow Injection Analysis. This was converted to the chloride concentration in the original soil water using the gravimetric water content. For a small number of samples, major ions concentrations and electrical conductivity were also measured on the same soil water extract.

Nitrate concentration was measured on a 1:10 soil/2M KCl extract, which was shaken for 1 hour and then analysed colorimetrically utilising Cd reduction by Flow Injection Analysis. Nitrate concentrations were not measured on core RN 19187.

Results from RN 19188 display evidence of contamination of samples from drilling fluids (higher water content and matric potential, and lower chloride concentration). Unfortunately problems with the drill rig mud pump meant that mud pressure was higher than anticipated for this hole. So while perhaps not a reliable test of the suitability of coring with mud, these results certainly illustrate that coring with mud for vadose studies might need very careful mud preparation and pumping if it is to provide meaningful data. Results from this core are not discussed further in this report, but are provided in Appendix 3.

3.3 Groundwater Sampling and Analysis

All four monitoring holes were sampled in September 2016. During construction no fluid other than compressed air was injected into the hole, and so it was assumed that a bailer should provide a representative uncontaminated sample of water from at or near the water table at each hole. These samples were obtained using a new plastic one litre disposable bailer for each hole. The bailer was lowered and retrieved using a reel of wire rope. The system of sampling was effective and water was easily retrieved from each hole.

Groundwater samples were analysed for pH, EC, alkalinity and major ions by Northern Territory Environmental Laboratories, and for pesticide and herbicides by Queensland Government Forensic and Scientific Services laboratories.

4. INFILTRATION PROCESSES

4.1 Infiltration Rates and Travel Times

Gravimetric water content and matric potential have been measured on soil cores obtained from RN 19379 and RN 19187 (under native vegetation) and from RN 19190 and RN 19191 beneath grapes (Figure 5). Profiles beneath native vegetation generally show increasing water content and matric potential from the soil surface to the water table. Although the matric potential below the water table should be zero, the filter paper method becomes inaccurate in such wet soils, and commonly records values between 1 and 10 kPa in saturated soils. Water contents of core samples from below the water table may also be slightly lower than in situ values, as they may have drained during sample collection.

Matric potential values beneath native vegetation are less than -10 000 kPa in the upper 2 m of the soil profile. This exceeds the ability of vegetation to extract water, and is due to soil evaporation. From 5 to 22 m depth, matric potentials increase from approximately -6000 KPa to -200 kPa, and then further increase to approximately -50 kPa at 45 m depth. An abrupt increase in matric potential below 45 m depth may indicate that 45 m is the maximum rooting depth of the vegetation. Water contents throughout the profile are mostly between 0.04 and 0.15 g/g, although between approximately 15 – 20 m depth in RN 19379 water contents are between 0.008 and 0.035 g/g. These low water contents probably indicate the presence of a sand layer.

The matric potential data clearly shows that soils beneath grapes are significantly wetter than those beneath native vegetation to depths of between 20 and 30 m. This is also apparent in the water content data, although there is more variability in water content as it is heavily influenced by soil texture. In the case of RN 19191, the soil profile appears significantly wetter than native vegetation profiles to approximately 23 m, and this depth appears to represent the limit of infiltration under grapes. Assuming a soil bulk density of 1.5 g cm^{-3}, the total volume of soil water stored in the profile above 23 m is calculated to be 2617 mm (Table 2). For RN 19190, the depth of infiltration under grapes appears somewhat deeper, as the soil profile is significantly wetter than native vegetation to approximately 30 m. Again assuming a soil bulk density of 1.5 g cm^{-3}, the total volume of soil water stored in the profile above 30 m in RN 19190 is calculated to be 3115 mm.

Between 40 and 47 m depth, profiles beneath grapes are significantly wetter than between 20 and 40 m, and also significantly wetter than between similar depths beneath native vegetation. This may reflect upward movement of groundwater into the dry soil by capillary processes, following clearance of the native vegetation.

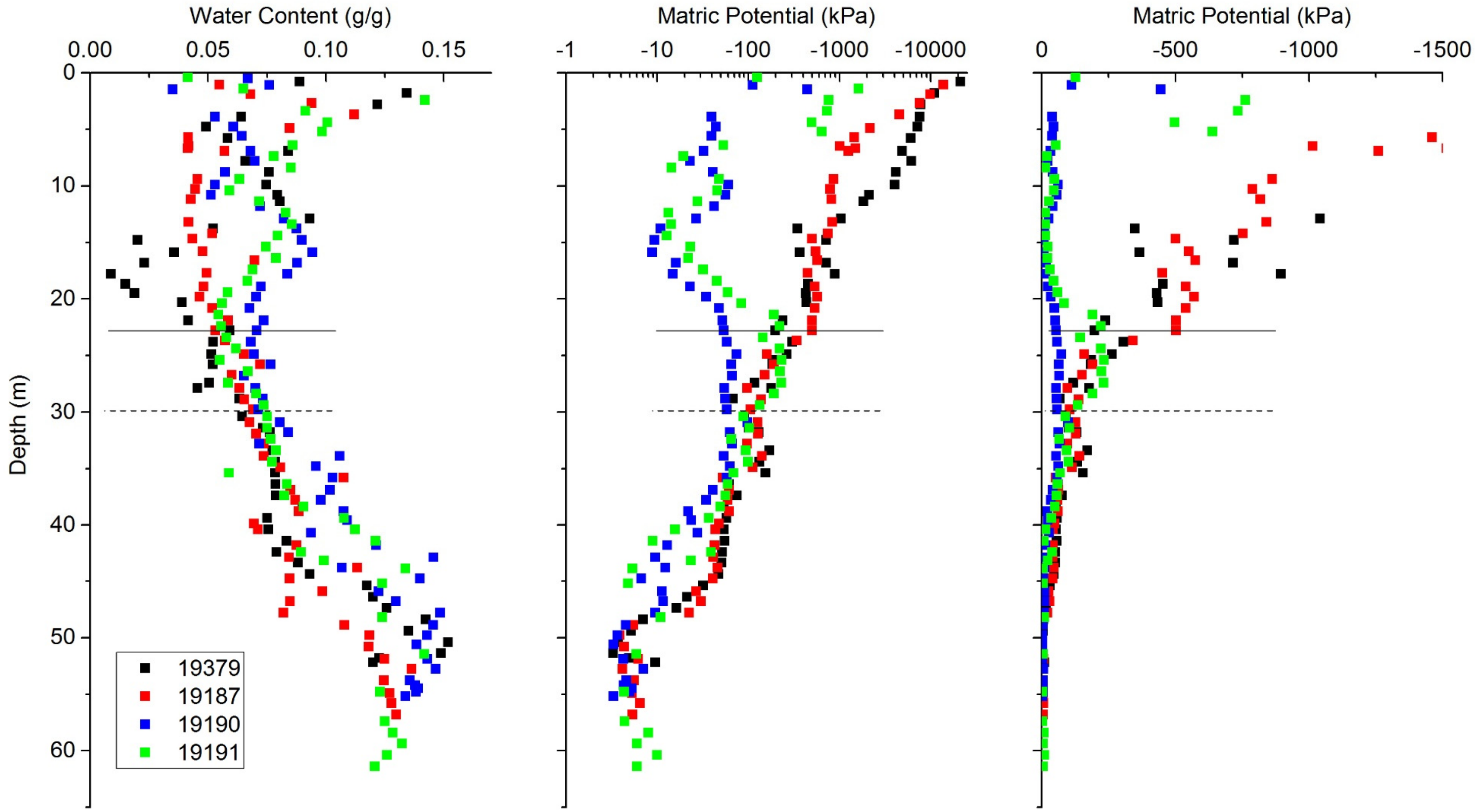

Figure 5. Soil profiles of gravimetric water content and matric potential (using both logarithmic and linear scales). Horizontal lines denote the inferred position of the pressure front at RN 19190 (broken line) and RN 19191 (solid line). The water table occurs between 50.9 and 55.4 m.

Figure 6 compares soil water contents and matric potentials measured on core samples from all four holes. Most of the data fall along a trend line, which represents an approximate moisture characteristic of the soils at the site. (A moisture characteristic is simply the name given to the relationship between water content and matric potential for a particular soil type.) The samples which fall significantly above this trend line probably reflect samples with a higher clay content.

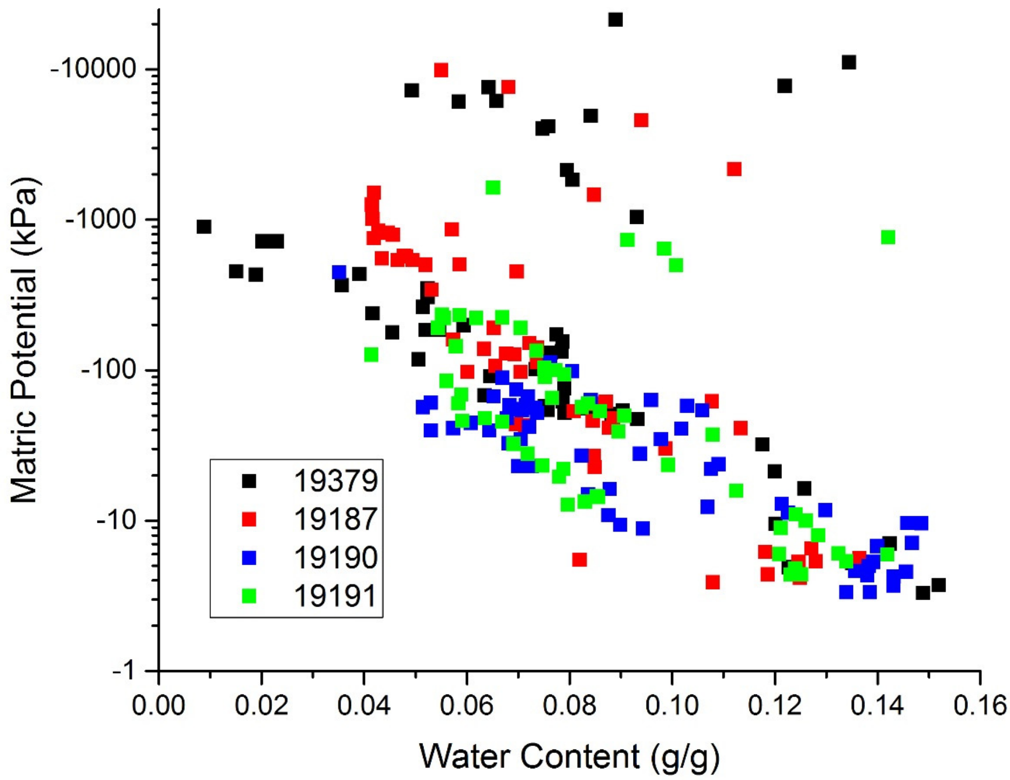

Figure 6. Relationship between gravimetric water content and matric potential for all core samples.

Calculation of the difference in soil water storage between native vegetation and horticultural profiles is complicated by differences in soil texture between the cored sites. For this reason, we have calculated the likely original water content profile for each of the horticultural core sites based on the observed moisture content – matric potential relationship. The process for doing this is described in Appendix 4. Figures 7 and 8 plot observed and simulated original water content profiles beneath horticultural sites. Changes in water storage above the pressure front are then calculated by summing water content differences with depth, assuming a soil bulk density of 1.5 g/cm^3. In the case of RN 19191, the total volume of soil water stored in the profile above the pressure front at 23 m depth is calculated to be 2617 mm (Table 2). The soil water content originally stored in the profile (i.e., under native vegetation) to this same depth is estimated to be 1394 mm. We therefore calculate an increase in soil water storage of 1223 mm (2617 minus 1394). Based on 15 years since development, this represents a mean infiltration rate of 82 mm/y (1223 mm divided by 15 years; Table 2 and Figure 8). For RN 19190, the total volume of soil water stored in the profile above the pressure front (which is at 30 m depth) is calculated to be 3115 mm. The water originally stored in the profile to this depth is estimated to be 1609 mm, and so the increase in water storage is estimated to be 1505 mm. Although RN 19191 is located between vineyard plots that were established in 2002 and 2004, for the purpose of the drainage rate calculations we have assumed that the site was developed in 2002. The increase in water storage therefore equates to a mean drainage rate of 100 mm (1505 divided by 15 years; Table 2 and Figure 8).

In southern Australia, where clearing for dryland agriculture has led to an increase in drainage, the water above the infiltration front under agriculture is fresher than at similar depths under native vegetation. However, this is not the case in Rocky Hill, in part because the infiltrating water is largely derived from groundwater, and so has a higher chloride concentration. The depth of the infiltration front is therefore not readily apparent from the chloride profiles (see below). Nevertheless, we can calculate the depth of the infiltration front using Equation 1. The infiltration front is calculated as the depth above which the total water storage is equal to the change in water storage above the pressure front. This is estimated to be approximately 9.4 and 15.5 m depth for RN 19191 and RN 19190, respectively (Table 2).

Even though irrigation of the vineyard has been taking place for up to 15 years, the recharge rate to the underlying aquifer does not increase until the pressure front reaches the water table. Estimating the time required for the pressure front to reach the water table (t_p) requires estimation of the water content that will occur throughout the profile once the pressure front reaches the water table. The mean matric potential above the pressure front in RN 19190 and RN 19191 is approximately 30 kPa. We assume that once the pressure front reaches the water table (and hence the entire profile has been 'wet up'), the matric potential below the current position of the pressure front will be 30 kPa (except for within 3 m of the water table, where the matric potential will be higher due to capillary processes.) This 'final' water content profile is then calculated as described in Appendix 4.

