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Use of Time Domain Reflectometry (TDR) to Determine Moisture and Temperature Regimes in Antarctic Soils

A thesis
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Abstract

Antarctic soil moisture and temperature data are important as the soil climate influence Antarctic ecosystems, and the data may provide information on climate change, and the effects of human activities on the Antarctic environment. The objectives of this study were to: (1) determine the limitations of Hydra (TDR) soil moisture probes (Stevens Water Monitoring Systems Inc., Oregon, U.S.A.) for use in Antarctic conditions and in hydrocarbon-contaminated soils; (2) describe the soil moisture and temperature regimes of soils located at Scott Base, Marble Point and in the Wright Valley using existing TDR data; and (3) investigate the temperature and moisture regimes at hydrocarbon-contaminated sites at Scott Base and Marble Point.

Determination of the limitations of Hydra (TDR) probes in Antarctic conditions was undertaken in the laboratory where experiments were undertaken to measure the effects of soil temperature, texture, salinity and hydrocarbons on TDR probe accuracy. Field investigations measured soil moisture content with the Hydra (TDR) probes and compared the results to gravimetrically determined soil moisture contents. Soil moisture and temperature data collected by soil climate stations at Scott Base, Marble Point and in the Wright Valley between 1999/2000 and 2001/02 summers, and in hydrocarbon-contaminated soils at Scott Base and Marble Point for the 1999/2000 and 2000/01 summers, were investigated.

The laboratory experimentation showed that soil temperature, texture, and salinity all influenced the soil moisture results recorded by the Hydra (TDR) probes. Hydrocarbons did not influence the soil moisture content recorded by the Hydra (TDR) probes. The cumulative and offsetting effects of soil texture, temperature and salinity were considered to be within the ±3% limit of accuracy of the Hydra (TDR) probe stated by the manufacturers.

Diurnal freeze-thaw cycles occurred throughout the summer at the 2-5 cm depth, and averaged 50 freeze-thaw cycles per summer at Scott Base, 79 in the Wright Valley, and 52 at Marble Point. At the 2 cm depth, the soil temperature was cumulatively >0°C for an average of 830 hours each summer at Scott Base, 1 680 hours in the Wright Valley, and 1 110 hours at Marble Point. Up to five soil-moistening events were identified each summer at Scott Base and Marble Point, while soil-moistening was detected once by one sensor over three summers in the Wright Valley. During the soil-moistening events, volumetric liquid soil moisture contents increased up to 23% at Scott Base, 32% at Marble Point, and 6% in the Wright Valley. At the 2 cm depth, the liquid soil moisture was cumulatively >5% for an average of 860 hours each summer at Scott Base, 1 hour in the Wright Valley, and 310 hours at Marble Point. The drying period following soil-moistening for surface soils (2-5 cm depth) was about 6 days, which was extended to about 12 days when freeze-thaw cycles were occurring. Soil moisture regimes of the hydrocarbon-contaminated soils were similar to those of the uncontaminated soils. Lack of replication, TDR θ_v accuracy, and spatial variability were limitations to the accurate comparison of hydrocarbon-contaminated soil data with that from neighbouring uncontaminated sites.

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Chapter 1 – Introduction

1.1 Background

Soils in Antarctica are limited to the ice-free regions of the Antarctic continent, and as a result are limited in their extent to less than 2.5% of the land surface (Warren, 1996). The ice-free regions of Antarctica are often referred to as cold deserts, due to their extreme aridity otherwise only seen in the hot deserts of the world, and the extremely cold temperatures that occur in Antarctica (Campbell *et al.*, 1998a). Although there are large quantities of water stored on the Antarctic continent in the form of snow and ice, there is limited liquid water available to the terrestrial ecosystems due to the cold temperatures and low precipitation (Campbell *et al.*, 1997a). Therefore, the Antarctic ice-free regions are unique in a global context (Campbell *et al.*, 1998a), and their soil moisture and temperature regimes have not been extensively studied (MacCulloch, 1996).

Antarctic soil climate data is of significance for several reasons. Soil moisture and temperature are key influences on the viability of micro-organisms and plants in Antarctic soil ecosystems, as well as for soil weathering processes. A long-term record of soil climate will help to determine the effect of global climate change on the Antarctic environment. Knowledge of the effects of human activities on Antarctic soils allows planning to minimise the risks and repercussions of future human interaction with the fragile Antarctic environment. In the Arctic, soil moisture and temperature data have been collected for a multitude of projects, such as construction of roads, airfields and pipelines, as well as for scientific reasons (MacCulloch, 1996). However, in Antarctica relatively little is known about soil climate, and the effect that it has on other processes, or the effect human activities have on the soil environment.

In order to study the soil climate of the ice-free areas in the Ross Island region of Antarctica (Figure 1.1), seven soil climate stations have been installed to monitor soil properties such as soil moisture and soil temperature (Balks *et al.*, 2003). Other meteorological variables are also measured, including air temperature, relative humidity, and wind speed and direction.

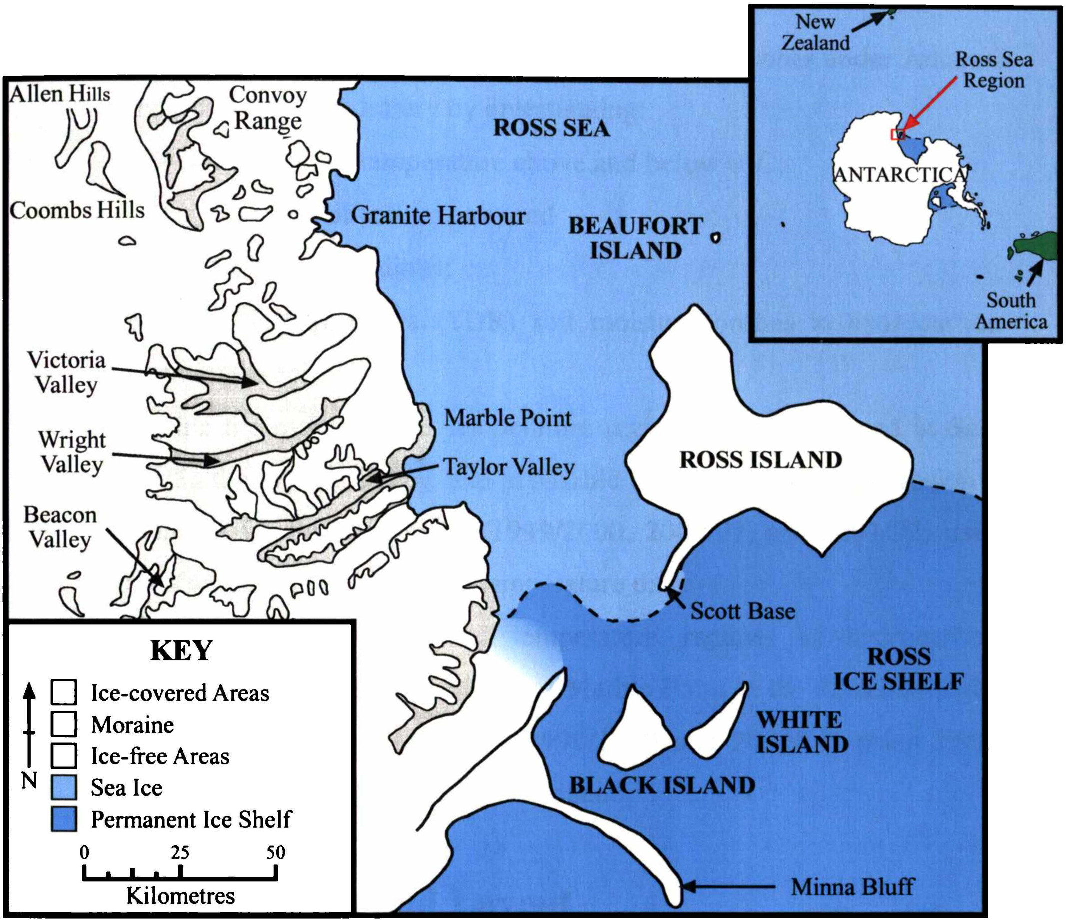

Figure 1.1: The Ross Sea region of Antarctica (including the Dry Valleys and Ross Island).

The measurement of soil moisture was made using Hydra (Stevens Water Monitoring Systems Inc.) moisture probes, which operate using the principle of time domain reflectometry (TDR). In order to analyse the soil moisture contents measured by the Hydra probes, the accuracy of the TDR probes needs to be determined in Antarctic soil conditions. The effect of soil temperature (including freeze-thaw), gravelly soil materials, and salinity on the probes needs to be considered before any confidence can be had in the moisture output from the Hydra probes.

1.2 Thesis Objectives

The broad objective of this thesis is to contribute to the characterisation and understanding of Antarctic soil moisture and temperature regimes. The specific objectives are:

- Undertake a literature review based on Antarctic soils, Antarctic soil moisture and temperature regimes, and soil moisture measurement by TDR;
- Verify the operation of Hydra (TDR) soil moisture probes under Antarctic conditions in the laboratory by investigating:
    - The effect of temperature above and below 0°C;
    - The effect of soil texture; and
    - The effect of salinity;
- Verify the use of Hydra (TDR) soil moisture probes in hydrocarbon-contaminated soil;
- Describe the moisture and temperature regimes of soils located at Scott Base, in the Wright Valley, and at Marble Point in the Ross Sea region of Antarctica for three summers (1999/2000, 2000/01, and 2001/02) using Hydra probe soil moisture and temperature data;
- Investigate the moisture and temperature regimes of hydrocarbon-contaminated soils at Scott Base and Marble Point in the Ross Sea region of Antarctica for two summers (1999/2000 and 2000/01) using Hydra probe soil moisture and temperature data.

1.3 Thesis Content and Layout

This thesis has been broken into four main sections. Firstly, soils from two sites (Scott Base and Wright Valley) were sampled and analysed for properties including pH and electrical conductivity (EC), dry bulk density, and moisture content. The soil data were used for verification of the Hydra probes under field conditions, and also to provide information for two of the sites that the soil moisture and temperature regimes were described. Site description and identification of the locations of the soil climate stations in the Ross Sea region were also described in this section (Chapter 4).

The verification of the Hydra (TDR) probes (Chapter 5) describes several experiments used to determine the accuracy of the TDR probes under different environmental conditions. The environmental conditions considered were soil temperature, texture, salinity, and hydrocarbon content. Other preliminary experiments considered included homogeneity of mixing technique, sample size, and replication of results between probes.

Chapter 6 described the soil moisture and temperature regimes of three soils in the Ross Sea region. The three soils were located at Scott Base, in the Wright Valley, and at Marble Point for three summers – 1999/2000, 2000/01 and 2001/02.

Chapter 7 described the soil moisture and temperature regimes of two soils (Scott Base and Marble Point) that have been subject to hydrocarbon contamination by due to various human activities.

The remainder of this thesis consists of a literature review (Chapter 2), a methods section (Chapter 3), and finally a discussion and conclusions section (Chapter 8).

Chapter 2 – Literature Review

2.1 Introduction

This literature review considers time domain reflectometry (TDR) as a method of measuring soil moisture content, Antarctic soils, climate, and soil moisture and temperature regimes, and finally the influence hydrocarbon-contamination has on the moisture and temperature regimes of Antarctic soils.

2.2 Time Domain Reflectometry (TDR)

2.2.1 Basis of the Technique (TDR in Soils)

2.2.1.1 Principle of TDR

Time domain reflectometry (TDR) measurement of soil moisture is based on a method used for determining where a break in a cable is located, whereby a cable tester propagates an electromagnetic wave of known velocity down the cable. The time taken for the wave to be reflected and return to the cable tester is directly related to the distance to the break in the cable by:

$$v = \frac{2L}{t} \qquad \textbf{2.1}$$

where, v is the velocity of the electromagnetic wave, L is the distance the wave travels in one direction, and t is the time taken for the wave to return to the cable tester (transit time) (Herkelrath *et al.*, 1991; Jones *et al.*, 2002).

The propagation velocity of an electromagnetic wave is a function of the dielectric properties of the medium through which it is travelling (Ledieu *et al.*, 1986), and so for the above case, where the electromagnetic wave is travelling through air, the dielectric constant is 1 (Handbook Of Physics and Chemistry (Lide) 1997/98). The relationship between dielectric constant (ε) and the velocity of a propagating electromagnetic wave can be expressed by:

$$\varepsilon = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \qquad \textbf{2.2}$$

where, c is the speed of light (velocity of electromagnetic wave) in vacuum (3×10^8 m s^{-1}) (Jones *et al.*, 2002).

To determine soil moisture content, the cable tester (or TDR unit) is used to determine the dielectric constant down the length of a TDR probe that is immersed in the soil. The volumetric soil moisture is then calculated using calibration curves and equations that relate the dielectric constant of the soil to the volumetric moisture content of the soil (Jones *et al.*, 2002).

A TDR unit generally consists of three main components – a pulse generator, a sampler, and an oscilloscope (Spaans and Baker, 1993). The pulse generator produces a voltage step that propagates down the transmission line, which is then reflected, and returned to where it is detected by the sampler, before being displayed in a visual sense by the oscilloscope. The pulse generator produces a pulse that has a very short (fast) rise time (e.g. Ledieu *et al.* (1986) used 140 picsec, while Spaans and Baker (1993) used 110 picsec), which corresponds to a very large frequency spectrum (up to the microwave range of frequencies). The oscilloscope then records any voltage changes due to reflections of the voltage pulse (Herkelrath *et al.*, 1991).

2.2.1.2 Dielectric Properties of Soils

The dielectric behaviour of a material is characterised by its permittivity. The relative permittivity (ε_p) of a non-conducting material is generally defined as the factor of increase that the capacitance of a plate capacitor increases when the vacuum or air between the plates is replaced by the non-conducting medium. Therefore, for vacuum and air, the relative permittivity (ε_p) = 1, with the absolute permittivity of a vacuum (and air), ε_o, equal to 8.854 ×10^{-12} F/m. Relative values of permittivity are more often used, and are referred to (misleadingly) as the dielectric constant (Dirksen, 1999).

The dielectric permittivity of a material is generally complex, and a function of frequency, which can be expressed by:

$$\varepsilon_{\mathrm{p}} = \varepsilon.\varepsilon_{\mathrm{o}} \qquad \mathbf{2.3}$$

where, the relative permittivity, ε_p, is proportional to the dielectric constant ε, and the permittivity of vacuum (ε_o). The dielectric constant (ε) can be divided into real (ε_r) and imaginary (ε_i) dielectric constants, such as (Campbell, 1990):

$$\varepsilon = \varepsilon_{\mathrm{r}} - i\varepsilon_{\mathrm{i}} \qquad \mathbf{2.4}$$

The effects of an imaginary dielectric constant are identical to those produced by a purely real conductivity (σ), and are interrelated by:

$$\varepsilon_{\mathrm{i}} = \frac{\sigma}{\omega\varepsilon_{\mathrm{o}}} \qquad \mathbf{2.5}$$

where, ω is the angular frequency (Dasberg and Dalton, 1985). The imaginary and real dielectric constants represent the behaviour of the medium due to polarisation and energy absorption (Dirksen, 1999).

In the frequency range of 1 MHz to 1 GHz (Pepin *et al.*, 1995) (Ledieu *et al.* (1986) suggest the range is 100 MHz to 3 or 4 GHz) the dielectric properties of soils, particularly the properties of the water in the soil, are not frequency dependent (Hoekstra and Delaney, 1974). Therefore, the bulk dielectric constant (ε_b) of the soil is largely a function of the real dielectric constant (ε_r) (Topp *et al.*, 1980). Therefore, since $\varepsilon \approx \varepsilon_r$, and thus $\varepsilon_p \approx \varepsilon$, the relative permittivity is referred to (misleadingly) as the dielectric constant, and the symbol ε is used for both many instances (Dirksen, 1999).

At 20°C and 1 GHz the dielectric constant of the three main constituents of a soil – water (w), air (a) and soil minerals (s) are $\varepsilon_w = 80.36$, $\varepsilon_a = 1$, and $\varepsilon_s = 3\text{-}5$ respectively (Roth *et al.*, 1990; Handbook of Physics and Chemistry, (Lide) 1997/98). Therefore, the dominant component of the bulk dielectric constant of the soil will be the contribution of the soil water (Jones *et al.*, 2002). Water's high dielectric constant is a result of the permanent dipole of water molecules (Dirksen, 1999). Many authors (Or and Wraith, 1999; Ponizovsky *et al.*, 1999; Yu *et al.*, 1999) suggest that bound water needs to be considered as a fourth dielectric component of a soil, whereby the dielectric constant of bound water is approximately 3. The dielectric constant of bound water is lower than the dielectric constant of free water because the bound water is held in a monolayer around the soil particles, and therefore has restricted rotational freedom (section 2.2.2.3). When the temperature drops sufficiently, and the soil water freezes, the use of TDR is somewhat limited. Once the soil water has frozen, the bulk dielectric constant of the soil is also lowered because the dielectric constant for frozen water (ice) is close to that of the soil minerals, where $\varepsilon_{ice} = 3.2$ (Spaans and Baker, 1995). Therefore, determining the actual water content of frozen soils is limited by TDR, with the technique only determining the contribution of the liquid water in a frozen soil (Jones *et al.*, 2002). Consequently, the composite dielectric constant of a heterogeneous material, i.e. the soil in this case, reflects both the proportion of soil minerals, air and soil water (free water, bound water, and ice) and their respective dielectric constant (Altharhi and Lange, 1987).

2.2.1.3 Application of TDR to Soil Moisture Determination

The first application of TDR used to measure volumetric moisture content was made by Fellner-Feldegg, (1969) who attempted to obtain, in one measurement, the frequency dependence of the dielectric constant of liquids. From this point, advances where made through the 1970's and in 1980, Topp *et al.* published a paper outlining the use of time domain reflectometry for measuring the moisture content of soils.

Measuring the bulk dielectric constant of a soil using TDR applies the basic principles outlined previously, whereby an electromagnetic wave is propagated along a transmission line, which is then reflected, with the reflected voltage then detected. However, there are several subtle differences in the method. A pulse is generated, as per usual, and then travels down the transmission line, which can be coaxial cable, cable with parallel conductors (commonly referred to as antenna wire), waveguides embedded in soil, or any combination of these transmission lines joined in series (Spaans and Baker, 1993). The impedance of the transmission line is then a function of the permittivity of the medium that it is placed in (i.e. the soil). There are several methods to determine the bulk dielectric constant of the soil. Generally a waveguide, or probe, of length L is embedded in the soil, and the travel time determined. The travel time is calculated based on the 'apparent' or electromagnetic length of the probe, which can be seen from the waveform, where x_1 marks the entry of the signal to the probe, and x_2 marks the reflection at the end of the probe. The apparent probe length ($x_2 - \mathrm{x}_1$) increases as the water content (and hence bulk dielectric constant) increases (due to reduced propagation velocity). This relationship was outlined by Jones *et al.* (2002) as:

$$\varepsilon_{\mathrm{b}} = \left(\frac{x_2 - x_1}{V_{\mathrm{p}} L} \right)^2 \qquad \textbf{2.6}$$

where, V_{p} is a user selected relative propagation velocity. A second approach, outlined by Hook *et al.* (1992) used a similar technique, whereby v was estimated by physical discontinuities in to the transmission line at two known locations along the line, X_1 and X_2. As the electromagnetic wave was propagated along the line, it was reflected at the two discontinuities, and returned to the TDR instrument. T_1 was designated as the time when X_1 reached the detector after reflection, and similarly T_2 when X_2 was detected. Thus, the velocity of the wave could be determined by:

$$v = \frac{2(X_2 - X_1)}{T_2 - T_1} \qquad \textbf{2.7}$$

This then allowed the bulk dielectric constant to be determined by equation 2.2.

Using TDR principles Topp *et al.* (1980) concluded that in the frequency range of 1 MHz to 1 GHz, the real part of the dielectric constant (ε_r) is not strongly frequency dependent, but is sensitive to the volumetric water content (θ_v), and weakly sensitive to soil type and density. Using this knowledge, and the conclusions of Davis and Annan (1977) that the dielectric loss was considerably less than ε_r in the 1 MHz to 1 GHz frequency range, Topp *et* al. (1980) concluded that a relationship between ε_b and θ_v could be developed. Because there was a small electrical loss in estimating ε_r, they termed the measured dielectric constant the apparent dielectric constant ($\varepsilon_{\text{app.}}$), which for low-loss, nearly homogeneous materials, was the same as ε_r. Consequently, Topp *et al.* (1980) fitted a third degree polynomial to data from four mineral soils that they studied:

$$\varepsilon_b = 3.03 + 9.3\theta_v + 146.0\theta_v^2 - 76.7\theta_v^3 \qquad \textbf{2.8}$$

and hence:

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_b - 5.5\times10^{-4}\varepsilon_b^2 + 4.3\times10^{-6}\varepsilon_b^3$$

$$\textbf{2.9}$$

which became universally known as the Topp calibration curve.

From these beginnings TDR's use for determining soil moisture content was developed with further calibration curves and mixing models proposed.

2.2.1.4 Calibration Curves and Mixing Models

There have been several proposed methods to calibrate TDR, all of which are based on either a calibration curve (e.g. Topp *et al.*, 1980), or a mixing model (e.g. Roth *et al.*, 1990). These models develop a relationship between the dielectric constant of the soil, and the corresponding volumetric moisture content.

Topp *et al.* (1980) developed the first empirical approach to calibrating TDR for measuring soil moisture content (equation 2.9), whereby the bulk dielectric constant of the soil was related to the volumetric moisture content by a third order polynomial. This relationship was considered by Topp *et al.* (1980) to be independent of soil density, texture and salt content, and accurate over the moisture content range of 0 to 55% for mineral soils. Jones *et al.* (2002) suggest that this calibration is still accurate for moisture contents <50% for most mineral soils, with an estimation error of about 1.3%. However, for other soil types and materials another calibration model is required.

Another empirical approach to calibration of TDR proposed by Ledieu *et al.* (1986) involved a linear relationship between the transit time of the generated wave (t) and the volumetric moisture content (θ_v). This was expressed as:

$$\theta_v = 5.69t - 17.58 \qquad \mathbf{2.10}$$

This implies that θ_v is linearly related to $\varepsilon_b^{0.5}$ since ε_b is a function of t^2.

However, since empirical equations such as the Topp calibration curve are not considered universal, there is the need for other calibration techniques, and therefore a mixing model can be used (Dirksen and Dasberg, 1993). In its simplest form, the mixing model approach uses dielectric constants and volume fractions for each of the soil constituents (e.g. solid, water, air) to derive a relationship between the bulk dielectric constant and the volumetric moisture content (Jones *et al.*, 2002). A three layer mixing model was developed by Roth *et al.* (1990) to take into account the solid, aqueous, and gaseous phases within the soil. This is expressed as:

$$\varepsilon = \left[\theta\varepsilon_w^{\alpha} + (1-\phi)\varepsilon_s^{\alpha} + (\phi-\theta)\varepsilon_a^{\alpha}\right]^{1/\alpha} \qquad \mathbf{2.11}$$

where, ε is the dielectric constant, θ is the volumetric moisture content, ϕ is the soil porosity, ε_s, ε_w, and ε_a are the dielectric constants of the solid, aqueous and gaseous phases respectively, and α is a parameter which summarises the geometry of the medium in relation to the applied electric field ($\alpha = 1$ if the electric field is parallel to the layering, and $\alpha = -1$ if the field is perpendicular to the layers). The value used for α in such models (three-phase models) is generally 0.5.

Further mixing models were also developed in order to take into account a fourth phase, bound-water. These models were based on the approach used by Roth *et al.* (1990), but had a fourth component, where the volume of bound water and it's dielectric constant was also taken into account. However, when a four-phase mixing model was used, the researchers have found that α tended to be closer to 0.65, rather than 0.5 as used in the three-phase mixing models (Dirksen and Dasberg, 1993). The one major problem with using a four phase mixing model is estimating the volume fraction, and the dielectric constant for bound water (section 2.2.2.3).

There have been several proposed methods for calibration of TDR for use in measurement of soil moisture. One of the major advantages for using TDR in measuring soil moisture is that little calibration is required (Jones *et al.*, 2002), but depending on the calibration used, this may not necessarily be accurate. For example, a soil with a high water content may not be able to use a Topp calibration, and hence require one of the other approaches to determine the actual volumetric water content. Therefore, care must be taken when using a TDR probe that has been calibrated using a certain method.

2.2.1.5 Types of TDR Instruments

There are several types of TDR probes that have been developed and used, with differences in the number of probes, the structure of the probe set up, and also factors such as probe length and width (Heimovaara, 1993).

One difference between many probes is the use of a balun, with several types probe incorporating a balun, while others do not (Heimovaara, 1993). Baluns are a subset of broadband, impedance-matching transformers, and have two purposes: (i) to change an electrical field from balanced to unbalanced and vice versa, and (ii) to match lines of different impedances (Spaans and Baker, 1993). The importance of having a balanced field is to provide a signal that is free from unwanted noise and signal loss (Jones *et al.*, 2002). This tends to be a larger problem with two-wire probes, where an unbalanced signal is produced, while the inclusion of a balun becomes irrelevant when three- and four-wire probes are being used (Zegelin *et al.*, 1989). A balanced field is one in which the potential on each of the wires on the two-wire transmission line is equal and opposite (Whalley, 1993). However, it has also been reported that the use of TDR with a two-wire probe without a balun produces water content results consistent with those were a balun was used (Stein and Kane, 1983). One advantage of using the two-wire probe over the three- and four-wire probe is decreased soil disturbance when sampling (Zegelin *et al.*, 1989).

Aside from the obvious differences such as use of a balun, and the number of wires in the probe, there are also differences relating to factors such as the length of the probe itself. Probe lengths can range from 0.08 m (Malicki and Skierucha, 1989) to >1 m (Patterson and Smith, 1981). The maximum length of the probe depends on the attenuation in the soils (Heimovaara, 1993), whereby distinguishing the second reflection from the first becomes more difficult in a shorter probe compared to a longer probe. Heimovaara (1993) also found that the rise times for the reflections were smaller in a shorter probe, than those found in the longer probes. One concern with the length of the probe is that for all conventional probe designs, water content is often assumed to be uniformly integrated along the probes longitudinal axis (Jones *et al.* 2002). However Chan and Knight (1999) warn against assuming that the same measured dielectric constant results when either the water is evenly distributed along the rods or concentrated in one or more ‘pockets’. Chan and Knight (1999)’s warning is due to scattering, which may occur in the transition zone between soil layers. Aside from probe length, there are also differences in probe width, with probe widths ranging from 0.01 m in diameter (Malicki and Skierucha, 1989) to 0.2 m (Zegelin *et al.*, 1989).

Basic TDR probes can now also be automated and multiplexed to enable continuous and numerous measurements to be made at remote locations (Heimovaara and Bouten, 1990). One of the first automated and multiplexed systems for monitoring soil moisture contents using TDR was developed by Heimovaara and Bouten (1990). Heimovaara and Bouten (1990) designed a system to measure the soil moisture content on any one of 36 probes from one computer three times daily, while only visiting the site on a once a week basis.