The difference between the current water storage between the present position of the pressure front and the water table, and the final water storage that will occur once the pressure reaches the water table is divided by the drainage rate to calculate the additional time lag (Table 2 and Figures 7 and 8). This soil water deficit must be filled before the recharge rate will increase. In the case of RN 19191, the soil water deficit between the

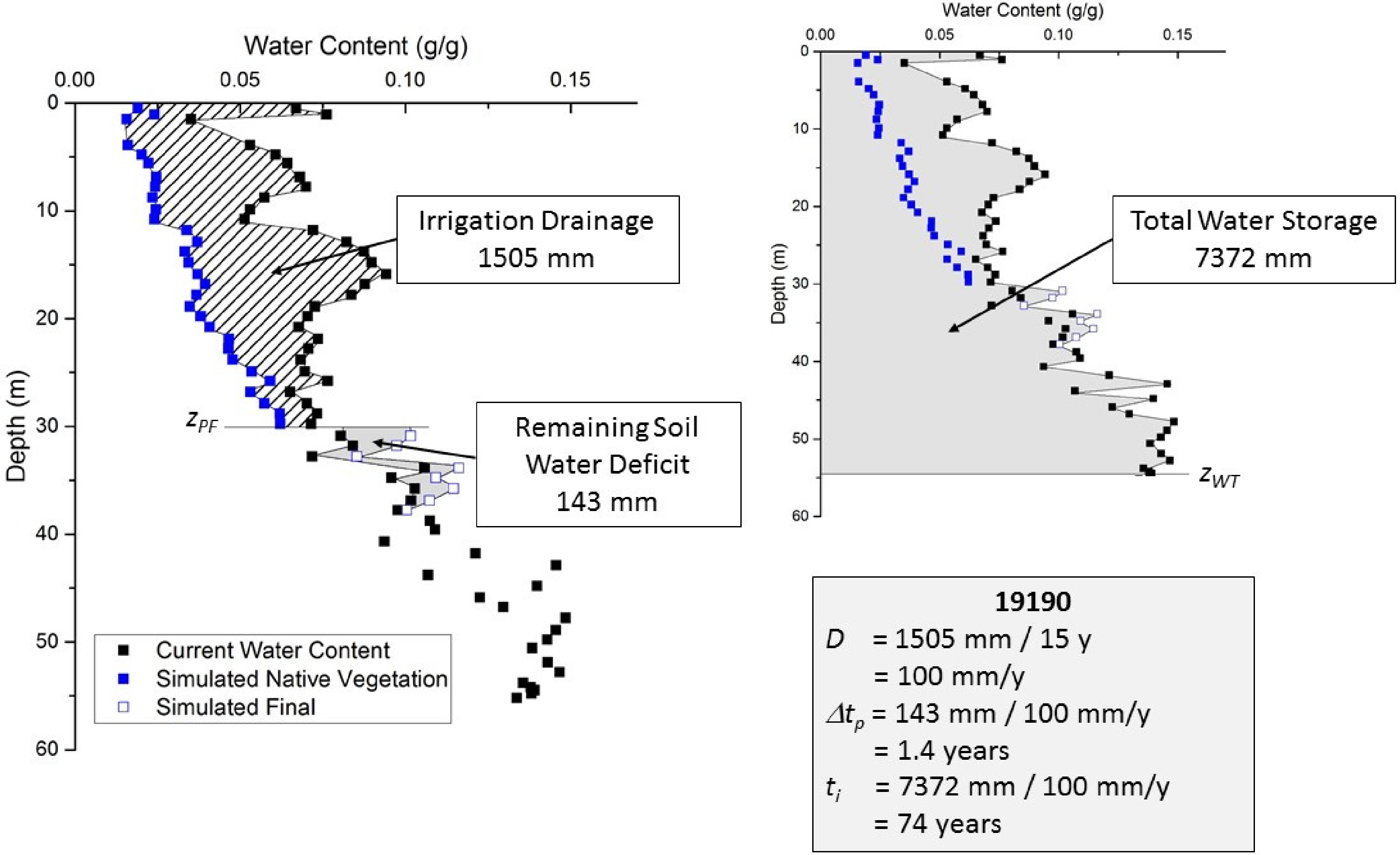

Figure 7. Soil profiles of gravimetric water content for RN 19190 under viticulture, together with simulated water content profiles prior to clearing of native vegetation, showing calculations of drainage flux and pressure and infiltration time lags.

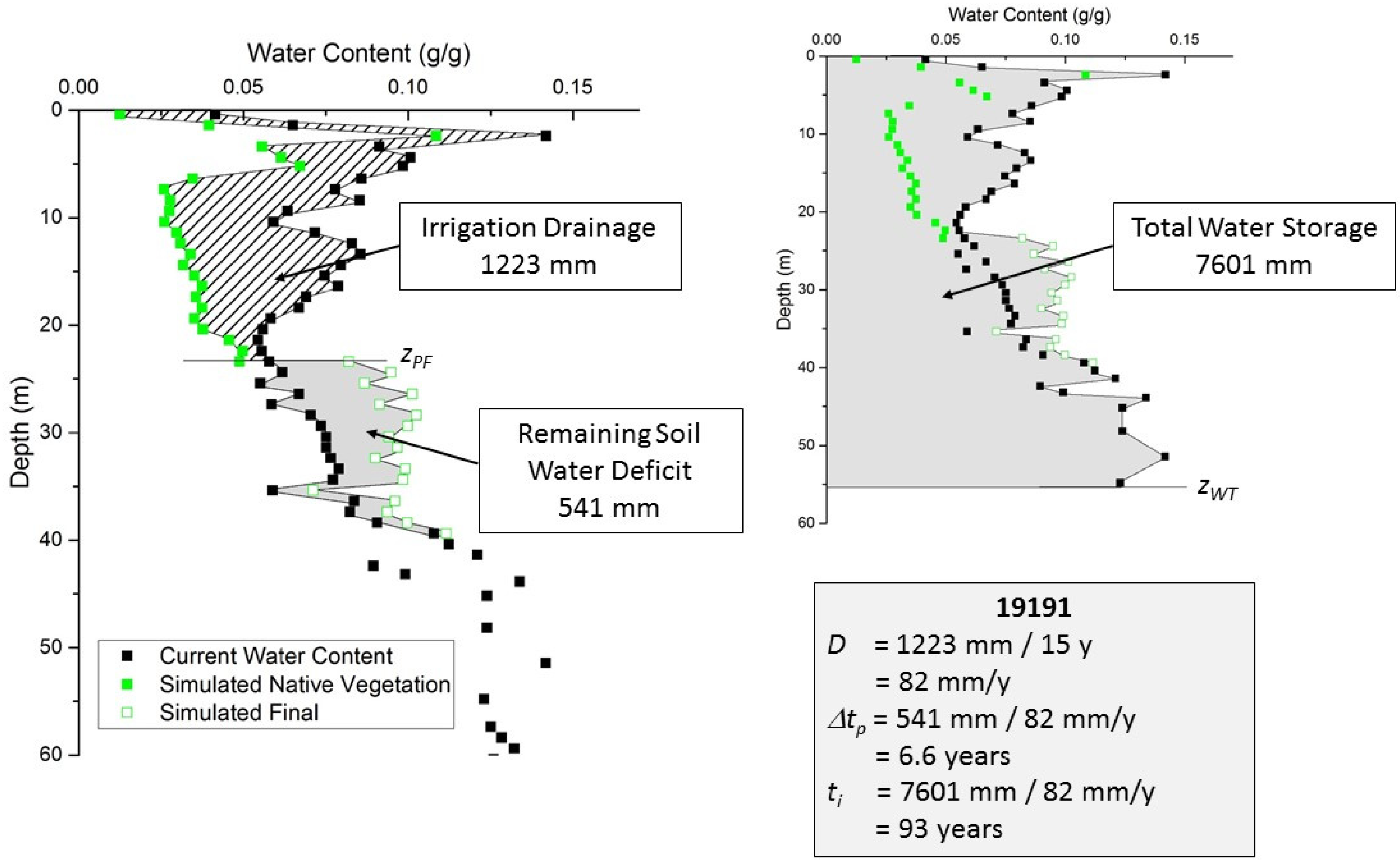

Figure 8. Soil profiles of gravimetric water content for RN 19191 under viticulture, together with simulated water content profiles prior to clearing of native vegetation, showing calculations of drainage flux and pressure and infiltration time lags.

Table 2. Depths of infiltration and pressure fronts, and water storage beneath horticultural sites.

	Description	Notation	Calculation	RN 19190	RN 19191
A	Water table depth (m)	z_{WT}	-	54.1	55.4
B	Time since development (y)		-	15	15
C	Depth of Pressure Front (m)	z_{PF}	-	30.0	23.0
D	Water stored above pressure front (mm)	$\int_0^{z_{PF}} \theta \, dz$	-	3115	2617
E	Water stored above this depth under native vegetation (mm)	$\int_0^{z_{PF}} \theta_d \, dz$	-	1609	1394
F	Increase in water storage above pressure front (mm)	$\int_0^{z_{PF}} (\theta - \theta_d) \, dz$	D – E	1505	1223
G	Drainage Rate (mm/y)	D	F / B	100	82
H	Depth of Infiltration Front (m)	z_{IF}		15.5	9.4
I	Total unsaturated water storage (mm)	$\int_0^{z_{WT}} \theta_w \, dz$		7372	7601
J	Soil water deficit below pressure front (mm)	$\int_{z_{PF}}^{z_{WT}} (\theta_w - \theta) \, dz$		143	541
K	Remaining pressure time lag (y)	Δt_p	J / G	1.4	6.6
L	Time lag for pressure response (y)	t_p	B + L	16	22
M	Time lag for infiltration (y)	t_i	I / G	74	93
N	Remaining infiltration time lag (y)	Δt_i	M – B	59	78

pressure front and the water table is calculated to be 541 mm. As the drainage rate is 82 mm/y, it will take a further 6.6 years for this soil water deficit to be filled, and hence for the pressure front to reach the water table. In the case of RN 19190, the remaining soil water deficit is only 143 mm, and the time remaining before the pressure front reaches the water table at this site is calculated to be only Δt_p = 1.4 years. Once the pressure front reaches the water table, the recharge rate increases, and solutes originally stored within the profile will be leached into groundwater at a faster rate.

Solutes in irrigation drainage do not reach the water table until the infiltration front reaches the water table. The time for the infiltration front to reach water table is calculated by dividing the total final water content profile (the current soil water storage above the pressure front plus the assumed final water storage below the pressure front; Row I in Table 2) by the drainage rate. This is estimated to be 93 and 74 years for RN 19191 and RN 19190, or a further 78 and 59 years, respectively (Figures 7 and 8).

As a check upon these fluxes and timelags, a one-dimensional numerical model was also developed to simulate changes in water content and matric potential following development of irrigation. The model used the native vegetation data as initial condition, and was calibrated to measured soil profile data from beneath the vineyard. The model used a saturated hydraulic conductivity of 0.15 m/d, and assumed a homogeneous soil and used a single moisture characteristic to represent the soil hydraulic properties. Details of the modelling approach are described in Appendix 5.

The model was calibrated to the field data using a drainage flux under viticulture of 128 mm/y, and predicted that recharge to the water table would begin to increase approximately 23 years after commencement of irrigation, with a steady state flux (of 128 mm/y) occurring after approximately 28 years. The model also predicted that drainage water would reach the water table after approximately 49 years, and that all the original soil water would be flushed from the profile after approximately 68 years. These results are broadly consistent with those obtained from water balance calculations. Differences largely reflect uncertainty related to the hydraulic properties of the soils.

4.2 Chloride and Nitrate Fluxes to Groundwater

Chloride concentrations in soil water show a characteristic bulge shape, with maximum concentrations in excess of 6000 mg/L at all sites (Figure 9). For profiles beneath native vegetation, the high concentrations reflect very high rates of water extraction within the root zone of the vegetation. Concentrations decrease below 25 m, and measured concentrations on samples collected from below the water table range between 13 and 64 mg/L. Samples collected between 12 and 15 m on RN 19190 are somewhat anomalous, having significantly lower concentrations than other samples above and below, and from samples from these depths at other sites. Interestingly, these low chloride concentrations are immediately above the estimated position of the infiltration front. Matric potentials are also greatest at these depths. The low chloride concentrations may therefore reflect water that infiltrated the profile soon after establishment of the vineyard. Groundwater extraction records indicate that irrigation rates were relatively high soon after the commencement of irrigation, and since newly planted vines would use less water than established vines, this might explain the lower chloride concentrations at these depths.

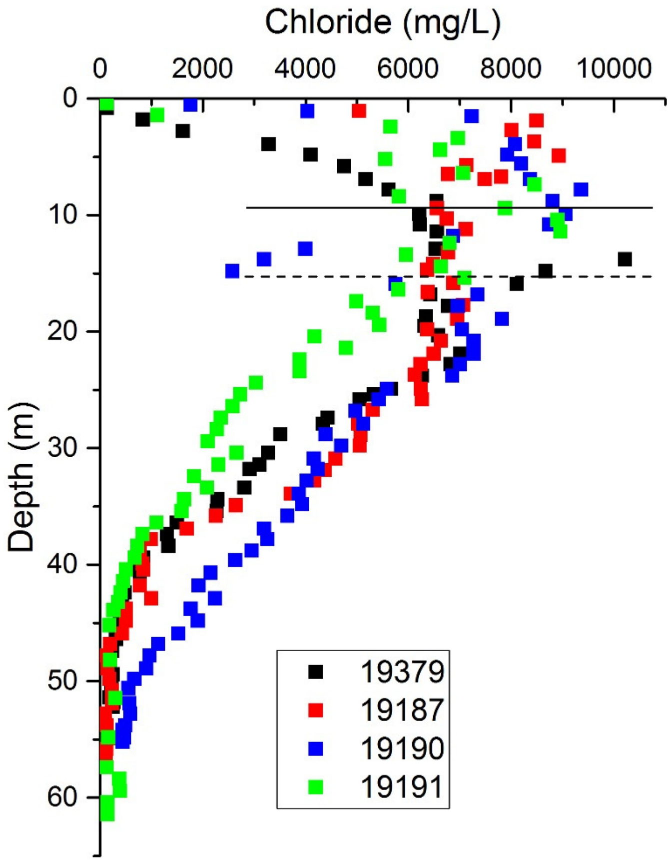

Figure 9. Soil profiles of chloride concentration in soil water. Horizontal lines indicate the estimated depth of the infiltration front in RN 19190 (broken line) and RN 19191 (solid line).

Based on the estimated recharge rates of 100 and 82 mm/y, and assuming an irrigation application rate of 1000 mm/y, and a mean chloride concentration of irrigation water of 100 mg/L (see Section 6, below), the chloride concentration of drainage water would be expected to be 1000 and 1220 mg/L, for RN 19190 and RN 19191, respectively (Equation 6). However, the mean chloride concentration above the infiltration front is approximately 6600 mg/L at RN 19190 and 6100 mg/L at RN 19191. A number of factors might contribute to this observation, including

- Soil water is not completely displaced by the infiltrating irrigation drainage water, so that some chloride remains from the original soil profile.
- Addition of chloride in fertilisers
- Uneven infiltration and evaporation. Irrigation water is supplied through drippers located along the vineyard rows, and this would lead to some three-dimensional redistribution of water, and possible accumulation of chloride between vineyard rows and between the vineyard blocks, where there is no direct application of irrigation water. High salinity between rows has been observed in some vineyard areas of South Australia (John Hutson, pers. comm.).

The total mass of chloride stored within the unsaturated soil profiles is calculated to be 21.5 and 16.0 kg/m^2 in RN 19187 and RN 19379, respectively. We assume that this salt will eventually be flushed into the aquifer by the irrigation drainage water. Assuming piston flow conditions, this salt mass will begin to be flushed into the aquifer between 1.4 and 6.6 years from present (Δt_p in Table 2), and will continue for a further 57 – 62 years ($\Delta t_i - \Delta t_p$). This represents a chloride flux of approximately 0.3 kg/m^2/y. Multiplying by an approximate area under grapes of 0.6 km^2, gives 200 tonnes per year of chloride. The actual flux will be somewhat slower than calculated here if the flushing process takes longer than assumed by piston flow, but the total mass (11,000 tonnes) will not change. The chloride mass will also be slightly delayed because the planting of the vineyard took place over a period of approximately 10 years.

Based on the proximity of production bores to the vineyard, and in the absence of pumping from the proposed PWC borefield within NT Portion 4704, leakage beneath the vineyard is expected to be drawn into the production bores. Based on the current pumping rate, the travel time for groundwater beneath the vineyard to the production bores is estimated to be only a few months to years. Assuming that the chloride flux to the groundwater beneath the vineyard (200 tonnes per year) is added to the pumping water with only a short time delay, then this could lead to increases in chloride concentration of pumping water of around 300 mg/L (200 tonnes/y divided by 600 ML/y).

After the infiltration front reaches the water table, the chloride concentration in infiltrating water is expected to decrease. Based on the current irrigation rate (1000 mm/y) and chloride concentration of irrigation water (100 mg/L), this flux is estimated to be approximately 100 $g/m^2/y$. Multiplying by the vineyard area of 0.6 km^{-2}, gives 60 tonnes per year across the current area of vineyard. The flux may be slightly higher if there is significant leaching of salts present in applied fertilisers.

We can calculate the total salt flush based on these chloride fluxes, using the relationship between chloride concentration and electrical conductivity determined on a subset of soil samples (Appendix 6), and an assumed relationship between electrical conductivity (in $\mu S/cm$) and total dissolved salts (in mg/L) of 0.6 (i.e., TDS = EC x 0.6). In this way, we estimate that total dissolved salt concentration (TDS) can be estimated by multiplying the chloride concentration by 4.4. Thus the total salt stored within the soil profiles in the area of the vineyard is estimated to be 50,000 tonnes (11,000 tonnes of chloride), and the total salt flux will be 1.3 $kg/m^2/y$ or 900 tonnes per year (chloride flux of approximately 0.3 $kg/m^2/y$ or 200 tonnes per year). After the infiltration front reaches the water table, the salt flux will be approximately 450 $g/m^2/y$, or 260 tonnes per year across the current area of vineyard.

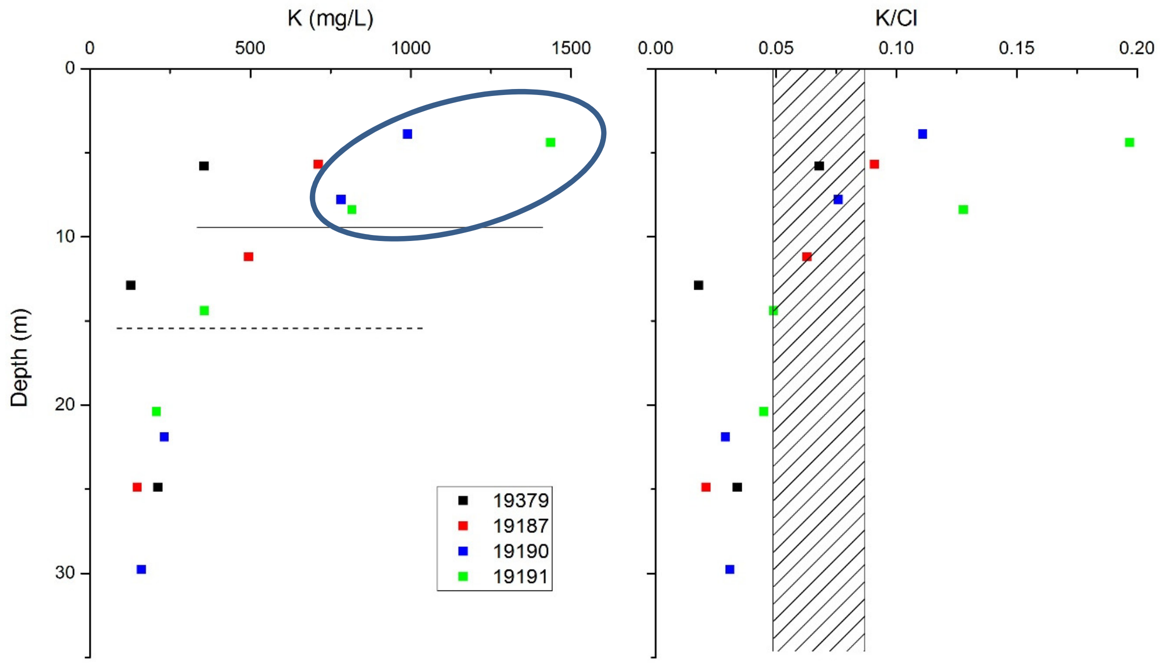

Figure 10. Soil profiles of potassium concentration in soil water, and potassium/chloride molar ratio. Horizontal lines indicate the estimated depth of the infiltration front in RN 19190 (broken line) and RN 19191 (solid line). Samples collected from above the infiltration front in these profiles have highest potassium concentrations, and are enclosed by the blue ring. The shaded area indicates the range of K/Cl ion ratios in bore water (0.073 in RN 17817 and 0.047 in RN 17035).

Potassium concentrations measured on a small number of soil samples are depicted in Figure 10. Interestingly, the samples from above the infiltration front in RN 19190 and RN 19191 are the four highest values measured in any of the profiles. K/Cl molar ratios for three of these samples are also significantly higher than for any of the other samples, and also higher than K/Cl molar ratios measured on irrigation water from production bores RN 17817 and RN 17035. These high potassium concentrations might be derived from fertilisers, or may result from cation exchange processes, having been displaced by other cations present in irrigation water or applied fertilisers.

Nitrate profiles under the two horticultural sites and under native vegetation site RN 19379 are depicted in Figure 11. Nitrate concentrations under native vegetation show a general decrease with depth, with concentrations between 6 and 34 mg/L in the upper 20 m of profile, but less than 6 mg/L below 30 m depth. High nitrate concentrations are common in central Australian groundwater, and commonly attributed to bacteria associated with termite mounds (Barnes et al., 1992). Two peaks are apparent, the first at 5.5 m depth, is probably related to production of nitrate within the root zone. A second peak at approximately 20 m depth may be an artefact of measurement. Nitrate concentrations were determined by dividing measured nitrate loads (mg/kg) by water content, and this zone of high nitrate concentration corresponds to a very low soil water content at these depths. However, since water content and nitrate load were not measured on the same soil sample, the water content of the nitrate sample may have been higher than the measurement indicates, and thus the nitrate concentration may be lower than shown in Figure 11.

Nitrate concentrations below horticultural land are elevated within the top 3.5 m of soil profile, with values up to 31 mg/L in RN 19191 and up to 63 mg/L in RN 19190. In comparison, values in the upper 3.5 m of profile are less than 15 mg/L in RN 19379. These high nitrate concentrations within the shallow soil zone probably reflect addition of nitrogen fertiliser to the grape crops. However, there is no evidence of high nitrate concentrations below 3.5 m depth under horticulture, and values are similar to or less than those beneath native vegetation. On average, nitrate concentrations beneath viticulture are approximately 30% less than those under native vegetation.

However while values are similar, the flux of nitrate to the groundwater will increase as the water flux increases. The total mass of nitrate stored under native vegetation at RN 19379 is 0.043 kg/m^2 NO_3-N. Although some denitrification may occur, we here assume that all of this nitrate is leached into the underlying aquifer. Assuming piston flow conditions, this salt mass will begin to be flushed into the aquifer in approximately 5 years, and will continue for a further 50 – 80 years. This represents a nitrate flux of approximately 0.7 g m^2/y NO_3-N. Multiplying by an approximate area under grapes of 0.6 km^2, gives 0.4 tonnes per year of NO_3-N.

Once the irrigation drainage water reaches the water table (in 50 – 80 years), the nitrate flux will decrease to about 0.2 – 0.3 tonnes per year.

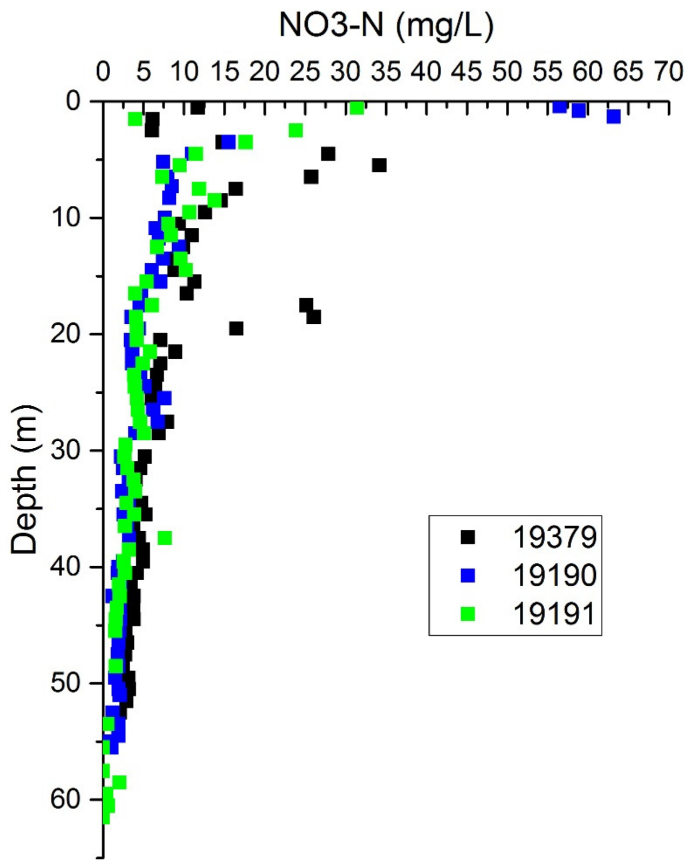

Figure 11. Soil profiles of nitrate concentration in soil water.

4.3 Piston Flow versus Preferential Flow

The above calculations assume that soil water moves predominantly by piston flow. If preferential flow occurs, then some fraction of infiltrating water will reach the water table earlier than the above calculations suggest, although the effect on solute fluxes is difficult to determine. However, while flow through fractures can be important for groundwater flow, in unsaturated soil profiles fractures and macropores are usually empty. (For example, at matric potentials less (drier) than -10 kPa, pores larger than 15 μm will be empty and so will not contribute to soil water flow; Marshall and Holmes, 1988 p.205). The assumption of piston flow for the Rocky Hill soils appears reasonable, because:

(i) Soils beneath the vineyard are uniformly wet above the pressure front, and do not show zones of wet and dry soil, as might be expected for a system dominated by preferential flow.

(ii) The increase in water content above the pressure front is consistent with drainage rates of 80 – 130 mm/yr, which represents approximately 10% of applied irrigation water. This is a typical leaching fraction for irrigation systems, and so is consistent with the piston flow assumption.

(iii) Soil matric potentials are mostly less (drier) than -10 kPa, and so macropores and most fractures would be filled with air, not water.

Thus, although some contribution of preferential flow cannot be ruled out, the available data and theory is consistent with soil water movement that is dominated by piston flow.

5. GROUNDWATER PUMPING AND WATER LEVEL DECLINE

Monitoring of water levels in the newly completed bores show a groundwater decline of between 0.3 and 0.7 m over a period of approximately three months. This apparent rate of decline is significantly higher than the regional rate of decline of between 0.1 and 0.2 m/y that has been observed across an area extending from the agricultural block west to the Santa Teresa road and south to Claypan Dam. The increased rate of water table decline may be the result of pumping from the production bores located immediately north of the vineyard. Importantly, there is no evidence of a water table rise in bores immediately beneath the vineyard, which is consistent with irrigation drainage not yet having reached the water table.

Table 3. Depths to groundwater on bores in the vicinity of the agricultural block measured in 2016. (Data are metres below ground level.)

	SWL (m BGL)			
Date	RN 19189	RN 19190	RN 19191	RN 19379
11 Aug	51.33	54.14	55.39	51.31
13 Sep	51.61	54.21	55.43	51.55
5 Oct	51.65	54.27	55.42	51.57
2 Nov	51.91			51.79
15-16 Nov	51.99	54.71	55.71	51.84

6. GROUNDWATER QUALITY

Groundwater samples were collected from the two sites under native vegetation and the two horticultural sites. Full ion chemistry of groundwater samples is given in Appendix 7. Laboratory pH, EC, and measured concentrations of selected ions are given in Table 4. Also included in this table, are results from analysis on samples obtained from production bores RN 19817, RN 17035 and RN 10669 in 2015.

Observed concentrations of chloride and nitrate in groundwater are very low, and do not provide any indication of contamination from horticultural activities. pH and alkalinity values are relatively high on RN 19191, which probably indicates that cement used during installation of the well casing has found its way to the watertable, or that some cement entered the bailer during sampling. Although this is not expected to affect nitrate and pesticide results, the possibility for trace contamination of groundwater samples through the borehole itself cannot be ruled out, particularly because newly installed wells were not purged prior to sampling. It is noteworthy that chloride concentrations in groundwater samples are significantly higher than those measured on core samples from near the water table. The reason for this is unclear.

The chloride concentration on the two bores that are used to irrigate the vineyard are approximately 65 and 130 mg/L and TDS values are 485 and 575 mg/L.

Groundwater samples were analysed for more than 200 pesticides, herbicides, and other organic compounds. All samples were below detection limit for most compounds, but results for compounds with measurable concentrations on at least one sample are listed in Table 4. Compounds with above background concentrations are:

- DEET (N,N-Diethyl-meta-toluamide, also referred to as simply diethyltoluamide). This is the most common active ingredient in insect repellents. It has been found to have a slight toxicity for some freshwater fish, and it also has been shown to be toxic for some species of freshwater zooplankton.

- 2,4-Di-t-butylphenol. This compound is used in industry as a UV stabilizer and as an antioxidant for hydrocarbon-based products ranging from petrochemicals to plastics.

- N-Butyl benzenesulfonamide (NBBS). NBBS is commonly used in the production of polyamide (nylon) plastics.

- Diuron. Diuron is the trade name for DCMU (3-(3,4-dichlorophenyl)-1,1-dimethylurea), a selective herbicide for broadleaf weeds and some annual grasses. It is used in many agricultural situations, and also for weed control in non-agricultural areas. Diuron has a relatively low tendency to sorb to soils and sediments, while its hydrolysis and aqueous photolysis half-lives are relatively long. Consequently diuron is both mobile and relatively persistent, and is therefore prone to off-site movement in surface runoff, and migration to ground water.[1]

- Triclopyr. Triclopyr (3,5,6-Trichloro-2-pyridinyloxyacetic acid) is a systemic, foliar herbicide and fungicide which is used mostly to control broadleaf weeds or rust diseases on crops. Triclopyr breaks down in soil with a half-life of between 30 and 90 days. Triclopyr degrades rapidly in surface water.[2]

In all cases, concentrations of organic compounds are very low – less than 1 μg/L. Drinking water standards are available only for Triclopyr and Diuron, and measured concentration are less than these values by more than a factor-of-ten. (The Australian drinking water standard for both of these compounds is 20 μg/L; Australian Drinking Water Guidelines, 2011.)

It is also noteworthy that similar concentrations of DEET were measured in production bores 17817 and 17035 during an initial sampling in August 2015, but were not measured during a subsequent sampling in September 2015. Because of the very low levels, it would be important to resample the wells, and also to sample some wells from the area which are beyond the influence of irrigation activities, before any firm conclusions regarding the presence or otherwise of these compounds could be drawn.

[1] See http://www.cdpr.ca.gov/docs/emon/pubs/fatememo/diuron.pdf

[2] See https://en.wikipedia.org/wiki/Triclopyr

Table 4. Results of selected groundwater chemical analyses.