2.2.2 Factors Affecting TDR Measurements of Soil Moisture

2.2.2.1 Cable Length

The length of cable connecting the soil moisture probe to the TDR instrument can have a significant effect on the accuracy of the resultant output from the TDR instrument if the cable becomes too long. A longer cable increases the rise time of the voltage pulse due to the filtering of the high frequency components by the cable (Heimovaara, 1993). The lower frequencies that result cause the real part of the dielectric constant (ε_r) to increase due to electrical conductivity effects, and hence a rise in the estimation of the apparent dielectric constant is seen. The effect of this is to cause reflections with smaller amplitudes and smaller slopes, which can make the first and second reflections in air mingle with each other, complicating analysis, particularly for short probes (Heimovaara, 1993). Another effect of longer cables is to increase transition times, which corresponds with increased transition time errors (Hook and Livingston, 1995).

The filtering effect of a long cable can have positive affects as well as negative (Herkelrath *et al.*, 1991). In the negative sense, the cables can cause the waveform to be smoothed, spread and attenuated, and thus losing some information. An example of this can be seen in analysis of a wetting front (Topp *et al.*, 1982), whereby the small reflection may no longer be visible in the trace. However, a little filtering of the waveform can remove unwanted noise from circuit elements, and thus also allow for easier interpretation of the waveform by computer algorithm.

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Due to signal deterioration in longer cables, Jones *et al.* (2002) suggest a practical length of between 20 and 30 m for cable length. However, Herkelrath *et al.* (1991) state that because the soil also attenuates the signal, the upper limit on cable length is dependent on the soil type, where longer cable lengths may provide reliable readings where soil salinity and clay content are low (Jones *et al.*, 2002).

2.2.2.2 Temperature

The effects of temperature influence the measured soil moisture contents when using TDR. There are several reported influences of temperature on TDR measurement, however these are seemingly inconsistent (Or and Wraith, 1999), but failure to account for these changes can lead to errors, particularly at high soil moisture contents (Pepin *et al.*, 1995). The most obvious influence of temperature is that the dielectric properties of water change with temperature, as the dielectric number of water is temperature dependent (Handbook of Chemistry and Physics (Lide), 1997/98). While this effect occurs with water, it is not so important for the other dielectric components of the soil, the minerals, and air, which are much less sensitive than water.

2.2.2.2.1 Temperature Effect in Unfrozen Soils

Changes in temperature lead to an error in the transit time, and from tables it has been deduced that between 0°C and 35°C, the influence of temperature on the transit time can be approximated by a single correction factor (Ledieu *et al.*, 1986). The influence of temperature on the dielectric number of wet soils decreases with water content (Roth *et al.*, 1990). The maximum variation in θ_v caused by a change in temperature occurs in saturated soils, where water becomes the predominant phase controlling the dielectric constant values of mixtures (Yu *et al.*, 1999). Yu *et al.* (1999) suggest that for $\theta_v > 20\%$ temperature does not alter the calibration curves, and found that for a temperature change of 40°C for a soil with a θ_v of 32.5%, the absolute error was 3%. This is the opposite of findings by Wraith and Or (1999), whose results show a substantial temperature influence on measured soil water content based on the bulk dielectric constant under certain soil and wetness conditions. According to Pepin *et al.* (1995), soils that have large active surface areas and surface charges, such as fine-textured and organic soils, are the most susceptible to the effects of temperature on the bulk dielectric constant of water. Pepin *et al.* (1995)'s results also suggest that the effect of temperature is more pronounced in free water, compared to water that is held in the soil matrix (bound water). Pepin *et al.* (1995) also suggest that the decrease in the dielectric number is balanced by the conversion of bound water to free water with increasing temperature.

2.2.2.2.2 *Temperature Effect in Frozen Soils*

When using TDR based moisture probes in frozen soils, the resultant output corresponds to the amount of liquid water present in the soils (Jones *et al.*, 2002). This occurs because the dielectric number of ice ($\varepsilon_{ice} = 3.2$) is much lower than that of water, and closer to the dielectric number of the soil minerals. However, the measurement of liquid water in a frozen soil is complicated due to the presence of the ice phase (Spaans and Baker, 1995). The total water content (θ_v) of the soil is made up of a liquid water component (θ_L), and a frozen or ice component (θ_i). Calibrations developed for unfrozen soils become somewhat non-applicable when dealing with wetting and drying of frozen soils. When soils freeze, ice forms *in situ* at the expense of liquid water. However, when the soil is drying the ice is replaced with air, which has a lower dielectric number than ice. Therefore, calibrations derived in unfrozen soils will result in systematic overestimation of liquid water because it assigns a higher value for ε to additional water rather than to the contribution from ice.

Several studies on liquid moisture measurement in frozen soils have been undertaken using TDR. One example is from Patterson and Smith (1981), who showed that a rapid decrease in the dielectric number of the soil was observed in a temperature change from 0°C to –1.0°C, with a decreasing rate of change at lower temperatures, suggesting that most of the liquid water froze quickly, while the remainder froze at a slower rate. They found that this effect was influenced by the texture of the soil, with the change in ε_b more rapid in coarser textured soils, while the dielectric constant was greater at any given negative temperature in finer materials, suggesting that there is more unfrozen water in finer textured soils.

Stein and Kane (1983) successfully applied TDR to monitoring of snowmelt infiltration into seasonally frozen soils under a variety of soil moisture conditions.

2.2.2.3 Bound Water and Soil Texture

Bound water is considered to have different dielectric properties to that of free water, and hence needs to be considered separately. Bound water is not precisely defined, but is generally considered the first water monolayer (Or and Wraith (1999) suggest it may be even two or three layers), which is bound tightly to the surface of the soil particle with surface forces (Ponizovsky *et al.*, 1999). The water molecules in this thin film have restricted rotational freedom and thus an inability to follow the alternating electrical field (Jones *et al.*, 2002), which results in a dielectric constant for bound-water of, $\varepsilon_{bw} \approx 3$, which is lower than that of free water ($\varepsilon_{fw} \approx 81$), and closer to that of ice (Roth *et al.*, 1990).

As a result of the reduced dielectric constant of bound water, bound water is often introduced as a fourth phase in mixing models for calibration of TDR instruments (Dobson *et al.*, 1985; Dasberg and Hopmans, 1992). In the four phase mixing models, water is divided into bound water and free water, with the other components of the model being air and solids. One such mixing model is outlined by Yu *et al.* (1999):

$$\varepsilon = \left[(\theta_v - \theta_{bw})\varepsilon_{water}^{\alpha} + \theta_{bw}\varepsilon_{bw}^{\alpha} + (1-\phi)\varepsilon_{solid}^{\alpha} + (\phi - \theta_v)\varepsilon_{air}^{\alpha}\right]^{1/\alpha} \tag{2.12}$$

where, ε, ε_{water}, ε_{bw}, ε_{solid}, and ε_{air}, are the dielectric constants for the bulk soil mixture, free-water, bound water, and soil solids, and air (= 1) respectively; θ_v, θ_{bw}, and ϕ are the volumetric moisture content, bound water content, and soil porosity respectively; and α is the measure of the geometry of the medium in relation to an applied electrical field. The volume of bound water can be determined by the magnitude and properties of the soil specific surface (colloidal active surface area per unit mass), which depend on clay content and clay mineral type (Dirksen and Dasberg, 1993). If this is not known, then the hygroscopic water content can be used to estimate the bound water fraction.

The influence of bound water on the dielectric constant of the soil is affected significantly by the soil texture. High surface area porous materials, such as clays and peats, bind more water to the soil particles, and thus decrease the bulk dielectric constant, compared to coarser textured soils. The amount of bound water is therefore related to the specific surface area, and also the thickness of the bound layer (Jones *et al.*, 2002), with finer textured soils having a decreased bulk dielectric number compared to the coarser textured soils (Ponizovsky *et al.*, 1999; Dirksen and Dasberg, 1993).

2.2.2.4 Electrical Conductivity and Salinity

2.2.2.4.1 Limitations of Measuring θ_v in High Salinity Soils

In soils with high salinity, TDR measurements of soil moisture are considered to be limited due to attenuation of the electromagnetic pulse (Dalton *et al.*, 1984). This is the case for all conducting mediums (which a saline soil is), were the voltage pulse is attenuated due to conductive losses into the medium (Dalton and van Genuchten, 1986). Attenuation of the electromagnetic pulse (due to higher salinity), leads to an overestimation of the dielectric number, which in turn leads to an overestimation of θ_v (Nadler *et al.*, 1999). Lower frequencies enhance the attenuation of the electromagnetic pulse as the real dielectric behaviour becomes complicated by the ionic conductivity (Dasberg and Dalton, 1985). The amount that the pulse is attenuated is directly related to the ionic conductivity of the soils, whereby the higher the salinity, the more the pulse is attenuated, until the final reflection cannot be detected (Spaans and Baker, 1993).

In contrast to the work of Dalton *et al.* (1984) and Spaans and Baker (1993), there have been several conflicting studies that show no effect of salinity on the accuracy of TDR measurements of soil moisture (e.g. Topp *et al.*, 1988; Dalton and van Genuchten, 1986; Nadler *et al.*, 1991). Another study, by Nadler *et al.*

(1999), showed that at high salinity levels (8 000-26 000 μS cm^{-1}), the dielectric number was not overestimated for sandy and loamy soils.

2.2.2.4.2 Measurement of Salinity and Electrical Conductivity Using TDR

Whether, salinity has an effect on the determination of soil moisture content or not, the attenuation of the electromagnetic pulse does allow for an estimation of the electrical conductivity of the soil. As the electromagnetic waves travel along the TDR probes buried in the soil, the signal energy is attenuated in proportion to the electrical conductivity along the travel path. Therefore, the proportion that the signal is attenuated is directly related to the bulk electrical conductivity (σ) (Jones *et al.*, 2002; Dirksen, 1999). Dalton *et al.* (1984)'s developments with regard to the effect of salinity on the electromagnetic pulse suggested that both electrical conductivity and soil moisture could be measured using the same instrument. Two methods for determining electrical conductivity using TDR were developed (Spaans and Baker, 1993). The first method was proposed by Dalton and van Genuchten (1986):

$$\sigma_{\mathrm{D}} = \frac{\varepsilon_0 c\sqrt{\varepsilon}}{L}\ln\left(\frac{V_1}{V_2 - V_1}\right) = \frac{\sqrt{\varepsilon}}{120\pi L}\ln\left(\frac{V_1}{V_2 - V_1}\right) \qquad \textbf{2.13}$$

which was modified by Topp *et al.* (1988) to account for multiple reflections:

$$\sigma_{\mathrm{D}} = \frac{\sqrt{\varepsilon}}{120\pi L}\ln\left(\frac{V_1(2V_0 - V_1)}{V_0(V_2 - V_1)}\right) \qquad \textbf{2.14}$$

where, c is the velocity of light in a vacuum (3×10^8 m s^{-1}), ε is the permittivity of the medium, ε_0 is the dielectric permittivity of free space (8.9×10^{-12} F m^{-1}), V_0 is the voltage of the incident pulse, V_1 is the voltage transmitted through the soil, and V_2 is the voltage of the first reflection from the open end of the wave guides.

The second approach is the Giese-Tiemann approach originally developed for thin sections, and reported by Topp *et al.* (1988) as:

$$\sigma_{\mathrm{GT}} = \frac{1}{120\pi L}\frac{Z_0}{Z_{\mathrm{u}}}\left(\frac{2V_0}{V_{\mathrm{f}}} - 1\right) \qquad \mathbf{2.15}$$

where, V_{f} is the voltage at $t(\infty)$ when all the reflections have died out, Z_0 is the characteristics impedance of the probe (Ω), and Z_{u} is the output impedance of the TDR (typically 50 Ω). The advantage of this method is that the dielectric constant of the soil need not be known. Therefore, the salinity of a soil can be easily measured using dielectric principals.

Methods for determining the electrical conductivity of the soil water with TDR use a relationship between the bulk soil electrical conductivity (σ_{a}), the soil water electrical conductivity (σ_{w}) and the soil moisture content (θ) (Hamed *et al.*, 2003). TDR probes measure both σ_{a} and θ using the same soil volume simultaneously, allowing σ_{w} to be determined by a σ_{a}-σ_{w}-θ model. Many different σ_{a}-σ_{w}-θ models (e.g. Rhoades *et al.*, 1976; Heimovaara *et al.*, 1995; Persson, 1997) have been developed, with all of these models containing one or more soil specific parameters. A recently presented linear σ_{a}-σ_{w}-θ model by Hilhorst (2000) was claimed to be only slightly dependent on the soil type, and thus much less soil specific, however was shown by Hamed *et al.* (2003) to still require soil specific calibration to produce accurate results.

2.2.2.5 Layered Soils

The effect of layering to TDR measurements of soil moisture content has been considered by several authors, including Topp *et al.* (1982), Yanuka *et al.* (1988), Nadler *et al.* (1991), Dasberg and Hopmans (1992), and Schaap *et al.* (2003). When probe length covers more than one layer of the soil, there is potential to affect the resultant soil moisture content value in several ways. These include: (i) reduced accuracy in determination of θ_{v} (especially when the wet horizon is also saline and the trace becomes flat); (ii) false identification of the upper layer travel time; or (iii) erroneous θ_{v} when the dielectric difference between the two layers makes it almost impossible to identify the inflection point on the trace (Nadler *et al.*, 1991).

Dasberg and Hopmans (1992) analysed several different layering scenarios and found that when a dry soil overlies a wet soil two well-defined minima in the TDR trace allow accurate interpretation. However, when a wet soil overlies a dry soil, an immediate minimum is obtained representing the reflection from the wet-dry interface, while the second reflection at the end of the TDR probe is difficult to identify on the trace, and hence can cause false interpretation of the signal. When there is a complex mixture of wet and dry layers, Dasberg and Hopmans (1992) found that several inflection points occur, thus making interpretation of the signal extremely difficult, particularly the last inflection point.

There have been various methods proposed for dealing with layered soils, in terms of measuring soil moisture content using TDR. Topp *et al.* (1982) found that adding the travel times through the layers corresponded in giving a weighted average of the actual moisture content of the layers. They found this to be the case even when there was a steep gradient or a wetting front present. Yanuka *et al.* (1988) developed a computer algorithm to calculate the dielectric constant for each of the layers, based on a model for multiple reflections from layered dielectrics. Hook *et al.* (1992) suggest that the use of three-diode probes allowed a high probability of correct readings layered soils.

Fortunately, there are few cases whereby there are combinations of extreme water contents at close proximity under natural conditions, with the exceptions being a wetting front moving through a dry soil, and a soil that has sharp horizon boundaries (Dasberg and Hopmans, 1992; Nadler *et al.*, 1991). Because most changes in moisture through the soil are gradual, most measurements of θ_v are free from this error.

2.3 Antarctic Soils

2.3.1 Distribution and Occurrence of Antarctic Soils

Antarctica's soils are restricted to the ice-free areas, which are scattered mainly around the outer edge of the Antarctic continent (Beyer *et al.*, 2000a), with the most extensive areas being the Trans-Antarctic Mountains, and the McMurdo Dry Valley region (Beyer *et al.*, 1999). The environment in which Antarctic soils form has been termed a cold desert (Tedrow and Ugolini, 1966) characterised by extremely cold temperatures, and very low soil moisture contents (Campbell and Claridge, 1977). As a result of the extremely cold temperatures, and the occurrence of permafrost within the first metre, Antarctic soils fall into the Gelisols soil order according to U.S. Soil Taxonomy (Soil Survey Staff, 1998).

Antarctic soils have had several classifications, with McCraw (1960) originally designating the zonal soils of the Trans-Antarctic Mountains to the frigic group, which Tedrow and Ugolini (1966) referred to as ahumic soils. Campbell and Claridge (1969) divided the frigic soils into ultraxerous, xerous and subxerous sub-groups based on moisture content, where ultraxerous soils have very little moisture, subxerous soils have the most moisture, and xerous soils are intermediate. Antarctic soils were formerly classified as Entisols by Soil Taxonomy (U.S. Soil Survey Staff, 1975), prior to the development of the Gelisols soil order (Soil Survey Staff, 1998). Bockheim (2002) found that in the Dry Valleys, 30% of the soils examined were Turbels, while the remainder were Orthels according to Soil Taxonomy (Soil Survey Staff, 1998). Campbell and Claridge (1969) also outlined the intrazonal soils, which differ from the zonal soils due to the influence of a locally important factor. Campbell and Claridge (1969) identified four locally important factors causing zonal soils, including: (i) soils formed under the influence of saline groundwater; (ii) soils with a dominant organic constituent; (iii) avian soils; and (iv) soils formed under the influence of hydrothermal waters. Also outlined were the azonal soils, which are soils that as yet haven't developed into zonal soils. These grade into and are hard to distinguish from weakly zonal frigic soils.

Antarctic soils have been studied since the 1950's and 1960's (e.g. McCraw, 1960; Tedrow and Ugolini, 1966; Campbell and Claridge, 1967; McCraw 1967a; Claridge and Campbell, 1968), and generally consist of unconsolidated bouldery to pebbly sandy gravel, with horizons mainly separated on the basis of colour (Campbell and Claridge, 1977). The other main characteristics of Antarctic soils are the presence of permafrost, and the accumulation of water-soluble salts.

Due to the severe conditions that occur, the soil forming processes operate very slowly (Bockheim, 1997). However, there are still regional, local, and micro spatial differences in the soils due to climate, topography, and parent material (Campbell *et al.*, 1997b; Campbell *et al.*, 1998b).

2.3.2 Soil Formation and Processes Operating

2.3.2.1 Polygenesis of Antarctic Soils

Campbell and Claridge (1977) identified two main polygenetic processes resulting from fluctuations in soil forming conditions. The first of these involves additions of new material either at the surface by deposition, or at the base of the profile by ablation of ice, while the second involves redistribution of soil material by cryoturbic processes. Addition of surface material has also been reported to occur when an ice lobe advances over a pre-existing soil surface, and deposition of a thin morainal cover occurs following ice retreat. Subsurface additions to the soil profile occur when glaciers ablate, and thus deposit material at the base of the profile. The thickness of subsurface additions is related to the rate of melting of the glacier, and thus the soil temperature. Redistribution of soil material occurs through the fragmentation and disintegration of surface boulders by exfoliation and freeze-thaw action.

2.3.2.2 Soil Weathering

Weathering of soils in Antarctica is a slow process (Bockheim, 1997) and as a result, the effects of weathering are negligible on soils younger than about 50 000 years, but are much more prominent on soils that are much older (Campbell *et al.*, 1998c). The weathering products resemble regolith more than a true soil, but have long been considered soils where the effects of living organisms are minimal (Campbell and Claridge, 1982).

The degree of weathering is related, in most cases, to the age of the soil (Campbell and Claridge, 1975; Bockheim, 1979), but other factors also influence the rate of weathering (Bockheim, 1990). A more weathered soil can be seen to have: developed a distinctive colour profile; an increased amount of rounding, polishing and staining of surface rocks; an increased amount of soluble salts; an increased (but still small) quantity of clays in the upper horizons; and an increase in the depth of soil to underlying glacial ice where soils are formed on ablation moraines (Campbell and Claridge, 1987). Due to the various degrees that Antarctic soils have been weathered, Campbell and Claridge (1977) developed six weathering stages for Antarctic soils. Under this classification, the least developed soils fall into weathering stage 1, while the most weathered soils fall into weathering stage 6. These are related to glacial events and have associated ages ranging from up to 50 000 years for stage 1 to >>3.5 m.y. for stage 6.

2.3.2.3 Salinisation

Salinisation is considered to be one of the two main soil forming processes (along with oxidation) operating in Antarctica (Beyer and Bölter, 1998). Salinisation refers to the accumulation of soluble salts in the soil, with the salts being sulphates, nitrates and chlorides of sodium, magnesium, potassium and calcium (Bockheim, 1990). The salts in Antarctic soils increase with both depth, and increasing soil age. Salts in Antarctic soils are dealt with separately in section 2.3.4.

2.3.2.4 Oxidation / Rubification

The process of rubification refers to the gradual reddening of the soil due to the oxidation of Fe^{2+} to Fe^{3+} during chemical weathering of iron bearing minerals. Bockheim and Ugolini (1990) considered rubification to be particularly important in the coastal regions of continental Antarctica, where MacNamara (1969) reported deeply oxidised B-horizons, and observed iron-enriched coatings on the peds. The soils of continental Antarctica contain staining caused by rubification, and have relatively high concentrations of dithionite-extractable Fe (Bockheim and Ugolini, 1990). The reddish hue is attributed to oxidation of Fe^{2+} released from weathering of amphiboles, biotite, pyroxenes, and magnetites. The staining is considered to increase with time, as the older soils are more deeply stained, and hence are redder than the younger soils (Campbell and Claridge, 1987).

2.3.2.5 Formation of Desert Pavement

Desert pavement refers to the lag surface of gravel and coarser clasts typical of desert regions (Bockheim and Ugolini, 1990). In Antarctica, desert pavement formation is attributed to deflation of fine materials by wind (Lindsay, 1973). This is in contrast to hot desert pavements, which form by upward movement of stones by wetting and drying processes, or by input of eolian dust, which accelerates break up of clasts. Upward migration of clasts may be important in coastal areas of East Antarctica, but in the Trans-Antarctic Mountains, the soils often do not contain enough moisture. Bockheim (1997) reported the proportion of rock and coarse fragments of desert pavement as being ≥90%, with the voids being filled with coarse sand.

Desert pavement is limited to continental Antarctica, and increases with an increase in latitude (Bockheim and Ugolini, 1990). Tedrow and Ugolini (1966) noted that desert pavement follows no specific pattern with regard to age or composition of the deposit. This is in contrast to Bockheim (1982) who suggested that the desert pavement becomes more distinct in older landscapes, where the clasts become more rounded, and more desert varnish and ventifaction is present. Desert pavement however, tends to be more of a geological process than a pedological process (Bockheim and Ugolini, 1990).

2.3.2.6 Other Soil Processes

Bockheim and Ugolini (1990) considered and reviewed the effects of several soil forming processes in the southern circumpolar region, and found that most of the processes considered were not occurring in continental Antarctica. The process of carbonation/decarbonation was concluded to be unimportant in continental Antarctica, however, may be more important in coastal areas of East Antarctica, and in the Maritime Antarctic Zone where there is abundant available water and greater pCO_2.

The process of pervection, (used to describe the migration of silt and clay and the development of silt caps on stones and silt-enriched horizons in Arctic soils), was not considered to be important (Bockheim and Ugolini, 1990). For pervection to occur, there must be sufficient moisture present, suggesting that unless the soil is poorly drained, pervection is not a prominent process in continental Antarctica.

Podzolisation and melanisation were also considered by Bockheim and Ugolini (1990), and in both cases were deemed to become less important as the latitude increased. For melanisation to occur, organic material is required to lead to the formation of a relatively deep black surficial horizon, and since organic material is extremely sparse in continental Antarctica, melanisation isn't reported to occur. Similarly, podzolisation requires organic acids, particularly fulvic acids, to be present to mobilise and transport metals (especially Al and Fe) downwards. There have been no reported occurrences of podzolisation in continental Antarctica.

2.3.3 Soil Properties

2.3.3.1 Physical Properties

Most soils in Antarctica have been reported to have a loamy sand or sand texture with abundant coarse fragments (Bockheim, 1997). Campbell and Claridge (1982) outlined a typical profile as having a surface desert pavement of lag gravels, which are stained, ventifacted or polished, and are underlain by a thin sandy horizon formed by the physical breakdown of surface stones. Beneath this, finely textured material is usually present, often occurring as a matrix in bouldery or cobbly moraine.

The colour of Antarctic soils ranges from light grey (5Y 7/1 and 5Y 6/3) through yellowish brown and strong brown (10YR 5/4 and 7.5YR 5/6) to yellowish red and dark red (5YR 5/8 and 2.5YR 3/6). The colour of the soil is related, in part, to the degree of weathering that has occurred, as well as the colour of the parent material. The increasing redness of the profile due to weathering is related to the increasing degree of oxidation (Fe^{2+} to Fe^{3+}) that has occurred (Campbell and Claridge, 1987).

2.3.3.2 Chemical Properties

Although Antarctic soils are often considered to be alkaline with high pH's, a range of pH values have been found (Claridge and Campbell, 1977). In general, the pH of the soil has been found to be influenced by proximity to the coast. For example, soils found in the south at high altitudes are acidic, with a pH between 6 and 6.5, while areas closer to the coast, with a stronger marine influence, have a pH just above 7. In the McMurdo oasis, soil pH is around 8, while in the soils subject to the strongest marine influence, the pH rises to 9.

The occurrence of salts in Antarctic soils is also an important chemical property, and is reviewed in section 2.3.4.

2.3.3.3 Biological Properties

Due to the extreme conditions in Antarctica, the soils have very few biological properties. During the warmer periods in December and January, biological activity may occur (Virginia and Wall, 1999), although it tends to have a very small influence on the soils (Campbell and Claridge, 1982).

Fauna in Antarctic ecosystems are simple and consist of almost entirely soil micro-invertebrates, with biotic diversity decreasing along an environmental gradient between the sub-Antarctic islands and continental Antarctica (Convey and Wynn-Williams, 2002). Consequently, the soil environment contains only simple communities, which are thought to be particularly susceptible to disturbance or change processes (Convey and Wynn-Williams, 2002). Microbial activity is generally considered to be greatest in the active layer, as it often contains the highest content of available water, nutrients and total organic carbon

(TOC), and obtains maximum summer temperatures in the summer months (Mohn and Stewart, 2000).

One of the limiting factors of microbial growth is considered to be temperature, where microbial growth is greater at higher temperature. However, indigenous micro-organisms in cold climates have often adapted to the environment in which they grow, and consequently temperature is less of a limiting factor in their growth (Gibb *et al.*, 2001). Soil moisture is thought to be another limiting factor to the distribution of soil invertebrates, as they require water for activity, and consequently their occurrence is limited to high-moisture locations. However, as with temperature, microbes have been found in dry habitats in the Dry Valleys (Virginia and Wall, 1999). Biodiversity studies by Virginia and Wall (1999) in a transect from a stream to soil 32 m away showed the decreasing moisture content away from the stream corresponded with a decrease in the abundance of the microbes. A moisture content of 10-20% is considered optimal for microbial activity in the unsaturated zone (Børrensen *et al.*, 2003), and consequently soil moisture availability may be a limiting factor for near surface soil microbial activity at certain sites in the Ross Sea region (Balks *et al.*, 2002). The preferable pH for maximum rate of growth for micro-organisms in soil is an approximately neutral pH (pH = 7) (Wilson and Jones, 1993). In soils that exhibit a strong marine influence, soil pH may also be a limiting factor, where the soil pH may rise to as high as 9 (Campbell and Claridge, 1977). The major nutritional factors for microbial growth are nitrogen (as nitrate or ammonia) and phosphorous (as phosphate) (King *et al.*, 1992), both of which may be limiting factors to microbial growth in Antarctic soils (Balks *et al.*, 1998).