	Bore								
Analyte	19189	19190	19191	19379	17817		17035		10669
Sampling Date	13/09/16	13/09/16	13/09/16	13/09/16	24/08/15	17/9/15	24/08/15	17/9/15	17/9/15
Ph	7.9	7.9	12.1	8.0	7.9	7.8	7.7	7.8	8.0
EC (uS/cm)	1200	1960	4400	1030	794	779	1020	955	888
Alkalinity (mg/L)	310	243	971	351	275	275	229	243	270
TDS (mg/L)	800	1050	2350	640	490	480	580	570	570
Cl (mg/L)	147	335	117	126	67	65	131	127	79
NO3-N (mg/L)	.005	<0.005	0.38	0.08	2.27	2.08	1.56	1.52	1.71
NH3-N (mg/L)	0.095	0.025	4.02	0.06	0.015	<0.005	0.005	<0.005	<0.005
DEET (μg/L)	0.3	0.2	0.3	0.2	0.2	<0.1	<0.1	<0.1	<0.1
2,4-Di-t-butylphenol (μg/L)	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1
N-Butylbenzenesulfonamide (μg/L)	<0.1	0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1
Diuron (μg/L)	0.02	<0.01	<0.01	<0.01	0.001	<0.001	<0.001	<0.001	<0.001
Triclopyr (μg/L)	0.04	0.09	0.01	0.06	<0.002	<0.002	<0.002	<0.002	<0.002

7. CONCLUSIONS AND RECOMMENDATIONS

Development of irrigated agriculture in arid environments will inevitably lead to increased rates of groundwater recharge. There is potential for this recharge to impact water quality. Because concentrations of chloride, nitrate and other salts are naturally high in arid zone soils of central Australia, irrigation drainage will leach these salts into the underlying groundwater. Importantly, at the Rocky Hill site there is no convincing evidence of contaminants derived from irrigation activities (either fertilisers, pesticides or herbicides) in the groundwater. However, this might be due to the long travel times for water through the unsaturated zone.

Drainage rates beneath irrigated viticulture on the Undoolya Rocky Hill Agricultural Block have been estimated to be between 80 and 130 mm/y. This drainage water moves slowly down through the soil profile, pushing the pre-existing soil water ahead of it. After a period of time, this pre-existing soil water, which is pushed ahead of the irrigation drainage water, begins to recharge the underlying aquifer, which is at 50 – 55 m depth. Based on comparison of soil moisture profiles beneath the vineyards and adjacent native vegetation, we estimate that this water will reach the aquifer within the next 5 - 10 years. When this occurs, leaching of salts that were originally stored within the unsaturated soil profiles into groundwater will results in salt fluxes of approximately 1.3 kg/m^2/y into the underlying aquifer. Multiplying by an approximate area under grapes of 0.6 km^2, gives 900 tonnes per year over the next 50 – 80 years.

The flux of nitrate to the groundwater will also increase as the drainage water pushes the pre-existing soil water into the underlying aquifer. The total mass of nitrate stored under native vegetation is 0.043 kg/m^2 NO_3-N. Movement of this water into the aquifer will therefore result in a nitrate flux of approximately 0.7 g m^2/y NO_3-N over the next 50 – 80 years. Across the vineyard area, this represents 0.4 tonnes per year of NO_3-N. However, this is not expected to increase groundwater concentrations of nitrate to above safe drinking water limits.

The irrigation drainage water is not expected to reach the water table for a further 50 – 80 years. Once this occurs, the chloride concentration in infiltrating water is expected to decrease, and the chloride flux will reduce to approximately 60 tonnes per year. In principle, the movement of irrigation drainage water into the underlying groundwater might result in contamination of the aquifer with substances that have been added to the crop or to the irrigation water. This might potentially include nitrate contamination from fertiliser applications, or pesticide and herbicide residues. Nitrate concentrations in soil water are less than beneath native vegetation, and so in 50 – 80 years the nitrate flux will decrease to about 0.2 – 0.3 tonnes per year.

This report has not specifically examined drainage rates or unsaturated zone travel times under onion or other crops, or the effect of solute fluxes beneath irrigation on the water quality of a proposed borefield within NT Portion 4704. Under current conditions, due to the proximity of the irrigation bores and in the absence of pumping from the borefield, most of the recharge from beneath the vineyard will be extracted by the irrigation bores. Simple calculations suggest that this might lead to an increase in total dissolved salt concentration of pumping water of around 1300 mg/L, with potentially significant implications for vineyard management. However, it is likely that flow lines would change with the commencement of pumping from a PWC borefield within NT Portion 4704, or if the locations of irrigation bores were to change. As the extraction rate from the proposed PWC borefield is likely to be high, groundwater from beneath the agricultural block is likely to be within its capture zone. However, groundwater which is derived from beneath the agricultural block will be diluted by groundwater from other areas, and so it is possible that salt fluxes beneath the irrigation areas may have little effect on concentrations of groundwater pumped by the borefield. A groundwater model is currently being developed of the Roe Creek and Rocky Hill – Ooraminna region, and this groundwater model should be used to calculate groundwater travel times to the borefield and the extent to which groundwater from beneath irrigation areas are diluted by groundwater from other parts of the aquifer. Such simulations could use a range of hypothetical bore locations and pumping rates.

This report has also not specifically considered the consequences of future expansions of irrigation on the potential water quality of the production borefield. As a starting point, it is reasonable to assume that solute fluxes to groundwater will be similar to those beneath the vineyard development. Thus, for example, if the area or volume of irrigation were to triple (in line with the recent increase in allocation), then it might be expected that the salt flux would also triple. If the groundwater model predicts that these solute fluxes are likely to have an adverse impact on the quality of groundwater sourced by the borefield, then additional studies to specifically examine drainage rates and travel times beneath other crops would be warranted.

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APPENDIX 1. INFILTRATION PROCESSES IN NON-UNIFORM SOILS

In a non-uniform soil profile, the remaining time lag for the pressure front to reach the water table is given by

$$\Delta t_p = D^{-1} \int_{z_{PF}}^{z_{WT}} (\theta_w - \theta)\, dz$$

where D is the drainage rate, θ is the volumetric soil water content, θ_w is the estimated volumetric soil water content that will occur once the pressure front reaches the water table, z_{PF} is the current depth to the pressure front, and z_{wt} is the water table depth. The total time lag between the change in land use and arrival of the pressure front at the water table (tp) is therefore simply Δtp plus the time since the change in land use.

The infiltration time lag is

$$t_I = \int_0^{z_{WT}} \theta_w \, dz.$$

APPENDIX 2. BORE LOGS

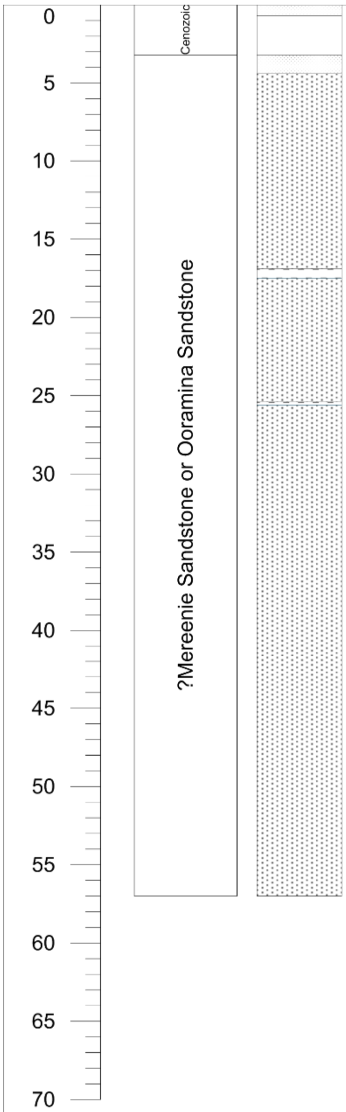
RN019187 Rocky Hill Coring Project
July to August 2016

Location Easting: 408215 Northing: 7360120
GDA 94 Zone: 53

Start date: 20/07/2016
Completion date: 25/07/2016
Total drilled depth: 57 mbgl
Comments: Backfilled coring hole. RN019189 constructed as watertable monitoring bore nearby.

Electrical conductivity: Not sampled
pH: Not sampled

Depth (m)	Formation	Lithological Log	Lithological description	Bore Construction



SAND Red-brown, calcretised, silt to medium iron-stained quartz sand with sub-angular gravel-size fragments white calcrete.

CALCRETE Cream to white, very hard, calcareous silt to medium sand. Minor pinkish stains (pisolite formation).

SAND Grey, slightly clayey, friable, moderately stiff, moderately-well-sorted, fine quartz sand. No laminations observed in core.

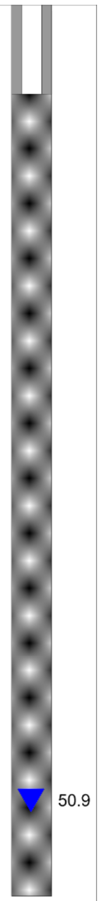
SANDSTONE Grey, friable, moderately-well- to well-sorted, sub-angular to sub-rounded, fine quartz sand. Calcareous bands 1-2cm thickness horizontal occurring at 9.8, 10.2, 10.6, 11.2, 11.5, and 11.8mbgl. Iron-cemented sands 13.6-13.8mbgl. Finely and feintly laminated in places.

CLAY White, smooth, plastic clay. Contains live tree roots 3-5mm diameter. Salty taste.

SANDSTONE Grey, very-stiff, non-calcareous, well-sorted, fine quartz sand. Partially cemented with white ?clay. Slight yellow to orange mottles in places. No laminations observed. White, very stiff, calcareous band 45 degrees to horizontal at 21.55-21.6mbgl.

CLAY Grey, slightly silty, stiff clay with 1-2mm spots of orange to red iron oxide staining.

SANDSTONE Grey, very-stiff, non-calcareous, well-sorted, fine quartz sand. Partially cemented with white ?clay. Slight yellow to orange mottles or bands in places (30-32mbgl; 35-36mbgl; 40.5mbgl). No laminations observed, weakly laminated 45-48mbgl. Appears clayey below 51mbgl. Minor grey and white weathered ?feldspar from ~45mbgl.

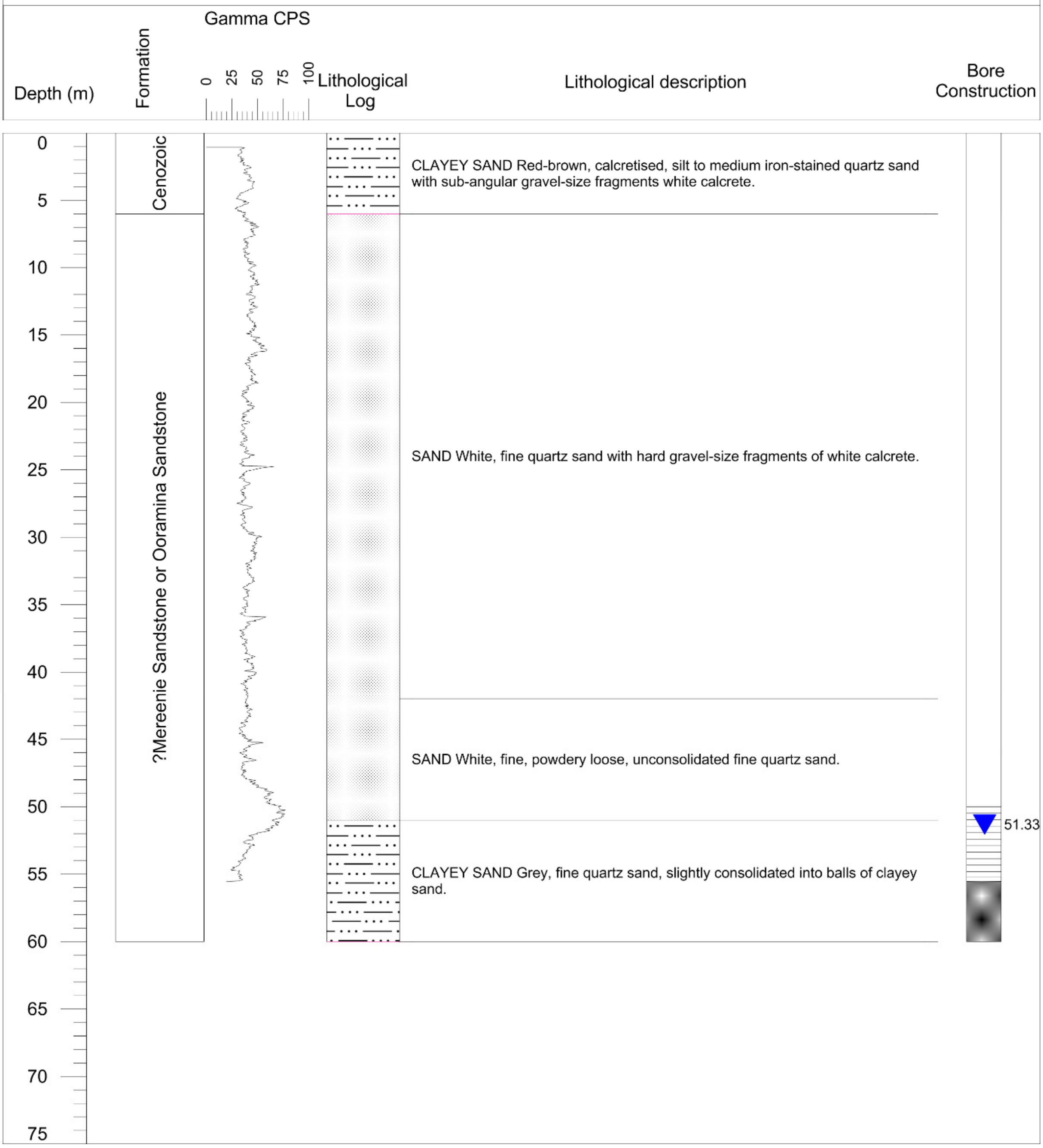


RN019189 Rocky Hill Coring Project
July to August 2016

Location Easting: 407400 Northing: 7359960
GDA 94 Zone: 53

Start date: 30/07/2016
Completion date: 03/08/2016
Total drilled depth: 57 mbgl
Comments: RAB drilled hole, drill cuttings only - not cored.
Bore constructed with 100mm PVC and inline screens.

Electrical conductivity: 1200 µs/cm
pH: 7.9



RN019190 Rocky Hill Coring Project
July to August 2016

Location Easting: 408215 Northing: 7360120
GDA 94 Zone: 53

Start date: 03/08/2016

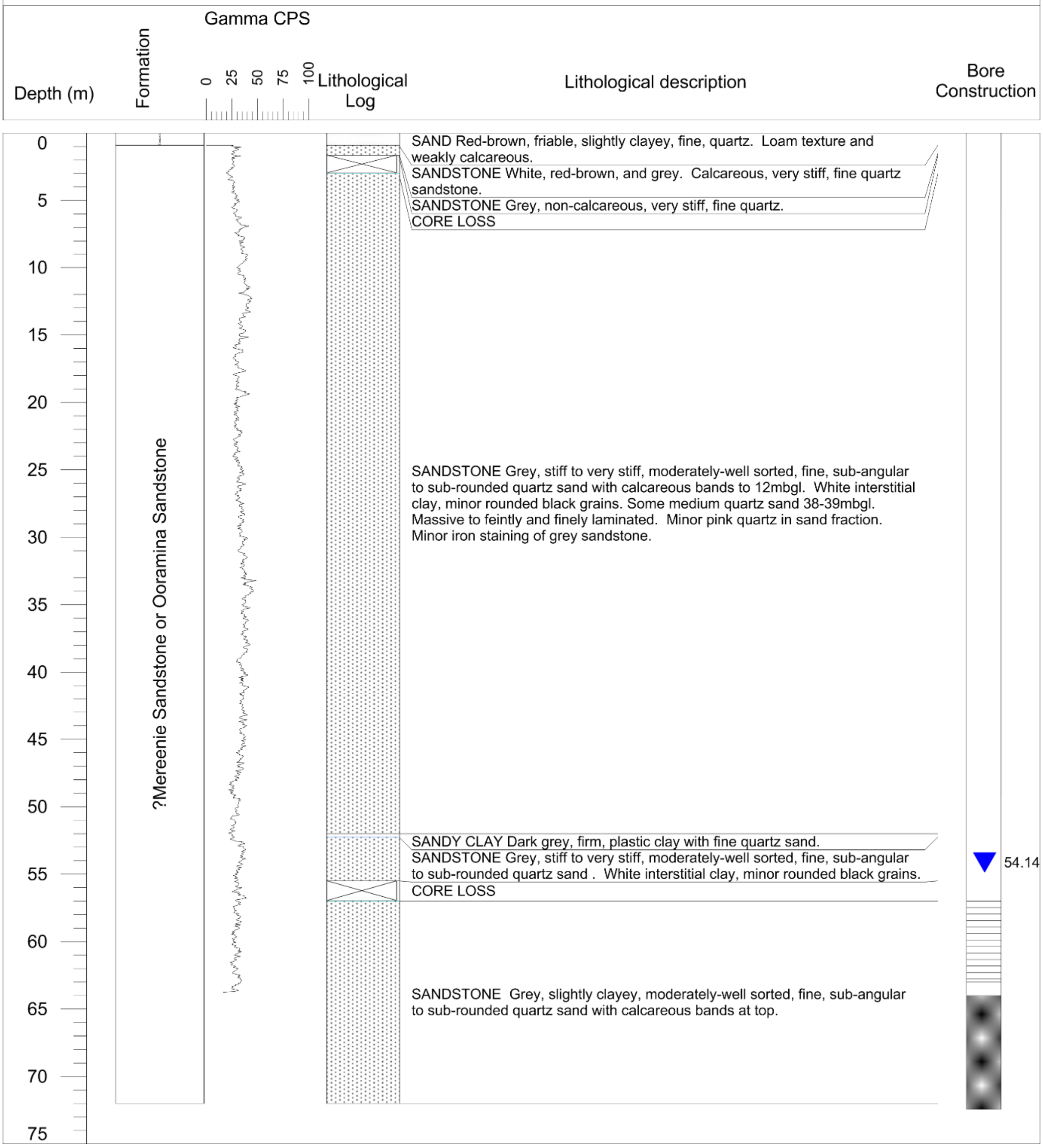
Completion date: 17/08/2016

Total drilled depth: 74.2 mbgl

Comments: Cored from 0-57m, RAB drill cuttings only every three metres from 57-60m. Bore constructed with 100mm PVC and inline screens.

Electrical conductivity: 1960 µs/cm

pH: 7.9



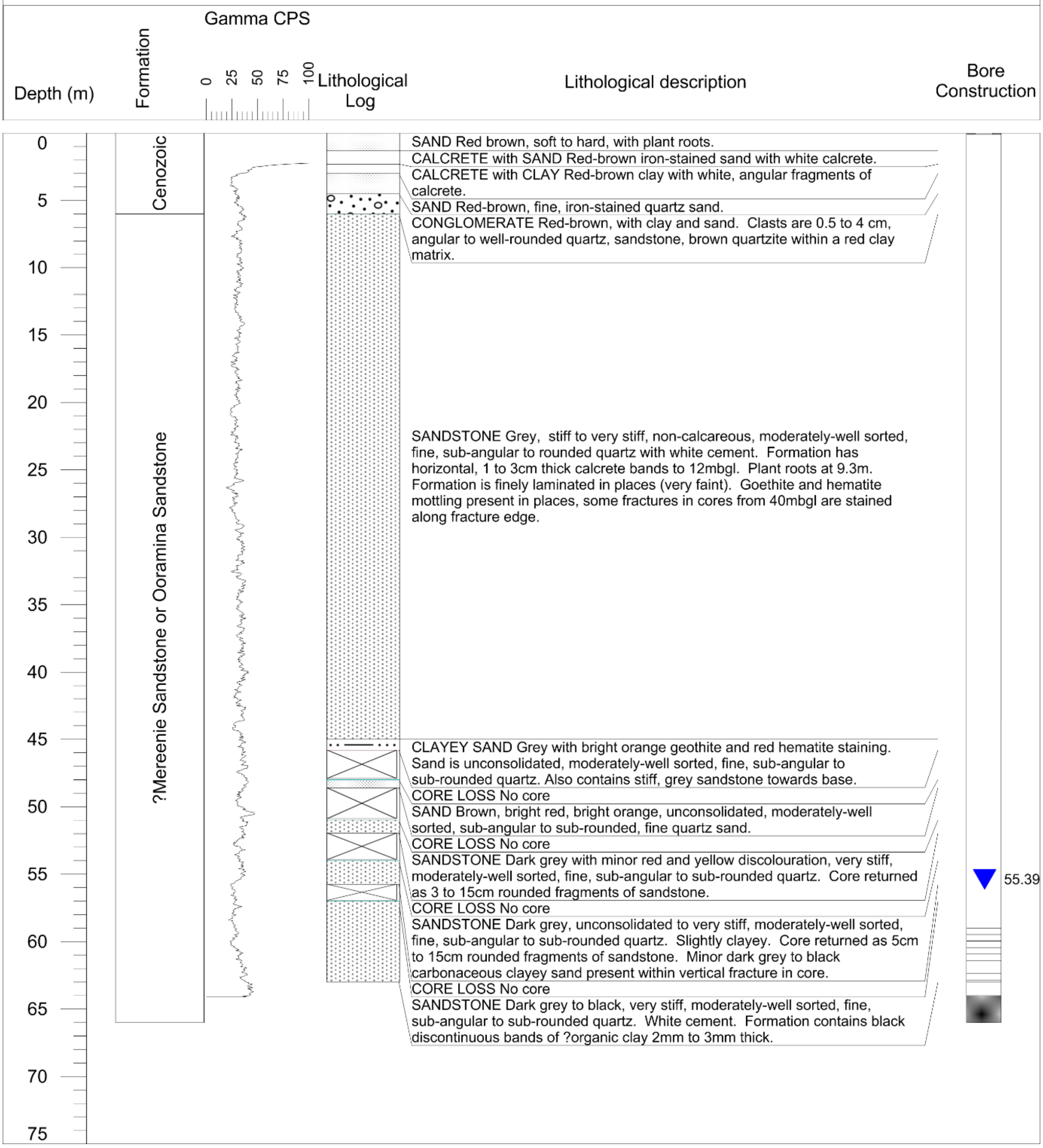
RN019191 Rocky Hill Coring Project
July to August 2016

Location Easting: 480480 Northing: 7360120
GDA 94 Zone: 53

Start date: 17/08/2016
Completion date: 25/08/2016
Total drilled depth: 66 mbgl

Electrical conductivity: 4400 µs/cm
pH: 12.1

Comments: Annular cement above gravel pack disappeared into ?formation during grouting at 43.6m. Bore constructed with 100mm PVC and inline screens.

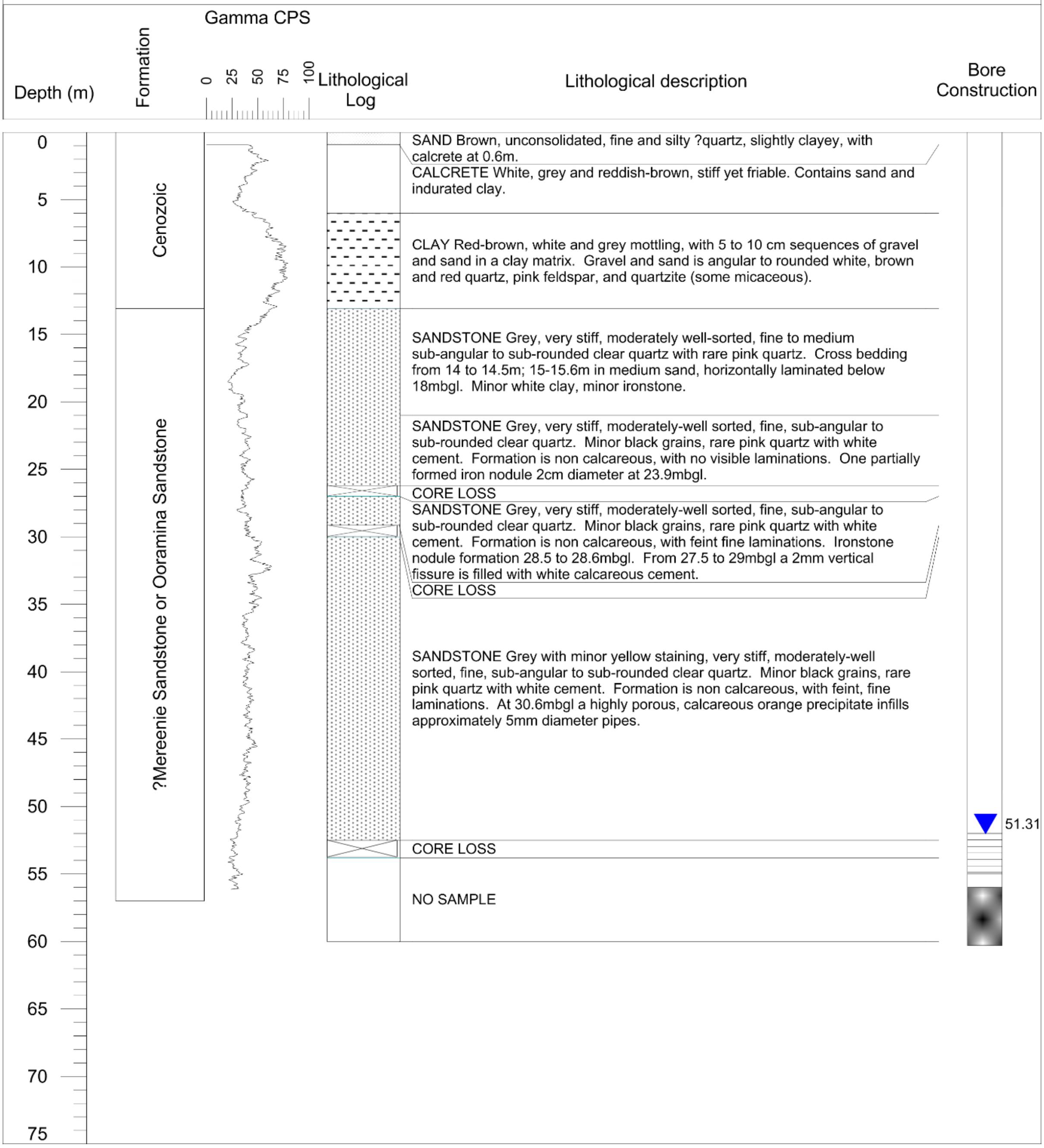


RN019379 Rocky Hill Coring Project
July to August 2016

Location Easting: 407020 Northing: 7359490
GDA 94 Zone: 53

Start date: 24/08/2016
Completion date: 31/08/2016
Total drilled depth: 60.3 mbgl
Comments:
Bore constructed with 100mm PVC and inline screens.

Electrical conductivity: 1030 µs/cm
pH: 8



APPENDIX 3. RESULTS OF SOIL WATER ANALYSES

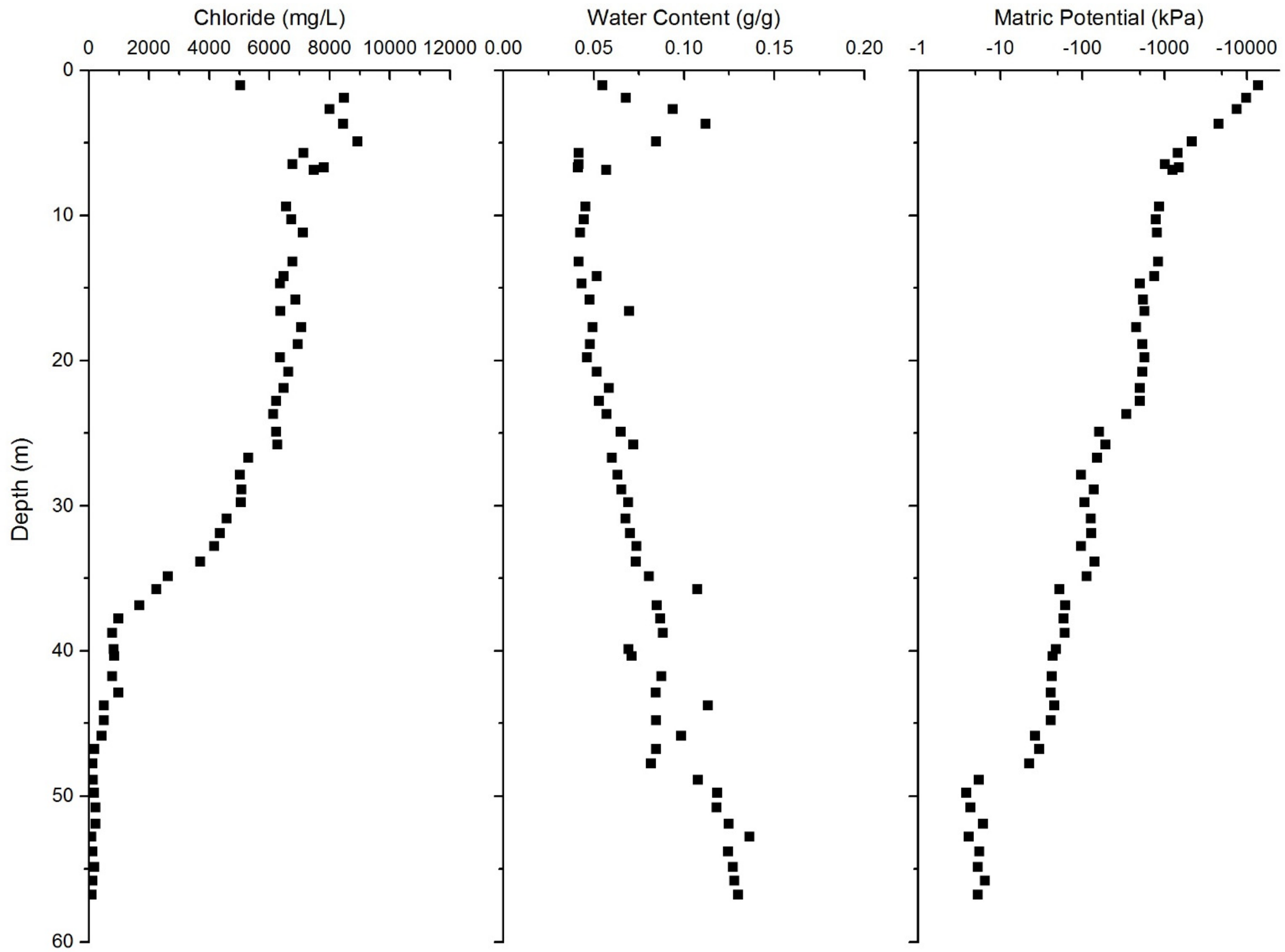


Figure A3.1. Profiles of chloride concentration, gravimetric water content and matric potential on core RN 19187.