2.3.4 Salts in Antarctic Soils

Salts are an important part of the soils of Antarctica (Claridge and Campbell, 1977). Salts accumulate in the soils due to the process of salinisation (section 2.3.2.3), and are found in most soils in Antarctica (Campbell *et al.*, 1998d). In many of the arid inland regions, thick salt horizons are commonly found, while in the moister coastal regions the salts are rarely found in such thick horizons, and more typically are dispersed through the entire profile (Beyer *et al.*, 1999).

Bockheim (1990) identified six morphological stages of soil development, and related them to the electrical conductivity in the salt enriched horizon and absolute age. This showed that the salt content tended to increase with age, with the indurated salt horizons present in the oldest soils. Tedrow and Ugolini (1966) suggested that evaporite soils were a common feature of the Dry Valley's, where the salts accumulate in the depressions, basins, and low, flat drainage ways. In these soils, the only morphological feature is an accumulation of salt, up to an inch or more thick.

While there are variations from soil to soil in the exact salt present, the salts consisted largely of chlorides, nitrates, and sulphates of sodium, potassium, calcium, and magnesium (Claridge and Campbell, 1977). The order for most dominant to least dominant cation follows the following trend (Bockheim, 1997):

sodium > calcium or magnesium > potassium

In terms of the anions in the salt, differing trends are observed, whereby chlorides are dominant in subxerous soils, while sulphates or nitrates are most common in the xerous and ultraxerous soils.

The mechanism of salt movement in Antarctic soils is generally poorly understood. Observations lead to the opinion that salts accumulate on the surface from sublimation of snow, and then are flushed into the soil during melting of occasional heavy summer snowfalls (Bockheim, 1997). A lack of moisture is also considered part of the reason salts accumulate in Antarctic soils, as there isn't sufficient moisture to flush the salts out of the soil (Campbell *et al.*, 1998d). The low degree of leaching is associated with a linear increase in salt concentration with time, which has been observed in soils of differing ages throughout the Trans-Antarctic Mountains (Bockheim, 1990).

Salts in Antarctic soils tend to follow a general distribution pattern within the soil profile. With the exception of soils modified by burial, the zones of highest salt content have been reported to coincide with the zones which contain a large fine material fraction, with Bockheim (1982) noting the relationship between clay content and salinity, while Campbell (2000) found a similar relationship, but with silt material instead of clay. Campbell (2000) also noted a trend of decreasing electrical conductivity from the surface downwards, before increasing values in the lowest horizons, including the ice-cemented ground. This correlates with findings by Campbell *et al.* (1998d), who found high salinities at the surface, and suggested this was due to evaporation concentrating the salts. The salt enriched horizons have had reported electrical conductivities of up to 25 000 μS cm^{-1} (Bockheim, 1979).

2.3.4.1 Sources of Salts in Antarctic Soils

Four possible sources for the salts in Antarctic soils have been proposed: (i) marine aerosols; (ii) rock weathering; (iii) marine incursions; and (iv) volcanic activity (Bockheim, 1979). Marine aerosols provide the main source of sodium salts, while smaller quantities of calcium, magnesium, and potassium are also of marine origin. Sodium is also derived from weathering of sodium feldspars, etc, but this is a minor source (Claridge and Campbell, 1977). Rock weathering provides inputs of calcium and magnesium from weathering of ferromagnesian minerals (e.g. augite, hornblende, etc) in the Ferrar Dolerites, and biotite, etc in the granites. Potassium is derived from weathering of muscovite micas, and to a smaller extent potash feldspar. The anions are mostly from a marine aerosol origin, with distance from the coast and preferential precipitation affecting the location of the sulphates, chlorides, and nitrates (Campbell *et al.*, 1998d). A direct marine origin in the McMurdo ice-free areas has also been proposed as a source of salts, due to evidence from the Wright Valley suggesting it was a fiord at the end of the Pliocene. Biological, volcanic and hydrothermal activity are locally important as a source of ions, particularly in the McMurdo region (Keys and Williams, 1981).

2.3.4.2 Effects of Salts in Antarctic Soils

Salts have the potential to affect other aspects of the soil, including the soil thermal regime (Campbell *et al.*, 1998b), particularly in relation to the phase of the moisture in the soil. A higher salt content causes the freezing point of the soil solution to be depressed (Campbell *et al.*, 1998c). Therefore soil salinity plays an important role in determining the type of permafrost (ice-cemented or non ice-cemented) and also the thickness of the active layer.

Studies by Campbell *et al.* (1997b) showed that at three sites with broadly similar moisture contents, the non-saline soil had a definite ice-cement zone which coincided with soil temperatures of approximately 0°C. It has also been found that in soils with high salinity, latent heat changes are less than in non-saline moist soils, and consequently diurnal temperature changes continue throughout the profile in response to downwards or upwards heat conduction (Campbell *et al.*, 1998b).

2.3.5 Permafrost and the Active Layer

2.3.5.1 Definitions of Permafrost and Active Layer

Permafrost is defined as soil and/or rock which remains below 0°C for at least two consecutive years, and was first defined by Muller in 1943. There are two types of permafrost; the first relates to permafrost that is ice-cemented, while the second is dry permafrost, where there is insufficient water present to form ice-cement (Bockheim *et al.*, 1997). Both of these forms of permafrost are found in Antarctica.

Permafrost affected soils cover 13% of the earth's land surface, primarily in Russia and Canada, and to a lesser extent in northern Alaska, China, Greenland and Antarctica (Bockheim *et al.*, 1997). In Antarctica, it has been suggested that soils south of 60°S are affected by permafrost (Blume *et* al., 1998), while Bockheim (1995) states that the northern limit of permafrost is the location of the –1°C isotherm. However, since much of the landmass below the massive East Antarctic Ice Sheet is above the pressure of melting point and is unfrozen, only about 25% of the Antarctic continent contains permafrost (Bockheim and Hall, 2002). Permafrost is linked to the atmosphere by the intervening active layer, vegetation (if present), and snow cover, which vary with time and location (Romanovsky and Osterkamp, 1992). Data from the Dry Valley Drilling Project

(DVDP) suggest that permafrost is 140 to 500 m thick on Ross Island and 240 to 970 m thick in the Dry Valleys (Bockheim, 1995).

The active layer refers to the part of the soil profile that seasonally thaws out (Bockheim *et al.*, 1997), with the active layer depth defined as the depth of the summer thaw (Zhang and Stamnes, 1998; Putkonen, 1998). In an ideal situation, the base of the active layer would be defined as the point at which temperature is 0°C (Burn, 1998), however, this may be depressed by several degrees Celsius in the presence of salts in the soil. The active layer forms a zone across which heat energy and moisture migrate between the atmosphere and perennially frozen parts of the solid earth (Hinkel *et al.*, 1996). Active layer thawing is restricted to periods when the surface is exposed to the atmosphere after any snow has melted away (Romanovsky and Osterkamp, 1992).

2.3.5.2 Antarctic Permafrost

2.3.5.2.1 Ice-Cemented Permafrost

Ice-cemented permafrost is the most common form of permafrost in Antarctica, with Bockheim and Hall (2002) outlining four main regions where ice-cemented permafrost occurs. These included the Ross Sea drift in coastal areas, alpine drift in the Dry Valley's, sediments at elevations above 2 000 m in upland valleys and along the edge of the polar plateau, and below the dry permafrost at depths exceeding 100 cm. The depth to ice-cemented permafrost differs depending on location, but ranges from a few centimetres to up to 2 m (Campbell *et al.*, 1998b). It is suggested that for soils to be ice-cemented, a gravimetric moisture content of 5% or greater in the soils is required (Bockheim and Hall 2002).

Values for the moisture content of ice-cemented permafrost have been reported over a wide range. Campbell (2000, 2003) reports ice-cement gravimetric moisture values of 12.3% in the Taylor Valley, while undisturbed soils at Marble Point and Pram Point show permafrost volumetric moisture contents of 10-25% (Campbell *et al.*, 1994). In some of the coastal sites, the gravimetric moisture content of the permafrost is of the order of 35-40%, and can rise up to >140%

when ice senses are present in the soil (Campbell *et al.*, 1997a). These sites also exhibit permafrost moisture contents much higher than the overlying active layer.

2.3.5.2.2 Non Ice-Cemented Permafrost

Non-ice cemented or dry permafrost is only found in a few locations on the Antarctic continent. It is limited mostly to the Trans-Antarctic Mountains, including the Dry Valley's, and accounts for less than about 1% of all permafrost (Bockheim *et al.*, 1997). Soils containing dry permafrost are much drier than their ice-cemented counterparts. In soils with dry permafrost, moisture content is so low that the ice present is insufficient to cement the soil materials, which can cause confusion in identifying the permafrost-active layer boundary (Campbell *et al.*, 1994). Dry permafrost moisture contents are generally similar or slightly higher than those that are measured in the overlying active layer (Campbell *et al.*, 1998c). Campbell *et al.* (1997a) report dry permafrost values (gravimetric) of 1.1 to 2.7% in the Wright Valley.

2.3.5.3 The Active Layer of Antarctic Soils

In Antarctica the active layer can vary in depth from 20 cm to greater than 200 cm near the northern limit of permafrost (Bockheim *et al.*, 1997). The depth of the active layer is determined by soil physical properties and the radiation and climatic environment (Campbell *et al.*, 1998c). Guglielimin *et al.* (2003) suggest that the active layer of soils in northern sites is thicker than that of southern sites, which probably reflects the higher moisture content of the more northern sites.

The moisture content of the active layer in Antarctic soils varies according to location and environment. For example, soils in the Dry Valley's are generally drier than coastal soils. Active layer gravimetric moisture contents have been reported to be 1.5% to 3% in locations where dry permafrost was encountered (Campbell *et al.*, 1998c), while moisture contents of the active layer in coastal regions are upward of 5% (Campbell *et al.*, 1997a). Beyer *et al.* (1999) suggest that in coastal regions, the moisture content of the active layer increases downwards, with a sharp increase when permafrost is encountered.

2.4 Antarctic Climate

2.4.1 General Trends of Antarctic Climate

2.4.1.1 Air Temperature

Antarctica has the coldest climate on Earth, primarily due to the high average altitude and high latitude (Beyer *et al.*, 2000a), but still shows considerable variation in air temperature over the continent (King and Turner, 1997). During winter, air temperatures tend to show a greater day-to-day variation than in summer. This is due to the strong temperature inversions that occur on calm, clear days giving the lowest temperatures, while the formation of clouds or mixing of warmer air with surface air by winds can destroy the inversion within a few hours giving warmer temperatures (Warren, 1996). Temperatures on the Antarctic continent also vary according to a latitudinal temperature gradient, whereby there is a general pattern of temperature decrease with an increase in latitude (Harangozo *et al.*, 1997). Studies on the Antarctic Peninsula suggest that the gradient ranges from 0.3°C to 1.9°C per degree of latitude for that region, depending on season and location (Phillpot, 1985). Phillpot (1985) suggests an average of 0.66°C / degree of latitude for a given altitude over the entire continent. Air temperatures reported for several stations around the Antarctic continent all show mean summer air temperatures below zero (Warren, 1996). However, while mean summer temperatures are below zero, there are several periods where air temperature rises above zero, particularly in regions near to the coast. Thompson *et al.* (1971a) found that midsummer temperatures in the Wright Valley were, on average, 7°C cooler than those recorded at both Marble Point and Scott Base on the coast. In Antarctica, the lag between peak summer air temperatures and the summer solstice is only 8 days, which differs from the rest of the world, where the lag is about 30 days. Average winter air temperatures reported around the Antarctic continent are all well below zero.

2.4.1.2 Precipitation

Precipitation in Antarctica is mostly in the form of snow, although instances of rain have been recorded during summer periods when the temperature has warmed sufficiently to allow liquid moisture to fall (King and Turner, 1997). Precipitation is generally very low in Antarctica, but like temperature, there is spatial variation in the precipitation patterns. Coastal regions tend to experience more precipitation than the interior due to both frontal cyclonic systems, as well as adiabatic cooling of moist air as it rises up over steep topography, combining to produce snowfalls (and occasional rainfall) (Warren, 1996). Adiabatic systems are the most important source of precipitation in the coastal regions. The interior of the continent, however, has precipitation produced dominantly by frontal cyclonic systems. Precipitation over the interior of the continent is generally in the form of ice crystals falling from thin, isolated cloud or apparently clear sky (King and Turner, 1997). Reported annual precipitation values show that there is a great range in Antarctica, with the Antarctic Peninsula recording between 1 260 mm and 310 mm depending on location (King and Turner, 1997), while the ice-free areas of the Dry Valleys record as little as 45 mm of annual precipitation (Bockheim, 1997). Precipitation in maritime East Antarctica ranges from 300 to 700 mm (Bockheim, 1995).

2.4.1.3 Wind

Winds in Antarctica are an important climatic factor. The general circulation of the Antarctic troposphere comprises of poleward flow in the middle troposphere, subsidence over the ice sheet, and a downslope outward flow (turned left by the Coriolis force) at the surface. When this wind nears the coast, the slopes steepen, and the inversion wind transitions to a katabatic wind. The katabatic wind is a down-slope drainage wind resulting from gravity acting on the dense layer of air just above the sloping snow surface. Winds over the surface tend to be influenced significantly by the local topography through katabatic forcing, suggesting that synoptic-scale (scale of 1 000 to 2 500 km) weather systems are relatively weak. Wind speeds tend to be closely related to the local topography, with the strongest winds on the steepest slopes, while the weakest winds occur on the flatter areas of the high plateau (Warren, 1996).

Winds recorded by Thompson *et al.*, (1971b) in the Wright Valley, and Doran *et al.* (2002) in the Wright and Taylor Valley's showed that the wind direction influenced the air temperature, with a westerly wind tending to bring an immediate increase in temperature, while an easterly wind corresponded to cooling in temperature. Everett (1971) reported that the Dry Valley area is subject to constant and frequently strong winds, and that the higher average and maximum velocities were recorded in the valley floor compared to the valley sides.

2.4.1.4 Other Climatic Variables

Clouds are common over the Antarctic continent, with about 50% cloud cover on average, which is similar to other continents. The difference between the Antarctic continent and other continents is that the clouds are generally thinner, and convective clouds (cumulus and cumulonimbus) are rare (Warren, 1996). These clouds have little effect on the short-wave radiation balance as they have a similar albedo to the snow (King and Turner, 1997).

The level of incoming solar radiation to the Antarctic continent is only small (Beyer and Bölter, 1998), but exhibits a large seasonal change (Beyer *et al.*, 2000a). For much of the year, the level of solar radiation arriving at the surface is minimal or non-existent, except in summer where the combination of clear skies and 24-hour insolation provides the surface with the largest solar receipt in the world (Campbell *et al.*, 1998a). In winter, when there is no incoming solar radiation, there is a net loss of about 110 Wm^{-2} of infrared radiation to space in the Earth-atmosphere system over Antarctica. This is balanced by an equal import of heat from the lower latitudes carried by the tropospheric winds (Warren, 1996). The net radiative loss of heat from the surface causes a strong cooling of the surface and the lowest layers of the atmosphere, and gives rise to the temperature inversions that are characteristically found (Tedrow and Ugolini, 1966).

2.4.2 Sources of Moisture

Soil moisture plays an important role in influencing many processes that occur in soils; hence the sources from which the soil gets this water are also important. Obviously soil moisture can be derived from the various forms of precipitation that occur on the Antarctic continent, however, not all of that is available to the soil, as much is lost via sublimation (Campbell *et al.*, 1998c).

Soils of the Dry Valley's region are dry because potential evaporation exceeds annual snowfall by about 1 cm yr^{-1} (McKay *et al.*, 1998). Since snowfall is only a minor source of moisture to these soils, liquid moisture is obtained from other sources, such as stream flows originating alongside thawing glacier margins (primarily), from thawing of a few permanent snow drifts in higher altitude gullies, or from seasonal thawing of frozen lakes. This however, only provides moisture to the soils that are close to where these processes are occurring, and a trend of diminishing soil moisture contents with increased distance from the water source was noted because the limit of the capillary flow that transports the moisture is only several metres (Campbell *et al.*, 1998d). Sources of moisture are generally restricted to the small period of time when temperatures allow the streams to flow (Tedrow and Ugolini, 1966). Increased salt contents can depress the freezing point of water allowing liquid water to flow at temperatures less than 0°C (Campbell and Claridge, 1969).

The floors of the Dry Valley's are at the extreme end of the scale in terms of sourcing moisture using differing methods. Near the coast, the main source of moisture is from precipitation caused by adiabatic cooling of air as it rises up the steep topography (King and Turner, 1997). As a result, precipitation is greatest near the coast (Beyer *et al.*, 1999), and decreases towards the interior (Warren, 1996). The sides of the Dry Valleys receive more snowfall than the Valley floors (Campbell *et al.*, 1998d).

2.5 Antarctic Soil Moisture and Temperature

2.5.1 Soil Temperature

2.5.1.1 Soil Temperatures Trends

Antarctic soil temperatures can rise above 0°C for short periods of time during the summer season, particularly at lower altitudes such as in coastal regions, while at the higher altitudes, the soil temperatures may rise above 0°C briefly, but the mean daily temperature is usually still below freezing (Campbell *et al.*, 1997b).

2.5.1.1.1 Regional Soil Temperature Trends

The soil temperatures of Antarctica show some clear regional trends, for example, at the time of maximum thaw coastal soils are the warmest, and thawing to depths of 50 to 60 cm occurs. Inland at higher altitudes, the soils are much cooler and the depth of thawing seldom exceeds 10 cm. The lower altitude Dry Valleys have soil temperatures that are in between those of the coastal areas and inland higher elevation regions (Campbell *et al.*, 1998b). Mean annual temperatures of the Valley floors are probably similar to those found in coastal areas, but temperature extremes are likely to be greater (Campbell *et al.*, 1998d).

2.5.1.1.2 Seasonal Soil Temperature Trends

Annual trends of soil temperature at Marble Point showed soil warming with diurnal cycles beginning to occur and become visible from late September with marked warming of the soils occurring near the end of November, and temperatures above freezing from mid December through to early February (Balks *et al.*, 1995). After February, surface temperatures began to fall below freezing again, with the surface temperatures cooler than the subsurface temperatures through to September, except for occasional winter warming event. At Marble Point, the soil surface temperatures ranged between +14 and –38°C, while at 55 cm depth, the range was +2 to –32°C. The average for all horizons was close to –16°C. Similar results were recorded at Lake Vanda over the 1969-71 period (Thompson *et al.*, 1971a). During December and January, the surface soil temperatures at Vanda were consistently above freezing. The soil temperature dropped below 0°C in February and continued to cool through to approximately September before warming again. At 8 cm depth, the maximum soil temperature was 11.6°C, while the minimum was –50.0°C.

2.5.1.2 Factors Affecting Soil Temperatures

2.5.1.2.1 Solar Radiation and Albedo

It is generally considered that the maximum soil surface temperatures are primarily radiation controlled (Campbell *et al.*, 1998c), with the global location of Antarctica providing 24-hour incoming solar radiation during summer and none during winter (Beyer *et al.*, 2000b). Minimum soil temperatures, contrastingly, have been strongly linked to the air temperature, and thus the greatest range of soil surface temperatures are found in the highest and coldest environments at inland locations (Beyer *et al.*, 1999).

The amount that soil temperatures can be warmed by incoming solar radiation is controlled by the albedo of the surface. The albedo of the surface determines how much of the incoming solar radiation is absorbed by the surface, and thus able to warm the soil. A lower albedo results in more of the incoming solar radiation being absorbed (Campbell *et al.*, 1997b), while snow, having a high albedo, reflects much of the solar radiation. Snow, however, is a good insulator of the soil from air temperatures, hence snow cover can increase mean annual ground temperatures by several degrees (Goodrich, 1982).

The gain and loss of radiation at the surface is the main driver of the diurnal soil temperature patterns (Campbell *et al.*, 1997b). In summer there is a diurnal temperature pattern, and the soil surface temperature is always greater than that of the overlying air due to the 24-hour insolation (Campbell *et al.*, 1997b), with surface temperatures being up to 15°C warmer than the overlying air in the middle of summer (McKay *et al.*, 1998).

2.5.1.2.2 Soil Thermal Properties

The thermal regime of a soil is dependent on the thermal properties of the soil as well as the energy balance. The key soil thermal properties are the soil heat capacity (C_s), thermal conductivity (k_s) and the soil thermal diffusivity (κ_s). The soil heat capacity is a function of the individual heat capacities of all the soil components, while the thermal conductivity defines the soil's ability to transport heat. The soil thermal diffusivity describes the ability of a soil to diffuse temperature changes and is defined by:

$$\kappa_s = \frac{k_s}{C_s} \tag{2.16}$$

Soils with a high thermal diffusivity transport heat rapidly into the soil so that temperature changes are spread over a greater depth, causing these soils to have a less extreme thermal regime than soils with a low κ_s (Campbell *et al.*, 1997b).

2.5.1.2.3 Soil Salinity

Soils with high salinity have latent heat changes which are less than in non-saline soils, consequently diurnal temperature changes continue throughout the profile in response to downwards or upwards heat conduction (Campbell *et al.*, 1998b)

2.5.2 Soil Moisture Trends

2.5.2.1 Regional Soil Moisture

Soil moisture values have been reported for many sites in Antarctica, particularly in the Ross Sea region. The soil moisture data can be broken into regional zones – coastal, dry valley floor and sides, and upland and mountain regions, all of which show clear differences (Campbell *et al.*, 1997c). The regional zones broadly correspond to the three moisture zones – ultraxerous, xerous and subxerous, recognised by Campbell and Claridge (1969).

2.5.2.1.1 Coastal Regions / Subxerous Soils

The coastal regions correspond to soils in the subxerous moisture zone (Campbell and Claridge, 1969). Subxerous soils occur in the regions where the temperature is higher, and moisture is available from the melting and thawing of snow over the summer period. The higher moisture and humidity levels are indicated by the presence of ice crystals in the soil, and after summer snow, the soil may be moistened to a depth of 1 to 5 cm for short periods. Any ice held in the soil may also melt as soil temperatures rise (Campbell and Claridge, 1982).

Investigations of coastal soils show that active layer gravimetric moisture contents average approximately 5%. This average gravimetric moisture content takes into account an increasing moisture content with depth, as surface measurements have moisture contents of <1%, while immediately above the ice-cemented permafrost, the moisture content rises to about 10% (Campbell *et al.*, 1994; Balks *et al.*, 1995; Campbell *et al.*, 1998d). The permafrost may have higher gravimetric moisture contents that can reach up to 150% where ice lenses are present in the permafrost. The soil moisture contents were mostly repeatable over time, although small differences between years were seen. Spatial variations in soil moisture contents can occur over very short distances, for instance, next to a melting snow patch due to capillary action. Campbell *et al.* (1998d) found gravimetric moisture contents in coastal zones of 15% at the edge of a thawing snow patch, 12% at a 1.5 m distance and 2.5% 4 m away from the snow patch. As the snow patch retreated and disappeared, the soil proceeded to dry out and the gravimetric moisture content dropped to <1% over 14 days.

2.5.2.1.2 Dry Valley Floors and Sides / Xerous Soils

Xerous soils are described as those that form in mid-altitude areas where both precipitation and temperature are lower than the subxerous soils. Xerous soils are the most widespread group of soils in the Ross Sea region, and are found between the coast and the Polar Plateau, including the Dry Valley region (Campbell and Claridge, 1969). The moisture supply is mainly from summer snowfalls, which probably enter the soil as vapour although some may occasionally melt slightly to moisten the surface. Xerous soils are characterised by having ice-cemented ground at the base of the profile, and by the presence of salts spread throughout the profile (Campbell and Claridge, 1982). The higher moisture content of xerous soils can be seen by the leaching and movement of soluble salts out of the profile. Upon excavation, Campbell and Claridge (1982) noted that salts could be seen precipitating immediately on the profile face as the soil water evaporated.

Soils of the Dry Valley floors and sides have a much lower moisture content than the coastal soils, with gravimetric moisture contents averaging 1% or less for both the active layer and the permafrost (dry) (Campbell *et al.*, 1998b). Investigation of soils at Lake Vanda in the Wright Valley showed gravimetric moisture contents of 0.5% in shallow soils, while at another location, moisture contents in the upper 40 cm for 12 sites gave an average value of 0.5%, which increased to 0.7% the following year at the same sites. This suggests some interannual variation in the soil moisture contents of the valley floor and sides (Campbell *et al.*, 1998d). The gravimetric moisture content at the surface averaged 0.3% and increased with depth in the profile, and where ice-cemented permafrost was present the gravimetric moisture content rose to 6%. The measured gravimetric moisture contents for the dry valley floors and sides are lower than those obtained for the upland and mountains zones (ultraxerous soils), however, are still considered to be part of the xerous moisture zone (Campbell and Claridge, 1982).

2.5.2.1.3 Upland and Mountain Zones / Ultraxerous Soils

Ultraxerous soils are those that rarely, if ever, become moistened (Campbell and Claridge, 1982). These are found in extremely cold, inland, high altitude situations where precipitation, which is derived from small amounts of snowfall or snowdrift, sublimates rather than melts, in the cold, dry atmosphere. As a result, ultraxerous soils are not widely distributed, and occur at elevations greater than ca. 1 500 m and/or latitudes above ca. 82°S (Bockheim, 1982). Campbell and Claridge (1982) suggest that soil moisture of such soils is probably in the form of small ice crystals, which change to water films and water vapour with seasonal and diurnal soil temperature changes, with the moisture moving into the profile in the form of vapour rather than liquid, as snow ablates. Because the ultraxerous soils are well inland, high salt contents are also observed, allowing for the moisture to remain in liquid at lower temperatures than in some other soils.

Measurements made at several localities near Beacon Heights and in the Coombs Hills and Convoy Range by Campbell *et al.* (1998b) show active layer gravimetric moisture contents of 1.3% to 3.5%. These are higher than those found in the Dry Valley's but still less than the moisture contents of the coastal sites. In theses upland and mountain regions, the active layer thickness averages about 10 cm, and the permafrost is predominantly dry-frozen. The higher soil moisture values are found in areas where there is more precipitation (Campbell *et al.*, 1998c).

2.5.2.2 Seasonal Soil Moisture

Campbell *et al.* (1998a) found that while soil moisture contents of the Coastal region were mostly constant, there was some interannual difference in the measured values. The differences occur because melting snow can potentially add moisture to the soil, just as evaporation during the warmer parts of the year can remove water from the profile (MacCulloch, 1996; Zhang *et al.*, 1997). Examination of 12 sites near Vanda in January 1995, and again in December of the same year showed average soil moisture contents of the 12 sites to be 75% greater in the December than in the previous January (Campbell *et al.*, 1997a).