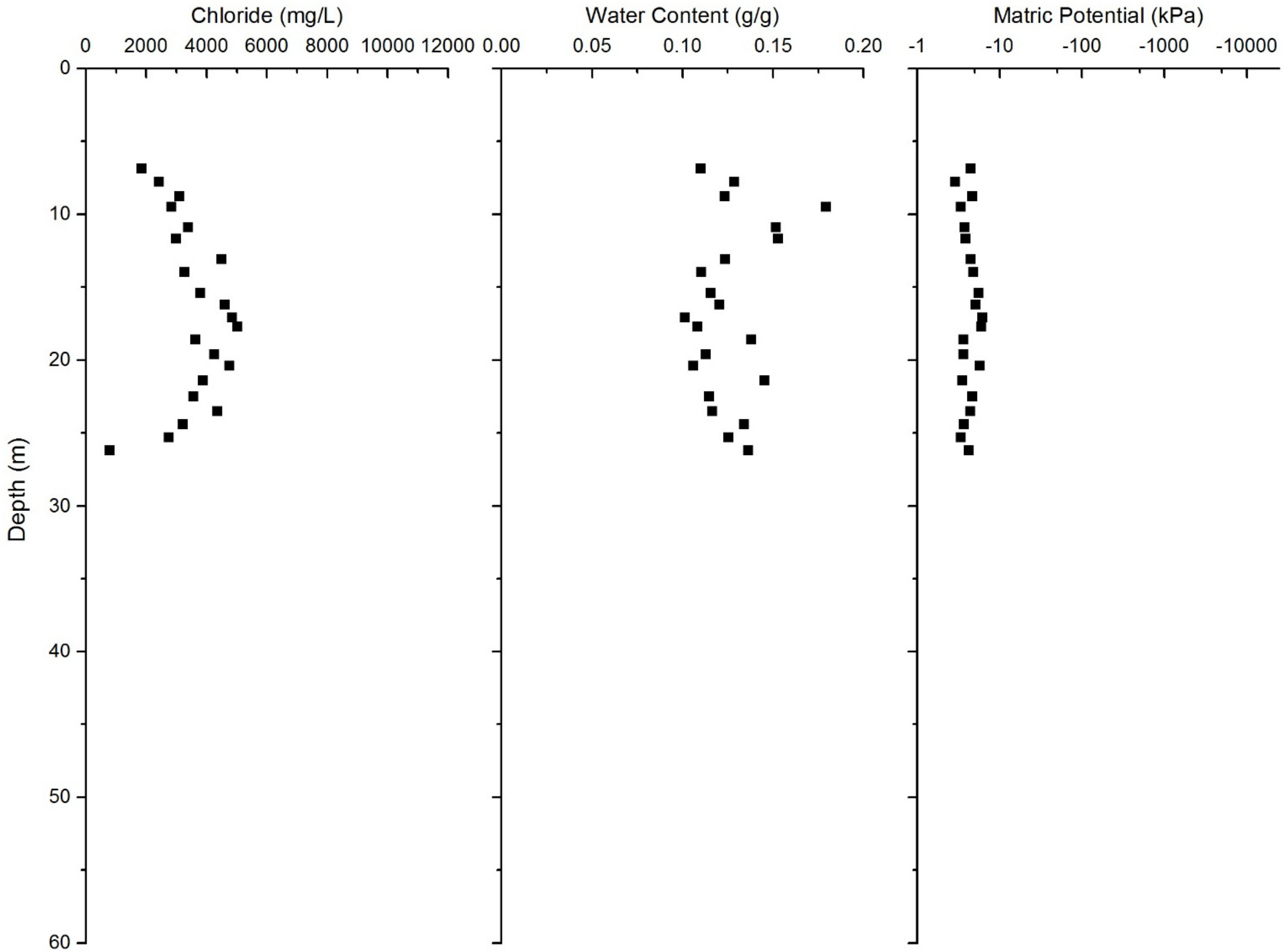


Figure A3.2. Profiles of chloride concentration, gravimetric water content and matric potential on core RN 19188.

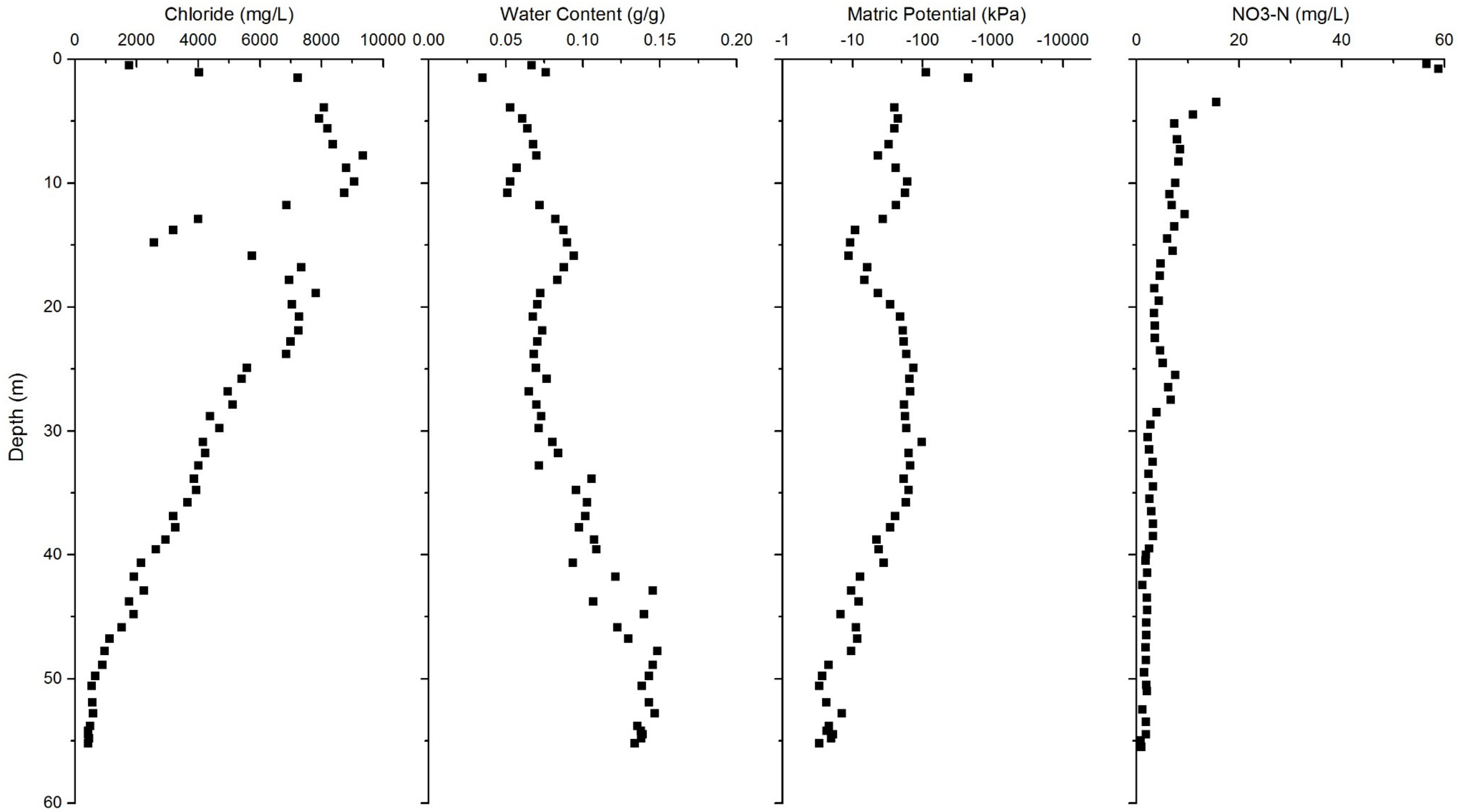


Figure A3.3. Profiles of chloride concentration, gravimetric water content, matric potential and nitrate concentration on core RN 19190.

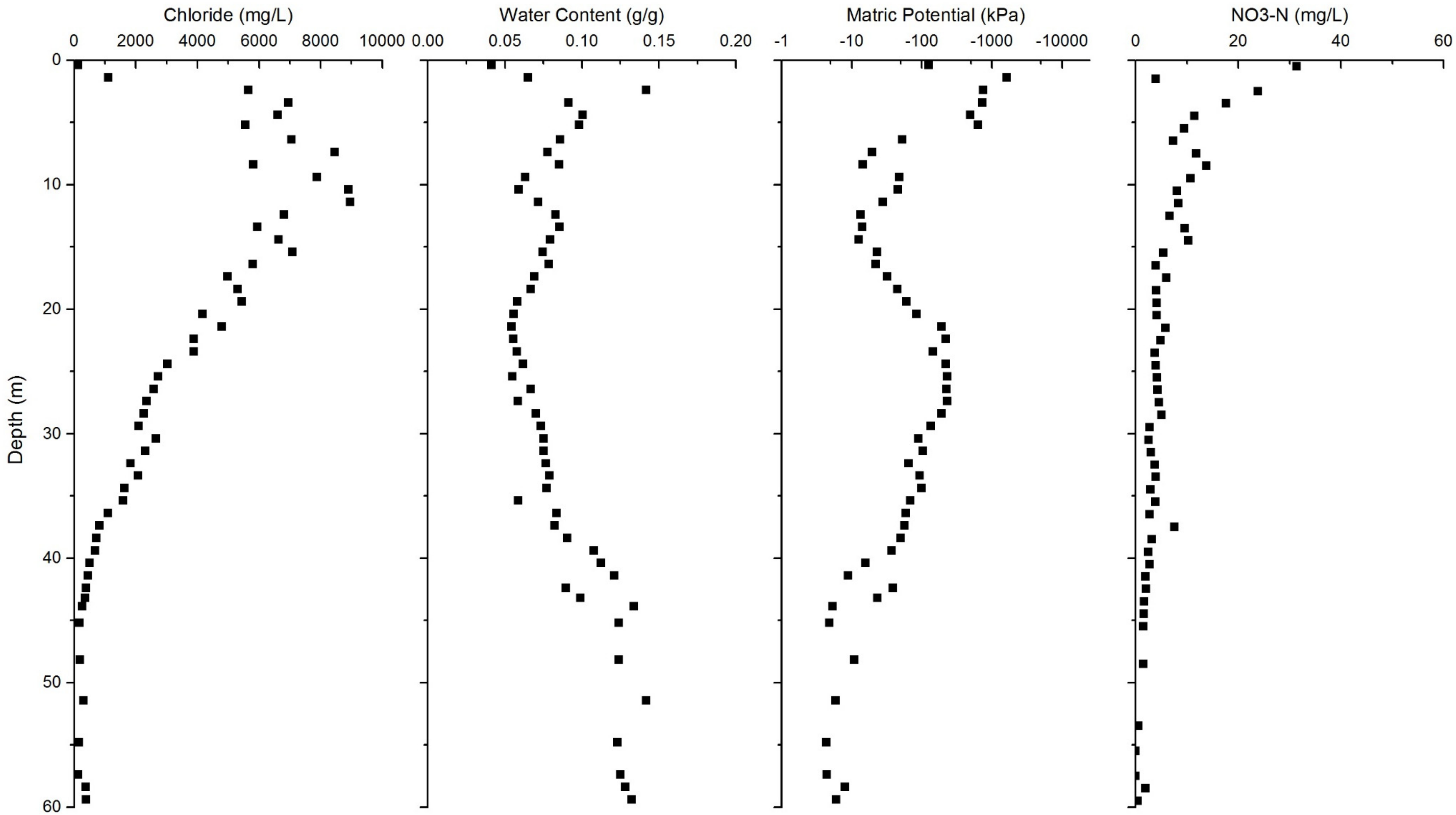


Figure A3.4. Profiles of chloride concentration, gravimetric water content, matric potential and nitrate concentration on core RN 19191.

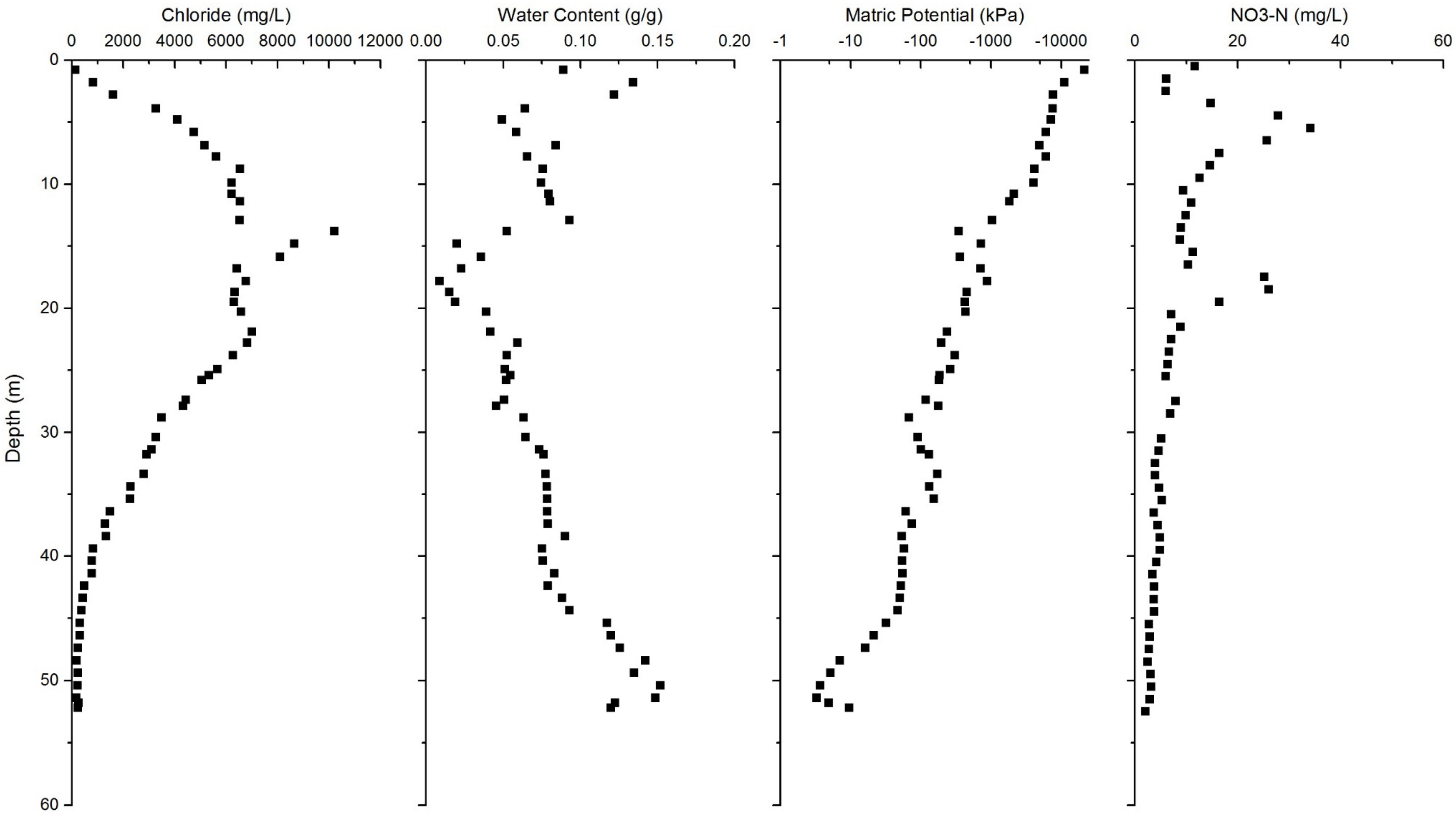


Figure A3.5. Profiles of chloride concentration, gravimetric water content, matric potential and nitrate concentration on core RN 19379.

APPENDIX 4. CALCULATION OF ORIGINAL AND FINAL WATER CONTENT PROFILES BENEATH HORTICULTURAL SITES

Calculation of the difference in soil water storage between native vegetation and horticultural profiles is complicated by differences in soil texture between the cored sites. For this reason, we have calculated the likely original water content profile for each of the horticultural core sites based on the observed moisture content – matric potential relationship. The process for doing this is described below.

We first calculate the average matric potential profile of the two native vegetation core sites, using the harmonic mean. This is assumed to reflect the original profile at the two horticultural sites and is shown in Figure A4.1. We next a functional form of the water content – matric potential relationship, based largely on the observed relationship shown in Figure A4.2. We use the van Genuchten Equation to relate volumetic water content to matric potential, which is given by

$$\theta(\varphi) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\varphi)^n]^{-m} \qquad \text{(A4.1)}$$

where φ is matric potential (cm), θ is volumetric water content (g/g), and θs is the soil water content at saturation, θ is the residual water content, and α, n and m are soil parameters. This is overlain on the observed data for a range of values of α and fixed values of other parameters in Figure A4.2. These curves are the best fit to the field water content – matric potential data, and also most closely approximate moisture characteristics measured on core samples from other geological formations in the Rocky Hill area (Read and Paul, 2000, 2002).

The procedure for reconstructing the original water content profile for each site is as follows. For each core sample from beneath horticultural sites, the value of the α parameter is calculated based on the measured gravimetric water content and matric potential values. The original water content is then calculated using Equation A4.1 based on the assumed native potential profile and the value of the α parameter for the particular depth.

A similar procedure is used for calculating the water content profile that will exist at each site once the pressure front reaches the water table. In this case, the final water content profile is calculated by assuming that the final matric potential in the region below the current pressure front will eventually be 30 kPa. (Note that within three metres of the water table, we assume that the final matric potential will be equal to the equilibrium value for a static profile.)

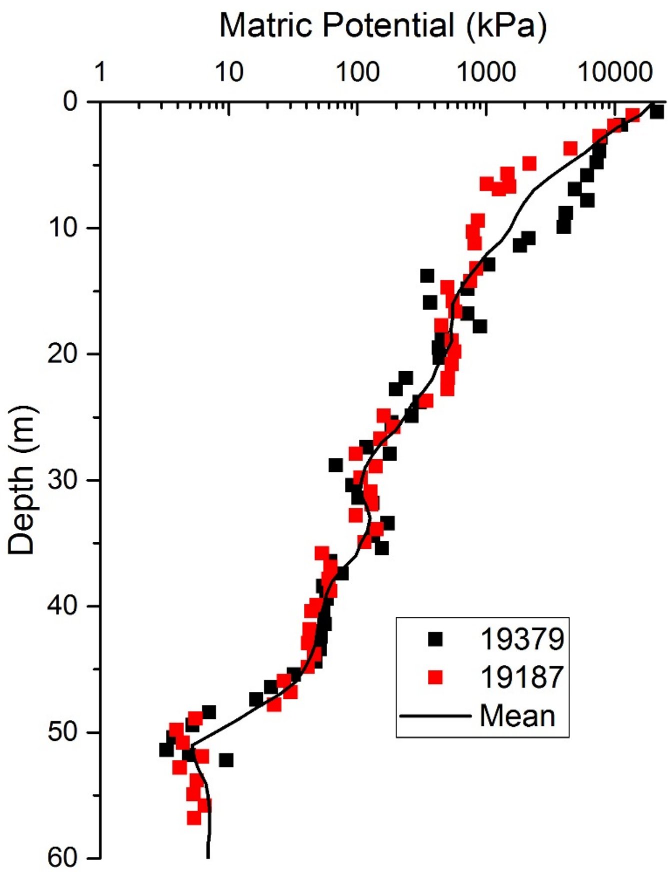


Figure A4.1. Soil profiles of matric potential under native vegetation, together with average profile used for reconstructing original water content profiles under horticultural land.

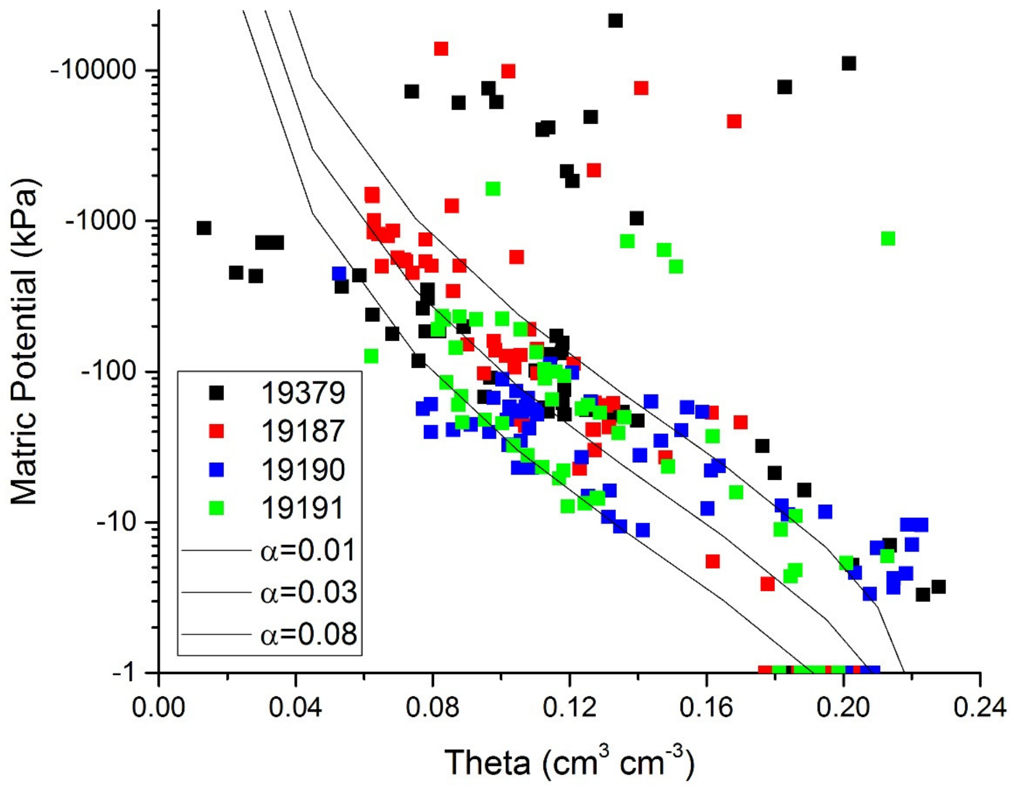


Figure A4.2. Estimated relationship between volumetric water content and matric potential for core samples. Volumetric water contents have been estimated from measured gravimetric water contents by assuming a soil bulk density of 1.5 g cm^{-3}*. Water contents for samples below the water table are plotted along the x-axis. Also shown are estimated soil moisture characteristics based on the van Genuchten Equation with parameters n = 0.8, m = 0.3,* θ_s *= 0.23,* θ_r *= 0, and for different values of* α.

APPENDIX 5. 1D NUMERICAL GROUNDWATER MODEL

Modelling objectives

The objectives of the unsaturated zone model are to:

- determine the likely unsaturated parameters of the soil underlying the study site;
- use the estimated parameters and input fluxes to estimate the time required for the infiltrating water to produce a pressure response at the water table; and
- using solute transport and estimates of soil dispersivity determine the timeframe for the infiltrating water to reach the water table.

Model setup

The model used to investigate the unsaturated zone beneath the study site was setup as an homogeneous, isotropic 1D column 1 metre wide x 60 metres high. The bottom left of the model domain is 0, 0 with the top of the model set at an elevation of 60 metres.

The finite element mesh was generated using the Transport Mapping method and the final mesh comprised 735 quadrilateral elements with a height 0.08 m. The mesh geometry is presented below in Figure A5.1.

The simulation period for the model during calibration was 5475d (15 years), which is consistent with the estimated time that the site has been under irrigated horticulture.

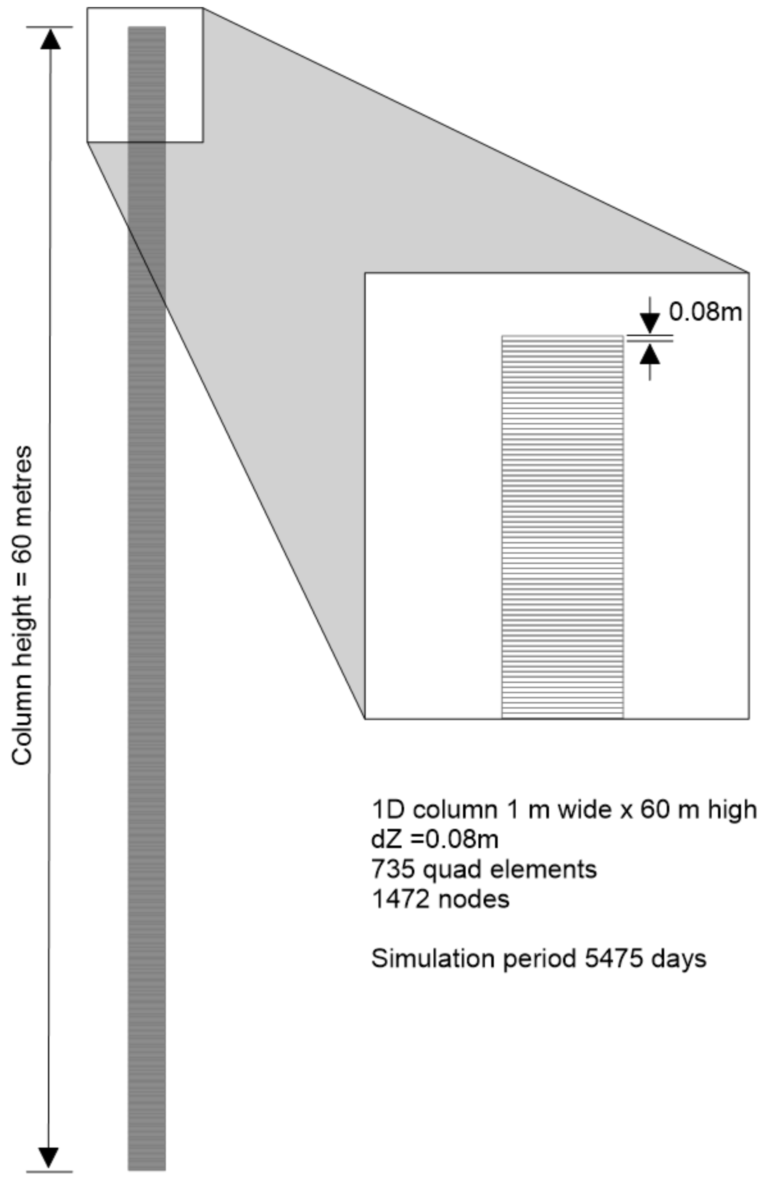


Figure A5.1. 1D unsaturated column finite element mesh setup.

Model Input Parameters

The unsaturated flow processes were simulated using the Richard's equation with the pressure head vs. saturation and relative conductivity vs. saturation relationships described using the Modified Van Genuchten model (MVG). The MVG model combines the Van Genuchten relationship for the pressure head vs. saturation curve with an exponential model for the relative conductivity.

Relative hydraulic conductivity is expressed as:

$$K = Ksat * \theta(\psi)^{\delta}$$

and the relationship between moisture content and matric potential is expressed as:

$$\frac{(\theta(\psi) - \theta r)}{(\theta s - \theta r)} = \begin{cases} [1 + (-\alpha\psi)^n]^{-m}, & \psi < 0 \\ 1, & \psi \geq 0 \end{cases}$$

where

Kr	Relative hydraulic conductivity	[L/T]
$\theta(\psi)$	Observed moisture content for a given matric potential	[v/v]
θs	Saturated moisture content	[v/v]
θr	Residual moisture content	[v/v]
ψ	Pressure head	[L]
α	Fitting parameter	[L^{-1}]
n, m, δ	Fitting parameters	[-]

Material properties

Saturated hydraulic conductivity (Ksat) was taken from Read & Paul (2000).

The saturated water content (θs) was estimated from the analysis of the core and also from the estimates of porosity presented by Read & Paul (2000).

The Van Genuchten parameters were determined by fitting calculated moisture retention curves to the observed moisture characteristics determined from the core samples from site. The range of material parameters used in this modelling study are presented below in Table A5.1.

Table A5.1. Material Parameters

Parameter	Value	Unit	Comment
Ksat	0.15	m/d	Determined from core permeability values (Read & Paul, 2000).
ε	0.22	-	Determined from core porosity (Read & Paul, 2000)
α	0.01 – 0.08	1/cm	Determined from fitting to observed data
N	0.8	-	Determined from fitting to observed data
M	0.3	-	Determined from fitting to observed data
δ	11.5 – 12.5	-	Determined through calibration

Boundary conditions

Boundary conditions were applied to the nodes at the top of the column to represent infiltration under horticulture and at the bottom to represent the ambient groundwater table. The top of the column was assigned as a constant flux of 0.000353 m/d equivalent to 0.128 m/y.

The lower 5 metres of the column (ie 55 metres below top of column representing the measured groundwater depth below ground surface) were assigned constant head boundary conditions 5 m.

Boundary condition values are summarised below in Table A5.2.