2.6 Hydrocarbon Contamination of Antarctic Soils

Antarctic soils are susceptible to human-induced damage (Campbell *et al.*, 1998d), and a relatively common contaminant is fuel spills (Cripps and Priddle, 1991). While fuel infiltration rates have been found to decrease as ice saturation increases (McCauley *et al.*, 2002), contaminant migration into permafrost and frozen soils may occur when there are unsaturated void spaces and fissures in the frozen soils (Biggar *et al.*, 1998).

One method proposed to clean up hydrocarbon-contaminated soils is bioremediation (Kerry, 1993), whereby micro-organisms or microbial processes are used to degrade the oil contaminants (Børrensen *et al.*, 2003). Because the

Antarctic Treaty prohibits the introduction of foreign organisms, indigenous hydrocarbon degrading microbes that degrade alkanes and aromatic compounds (Aislabie, *et al.*, 2000) are required, and have been identified in Antarctic soils (Kerry, 1990, 1993; Aislabie *et al.*, 1998). Studies have been previously undertaken to determine the effects that hydrocarbon spills have on micro-organisms in Antarctic soils. For example, Aislabie *et al.* (2001) found elevated numbers of culturable hydrocarbon degraders, bacteria and fungi in surface and subsurface soils at oil contaminated sites (compared to nearby control sites).

Bioremediation, however, is dependent on factors including temperature, type of contaminant and micro-organisms present, pH, and the availability of nutrients and water (Børrensen *et al.*, 2003). In cold-region soils, temperature and nutrient availability have been shown to be two of the more important limitations to biodegradation of soil petroleum hydrocarbons (Walworth, *et al.*, 2001). However, hydrocarbon-degrading soil communities have been found to be quite active at low temperatures (4-7°C), but with higher optimal temperatures (15-30°C) (Mohn and Stewart (2000). Biodegradation of hydrocarbons has been observed as low as -1.1°C, but lag periods were long and degradation rates low (Walworth *et al.*, 2001). Rates of microbial hydrocarbon degradation in soil have been shown to increase as temperatures increased (Westlake *et al.*, 1974; Sandvik *et al.*, 1986; Song *et al.*, 1990; Dibble and Bartha, 1979). Studies in both the Arctic (Mohn and Stewart, 2000; Braddock *et al.*, 1997) and Antarctic (Aislabie *et al.*, 1998) have found N and P to be limiting to hydrocarbon degradation. Results from studies where fertilisers were added have been mixed, with the additions enhancing, inhibiting and having no effect on the biodegradation of hydrocarbons (Braddock *et al.*, 1999; Roy and Greer, 2000). While a moisture content of 10-20% is optimal for microbial activity in the unsaturated zone, lower moisture contents in arid soils are capable of supporting active populations of hydrocarbon-degrading microbes (King *et al.*, 1992).

Because soil moisture and temperature have been identified as two of the limiting factors to bioremediation of hydrocarbon contamination in Antarctic soils, studies have been undertaken to consider the effects of hydrocarbon contamination on the

Antarctic soil moisture and temperature regimes. A study at Scott Base, and Marble Point showed that weekly maximum near surface soil temperatures during sunny, summer periods with no snow cover, were warmer (sometimes by more than 10°C) at hydrocarbon-contaminated sites when compared to nearby control sites (Balks *et al.*, 2002). The same study also examined a site in the Wright Valley, and found no significant differences between the contaminated and control sites. At Scott Base and Marble Point, the soil surface albedo was lower than that at the control site due to darkening by the hydrocarbons. The increased soil temperatures at the hydrocarbon-contaminated site were attributed to the decreased surface albedo.

Chapter 3 – Methods

3.1 Introduction

The key measurements undertaken in this thesis were determination of soil pH, soil electrical conductivity (EC), soil dry bulk density (ρ_b), and determination of volumetric soil moisture content using both gravimetric, and time domain reflectometry (TDR) methods. Determination of the soil moisture content using both gravimetric and TDR methods was undertaken to calibrate the TDR probes, while the soil pH, electrical conductivity, dry bulk density and gravimetric moisture contents were used to characterise the different soils.

3.2 Soil Analysis

3.2.1 Soil pH

There are several different solutions that can be used as the medium to suspend the soil in for soil pH determination. Solutions include water (H_2O), calcium chloride ($CaCl_2$), potassium chloride (KCl), sodium fluoride (NaF), and hydrogen peroxide (H_2O_2) (Blakemore *et al.*, 1987). In this thesis, distilled water was used as the suspending medium, with a soil to water ratio of 1:2.5. In order to create a standard testing procedure, sieved (< 2 mm) and air-dry soil was used.

The soil pH was measured using the following method (Blakemore *et al.*, 1987):

1. 10 g (± 0.01 g) of soil (< 2 mm, air-dry) was placed in a plastic 50 ml container with 25 ml of distilled water;
2. The sample was mixed using a high speed mechanical stirrer for 15 sec, and left to stand overnight;

3. Soil pH was determined using an Orion pH meter (Model 420A, Therm Electron Corporation, Beverly, Massachusetts, U.S.A.) calibrated using pH 4.0 and pH 7.0 LABCHEM Buffer Solutions (Asia Pacific Specialty Chemical Limited). The electrode was thoroughly rinsed with distilled water between measurements.

3.2.2 Soil Electrical Conductivity

In order to determine the electrical conductivity of the soil, the soluble salts were firstly extracted from the soil. The soluble salts were extracted from the soil using distilled water (in a 1:5 soil:water ratio) following the method outlined by Blakemore *et al.* (1987) on sieved (< 2 mm), air-dry soil. The extracts were then measured for electrical conductivity.

The method for extraction of soluble salts and determination of electrical conductivity (EC) was as follows:

Extraction of soluble salts:

1. 5 g (± 0.01 g) of soil was weighed into a 50 ml centrifuge tube with 25 ml of distilled water and placed on an end over end shaker for 30 minutes at about 20°C;
2. The sample was centrifuged using a IEC Centra GP8 centrifuge (IEC International Equipment Company, Needham Heights, Massachusetts, U.S.A) for 10 minutes at 2000 rpm;

Determination of electrical conductivity:

3. EC was determined immediately following extraction using a GP 383 conductivity meter (EDT Instruments Limited, Dover, Kent, U.K.) calibrated using 0.01M KCl (which gives an electrical conductivity of 1413 $\mu S\ cm^{-1}$). The results were given in $\mu S\ cm^{-1}$;
4. The results were corrected for the cell constant and temperature to 25°C using equation 3.1:

$$K_{25^\circ} = \text{reading} \times \text{cell constant} \times \text{temperature correction factor } (f_t) \qquad \textbf{3.1}$$

where: cell constant = 1; and temperature correction factor for 20°C is 1.118.

3.2.3 Soil Dry Bulk Density

There are several methods available for determining the dry bulk density of soils, including the core method, clod method and sand replacement method (also called the excavation method) (Blake and Hartge, 1986). The core method is used in stone-free soils whereby the soil can be sampled using a core, while the clod method uses Archimedes principle to determine the bulk density of clods or coarse peds. However, neither of these methods are suitable for determining the bulk density of the dry, stony Antarctic soils. The sand replacement method was used, whereby the soil was excavated, dried and weighed, and the volume of the excavated hole was determined using sand replacement (Burke *et al.*, 1986):

The sand replacement method involved the following steps:

1. The soil surface was smoothened at the desired level in the soil profile pit;
2. A small hole was dug, generally cylindrical in shape, with a diameter of ~5–7 cm, and a depth of ~5–7 cm, with the sample collected and placed in a plastic bag which was then sealed;
3. The volume of the hole was then determined by replacing the excavated soil with sand. Due to the strict environmental rules that occur in Antarctica, no foreign materials could be used as the replacement sand. Therefore, the sand used was *in situ* material that had been sieved to <2 mm. The volume was determined by placing the sieved sand in a 1 000 ml measuring cylinder noting the initial volume, before filling the excavated hole with sand and reading the final volume. The volume (v) of sand used was calculated as the difference between the initial (v_i) and final volume (v_f) reading on the measuring cylinder (equation 3.2);

4. In order to calculate the bulk density, the moisture factor (section 3.3.3) of the soil was calculated, thus allowing the dry weight of the soil (m_d) to be determined. The bulk density was then calculated using equation 3.4.

$$v = v_i - v_f \qquad \textbf{3.2}$$

$$m_d = \frac{m_w}{MF} \qquad \textbf{3.3}$$

$$\rho_b = \frac{m_d}{v} \qquad \textbf{3.4}$$

Where: v = sand volume; v_i = initial sand volume reading from measuring cylinder; v_f = final sand volume reading from measuring cylinder; m_d = dry weight of the soil; m_w = wet weight of the soil; MF = moisture factor (section 3.3.3); and ρ_b = soil dry bulk density.

3.3 Soil Moisture Determination

3.3.1 Gravimetric Soil Moisture Determination

Gravimetric moisture content (θ_g, kg kg^{-1}) determination involved weighing, drying and then re-weighing the soil and calculating the moisture content as the difference between the two weights (McLaren and Cameron, 1996).

1. Soil samples were collected using excavated material from the bulk density sampling procedure. Only material small enough to fit between the TDR probe tines was collected as it is this material for which the TDR probe determines soil moisture content;
2. An aluminium foil tray was weighed (m_t);
3. A 10-15 g sub-sample of the soil material was placed on the aluminium foil tray and weighed (wet weight, m_w);
4. The samples were then dried in a oven at 105°C for 24 hours;

5. After cooling (in a desiccator in New Zealand. In the lab environment at Scott Base a desiccator was considered unnecessary due to the very low relative humidity in the Scott Base environment), the samples were then re-weighed (dry-weight, m_d);
6. The gravimetric moisture content was determined using equation 3.5:

$$\theta_g = \frac{(m_w - m_d)}{(m_d - m_t)} \qquad \textbf{3.5}$$

Where: θ_g = gravimetric moisture content; m_w = wet weight of the sample (and aluminium tray); m_d = dry weight of the sample (and aluminium tray); and m_t = weight of aluminium tray.

3.3.2 Volumetric Soil Moisture Determination

Volumetric moisture content (θ_v, m^3 m^{-3}) was calculated using the determined gravimetric moisture content and the soil's dry bulk density. The volumetric moisture content was calculated using the following equation (3.6):

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w} \qquad \textbf{3.6}$$

where: θ_v = volumetric moisture content; θ_g = the gravimetric moisture content; ρ_b = soil dry bulk density; and ρ_w = density of water (assumed to be 1.0 g cm^{-3}).

3.3.3 Moisture Factor Determination

Often soil properties are required to be converted to an oven-dry basis. This can be done using the moisture factor (*MF*, unitless), which is the ratio of wet soil to dry soil. Moisture factor was determined using the following equation (3.7):

$$MF = \frac{(m_w - m_t)}{(m_d - m_t)} \qquad \textbf{3.7}$$

where: MF = moisture factor; m_{w} = mass of wet soil (and aluminium tray); m_{d} = mass of dry soil (and aluminium tray); and m_{t} = mass of aluminium tray.

3.3.4 Soil Moisture Determination Using TDR

3.3.4.1 TDR Probe Specifications and Operation

Hydra soil moisture probes (Stevens Water Monitoring Systems Inc., Oregon, U.S.A.) use the principle of time domain reflectometry (TDR) in order to determine the volumetric soil moisture content ($_{\mathrm{v}}$), salinity and soil temperature. The Hydra soil moisture probes (referred to from here on as TDR probes), originally developed by Vitel Inc. (which was sold to Stevens Water in 2000), make high frequency (50 MHz) complex dielectric constant measurements (Vitel, Inc., 1994). The probe (Figure 3.1) consists of four prongs, with three used for determining the soil moisture content and conductivity properties, while the fourth is used for determining the soil temperature. The probe has a length of 12.4 cm, and a diameter of 4.2 cm, with a cylindrical sensing region of 5.7 cm in length and 3.0 cm in diameter (Stevens Water Monitoring System Inc., 2003).

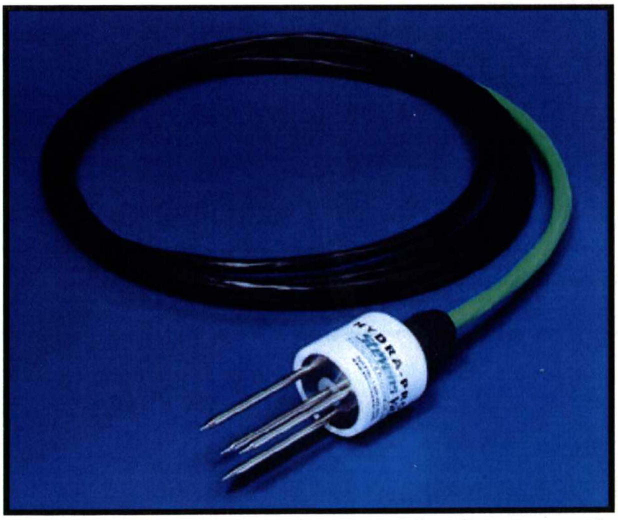

Figure 3.1: TDR soil moisture probe (Hydra probe).

The TDR soil moisture probe is powered by a 7 to 30 volt DC supply (7–12 V is recommended), with a current draw of 35 to 40 mA. The current activates the probes, with each of the four prongs (labelled V1, V2, V3 and V4) producing a voltage output related to the soil dielectric constant. Using a computer software program (called Hyd_file.exe), the soil dielectric constant (to ± 1.5% or ± 0.2), and subsequently volumetric soil moisture (to ± 0.03), electrical conductivity (to ± 2.0% or ± 0.0002 S m^{-1}), and temperature (to ± 0.6°C) are calculated. Because soils are of different textures ranging from clays through to sands and gravels, the Hyd_file.exe program also allows a texture option to be used in calibration. Three texture options are available: 1 – sand, 2 – silt, and 3 – clay (Vitel Inc., 1994). In the case of Antarctic soils, they have a texture closer to sand than any of the other options, and thus option 1 was used in calculations.

The TDR soil moisture probes can operate in environmental conditions that include soil temperatures of freezing to 65°C, and air temperatures of –10°C to 65°C. They are also able to withstand full immersion in water, while the cable can be buried and is UV resistant (Stevens Water Monitoring Systems Inc., 2003). The measurement range and accuracy of the four parameters measured are outlined in Table 3.1.

Table 3.1: Measurement parameters, range and accuracy of TDR soil moisture probes (from Stevens Water Monitoring Systems Inc., 2003).

Parameter	**Range**	**Units**	**Accuracy**
Dielectric Constant	1–65 (where, 1 = air, 78 = distilled water)		± 1.5% or ± 0.2 which-ever is typically greater
Volumetric Soil Moisture	Completely dry to fully saturated	$m^3\ m^{-3}$	± 0.03 water fraction by volume in typical soil
Electrical Conductivity	0–2 S m^{-1} (0–20 000 µS cm^{-1})	S m^{-1}	± 2.0% or ± 0.0002 S m^{-1} which-ever is typically greater
Temperature	-10–65	°C	± 0.6°C

3.3.4.2 TDR Probe and CR10X Datalogger Set Up

In order to record the soil moisture results determined from the TDR probes, the TDR probes were connected to a CR10X datalogger (Campbell Scientific Inc., Logan, Utah, U.S.A.). The CR10X is a fully programmable datalogger / controller which can be used for day-to-day measurements or research. It can be connected to any number of sensors, and is able to record the resultant output from such devices or can respond to site-specific conditions (e.g. opening or closing flood gates) (Campbell Scientific Inc, 2002). The power source for the datalogger (a 12V battery) is used to power all the sensors including the TDR probes.

Because soil moisture data were recorded for two different purposes, two separate TDR probe and CR10X set-ups were used. The first purpose was to gain a single time independent measurement, and involved just one TDR probe operating on an external switch connected to the datalogger, while the second purpose was to collect time series data using more several TDR probes, and involved several TDR probes connected to the CR10X datalogger using an AM416 multiplexer (Campbell Scientific Inc., Logan Utah, U.S.A.). In each case, a program was written to instruct the CR10X datalogger to firstly activate the TDR probes (and any other sensor), and secondly to record the resultant output.

Where one TDR probe was used, a time independent single measurement of the volumetric soil moisture content was required. As a result, the one TDR probe used was connected directly to the CR10X datalogger (Figure 3.2), with a switch used to determine when the probe was powered up. The resultant output voltages were then stored in the datalogger memory, along with the date and time, and following downloading, the data was then be converted to soil moisture contents.

Figure 3.2: Single TDR probe connected toCR10X datalogger.

As the CR10X datalogger only has 12 single-ended analog input ports, and each TDR probe required 4 ports, an AM416 multiplexer allowed the number of available ports to be increased. The AM416 multiplexer connects to four single-ended analog inputs on the CR10X, but then has 32 single-ended analog inputs (or 16 differential inputs) available to use. Where several TDR probes were used (i.e. at the soil climate stations), they were added to either any remaining ports on the CR10X datalogger or to the AM416 multiplexer, as were any other sensors (Figure 3.3).

In order to collect the data stored by the CR10X dataloggers, there are two possible methods. The first involves connecting the datalogger itself to a computer with compatible software and downloading the data directly. The second option involves incorporating a command in the datalogger program to download the data into a SM 192 storage module (Campbell Scientific Inc., Logan, Utah, U.S.A.), which can then be downloaded into a computer with compatible software. The storage module (Figure 3.3) was used to download data from the dataloggers where they were monitoring soil moisture content over time.

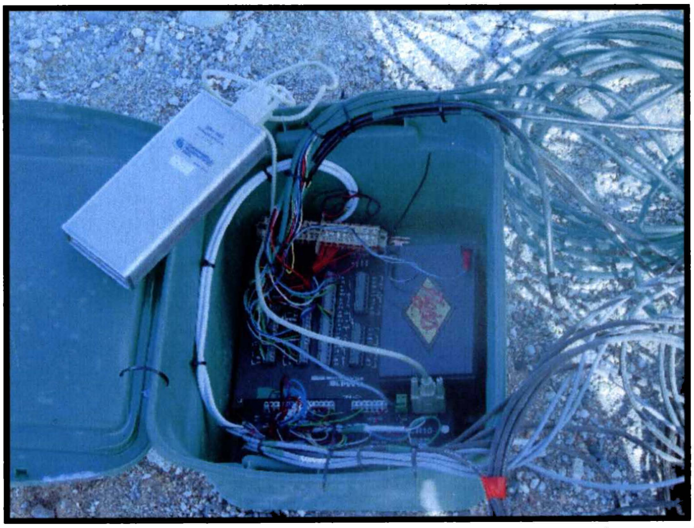

Figure 3.3: TDR probes connected to CR10X datalogger and AM416 multiplexer located in a plastic enclosure on the ground, with SM 192 Storage Module.

3.3.4.3 Installation of TDR Probes

When a one-off soil surface moisture measurement was required, the TDR probe was placed vertically into the ground surface (Figure 3.2). The ground surface was made as smooth as possible (by removing large surface pavement particles) in order to create a flat contact between the ground and probe. In these situations one of the problems encountered was the lack of consistency of the soil at the surface to support the probe in a vertical position. Where it was difficult to place the probe in the desired location due to larger pebbles and rocks or lack of support, the probes were moved until a suitable site was found.

When measurement of soil moisture content with increasing depth, or over time was required, a soil profile was excavated, the soil was described and classified, and soil samples were taken. Once the profile was excavated, vertical faces were created for the TDR probes to be inserted horizontally into the profile face. The aim was to get a smooth contact between the probe and soil, however in many situations, the soil lacked the cohesion to hold a vertical face. Having inserted the TDR probes at the desired depths (as well as any other sensors), the soil profile pit was back filled to reconstruct the natural environment, and to hold the probes in place. In the case of the soil climate stations, the probes and associated instruments were connected to a datalogger housed in an enclosure located on an A-frame, which also had the climate monitoring sensors on it (Figure 3.4).

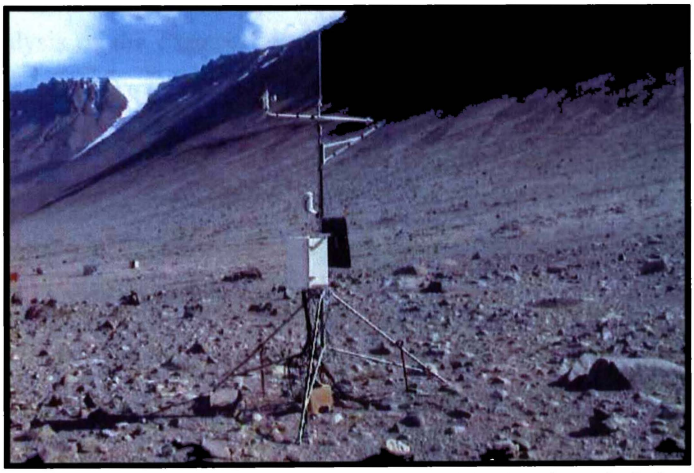

Figure 3.4: Soil climate station at Bull Pass with the CR10X datalogger and AM416 multiplexer located in the enclosure on the A-frame.

3.4 Measurement Error

Indicative measurement errors were calculated for the measurement of soil dry bulk density in both the field (using equation 5.1) and laboratory (using the equations outlined in section 3.2.3), and the gravimetric moisture content determination (using equations outlined in section 3.3.1). Values used in the error calculations were values that were typical of those in the applicable experiments. Measurement errors were calculated using the standard method of adding errors when adding and subtracting values, and adding percentage errors when multiplying and dividing values. The approximate measurement errors were:

Field soil dry bulk density:	±15%
Laboratory dry bulk density:	±5%
Gravimetric moisture content:	±0.02%
Field determination of θ_v from dry bulk density:	±15%

The errors determined for field bulk density and gravimetric moisture content do not take into account soil variability. Antarctic soils are variable, and consequently the actual errors in the field bulk density and gravimetric moisture content may be larger than those listed above.

3.5 Statistical Analysis

Statistical analysis of the experimental data (chapter 5) used x-y scatter plots and time series line graphs generated using Microsoft Excel (2000 and 2002 versions) to investigate relationships. Means, standard deviations, medians, maximums and minimums were also calculated using Microsoft Excel. Identification of statistically significant differences was undertaken using paired t-tests (Microsoft Excel) and an ANOVA calculation for statistically significant differences between more than two sets of data. An ANOVA calculation is an initial screening method that compares the means of more than two sets of data to determine if there appears to be a (statistically significant) difference between at least one pair of means. The ANOVA method is covered in more detail by Moore and McCabe (1999). A 'loess' smoother was applied to time series data in section 5.2.4 using Minitab (version 13.31). The 'loess' smoother undertakes a kind of regression where a regression is calculated as the method moves along the horizontal axis using only data points of intermediate vicinity. Only the closest points contribute to the fitted line and outliers are ignored, with a 'span' parameter determining how many points are used. The 'loess' smoothing method is covered in more detail by Cleveland (1979). Graphing of soil moisture and temperature data in Chapters 6 and 7 was undertaken using Matlab (version 6.5).

Chapter 4 – Soil and Site Description and Soil Properties

4.1 Introduction

In order to collect data on Antarctic moisture and temperature regimes, seven soil climate stations have been set up in the Ross Sea region of Antarctica. Each soil climate station has several TDR soil moisture probes (among other sensors) recording the soil moisture content of the soil. One of the major objectives of this study is to check the calibration and performance of the TDR probes in the Antarctic environment. The TDR probes were tested in two areas of contrasting soil and climate; Scott Base and Wright Valley/Bull Pass, although due to equipment malfunction, no useful TDR data was collected from the Wright Valley and Bull Pass.

4.2 Site Descriptions

4.2.1 Scott Base

Scott Base is located on the seaward end of a ridge of basaltic lava known as Pram Point on Hut Point Peninsula at the south end of Ross Island in the Ross Sea (Harrowfield, 1997). It is the site of New Zealand's permanent Antarctic research station, which was established in 1957. The geology and soils of the Scott Base region have been comprehensively investigated beginning with Scott's Discovery expedition in 1901-1904 (Cole *et al.*, 1971).

The area surrounding Scott Base has been impacted by human interaction since the construction of the base. Large portions of the hillside behind Scott Base have been disturbed as a result of activities ranging from walking, to operation of earth moving machinery. Areas that appeared to be undisturbed were selected for sample sites.

4.2.1.1 Study Site Layout and Sampling Locations

The Scott Base study site (Figure 4.1) included the area behind Scott Base, bound by the shoreline, and the road to McMurdo station. The area comprises variations of typical Scott Base soil, including undisturbed soil, areas with visible salt accumulation at the soil surface (usually disturbed sites), and hydrocarbon-contaminated soil (Scott Base HC Soil). Two areas on the Scott Base hillside were extensively investigated. However, many sites were sampled for single TDR probe volumetric soil moisture measurements and corresponding soil dry bulk density and gravimetric soil moisture sampling.

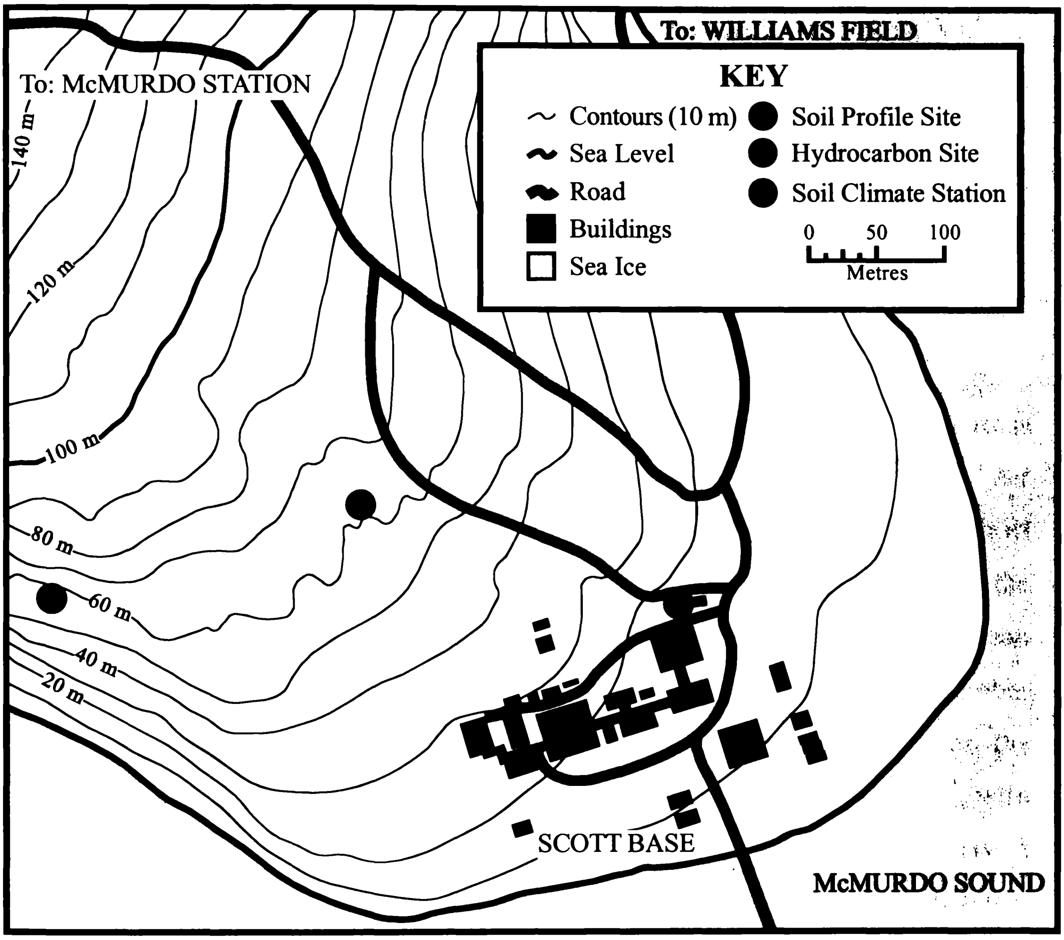

Figure 4.1: Sampling sites near Scott Base. Individual soil moisture samples were taken from areas throughout the map area.
(Adapted from: Balks, *et al.*, 1995, and Antarctica New Zealand, 2002)

The Scott Base HC site is a former storage area for drums of hydraulic and lubricating oils, where spills have occurred over the period from 1960 to 1998 when drums ceased being stored at that location (Balks *et al.*, 2002). Total Petroleum Hydrocarbon (TPH) analysis of the site by Balks *et al.* (2002) showed a hydrocarbon content of 25 100 $\mu g\ g^{-1}$ in the 0-2 cm depth.

4.2.1.2 Geology

The rocks of Hut Point Peninsula are generally of basaltic origin. Observation Hill is a flow-banded trachyte, and Castle Rock and the Boulder Cones are pyroclastic breccias (Cole *et al.*, 1971).

Scott Base is located on an olivine-clinopyroxene basaltic lava flow, with an estimated age of 0.4 m.y. originating from Crater Hill, 1.75 km northwest of Scott Base. The lava flow overlies the original Crater Hill olivine-clinopyroxene basaltic eruptives, which are suggested to be the oldest deposits on the Hut Point Peninsula, with an age of 1.6 m.y. (Kyle, 1981).

4.2.1.3 Climate

Climatic observations have been made sporadically at various points on Ross Island since 1904, and continuously on Hut Point Peninsula since 1955. Air temperature in the summer (November to February) rises above freezing for short periods, while the average air temperature is approximately –5°C for the December/January period. Air temperature begins to fall in February, with mean temperature fluctuating between –20°C and –30°C over the March–October period. Temperatures begin to rise again in October and November upon the return of the sun. The winds at Scott Base average approximately 5.8 m s^{-1}, with the predominant wind direction being NNE. Precipitation (almost exclusively as snowfall) at Scott Base averaged 188 mm yr^{-1} over the 1957-79 period, which was distributed approximately evenly throughout the year (N.Z. Met. Service, 1983).

Climatic observations have also been made at the Scott Base soil climate station, where air temperature, wind speed and direction, solar radiation and relative humidity have been measured over the 1999-2002 period. Table 4.1 summarises the annual averages, as well as the maximum and (where applicable) minimum values, while Figure 4.2 shows the air temperature trend over the same time period for monthly averages.

Table 4.1: Climate data obtained from soil climate station at Scott Base (unpublished data supplied by Ron Paetzold, 2003).

	1999	**2000**	**2001**	**2002**
Air Temperature (°C)				
Average	-19.80	-19.40	-19.48	-19.34
Maximum	1.24	1.48	4.83	16.56
Minimum	-39.86	-39.79	-47.06	-46.25
Solar Radiation (MJ m^{-2} day^{-1})				
Average	8.8	9.6	10.0	9.4
Maximum	66.7	67.9	69.6	71.3
Wind Speed (m s^{-1})				
Average	4.98	5.01	4.85	4.98
Maximum	26.88	25.72	24.51	25.78
Relative Humidity (%)				
Average	69.0	71.4	69.5	70.5
Maximum	97.3	98.6	100.0	100.0
Minimum	24.1	22.7	24.5	15.0

The maximum air temperature recorded in 2002 of 16.56°C was a lot warmer than the maximum air temperatures in any of the previous years. The maximum air temperature recorded at the nearby NZ Meteorological Service climate station was only 6.54°C for the same year (Niwa Climate Database (CLIDB)). Changes to the shading of air temperature sensor on the soil climate station may led to increased air temperatures being recorded.

Monthly average air temperatures (Figure 4.2) in December/January range between approximately –5°C to –10°C, with temperature dropping in February and averaging –20°C to –30°C through until October when air temperatures start to warm again. Over the winter period there is a slight warming in the May-July period followed by the coldest month of the year in August. The period of warming during the middle of winter is known as the 'coreless winter' (Wexler, 1959; van Loon, 1967).

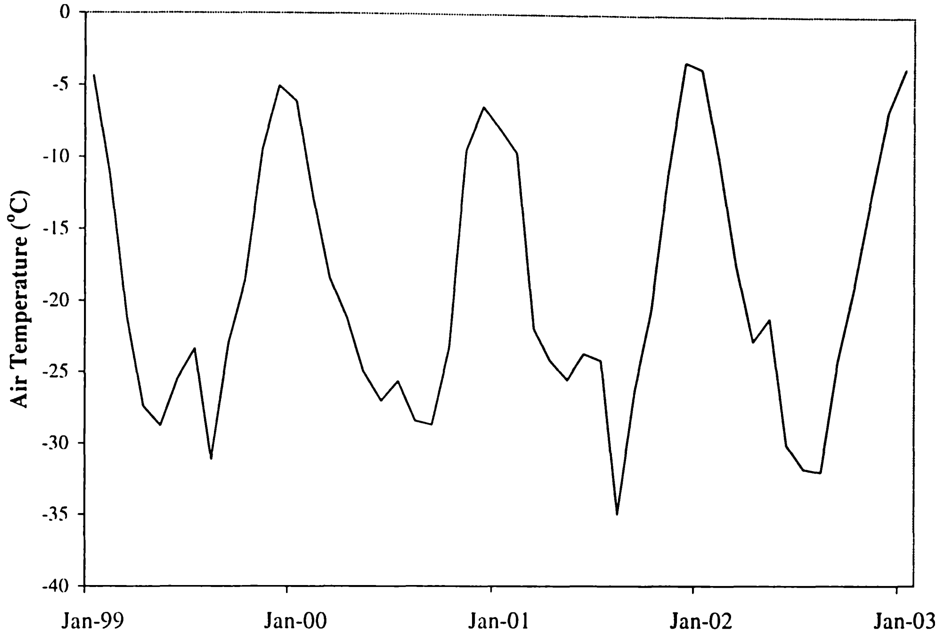

Figure 4.2: Average monthly air temperature for Scott Base 1999-2002 recorded from Scott Base soil climate station (Unpublished data supplied by Ron Paetzold, 2003).

4.2.1.4 Soils

The soils at Scott Base are derived predominantly from basalt parent material, and are considered to be Typic Anhyorthels (Guglielmin *et al.*, 2003) following USDA Soil Taxonomy (Soil Survey Staff, 1998). The soils near Scott Base have been described by several authors (e.g. McCraw, 1967b, Campbell, and Claridge 1987, Balks *et al.*, 1995, MacCulloch, 1996), and are typically dark coloured, coarse textured and contain few fine grains (Figure 4.3).

Soil description for Scott Base site (Extended site description in Appendix 1)

Site Location:	77° 50.914' S, 166° 45.281' E, 42 m altitude Situated on a spur facing south, on the southern flanks of Crater Hill, approximately 200 m NW of Scott Base.
Soil Classification:	Typic Anhyorthel

Depth (cm)	*Description*
0–11 cm	greyish yellow brown (5Y 3/2) gravelly sand, (estimate 50% gravel, 30% sand, 10% silt, 10% boulders), 2-6 mm rounded basalt gravel, <10 cm sub angular basalt boulders, 2% salts of 1 mm in size in random pattern, smooth (2-5 cm) irregular boundary;
11–25 cm	brownish grey (5Y 3/1) gravelly sand, (estimate 40% gravel, 40% sand, 15% silt, 5% boulders), 2-6 mm rounded basalt gravel, <10 cm sub-angular basalt boulders, smooth (2-5 cm) convolute boundary;
>25 cm	yellowish brown (10YR 3/2) sandy gravel, (estimate 20% sand, 15% silt, 5% boulders), 2-6 mm rounded basalt gravel, <10 cm sub-angular basalt boulders, ice-cemented below approximately 28 cm depth.

Figure 4.3: Scott Base soil profile.

4.2.2 Wright Valley and Bull Pass

The Wright Valley is an east-west running valley, and is one of the Dry Valley's located in the McMurdo Sound Region. Bull Pass is located on the northern side of the Wright Valley approximately 5 kilometres east of Lake Vanda. The Wright Valley/Bull Pass area provides an example of the cold, dry inland region of the Dry Valleys.

4.2.2.1 Study Site Layout and Sampling Locations

Bull Pass is the name given to the pass between the Mt Hercules/Mt Jason and Mt Orestes in the Olympus Ranges on the northern side of the Wright Valley. The study area (Figure 4.4) consists of Bull Pass, as well as the flanks of the Olympus Range, the outwash fan, and the surrounding Wright Valley floor.

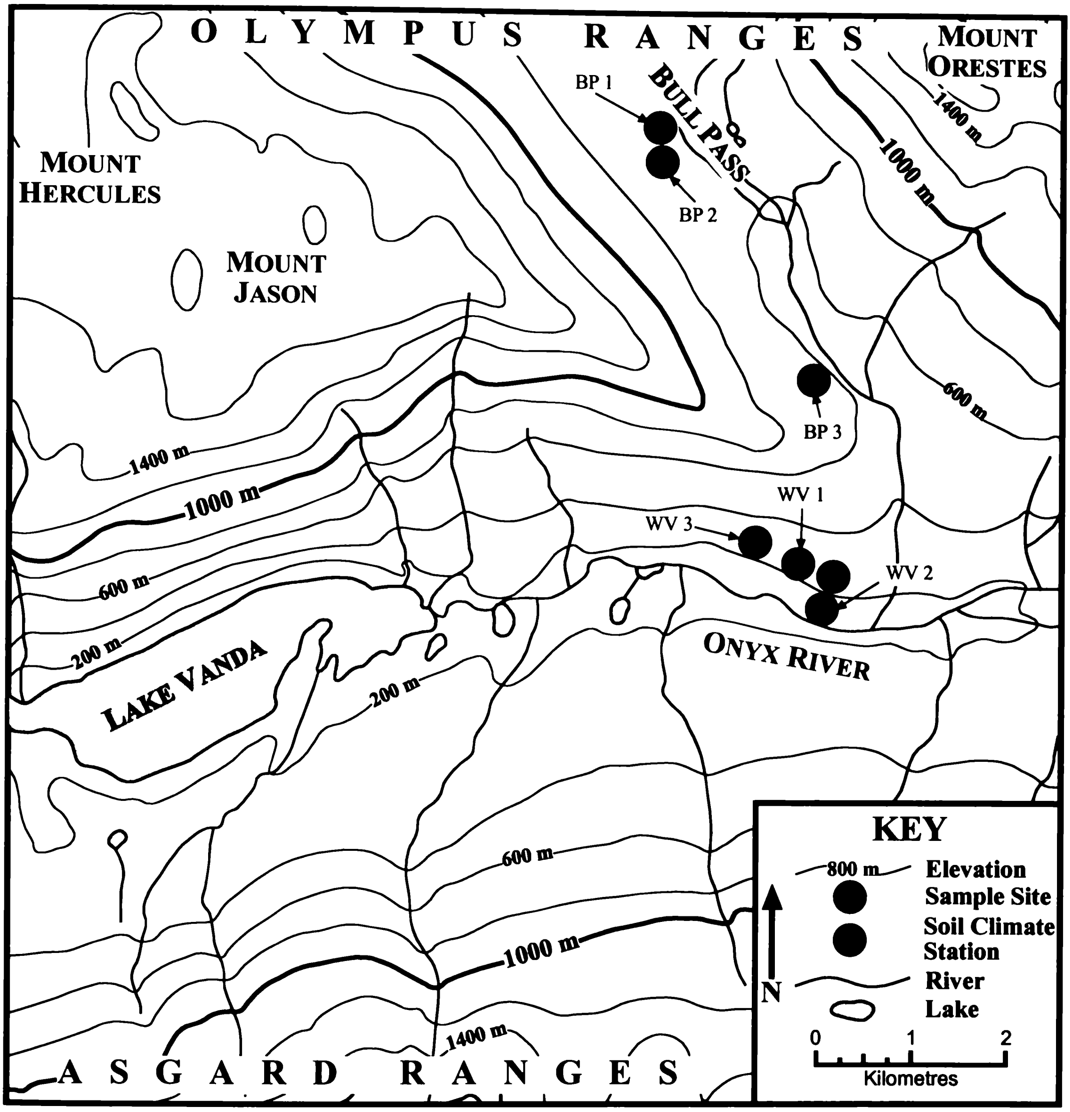

Figure 4.4: The Bull Pass / Wright Valley area.
(Adapted from: USGS, 1986)

Sampling of soils from the Wright Valley/Bull Pass area consisted of excavating and sampling six soil profiles (Appendix 1). Three profiles were located on the Wright Valley floor, and the remaining three were from up on Bull Pass. The three profiles in the Wright Valley were from a site near the established soil climate station (WV 1, Figure 4.4), on patterned ground at the edge of the outwash fan near the Onyx River (WV 2), and on the valley floor 200 m from the Wright Valley camp towards Lake Vanda (WV 3). The three profiles on Bull Pass included a site at the south end of the Pass (BP 3), and two sites further up Bull Pass (BP 1 and 2). Soil profile and/or site descriptions were made and measurements were undertaken for soil moisture using TDR probes at WV 2, and soil sampling for determination of gravimetric soil moisture, soil pH, soil electrical conductivity, and soil dry bulk density, was undertaken at all sites.

4.2.2.2 Geology

Glaciers flowing eastwards from the inland ice plateau through the coastal mountain ranges to McMurdo Sound cut the Wright Valley, along with the Victoria Valley system, in (about) the Oligocene (Turnbull *et al.*, 1994). In the area of Bull Pass, the geology consists of Quaternary to Recent age moraine and fluvioglacial deposits on the Wright Valley floor and the floor of Bull Pass. Rock outcrops in the base of the Wright Valley are composed of older granodiorite dikes and granite-gneiss, while higher up on the Olympus Range, granite, dolerite and Beacon sandstone are present. Further up the valley towards Lake Vanda, Vanda lampropyre and porphyry dikes are present (McKelvey and Webb, 1962).

4.2.2.3 Climate

Climate data from the Wright Valley has been collected from Lake Vanda. Temperature data from Thompson *et al.* (1971b) showed similar air temperature trends to that of Scott Base, with summer temperatures rising above freezing level, while winter temperatures averaged between –30°C and –40°C. The reported mean annual temperature for Vanda was –20°C, the same as for Scott Base (N.Z. Met. Service, 1983). Winds at Vanda tend to be stronger than at Scott Base, whereby the summer average is 8-10 m s^{-1}, while winter winds are generally lighter. The katabatic winds in the Dry Valleys can occasionally reach speeds of 40 m s^{-1}. Two years of continuous precipitation measurements recorded an annual average of 45 mm of precipitation, all from light infrequent snowfalls and wind blown snow. Precipitation tends to occur more commonly in summer than in winter (N.Z. Met. Service, 1983). Climatic data has been recorded in the Wright Valley at the foot of Bull Pass over the 1999-2002 period. Measurements include air temperature, solar radiation and wind speed and direction (Table 4.2).

Table 4.2: Climate data recorded by soil climate station based in the Wright Valley at the foot of Bull Pass (Unpublished data supplied by Ron Paetzold, 2003).

YEAR	**1999**	**2000**	**2001**	**2002**
Air Temperature (°C)				
Average	-21.71	-19.59	-20.14	-20.25
Maximum	6.64	4.38	10.95	11.88
Minimum	-53.28	-51.35	-52.13	-49.75
Solar Radiation (MJ m^{-2} day^{-1})				
Average	–	9.1	9.6	8.6
Maximum	68.3	71.5	73.3	65.8
Wind Speed (m s^{-1})				
Average	–	4.03	3.93	3.65
Maximum	–	19.36	19.17	19.82

Similar trends in average annual air temperature to those described by Thompson *et al.* (1971b) are identified in the Wright Valley over the 1999-2002 period (Figure 4.5). Average monthly air temperatures rose to approximately freezing level (or slightly above) in January, while dropping down to the –30°C to –40°C range from February through to September/October when it began to rise again. This is a similar trend to that seen at Scott Base, except the range of temperatures is greater in the Wright Valley than at Scott Base.

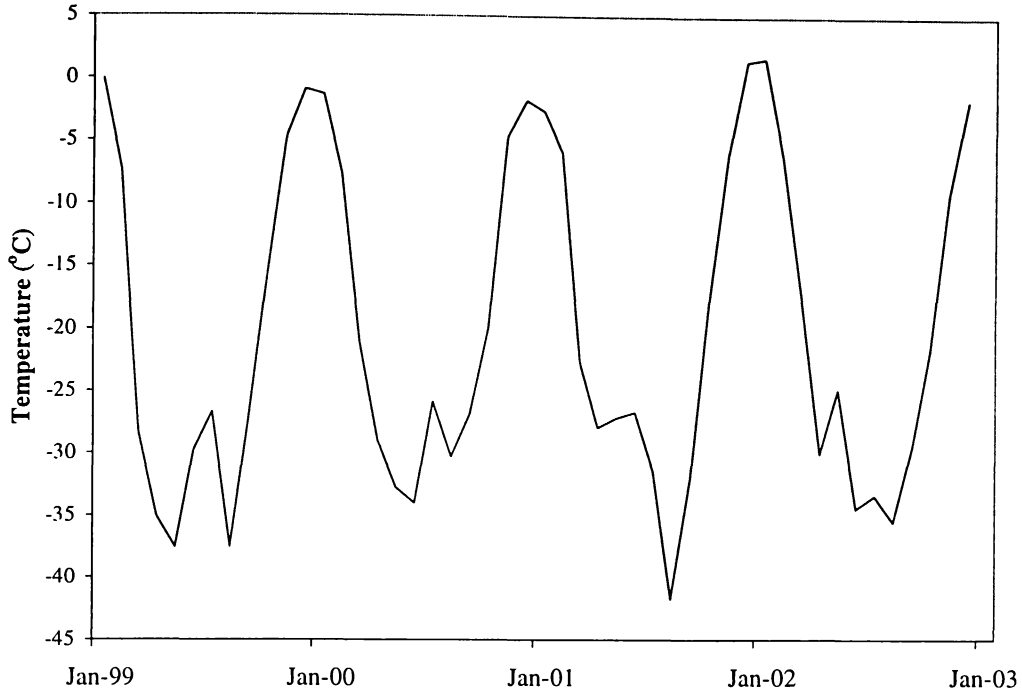

Figure 4.5: Average monthly air temperature for the Wright Valley 1999-2002, recorded from soil climate station located in the Wright Valley at the foot of Bull Pass (Unpublished data supplied by Ron Paetzold, 2003).

4.2.2.4 Soils

The soils in the Bull Pass / Wright Valley area have been described by several authors (Everett, 1971; Balks *et al.*, 1995), and are considered to be Typic or Nitric Anhyorthels (Guglielmin *et al.*, 2003) according to USDA Soil Taxonomy (Soil Survey Staff, 1998). The soils are formed from till, with predominantly granite and diorite parent materials, and textures ranging from coarse pebbles and occasional boulders through to fine silt in some locations (Figure 4.6).

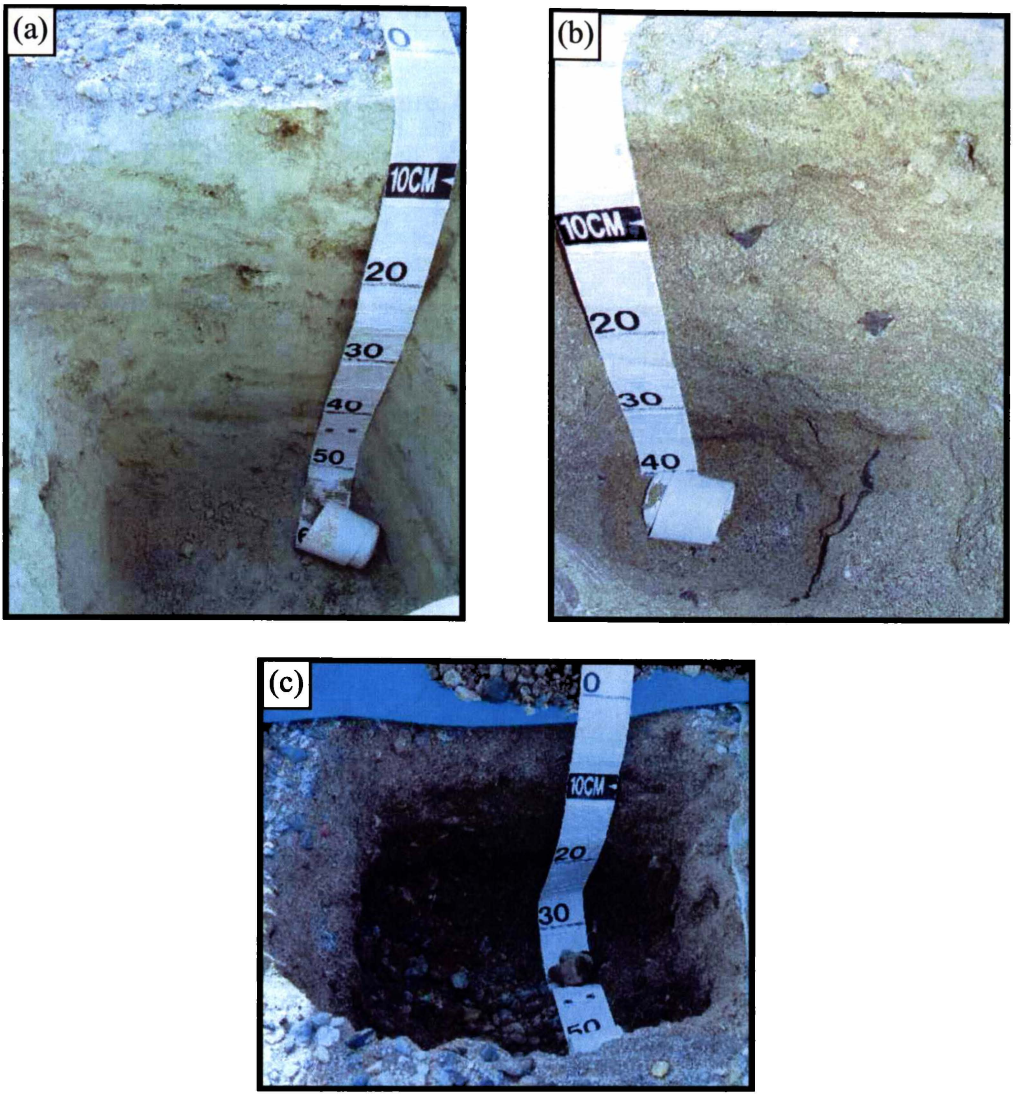

Figure 4.6: Soil profile at (a) Wright Valley Site 1, (b) Bull Pass Site 1, and (c) Wright Valley Site 2.

The soils of the Wright Valley/Bull Pass region are variable (Figure 4.6); however generally have a sandy texture, with variable silt contents. Many of the soils have very little silt, although there are isolated locations where the silt content was found to be very high. Boulders and gravel are common features on the soil surface, with the gravel forming part of the desert pavement. The soils in the Wright Valley were seen to have visible salts, and near the Onyx River ice-cement was encountered. The soils further away from the Onyx River, and on Bull Pass were generally too dry to for ice-cement to form. Soil profile and/or site descriptions for each of the soils described in the Wright Valley and Bull Pass region are in Appendix 1.

4.2.3 Soil Climate Station Sites

Seven soil climate stations (Figure 4.7) have been established by NZ Antarctic Programme K123 in the ice-free areas of the Ross Sea region since 1999 to monitor soil climate change.

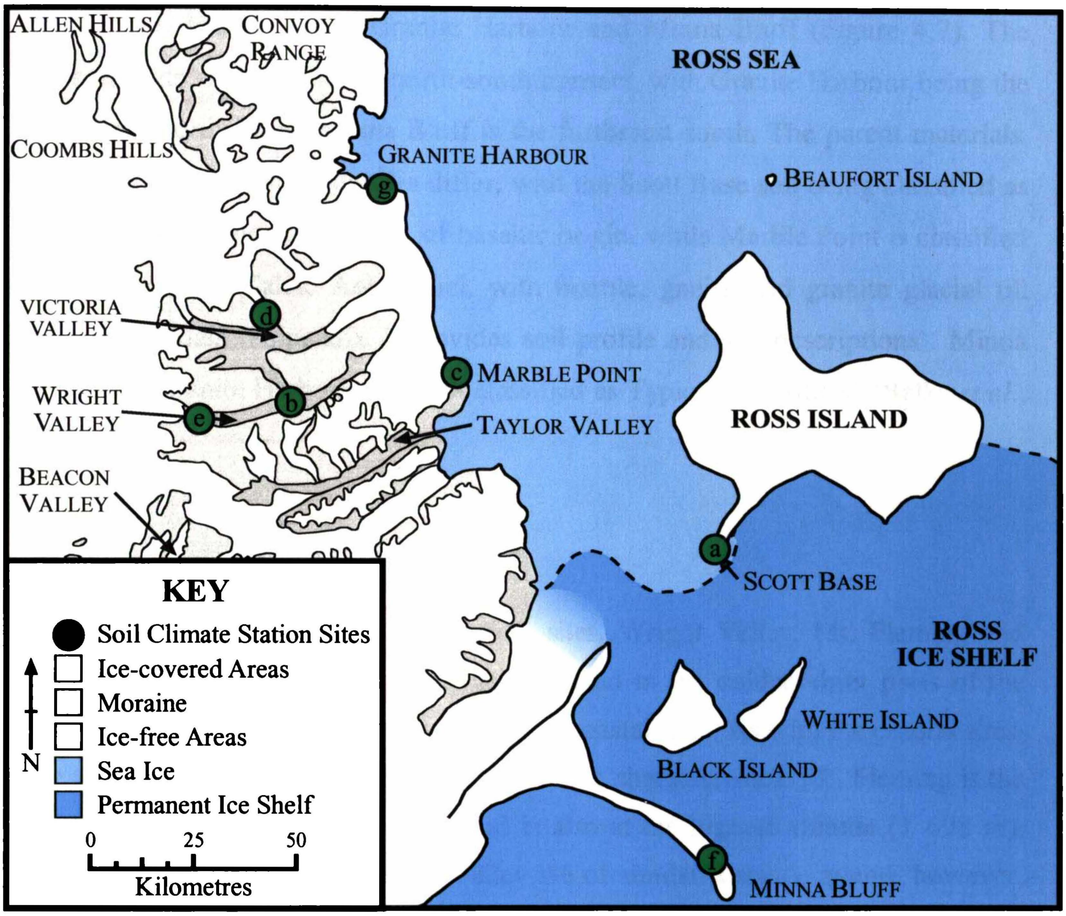

Figure 4.7: Soil climate station sites; (a) Scott Base; (b) Wright Valley; (c) Marble Point; (d) Victoria Valley; (e) Mt. Fleming; (f) Minna Bluff; and (g) Granite Harbour.