Table A5.2. Boundary conditions

Parameter	Value	Unit
Constant flux at surface	3.53e-04	m/d
Constant head at water table	5	m

Initial conditions

The initial conditions were taken from the matric potential profile for RN019191, which was considered representative of the soils beneath the horticultural blocks prior to the commencement of irrigation. The initial profile of pressure head and moisture content compared to the observed values are presented below in Figure A5.2.

Reducing alpha results in increasing the moisture content for the same matric potential.

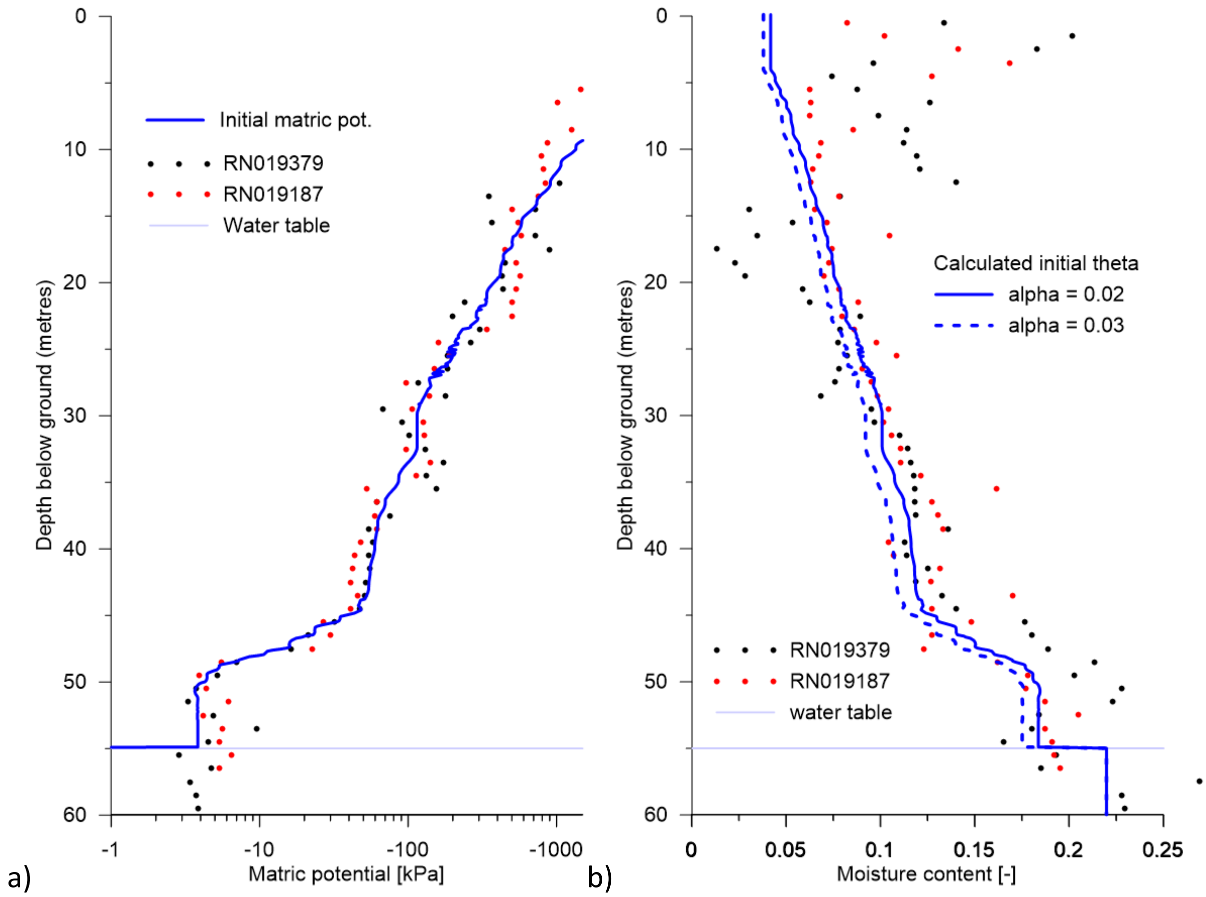


Figure A5.2 Matric potential and moisture content profiles used as initial conditions in the soil column model.

Calibration

The model was calibrated by matching the location of the infiltrating water front indicated at approximately 25 – 30 metres below ground level in the profiles for RN019190 and RN19191 by the increase in matric potential and decrease in moisture content.

The primary parameter adjusted was the hydraulic conductivity exponent (δ) used to determine the relationship between relative hydraulic conductivity and moisture content.

The value of delta was dependent on the value of alpha.

Results

The final fit to the observed matric potential and moisture content are presented below in Figure A5.3.

The upper portion of the curve matches the observed values satisfactorily.

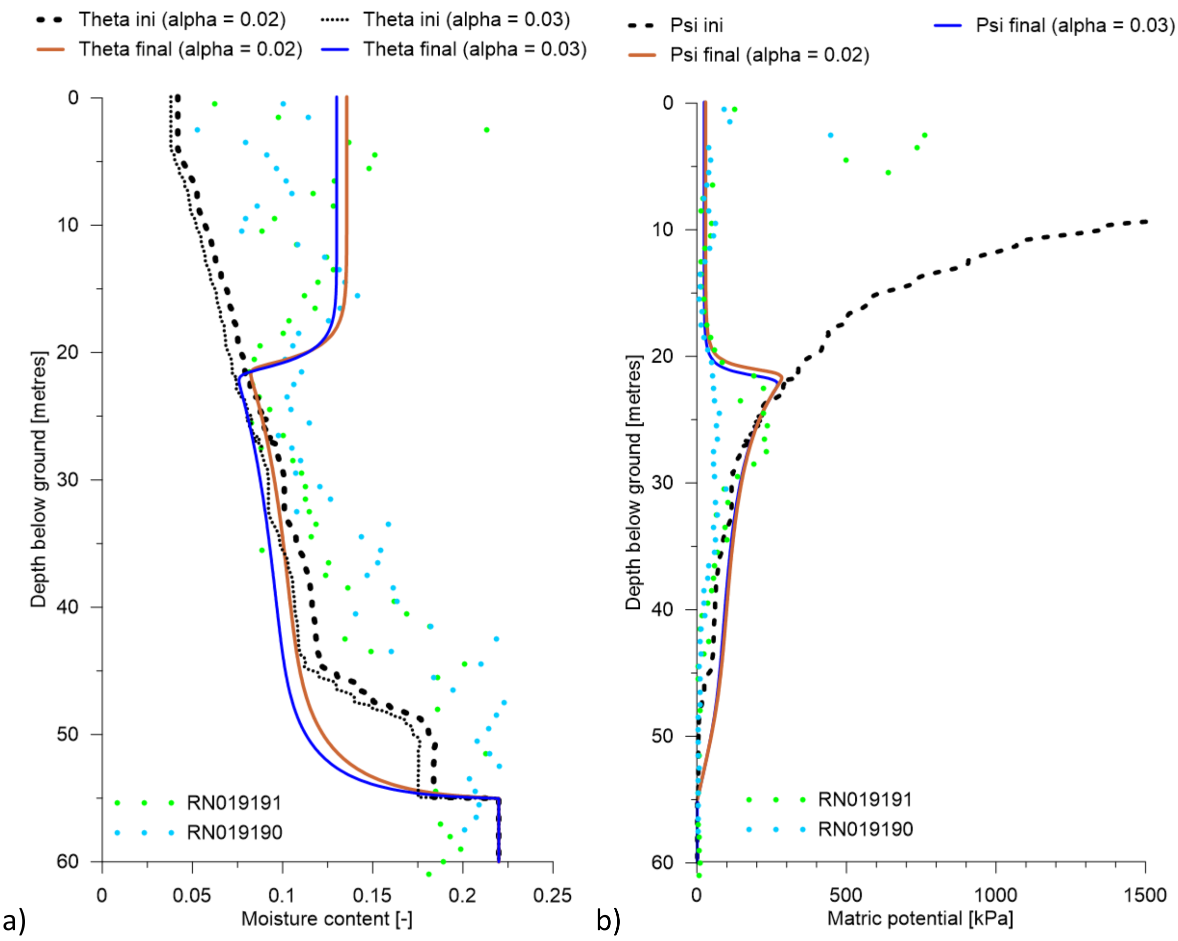


Figure A5.3 Calibrated results for a) moisture content and b) matric potential (psi).

Forecast results

Using the calibrated parameters the model was run forward to determine the likely timeframe for:

- the pressure response to be observed at the water table; and
- using solute transport provide an estimate of the timeframe for the infiltrated irrigation water to reach the water table.

Solute transport model setup

The model geometry and flow parameters were retained from the model described previously.

Transport material properties

The initial concentration in the model was set to 0 mg/L.

The solute transport model was setup with longitudinal and transverse dispersivity of 0.1 metres. This value was chosen to produce a relatively sharp concentration at the wetting front as the infiltration pulse moved down the column.

The porosity was set to the saturated moisture content of 0.22.

Table A5.3. Solute transport material parameters

Parameter	Value	Unit
Initial concentration	0	mg/L
Longitudinal and transverse dispersivity	0.1	M
Porosity	0.22	-

Transport boundary conditions

The nodes at the top of the model were assigned a constant mass concentration of 1 mg/L. The bottom of the model was not assigned a transport boundary condition, allowing mass to freely flow out of the model domain.

Table A5.4. Solute transport boundary conditions

Parameter	Value	Unit
Concentration at surface nodes	1	mg/L

Solute transport results

The time series presented below were generated to depict the time taken for the pressure response to reach the water table and the time taken for the infiltrating water to reach the water table.

An increasing in the flux at the water table is observed at approximately 8260 d (22.6 years) with a steady state flux of 0.000353 m/d (equal to the input flux at the surface) occurring after approximately 10240 d (28 years).

The increase in concentration observed at the water table occurs at approximately 18000 d (49.3 years). A concentration of 0.5 is observed after approximately 21500 d (58.9 years).

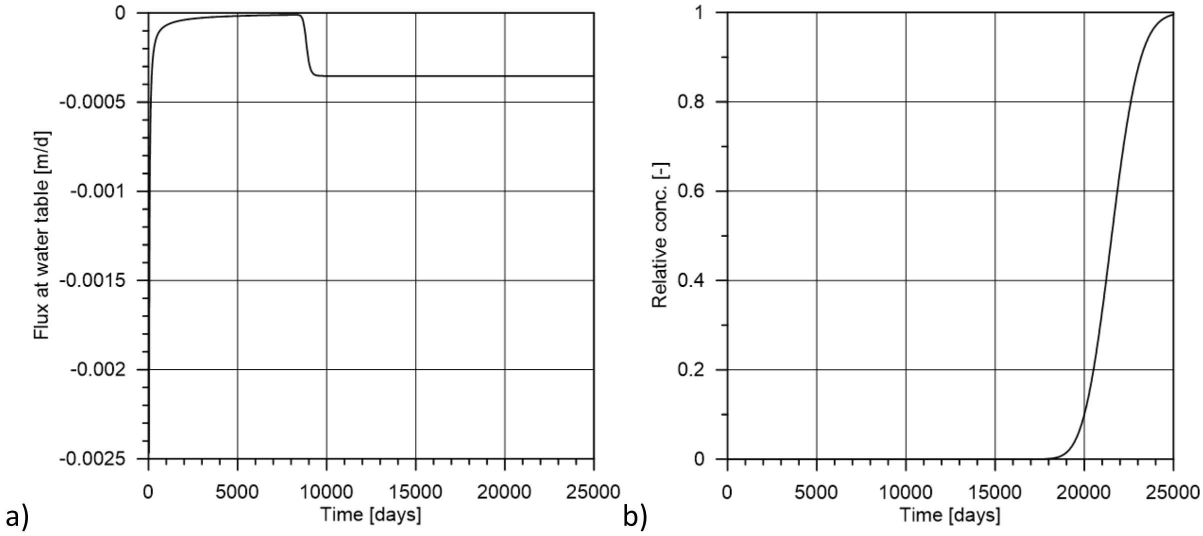


Figure A5.4. Simulated flux at the water table representing the pressure response to the infiltrating water at the surface and b) relative concentration representing the time for the infiltrating water to reach the water table.

APPENDIX 6. RELATIONSHIP BETWEEN CHLORIDE CONCENTRATION AND ELECTRICAL CONDUCTIVITY OF SOIL WATER

Electrical conductivity of the soil water solution was measured on a small number of soil samples. A comparison of electrical conductivity and chloride concentrations in given in Figure A6.1. The best-fit relationship is EC = 7.374 x Chloride.

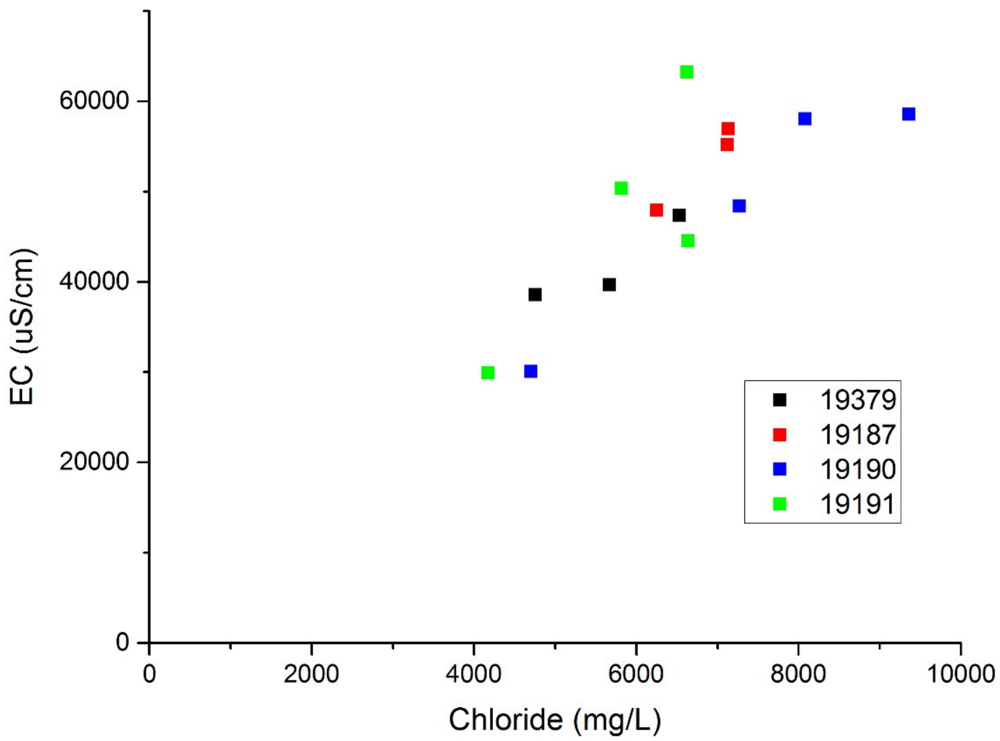


Figure A6.1. Relationship between chloride concentration and electrical conductivity of soil water, for selected soil samples.

APPENDIX 7. RESULTS OF GROUNDWATER QUALITY ANALYSES