Scott Base, Marble Point, and Wright Valley climate stations were installed in 1999 as control stations for comparison with climate stations installed in hydrocarbon contaminated sites at the three locations (Balks *et al.*, 2002), and are now being used to monitor soil climate change. Ron Sletten (of the University of Washington, Seattle, U.S.A.) also installed a climate station in the Victoria Valley in 1999. Soil climate stations at Mt. Fleming (2002), Minna Bluff (2003) and Granite Harbour (2003) have been subsequently added to the Antarctic soil climate station network (Balks *et al.*, 2003). The soil climate stations were installed and are managed as part of a network involving soil climate stations from Alaska and Tibet contributing data to the CALM (Circum-polar Active-layer monitoring) programme (Balks *et al.*, 2003).

4.2.3.1 Coastal Sites

Of the seven soil climate monitoring stations, four are located at coastal sites: Scott Base, Marble Point, Granite Harbour and Minna Bluff (Figure 4.7). The sites provide an approximate north-south transect, with Granite Harbour being the furtherest north, while Minna Bluff is the furtherest south. The parent materials, and hence soils of the four sites differ, with the Scott Base soil being classified as a Hypergelic Typic Anhyorthel, of basaltic origin, while Marble Point is classified as a Hypergelic Calcic Anhyorthel, with marble, gneiss and granite glacial till parent materials (Appendix 1 provides soil profile and site descriptions). Minna Bluff and Granite Harbour are both classified as Typic Anhyorthels[1] (Balks *et al.*, 2003).

4.2.3.2 Inland Sites

The remaining three soil climate station sites, Wright Valley, Mt. Fleming and Victoria Valley (Figure 4.7), are situated inland in the colder, drier parts of the Ross Sea region, providing a contrast to the coastal sites. As with the coastal sites, the three inland sites differ in terms of their site characteristics. Mt. Fleming is the furtherest inland of the three sites, and is also at the highest altitude (1 698 m), while Wright Valley and Victoria Valley are of similar distance inland, however, Victoria Valley is at a higher altitude (411 m) than Wright Valley (152 m). The parent material of the Mt. Fleming soil is predominantly granite with some marble and sandstone; Bull Pass soils are formed from diorite, granite and till; and Victoria Valley soils are derived from dolerite, sandstone, granite and glacial till. The key difference between the three sites is altitude and surface age, whereby the Mt. Fleming surface is much older than the other two. All three soils are classified as Nitric Anhyorthels[2] (Balks *et al.*, 2003). Soil profile and site descriptions in Appendix 1.

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[1] Provisional classification – made prior to chemical analysis.

[2] Mt Fleming and Victoria Valley classification are provisional – made prior to chemical analysis.

4.3 Soil Physical and Chemical Properties

Each of the soil samples collected was analysed for electrical conductivity, pH, soil dry bulk density and gravimetric and volumetric moisture content (Table 4.3). Full results for each sample are in Appendix 2.

Table 4.3: Soil pH, electrical conductivity (EC), dry bulk density (ρ_b), gravimetric moisture content (θ_g) and volumetric moisture content (θ_v) for Scott Base, Scott Base HC, and Wright Valley/Bull Pass soils.

	pH	**EC** (μS cm^{-1})	ρ_b (g cm^{-3})	θ_g	θ_v[a]
Scott Base Soil [b]					
No. of Samples	41	41	40	41	41
Mean	8.1	695	1.8	7.0%	12.5%
Median	8.1	354	1.8	5.7%	10.1%
Maximum	9.4	3 660	2.4	22.6%	40.1%
Minimum	6.7	47	1.1	1.9%	3.5%
Range	2.7	3 613	1.3	20.6%	36.6%
Scott Base HC Soil [c]					
No. of Samples	20	20	20	20	20
Mean	7.9	542	1.7	4.2%	7.0%
Median	7.8	166	1.6	2.9%	4.9%
Maximum	8.8	3 745	2.2	9.1%	15.1%
Minimum	7.4	69	1.4	1.4%	2.3%
Range	1.4	3 677	0.9	7.7%	12.8%
Wright Valley / Bull Pass Soils [d]					
No. of Samples	39	39	30	39	39
Mean	6.8	6 469	1.7	2.2%	2.9%
Median	6.7	2 970	1.8	0.9%	1.8%
Maximum	7.4	39 205	2.3	11.3%	10.2%
Minimum	6.1	454	0.7	0.3%	0.4%
Range	1.4	38 751	1.7	11.0%	9.8%

[a] Calculated using average bulk densities for each sample site

[b] All samples were from 0-10 cm depth except for four samples which were >10 cm

[c] All samples were from 0-10 cm depths

[d] Samples at varying depths (<36 cm) from six sites (between 5 and 8 samples at each site)

4.3.1 Soil pH

Soil pH (Table 4.3) follows similar trends to those reported by Campbell and Claridge (1977), which suggest neutral to slightly acidic soil pH's (i.e. pH ≤ ~7) inland, which increase with increased marine influence, while regions with the highest marine influences have pH values of about 8. The inland Wright Valley/Bull Pass soils have a mean pH of 6.8, while the Scott Base soils, which are subject to a much greater marine influence had mean pH's of 8.1 and 7.9 for the Scott Base and Scott Base HC soils respectively. A larger range of soil pH's is found at Scott Base than in the Wright Valley / Bull Pass soils (Figure 4.8). In all cases the median is close to the mean value, to suggest a symmetrical distribution of the soil pH's.

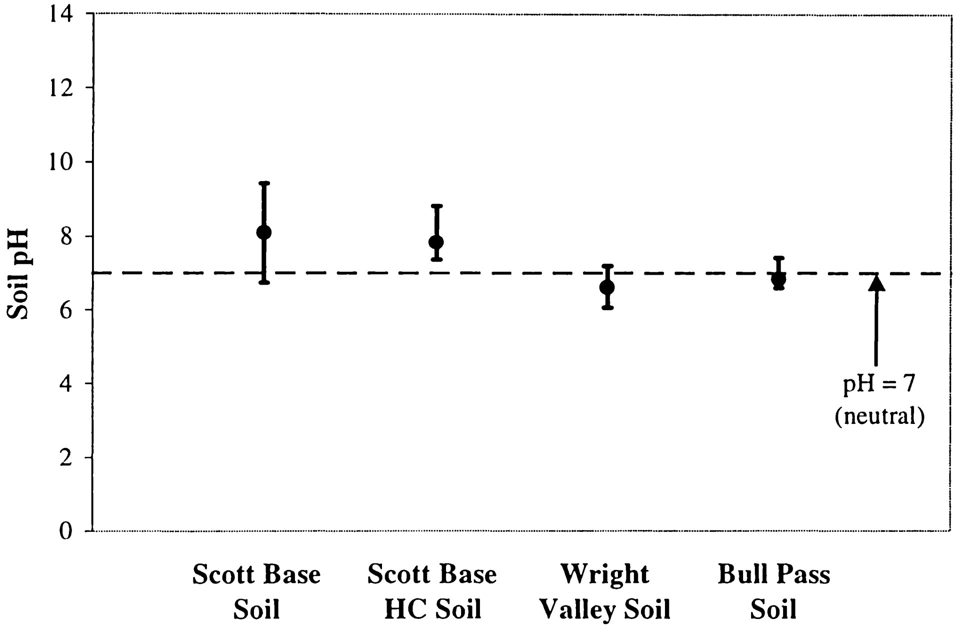

Figure 4.8: Soil pH ranges and median (•) value for Scott Base, Scott Base Oil and Wright Valley / Bull Pass soils (bars show maximum and minimum values).

4.3.2 Soil Electrical Conductivity

The electrical conductivity (mean) was up to ten times higher in the Wright Valley/Bull Pass soils, than the Scott Base soils (Table 4.3). Thicker salt horizons tend to accumulate in the arid inland regions when compared to the moister coastal regions of Antarctica, thus giving higher electrical conductivity values for inland soils (Campbell and Claridge, 1987).

At both Scott Base and Wright Valley/Bull Pass, the majority of the electrical conductivity measurements were at the lower end of their respective scales, with only a few larger measurements causing the mean to be higher than the median. This indicates a positive skew in the distribution of the soil electrical conductivities (Figure 4.9).

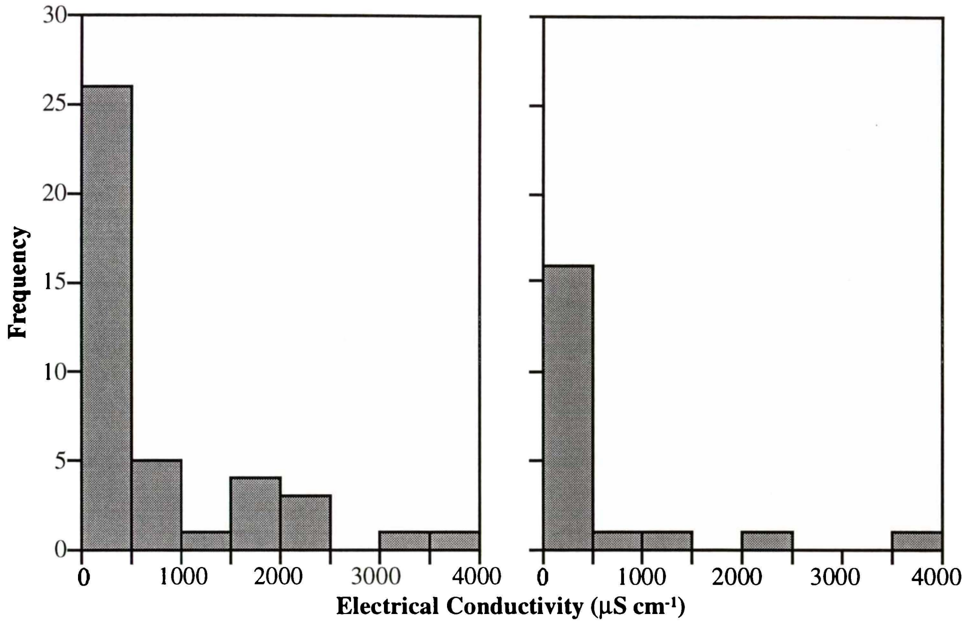

Figure 4.9: Distribution of electrical conductivity measurements for both Scott Base and Scott Base HC near surface soils.

Visible salts were present on many disturbed sites at Scott Base, and thus the relationship between the disturbed sites and the higher soil electrical conductivities was investigated using a hypothesis test (t-test). The t-test indicated that there was no significant difference ($p = 0.05$) between soil electrical conductivity for disturbed and non-disturbed sites at Scott Base.

A large range in electrical conductivities occurs in the Wright Valley/Bull Pass soils, which can be explained by several possibilities. One possibility is differences in micro-topography, whereby salts tend to accumulate in the depressions and low-lying areas (Tedrow and Ugolini, 1966). Another is soil texture, where salinity is greater where there is a higher fine fraction (Bockheim, 1982; Campbell, 2000). Decreasing salt contents with depth, and an increased salt content in the lowest horizons have also been noted (Campbell, 2000; Campbell *et al.*, 1998d). However, only two of the six sample sites (WV 3 and BP 1) had an increase in soil electrical conductivity with depth (Figure 4.10). At two sites (WV 2 and BP 3) the soil electrical conductivity decreased with depth, but in both cases the soils were relatively shallow (due to ice-cement at WV 2 and bedrock at BP 3).

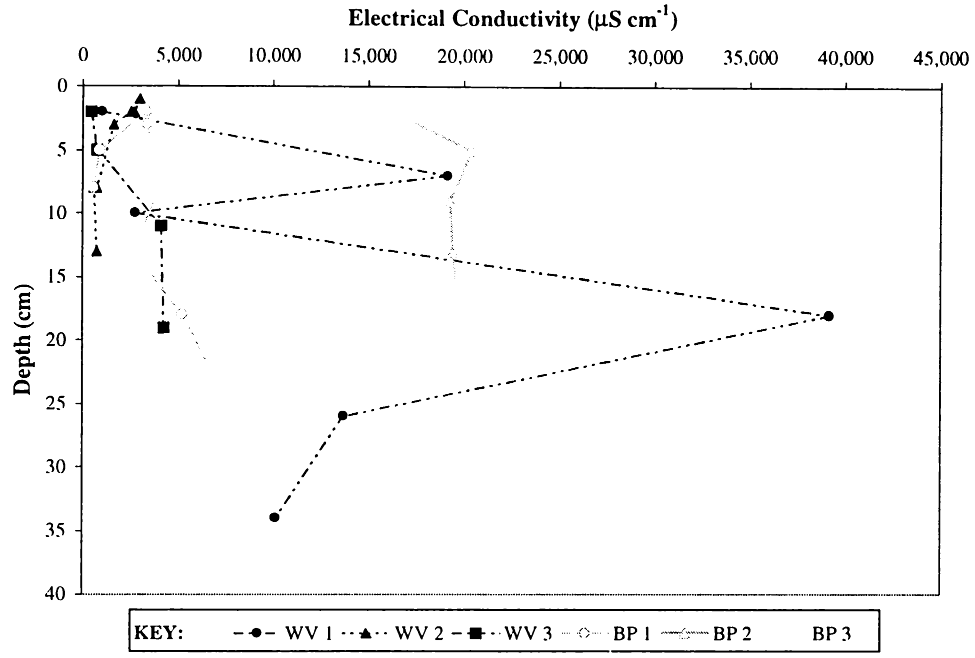

Figure 4.10: Electrical conductivity variations with depth in Wright Valley and Bull Pass soils.

4.3.3 Soil Dry Bulk Density (ρ_b)

A large range of soil dry bulk densities (Table 4.3) were determined for Scott Base soils (i.e. a range of 1.33 g cm^{-3} for the Scott Base soil and 0.86 g cm^{-3} for the Scott Base HC soil). One contributing factor to the range is the effect of large pebbles and rocks, which may have been contained in the sample. Large pebbles and rocks will increase the soil bulk density due to the high density of the (mostly) basalt material (i.e. density of basalt ranges from 2.7 to 3.1 g cm^{-3} (Murase and McBirney, 1973)). A second factor leading to the large range of soil dry bulk densities is the small sample size used. In order to minimise measurement error, the sand replacement technique requires larger samples (preferably about 0.5 m × 0.5 m × 0.2 m) than were taken (approximately 0.05 m × 0.05 m × 0.07 m). As a result, the average is a more useful indicator of the Scott Base soil dry bulk density. While the Wright Valley/Bull Pass soils also have a high range, partially due to the reasons mentioned above, the average bulk density isn't the best indicator of the region's overall soil dry bulk density. There is a great range in the soil dry bulk densities in the Wright Valley/Bull Pass region (Table 4.4). There were small patches of finer grained (i.e. higher silt content) soil with very low bulk density (ρ_b = 0.9 g cm^{-1}, BP 2) on Bull Pass. The three sites located on Bull Pass generally had lower soil dry bulk density than the three sites located in the Wright Valley.

Table 4.4: Soil dry bulk densities (ρ_b, g cm^{-3}) of the Wright Valley and Bull Pass sites.

	WV 1	**WV 2**	**WV 3**	**BP 1**	**BP 2**	**BP 3**
No. of Samples	6	6	4	6	5	3
Mean	1.6	2.1	2.0	1.7	0.9	1.6
Median	1.7	2.1	2.0	1.8	0.8	1.7
Maximum	1.9	2.3	2.3	1.8	1.3	1.8
Minimum	1.3	2.0	1.9	1.4	0.7	1.3
Range	0.5	0.4	0.3	0.5	0.6	0.5

4.3.4 Gravimetric (θ_g) and Volumetric (θ_v) Moisture Content

The lower moisture content for Wright Valley / Bull Pass soils, (θ_g (average) of 2.2%) compared to the two Scott Base soils (θ_g of 4.2% and 7.0% for the hydrocarbon contaminated and Scott Base soil respectively), was expected (Table 4.3). It is generally accepted that Scott Base soils are moister because they are in the moist coastal zone, while the Wright Valley/Bull Pass soils are drier due to being in the cold, dry inland zone. However, the differences may also be attributed to other factors, particular timing of sampling, as each sample was taken at just one point in time and not an annual average, and also with respect to snow melt, whereby moister soils are likely to occur where snow has recently melted away (providing a source of moisture).

The distribution of the soil moisture contents in all three soils is positively skewed, whereby the mean is larger than the median (Table 4.3). An example of this is the Scott Base soil, which has most measured gravimetric moisture contents between 0% and 15%, while having a few soils with high gravimetric moisture contents (>15%) (Figure 4.11). However, there were very few extremely dry soils recorded at Scott Base (gravimetric moisture content <2.5%).

Gravimetric moisture contents determined from the Scott Base HC soils may be affected by any hydrocarbons present in the soil. The hydrocarbons were evaporated during oven drying of the soil, and consequently be part of the calculated gravimetric moisture content.

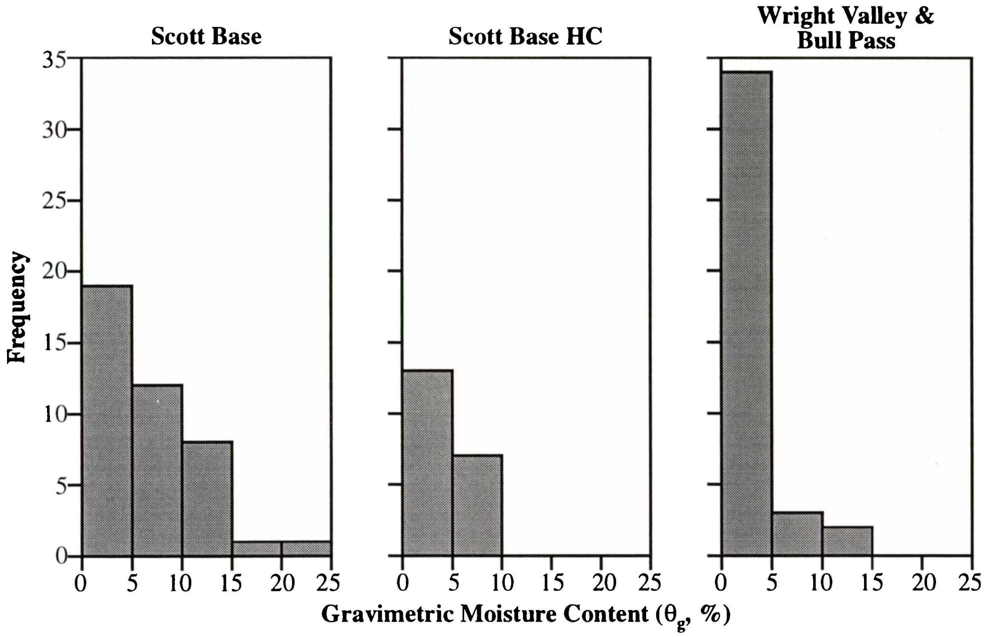

Figure 4.11: Gravimetric moisture contents measured in Scott Base and Wright Valley/Bull Pass soils.

The soil gravimetric moisture contents of the Bull Pass/Wright Valley area were generally low (<3%) throughout the depths sampled (Figure 4.12). The exception was at BP 3 where gravimetric moisture content ranged between 7-12%, possibly due to the finer texture, and hence greater water holding capacity of the soil.

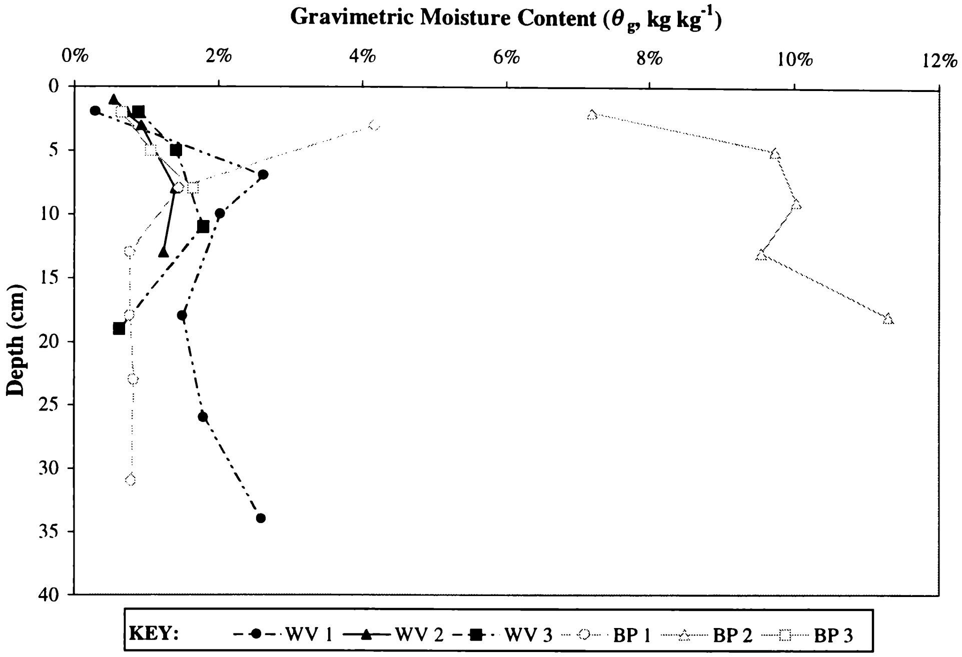

Figure 4.12: Gravimetric moisture content variations with depth for Wright Valley and Bull Pass soils.

4.3.5 Summary

Results obtained from analysis of the properties of soils collected from Scott Base and Wright Valley/Bull Pass region of Antarctica are consistent with those reported by other researchers. The Scott Base soils (including Scott Base HC soils) had higher pH's, and moisture contents, and lower electrical conductivities than the Wright Valley/Bull Pass soils. The mean soil dry bulk densities were similar for both areas, however the Wright Valley/Bull Pass soil dry bulk densities were more variable, where the light silty soil had a lower soil dry bulk density than the coarser textured soils.

The soil property data collected from Scott Base was used for calibrating the TDR probes in Antarctic soils. Of particular importance are the gravimetric moisture contents and soil dry bulk densities of the soils, as this allows volumetric moisture content to be calculated and compared directly to the TDR volumetric moisture contents.

Chapter 5 – Verification of TDR (Hydra) Probes

5.1 Introduction

In determining the volumetric moisture content, the TDR (Hydra) probes that are being utilised in this study have a manufacturers specified accuracy of ±0.03 water fraction by volume (Stevens Water Monitoring Systems Inc., 2003). However, they haven't been calibrated for the somewhat extreme soil and environmental conditions of the soils found in the Ross Sea region of Antarctica. Verification of the TDR soil moisture probes was undertaken under both laboratory and field conditions. A series of laboratory experiments were undertaken to isolate and investigate the effects of temperature, grain size distribution, sample size, and soil salinity. In the field the soil moisture content was measured using TDR probes, then using traditional gravimetric techniques to generate a comparison.

5.2 Laboratory Verification Experiments

The laboratory experiments varied parameters that may influence the operation of the TDR probes in Antarctic soils. In order to simulate Antarctic soils, samples were created using oven-dry beach sand to begin with a gravimetric moisture content of 0%, allowing the moisture content to be altered to the desired level. Prior to the verification experiments, the homogeneity of the moisture content of the sand samples following alteration to the desired moisture content was investigated. The six parameters tested were; sample size, differences between probes, temperature, texture, salinity, and influence of hydrocarbons. The experiments and results are described in the following sections, with summaries of the experimental results included in Appendices 2 (field results) and 3 (laboratory results).

In all experiments, measurement errors must be considered. The measurement errors (section 3.4) for the gravimetric moisture content determination were small (0.02%), while the measurement errors on the bulk density, and consequently the gravimetrically determined volumetric moisture content were larger (approximately 5%). All data collected in the laboratory experiments were an average of five replicates (unless otherwise stated), with the statistical variability being very small and consequently not included on the figures as error bars (standard deviations and are in Appendix 3 with the raw data). When the statistical variability was larger, error bars were included on the scatter plots.

5.2.1 Experiment 1 – Homogeneity of Mixing

In order to investigate the impacts of variables on the TDR probes, the samples needed to have a uniform moisture content. Experiment 1 was undertaken to determine the homogeneity of moisture content in sand samples that had distilled water added.

5.2.1.1 Method

1. Distilled water and sand (oven-dry) were mixed together by putting 3 kg of sand into a bucket, with a volume of distilled water, and mixed with a trowel for approximately 2 minutes (or until visually uniform);
2. Ten sub-samples were taken, and the gravimetric moisture content was determined (following the method outlined in section 3.3.1);
3. Steps 1 and 2 were repeated at four different moisture contents.

5.2.1.2 Results

Table 5.1: Gravimetric moisture contents (%) to determine sample moisture content homogeneity

	Mix A	Mix B	Mix C	Mix D
Number of Samples	10	10	10	10
Mean	3.5%	5.6%	8.0%	10.3%
Standard Deviation	0.3%	0.1%	0.1%	0.1%
Median	3.5%	5.7%	8.0%	10.1%
Maximum	3.8%	5.8%	8.1%	12.0%
Minimum	2.8%	5.4%	7.8%	9.8%
Range	1.0%	0.3%	0.3%	2.2%

Mixes A, B and C had gravimetric moisture contents (θ_g) within a range of 1% (Table 5.1), while Mix D was affected by an outlier. In all cases the mean and median are much the same suggesting that there is a normal distribution of the data. Since the gravimetric moisture contents measured fall mostly within 1% of each other, it was concluded that the sand and distilled water can be mixed to within ±0.9% (3 standard deviations) of the mean for a moisture content of 3.5%, and ±0.3% at higher gravimetric moisture contents up to 10%. The method of mixing described above provides an adequate way to mix samples homogeneously, and was employed in subsequent laboratory experiments.

5.2.2 Experiment 2 – Effect of Sample Size

This experiment was undertaken to determine whether the size of the sample affects the volumetric moisture content measurement of the TDR probe. Dirksen (1999) suggests that when calibrating TDR probes, the sample size needs to be twice the probe width and once the probe length in order to give accurate results. However, the Hydra Probe Users Manual (Vitel Inc., 1994) suggests the sensing area to be that between the tines. The Hydra Probe User Manual also suggests that results may be affected if steel sample containers are used for measurement (Vitel Inc., 1994). PVC piping was used as the sample container, with a cap sealed onto the bottom of the pipe. A cap was also placed on top of the sample, which had another piece of PVC pipe, with a diameter wide enough for the TDR probes to fit in snugly, glued on top (Figure 5.1). This ensured smooth probe insertion into the sample. Pipes of varying diameter were used to provide different sized sample containers.

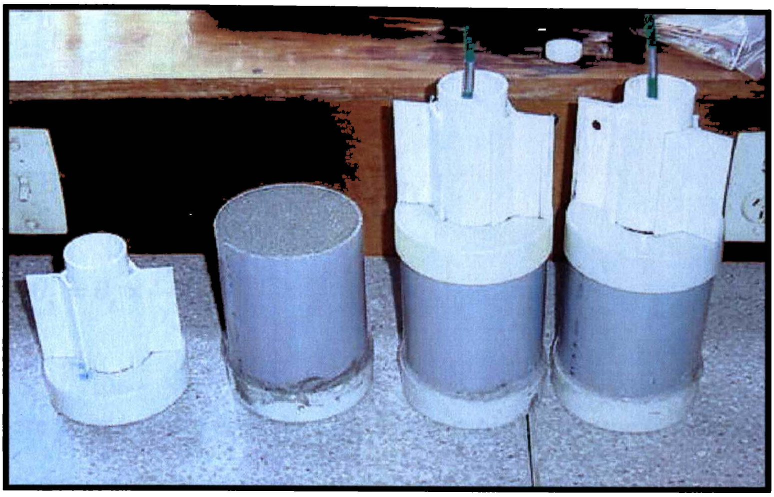

Figure 5.1: TDR probes placed into sample containers for recording soil moisture contents in the laboratory.

5.2.2.1 Method

1. The sample container (m_{cont}) was weighted. The sample container consisted of a piece of PVC pipe (X cm high (L_{cont}), and X cm in diameter (d_{cont})) with a cap glued to the base of the pipe to seal and waterproof the base;
2. Distilled water was added to sand to achieve the desired moisture content using the method outlined in section 5.2.1;
3. The sample container was packed using a standard re-packing technique (Dirksen, 1999), whereby 2 cm of sand was added, and then compacted using a standard weight (~700 g) dropped (once) from a height of approximately 15-20 cm. The surface was then roughened up by scraping the top using a spatula before adding the next layer;
4. The surplus sand was cleaned off the sample surface and the container, and the sample and container re-weighed ($m_{\text{sample + cont.}}$);
5. The TDR probe was inserted, and a smooth contact between the probe and the sand surface was ensured;
6. Five measurements using the TDR probe were made;

7. Five sub-samples were taken throughout the sample to measure gravimetric moisture content;
8. The volumetric moisture content was determined using Equation 5.2:

$$\rho_b = \frac{(m_{\text{sample+cont.}} - m_{\text{cont}}) \times MF}{\pi \left(\frac{d_{\text{cont}}}{2} \right)^2 \times L_{\text{cont}}} \qquad \textbf{5.1}$$

NOTE: L_{cont} is also depth of sample

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w} \qquad \textbf{5.2}$$

where ρ_b = soil dry bulk density; MF = moisture factor (section 3.3.3); and ρ_w = density of water (assumed to be 1.0 g cm^{-3}).

9. Steps 1-8 were repeated on larger sized sample containers, and at different moisture contents.

5.2.2.2 Results

Three sample sizes were used: small (4.3 cm diameter, volume of ~190 cm^3), medium (10.5 cm diameter, volume of ~1800 cm^3), and large (15.3 cm diameter, volume of ~3800 cm^3). The smallest sample container had a diameter that was wide enough to fit only the TDR probe in, while the other two were approximately two and three times the width of the TDR probe. All three samples were at least twice as long as the TDR probes. The sample sizes were chosen in order to satisfy the sample size requirements suggested by Dirksen (1999) and the Hydra Probe Users Manual (Vitel Inc., 1994).

For each of the three sample sizes, the TDR volumetric moisture content and the gravimetrically determined volumetric moisture content were measured at four moisture contents (Figure 5.2).

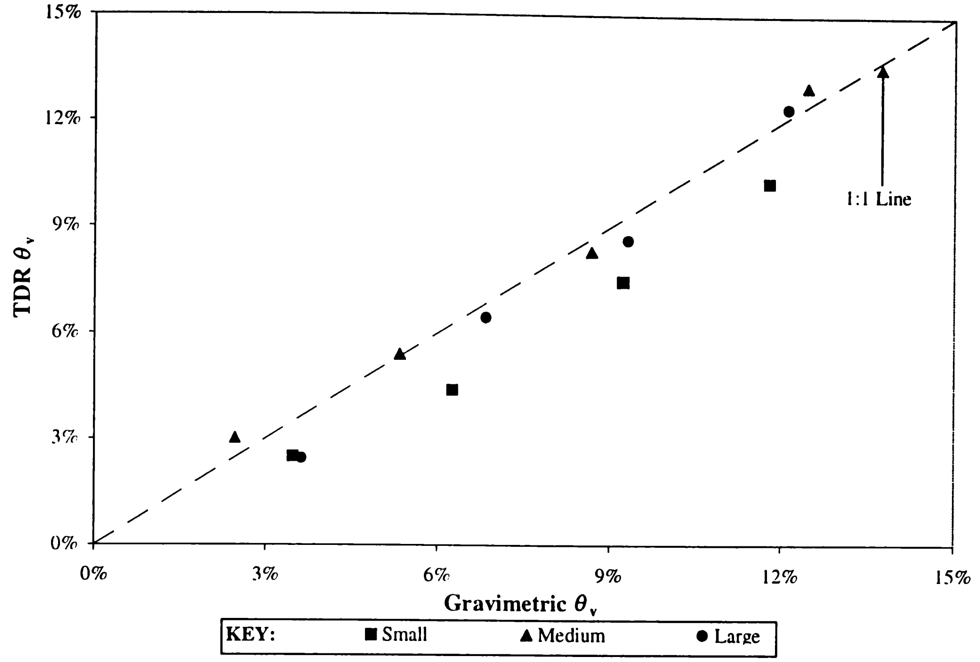

Figure 5.2: Effect of sample size on TDR probe accuracy.

Both the medium and large sample sizes had a near 1:1 relationship between volumetric moisture content determined using the TDR (TDR θ_v) and calculated from gravimetric moisture content and dry bulk density (gravimetric θ_v). For the small sample size, the TDR probes tended to underestimate the gravimetrical θ_v by an average of 1.5% (standard deviation of 0.4%), over the volumetric moisture content range of 0-13%. Since underestimation occurred in neither of the two larger sample sizes, the lower measurement may be a function of the constricting sample size.

5.2.2.3 Discussion

Investigation of the effect of sample size showed that when the sample size used was of approximately the same diameter as that of the probe the resultant outputs were slightly underestimating the volumetric moisture content determined gravimetrically. When two larger sample sizes were considered (two and three times the diameter of the probe) the TDR probe accurately determined the volumetric moisture content. The underestimate observed in the small sample size was approximately 1%, and when the manufacturer's specified error (±3%) is considered, the results are within the acceptable range. As a result, it is suggested that the size of the sample used when determining the volumetric moisture content using the Hydra probes is of little concern. However, for all subsequent experiments a sample size of twice the diameter of the TDR probe was used to ensure sample size was not influencing the results.

5.2.3 Experiment 3 – Consistency of Results between Different Hydra Probes

In order to confidently compare results obtained from different TDR Hydra probes, consistency between the probes needs to be shown. To show the consistency of the probes, both TDR θ_v and gravimetric θ_v were determined for each TDR probe at seven moisture contents.

5.2.3.1 Method

1. Steps 1–8 of experiment 2 (section 5.2.2) were followed for three separate probes (using a sample container of 10.5 cm in diameter);
2. Step 1 was repeated at seven different moisture contents (moisture contents weren't the same for each probe).

5.2.3.2 Results

When the TDR θ_v and gravimetric θ_v determined volumetric moisture contents of three TDR probes were compared (Figure 5.3), differences were observed between the probes.

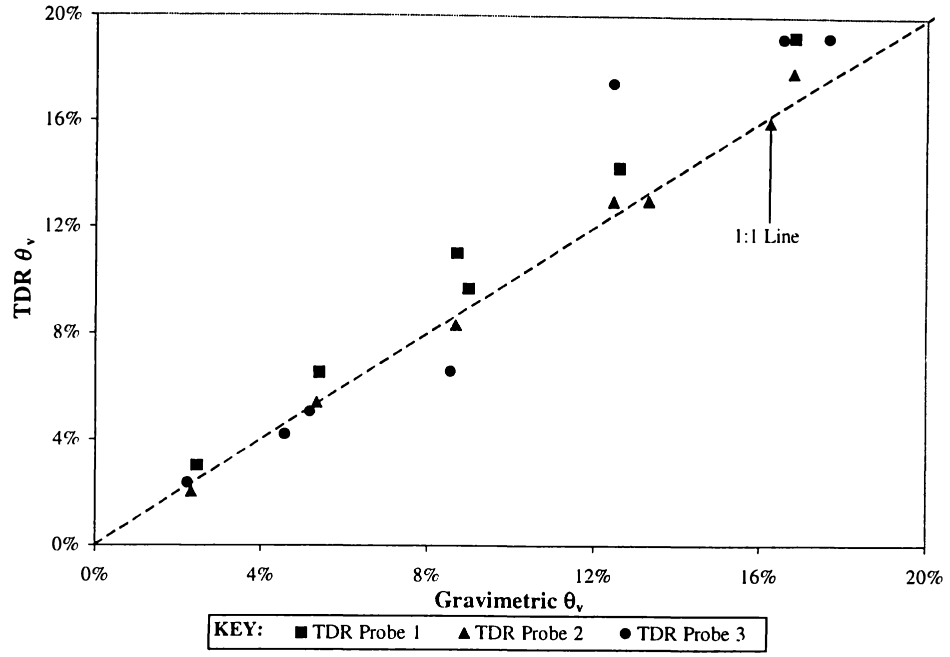

Figure 5.3: Differences between TDR probes.

A linear model simultaneously fitted three straight lines to the data for the three TDR probes, with the lines forced through the origin (i.e. no intercept). The lines were forced through the origin, because neither the TDR probe nor the gravimetric method records any moisture content when the sand is completely dry. The slopes of the fitted lines (Table 5.2) were then compared to the ideal – a 1:1 line between the two moisture content determination methods.

Table 5.2: Slopes, their standard error and 95% confidence intervals for each of the three TDR probes.

	Slope	**Standard Error**	**95% Confidence Interval**
TDR Probe 1	1.15	0.05	1.04-1.26
TDR Probe 2	1.02	0.05	0.92-1.12
TDR Probe 3	1.13	0.04	1.04-1.22

Three t-tests ($p = 0.05$) were undertaken on the slopes calculated for the three TDR probes. TDR probes 1 and 3 were significantly different from a slope of 1:1, while TDR probe 2 two was not, over the volumetric moisture content range of 0-20%.

When the actual difference between the gravimetric θ_v and the TDR θ_v (Figure 5.4) were considered, all except one of the data points plotted was within ±2.5% of the 1:1 line (difference = 0). Two of the TDR probes (probes 2 and 3) showed an even number of data points above and below the 1:1 line, while probe 1 consistently underestimated θ_v compared to gravimetric θ_v. The 5% underestimate of one of the data points for probe 3 suggests that this may have had a large influence on the determined slope for the relationship between the two methods for determining moisture content.

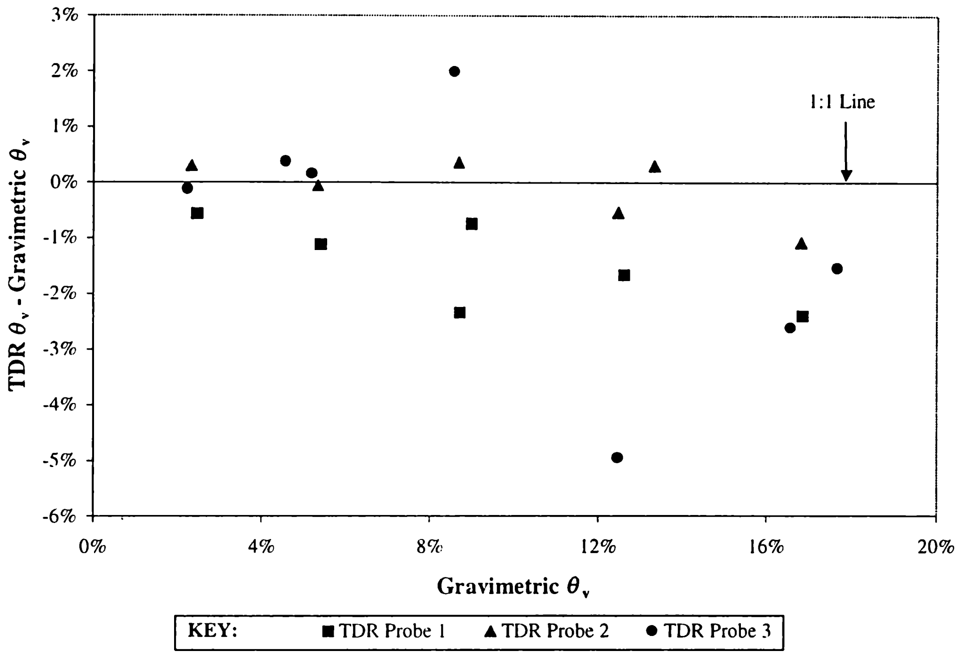

Figure 5.4: Differences between the TDR and gravimetric θ_v values.

5.2.3.3 Discussion

The three TDR probes used in this verification experiment suggest that there is a statistically significant ($p<0.05$) difference between individual TDR probes. The differences between the TDR recorded θ_v and the gravimetric θ_v, however, still remained within the specified manufacturers error of ±3% for each of the individual plots with the exception of one data point (Figure 5.4). Consequently, while there may be some statistically significant differences between individual

TDR probes, the differences were generally within the published error for the Hydra probes.

5.2.4 Experiment 4 – Accuracy of Hydra Probes at Different Temperatures

This experiment had two objectives. The first objective was to determine the behaviour of the TDR probes during freezing of soils. Four samples were made up to volumetric moisture contents ranging from 2.5-10%, and placed into a freezer. The TDR probes monitored the volumetric moisture content before, during and after freezing. Because the dielectric constant of ice is near that of soil minerals, (i.e. $\varepsilon_{\text{ice}} = 3.2$, $\varepsilon_{\text{soil minerals}} = 3\text{-}5$), it is expected that the TDR probe θ_v will provide a measure of the unfrozen water content. The freezer used had a temperature of approximately -12°C, thus still within the operating specifications of the TDR probes, while being cold enough to freeze the water in the samples.

The second objective of this experiment was to investigate whether the volumetric moisture content determined by the TDR probe is a function of the soil temperature. When soils freeze, the TDR probes are noted to record decreasing volumetric moisture contents as the temperature decreases, even in the above zero range. In order to verify whether the TDR volumetric moisture content was influenced by temperature, four samples were placed in a refrigerator, where the temperature of the soils decreased to approximately 4°C. If the volumetric moisture content measured is independent of the soil temperature, then the determined moisture contents would be expected to remain constant for the duration of the cooling in the refrigerator, and subsequent warming as the soil water is still in the liquid phase.

5.2.4.1 Method

1. Four sand and distilled water samples were prepared at different moisture contents;

2. The gravimetric moisture content and dry bulk density for each sample were measured as for experiment 2 (section 5.2.2.1). TDR probes were inserted into the cores and the moisture content was recorded every 5 minutes;
3. The samples were left at room temperature to equilibrate for a period of at least 48 hours;
4. The samples were then placed into the freezer (or refrigerator) and left for at least 48 hours;
5. The samples were removed from the freezer (or refrigerator) and allowed to thaw and equilibrate at room temperature (for at least 48 hours);
6. The gravimetric moisture content and dry bulk density were determined following removal of the TDR probes from the samples.

5.2.4.2 Results

5.2.4.2.1 Sub-zero Temperatures

Initially the four soil cores were left at room temperature (approximately 14°C with a diurnal temperature variation of less than 2°C) to equilibrate for 2 days with the volumetric soil moisture content being monitored by the TDR probes. During the 2-day period the volumetric moisture content (as measured by TDR) remained mostly constant, although with a fluctuation of about ±1% (Figure 5.5). At day 2, the four soil cores were placed in the freezer where the TDR volumetric moisture content reading dropped to a moisture content of 0%. Between days 2 and 4, the volumetric moisture content rose slightly, with this attributed to the freezer door not being completely sealed. As a result, the freezer (and subsequently the samples) warmed to approximately 0°C, and consequently, the ice in the samples began to melt leading to the increased TDR volumetric moisture content. At day 4 the freezer door was effectively sealed and liquid moisture content recorded by the TDR probes remained at 0%. The four soil cores were removed from the freezer on day 6 and the cores were then left to thaw and re-equilibrate to room temperature once again. In some cases, the moisture content following removal from the freezer was higher than initially (Table 5.3), which can be attributed to moisture from condensation (while the door was not completely sealed).

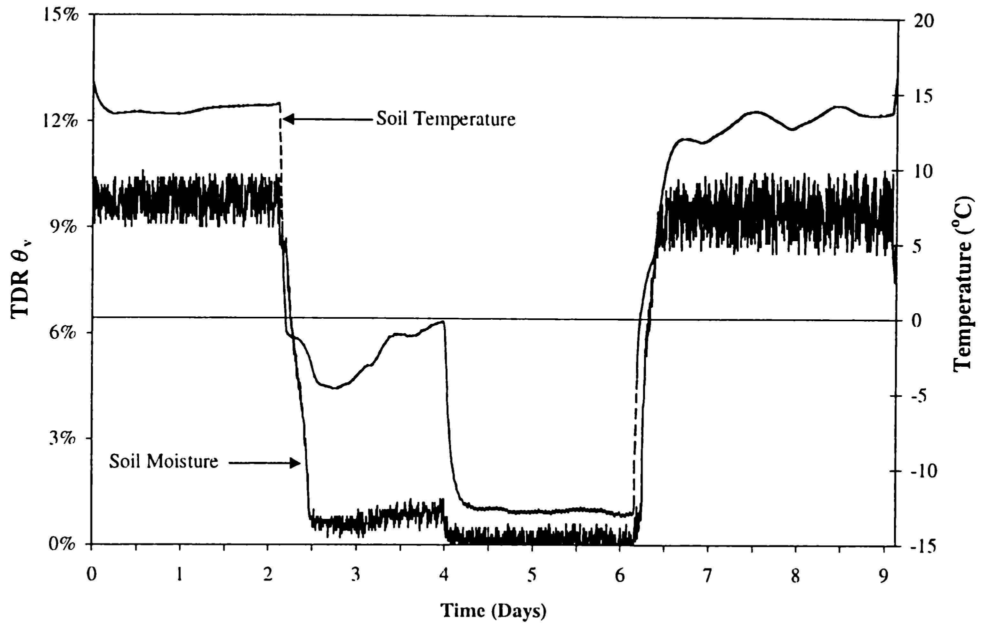

Figure 5.5: Soil moisture and temperatures for soil core 4 before, during and after freezing.

Table 5.3: Means, and standard deviations of θ_v before, during and after freezing events for the four soil cores.

	Before		**During**		**After**	
Probe	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Probe 1	6.6%	0.8%	0.0%	0.0%	11.6%	0.7%
Probe 2	5.3%	1.0%	0.2%	0.1%	8.4%	0.4%
Probe 3	3.2%	0.5%	0.1%	0.1%	5.2%	0.4%
Probe 4	9.8%	0.4%	0.2%	0.2%	9.5%	0.6%

In all cases, there is noise in the TDR moisture content results when the probes remain at a constant temperature and moisture content. This noise is approximately ±1-2%, and is evident even when the liquid moisture content is recorded as 0%. This experiment confirms that when the soil becomes frozen, the TDR probes determine only the liquid moisture content of the soils.

5.2.4.2.2 Volumetric Moisture Content Dependence on Soil Temperature

Four soil cores were left to equilibrate at room temperature (mean 17°C, with a diurnal variation of approximately 5°C) for 4 days, with the volumetric moisture content being monitored by the TDR probes. On day 4, the four soil cores were placed into the refrigerator, where a small decrease in volumetric moisture content (average 1% for 4 cores) was recorded by the TDR probes following cooling from 17°C to approximately 4°C (Figure 5.6). At day 7, the 4 soil cores were removed from the refrigerator, with the TDR recorded volumetric moisture contents increasing (by an average of 0.8% for 4 cores) as the soils warmed. Both before and following cooling, the TDR probes recorded a slight decrease in the volumetric moisture content over time, which may be attributed to evaporation of moisture from the samples. The soil core monitored by TDR probe 4 (Figure 5.6) provides an example of the volumetric moisture content variability as the soil temperature warmed and cooled. The four samples had volumetric moisture contents ranging between 2 and 8% (Table 5.4), with the gravimetric moisture contents measured before and after the experimental period. For all four soil cores, the gravimetric moisture contents before and after were with 0.3% indicating that the soil cores remained at a near constant soil moisture content over the measurement period.

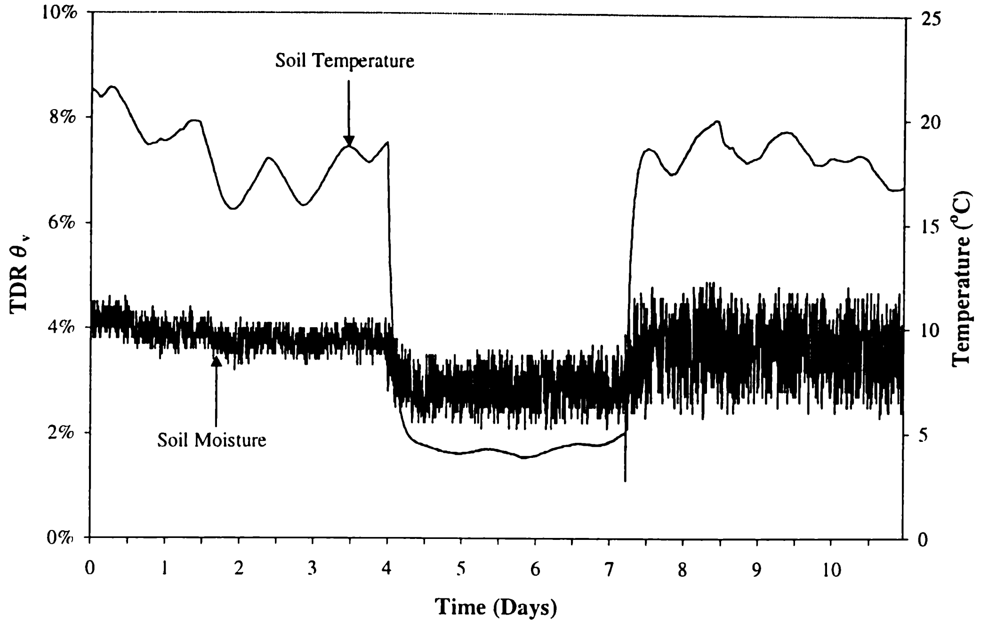

Figure 5.6: Soil moisture and temperatures for soil core 4 before, during and after cooling from 17°C to 4°C.

Table 5.4: Means, and standard deviations of θ_v before, during and after cooling events for the four soil cores.

	Before		**During**		**After**	
Probe	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Probe 1	2.3%	0.6%	1.3%	0.4%	2.0%	1.1%
Probe 2	5.1%	0.4%	4.1%	0.5%	5.1%	0.6%
Probe 3	7.2%	0.4%	6.0%	0.2%	6.7%	0.3%
Probe 4	3.8%	0.2%	2.9%	0.4%	3.7%	0.6%

Once again noise in the volumetric moisture content signal is evident in all samples. The results show that there is a small dependency of soil moisture content determined by the TDR probes on soil temperature at temperatures >0°C. This relationship is a drop in the θ_v as recorded by the TDR probe of approximately 1% over the temperature change from approximately 17°C to 4°C.

The same data set was analysed for moisture content changes occurring with diurnal temperature changes of a magnitude of approximately 4°C for a 4-day period. The soil moisture and soil temperature data recorded by the TDR probes were analysed involved using a 'loess' smoother (see section 3.5 for an explanation of the 'loess' smoother) and fitting a smooth trend curve through the soil moisture data. This eliminated a lot of the noise, and allowed the relationship to be identified between the two variables. The 'loess' smoother was applied to the soil moisture data recorded by the TDR probe from day 1 to day 4, giving almost four days of data. When the 'loess' smoothed moisture data and the soil temperature data are compared, a relationship was observed (Figure 5.7). Even with soil temperature changes of up to 4°C there was a soil temperature influence on the TDR reported soil moisture. The magnitude of the change in soil moisture content over the approximately 4°C temperature change was about 0.2-0.3%.

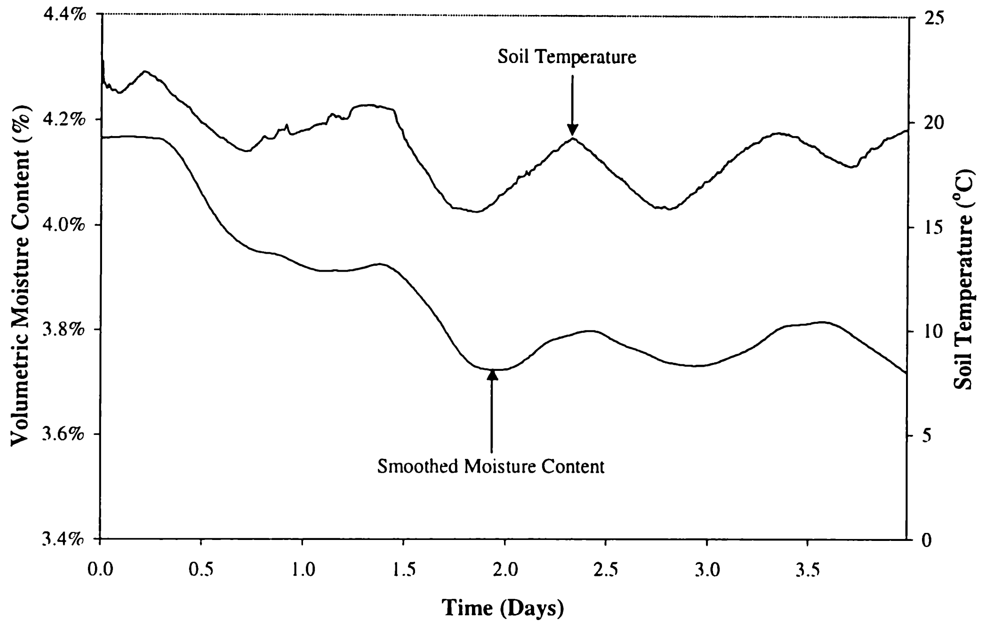

Figure 5.7: 'Loess' smoothed moisture content and air temperatures for a 4-day period.

5.2.4.3 Discussion

Soils in Antarctica are often at a temperatures below freezing, and consequently the soil moisture is often in the form of ice. With the principal of TDR measuring the volumetric moisture content using the dielectric constant, theory suggests that when the soil moisture is in the form of ice, the TDR probes will not measure it. By placing four soil cores in a freezer following equilibration at room temperature, this theory was confirmed, as the volumetric moisture content recorded was 0%. Previous literature (e.g. Patterson and Smith, 1981; Jones *et al.*, 2002) concluded similar findings, although suggesting that the salt content of the soils also affects the freezing point, and consequently the temperature to which the soil water remains liquid and can be detected.

It was hypothesised, as a result of observation of existing data that the TDR probe soil moisture content reading was influenced by soil temperature. In order to confirm this hypothesis, four soil cores were placed in a refrigerator, where they were cooled to approximately 4°C. As the soil cooled, the TDR reported volumetric moisture content also decreased, with the decrease being approximately 1% over the moisture content range 2.5-10%, while the gravimetric soil moisture content of the soil cores remained almost constant over the measurement period. A dependency of soil moisture content on soil temperature was also shown over diurnal soil temperature changes of approximately 4°C. The soil moisture content recorded by the TDR probes was influenced by the soil temperature (at above freezing levels), with larger temperature changes having a larger effect on the soil moisture content variations. Over the temperature range of 4-17°C the variability in soil moisture content was about ±1%. Soil moisture content dependency on soil temperature has been investigated by other researchers who have found that:

- TDR probe θ_v readings of soils that have a moisture content <20% are affected (Yu *et al.*, 1999);
- over a 40°C temperature change the soil moisture content differed by up to 3% (Yu *et al.*, 1999); and
- soil moisture content dependency on soil temperature was more pronounced in soils containing free water (Pepin *et al.*, 1995).

The ±1% moisture content change over the 4-17°C temperature range agrees with the findings of other authors.

5.2.5 Experiment 5 – Effect of Soil Texture on the Measurement of θ_v Using Hydra (TDR) Probes

The TDR probes require a soil texture descriptor (sand, silt, or clay) which best describes the texture of the soil being analysed in order to calculate the volumetric moisture content from the voltage outputs of the probes. A soil texture descriptor of sand was used for Antarctic soils, however, the soils are often coarser than sand, and thus the accuracy of the TDR probes in gravelly soils needs to be considered.

The effects of soil texture were tested by creating mixtures of sand and gravel sized particles in varying proportions. The samples were then made up to varying moisture contents, with the volumetric moisture contents determined using the TDR probes and also gravimetrically.

5.2.5.1 Method

1. 375 g of gravel was mixed with 2 625 g of sand (12.5% gravel by weight) into a homogeneous mix;
2. Steps 1–8 were followed as for Experiment 2[3] (section 5.2.2.1);
3. Steps 1 and 2 were repeated at five different moisture contents using the same texture;
4. Steps 1-3 were repeated for 25% gravel (by weight), 37.5% gravel, and 0% gravel (i.e. sand).

5.2.5.2 Results

TDR probes tended to underestimate the gravimetrically determined volumetric moisture content in the presence of gravel (Figure 5.8, Table 5.5). The sand plot had a near 1:1 relationship between the TDR θ_v and the gravimetric θ_v. The increase to 12.5% gravel caused the TDR probes to underestimate the gravimetric θ_v by approximately 1%, while each successive increase in gravel content caused a progressively larger underestimate. The increasing underestimate of the

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[3] When gravimetric moisture content was determined, a 25 g sub-sample was used instead of a 10 g sub-sample, as the gravel was included in the determination.

volumetric moisture content suggested that the TDR probes are sensitive to the texture of the soil.

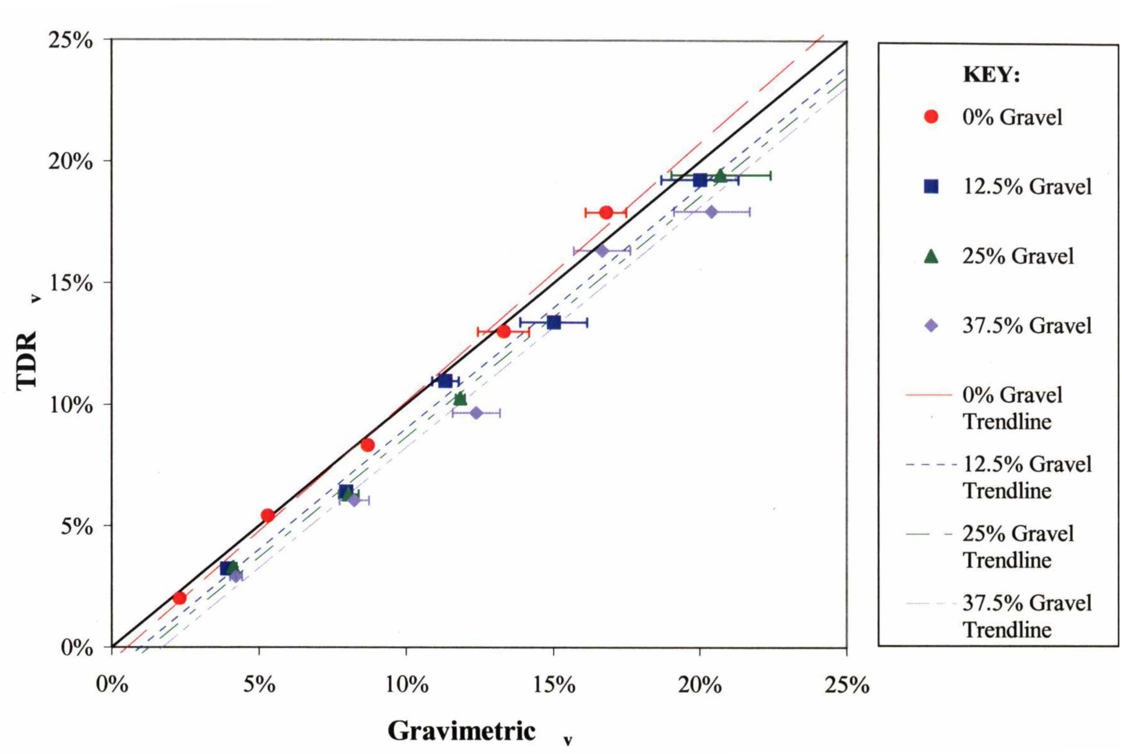

Figure 5.8: Effect of soil texture on TDR probes. Linear regression analyses are presented in Table 5.5.

Table 5.5: Linear regression analysis for Figure 5.8.

	Equation	**r^2 value**
0% Gravel	y = 1.0654x – 0.57	0.99
12.5% Gravel	y = 0.9964x – 0.96	0.99
25% Gravel	y = 0.9899x – 1.24	0.99
37.5% Gravel	y = 0.9913x – 1.69	0.98

5.2.5.3 Discussion

Antarctic soils are generally coarse textured, and often contain gravel ranging from 0% through to almost 100% by weight. The TDR probe calibration takes texture into account when converting the voltage outputs to volumetric moisture contents, however the three options available are sand, silt and clay, of which none adequately describe the texture of Antarctic soils. Since sand is the coarsest texture descriptor given, this was used in the calculations.

There was increased variation in the data points as the gravel content increased. This can be attributed to several possibilities, including natural scatter of the TDR probes and spatial variations in the gravimetric moisture content of the sample (due to the gravel, as homogeneity of the moisture content was more difficult to achieve than in just sand). When the volumetric moisture content of a soil is monitored in the field over time, the soil texture does not change, therefore the TDR probes will record all of the relative changes in soil moisture. While not precisely determining the volumetric moisture contents, relative changes will be recorded, which in the case of Antarctic soils are possibly more important because soil-moistening events can be identified. It can be concluded that texture (in the case where the soils are coarser than sand) does have an influence on the measured volumetric moisture content with variability of up to about ±2%.

TDR theory suggests that the finer the soil texture, the more bound water there will be in the soil, and because the dielectric constant of bound water ($\varepsilon_{bw} \approx 3$) is similar to that of soil minerals (Roth *et al.*, 1980), a fine textured soil would underestimate the volumetric moisture content (Ponizovsky *et al.*, 1999; Dirksen and Dasberg, 1993). The findings in this experiment using the Hydra (TDR) probes indicates that the coarser the soil texture the more the TDR probes underestimate the volumetric moisture content. The findings of the experimental results in this section, differs from TDR theory, which suggests that in coarse soils (such as Antarctic soils), the TDR θ_v recordings should, if anything, give an overestimate. The cause of the differing results between TDR theory and the experimental results may be due to the texture descriptor that aids in the conversion of the voltage outputs from the TDR probe to volumetric moisture contents. The coarsest texture descriptor associated with the conversion program is sand, however, many Antarctic soil have a coarser texture than sand.

5.2.6 Experiment 6 – Effect of Salts on Hydra Probe Soil Moisture Determination

The objective of this experiment was to determine the effect that electrical conductivity has on the accuracy of the TDR probes. One of the limitations of using TDR is high soil salinity, which causes attenuation of the TDR signal, and consequently an overestimation of the soil moisture content (Dalton *et al.*, 1984; Nadler *et al.*, 1999). The Hydra (TDR) probes are able to determine soil salinity up to 20 000 μS cm^{-1} (Stevens Water Monitoring Systems Inc., 2003). In order to determine whether soil salinity had an effect on the volumetric moisture content recorded by the TDR probes in Antarctic conditions, sand was mixed with water containing dissolved sodium chloride (NaCl) to concentrations of 1%, 2.5% and 5% by weight.

5.2.6.1 Method

1. Sand and distilled water containing 1% NaCl (10 g of NaCl salt in 1 L of distilled water) were mixed together;
2. Steps 1, 3–8 were followed as for experiment 2 (section 5.2.2.1);
3. Steps 1 and 2 were repeated for 2.5% and 5% NaCl solutions.

5.2.6.2 Results

The TDR probe overestimated the volumetric moisture content compared to the gravimetric θ_v in soils that had high soil solution electrical conductivities. The three water solutions, 1% NaCl, 2.5% NaCl, and 5% NaCl corresponded with electrical conductivities of 16 600 μS cm^{-1}, 36 000 μS cm^{-1}, and 61 000 μS cm^{-1} respectively. Only the 1% NaCl solution had a water electrical conductivity within the range (0-20 000 μS cm^{-1}) specified for accurate TDR operation by the manufacturers. However, the 1%, 2.5% and 5% NaCl solutions gave resulting soil electrical conductivities of 0-500 μS cm^{-1}, 400-1 400 μS cm^{-1}, and 400 to 2 000 μS cm^{-1} respectively, which are within the range found in Antarctic soils.

When the 1% NaCl salt solution was added to the sand, the TDR probes recorded higher volumetric moisture contents than were determined using the gravimetric technique. The difference between the TDR θ_v and gravimetric θ_v (Figure 5.9) was generally less than 5% for the 1% NaCl solution. For both the 2.5% NaCl and 5% NaCl solutions the TDR θ_v and was often up to 10% higher than the gravimetric θ_v. Most of the TDR θ_v values for the 2.5% and 5% NaCl solutions were within 10% of the gravimetric θ_v, however, there was one outlier for the 5% NaCl solution, and two differences of greater than 10% for the 2.5% NaCl solution (Figure 5.9).

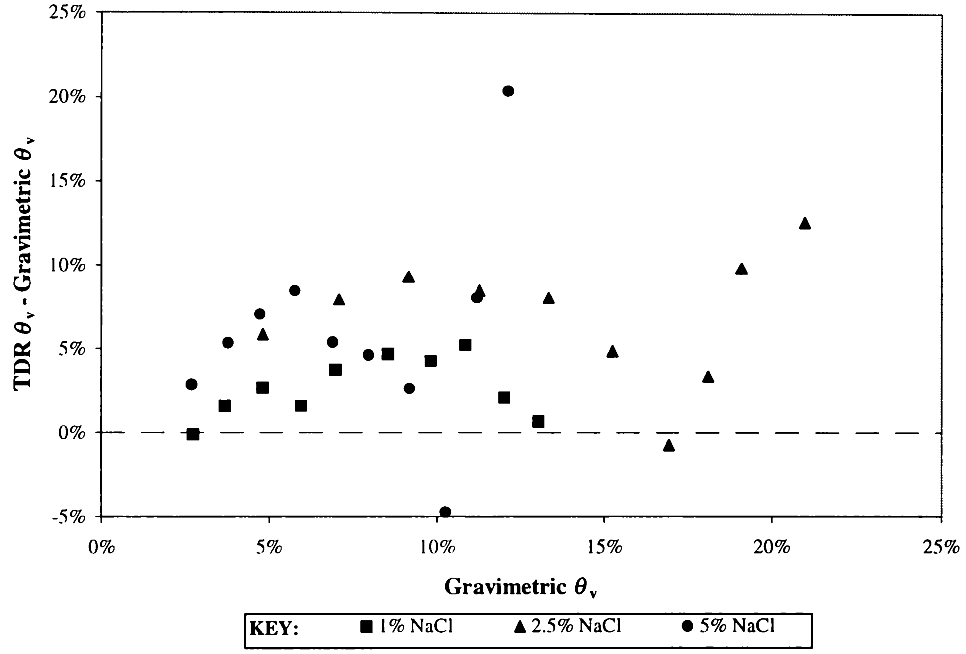

Figure 5.9: Difference between the TDR θ_v and gravimetric θ_v vs. gravimetric θ_v for sand and salt solution (1%, 2.5% and 5% NaCl) mixtures.

The soil electrical conductivities measured for the sand and salt solution mixtures were in the range of 0 to 2 000 µS cm^{-1} (Figure 5.10). For soil electrical conductivities <500 µS cm^{-1}, the overestimation by the TDR probes was generally <5%, while for soil electrical conductivities between 500 and 2 000 µS cm^{-1}, the overestimation was generally between 5 and 10%. The soil electrical conductivities were within the range (0–20 000 µS cm^{-1}) specified by the manufacturers for effective operation of the TDR probes, however, the TDR probes overestimated the volumetric moisture content of the sand and salt solution samples. The electrical conductivities of the salt solutions were higher than 20 000 μS cm^{-1}, and therefore it seems that the limit of accuracy of the TDR probes given by the manufacturers (0–20 000 μS cm^{-1}) refers to the electrical conductivity of the soil solution, not the electrical conductivity of the soil.

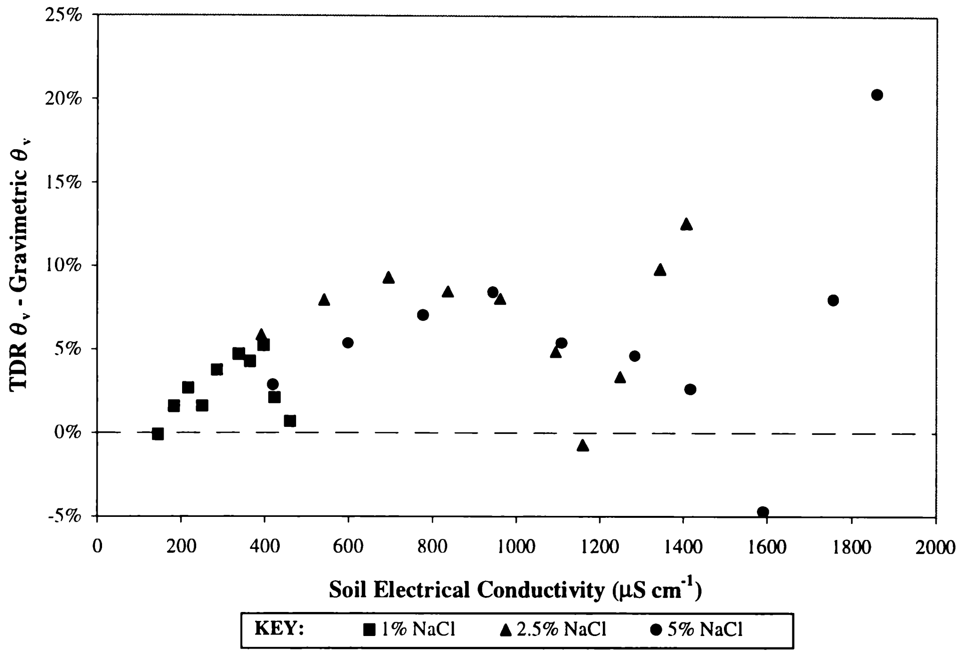

Figure 5.10: Laboratory measured soil electrical conductivities vs. the difference between the TDR θ_v and gravimetric θ_v measurements.

5.2.6.3 Discussion

Volumetric soil moisture contents measured by the TDR probes were influenced by the electrical conductivity of the soil solution. When the electrical conductivity of the soil solution was within the effective operation range specified by the manufacturers (0–20 000 μS cm^{-1}), the volumetric soil moisture was overestimated by the TDR probes compared to the gravimetric θ_v by up to 5%. When the soil solution had an electrical conductivity of greater than the 0-20 000 μS cm^{-1} range, the θ_v overestimate by the TDR probes increased up to and occasionally greater than 10%.

In the Antarctic environment freezing causes the salt content of soil solutions to vary. When the soil begins to cool below 0°C the soil water content will begin to freeze, and as the soil water freezes the remaining liquid water will have an increased salt content, which in turn further depresses the freezing point of the remaining liquid water (Anderson and Morgernstern, 1973). Consequently the salt content of the liquid soil solution in Antarctic soils can increase as the soil freezes, which may lead to electrical conductivities of the soil solution that are greater than the range specified for accurate probe operation. Investigation of data from the soil climate stations in Antarctica (chapters 6 and 7), however, show that as the soils freeze the soil liquid moisture content recorded by the TDR probes of the soil decrease, rather than increase as would be expected following the overestimation results obtained in this experiment. Taking the overestimation results obtained in this experiment and the investigation of the soil moisture regimes into account, suggests that the decreasing liquid moisture content as the soil freezes is the dominant process recorded in the soil moisture regime by the TDR probes, as opposed to the increased salinity of the remaining liquid water.

The range of electrical conductivities that were determined in this experiment were similar to those expected to occur in the Ross Sea region soils. However, in some soils where salt horizons occur, the soil electrical conductivity may be higher than 2 000 μS cm^{-1}. Reported electrical conductivities from soils in the Ross Sea region were predominantly <20 000 μS cm^{-1} (Claridge, 1965; Bockheim, 1979; Campbell and Claridge, 2000), however, some electrical conductivities measured by Bockheim (1979) in the Wright Valley were reported as being as high as 40 000 μS cm^{-1}.

The conclusion drawn from investigating the effect of salinity on the ability of the TDR probes to record volumetric soil moisture is that when the soil solution has an electrical conductivity in the range of 0-20 000 μS cm^{-1} (as specified by the manufacturers), the TDR probes soil θ_v may vary by up to 5% compared to the gravimetric θ_v.

5.2.7 Experiment 7 – Influence of Hydrocarbons on Hydra Probe Soil Moisture Determination

Hydrocarbon spills have occurred on Antarctic soils with two sites monitored to determine their soil moisture and temperature regimes. Therefore, the effects of hydrocarbons on the measurement of soil moisture using TDR probes needed to be determined. The dielectric constants of hydrocarbons are generally lower than the dielectric constant of soil minerals (i.e. less than 3), but are dependent on temperature and frequency (Sen *et al.*, 1992; Daniels *et al.*, 1995; Sastry and Raj, 1996). Because the dielectric constant of hydrocarbons is considerably lower than that of water, it was hypothesised that the hydrocarbons would not influence the moisture contents recorded by the TDR probe at hydrocarbon-contaminated sites.

At Scott Base a commonly used light diesel fuel is JP-5. Since JP-5 is a common contaminant in Antarctica, however, was unavailable for use in this experiment, a similar light diesel fuel, JP-8 (Jet-A-1), was used as a substitute.

In order to determine whether there were any effect of hydrocarbons on the TDR probe's ability to record soil moisture, JP-8 was added to a sand sample, with the moisture content then determined using the TDR probes. Following preliminary experiments determining the background moisture content of the sand, and the moisture content with only the addition of fuel to the sand, distilled water was also added to the sand in order to establish whether the fuel had any effects on the TDR probes ability to record soil moisture content.

5.2.7.1 Method

1. The background moisture content as recorded by the TDR probes of the oven-dry sand was determined;
2. JP-8 fuel was added to the sand and mixed thoroughly in a fumehood;
3. The moisture content of the sand and fuel sample was determined using the TDR probe then gravimetrically;
4. Distilled water was then added to the sand / fuel mix, with the moisture content determined using both the TDR probe and gravimetrically;

5. Step 4 was repeated at two more moisture contents.

5.2.7.2 Results

Because the dielectric constant of hydrocarbons is similar to the dielectric constant of the soil minerals, hydrocarbons were not expected to influence the results of the soil moisture determination using TDR. As a control the moisture content of the sand sample prior to the addition of fuel was measured, where the moisture content was recorded to be 0.1% by both the TDR probe and gravimetric θ_v determination. When the JP-8 fuel was added to a sand sample, and the moisture content determined using TDR probes, a very low moisture content (0.4%) was recorded (Table 5.6). Distilled water was then added to the sand and fuel mix, with the volumetric moisture content determined using both the TDR probe and by calculation from soil dry bulk density and gravimetric moisture content (gravimetric θ_v). In all cases the TDR probe underestimated the moisture content compared to the gravimetric technique (Figure 5.11). When fuel was included in the sample, this was the expected result as the gravimetric technique also includes evaporation of the fuel from the sand, i.e. TDR result = soil moisture; gravimetric result = soil moisture + fuel (Table 5.6).

Table 5.6: TDR θ_v, gravimetric θ_v, and the difference between the two methods for a: control (dry) sample, fuel only, and three different moisture contents added to sand.

	TDR θ_v	**Gravimetric θ_v**	**Difference**
Control (dry)	0.1%	0.1%	–
Fuel only	0.4%	3.9%	3.5%
Fuel + distilled water (1)	4.7%	7.3%	2.6%
Fuel + distilled water (2)	8.5%	11.1%	2.6%
Fuel + distilled water (3)	13.3%	14.9%	1.6%

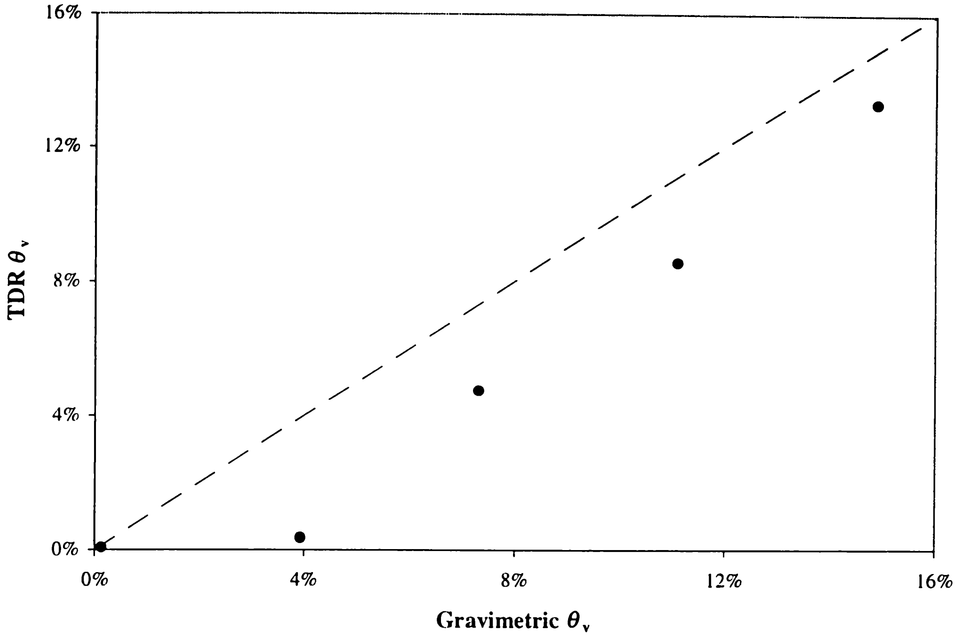

Figure 5.11: TDR θ_v and gravimetric θ_v measurements for fuel-contaminated sand.

The difference between the two methods decreased with the increasing moisture content, but this was also with increasing time from when the fuel was added to the sample. Consequently, the fuel was also evaporating at room temperature, and thus the fuel content in the sample decreased over time. The decreased fuel content over time led to a smaller difference between the two methods for each successive increased moisture content. The difference between the TDR and gravimetric method for the fuel only mixture was similar to that estimated by calculating the moisture content from the volume of fuel added.

5.2.7.3 Discussion

The experimental investigation confirms the theory that hydrocarbons have little effect on the measurement of soil moisture content in hydrocarbon-contaminated soils. For four different soil volumetric moisture contents between 0 and 14%, the gravimetric θ_v method overestimated the moisture content, while the TDR θ_v measurement correlated with the volumetric moisture content estimated when calculating volumetric moisture content from the addition of a known volume of distilled water. The measurement of minimal soil moisture by the TDR probes when only fuel was added to the sand sample suggests that the TDR probes more accurately determine the volumetric moisture content than the gravimetric method. Therefore, in soils which are contaminated with hydrocarbons, the soil moisture content would be better determined using the indirect method of TDR than the direct gravimetric technique.

5.3 Field Verification of TDR probes in Antarctic Soils

5.3.1 Method

Field verification of the TDR probes was undertaken by measuring the soil moisture content using the TDR probe(s), and then comparing the results to volumetric moisture contents calculated using the gravimetric technique. In order to measure the soil moisture content using TDR probes, a suitable site was located where the single probe (section 3.3.4.2) could be placed in the ground. No sampling pattern was used because the samples selected were purely for comparing the two different methods for measuring soil moisture content. Having placed the probe into the ground – usually at the soil surface – the TDR probes measured the soil moisture content five times before the probe was carefully removed so not to disturb the soil. In order to calculate the volumetric moisture content, the soil dry bulk density and gravimetric moisture content (in triplicate) were determined at each probe location. The soil material excavated in the dry bulk density determination was used to determine the gravimetric soil moisture content.

Field verification was undertaken on a range of soils near Scott Base, including soils affected by hydrocarbons (Scott Base HC soil). A total of 50 validation points were collected, with 35 samples representing Scott Base soils, and 15 samples representing the Scott Base HC soil.

In all of the field experiments, measurement errors were associated with the results. The measurement error (section 3.4) for the gravimetric moisture content determination was small (0.02%), while the measurement errors on the soil dry bulk density, and consequently the gravimetrically determined volumetric moisture content was larger (approximately 15%). All TDR probe data were averages of five measurements at each location, while the gravimetric moisture content data were averages of three sub-samples. The statistical variability was generally small and consequently not included on the figures as error bars.

5.3.2 Field Verification Results and Initial Discussion

5.3.2.1 Scott Base Soil

The Scott Base soils (Typic Anhyorthel, after Soil Survey Staff (1998)) were sampled from sites located on the hillside behind Scott Base. Sampling was undertaken over the December-January period of 2002-03. Surface (0-5 cm) samples were taken, which had varying aspects and moisture contents.

The relationship between the TDR volumetric moisture content and the gravimetric θ_v (Figure 5.12) showed a near 1:1 linear relationship (r^2 = 0.85). Some of the higher moisture contents were located in sites that had accumulated water following melting of snow patches and subsequent ponding of the meltwater.

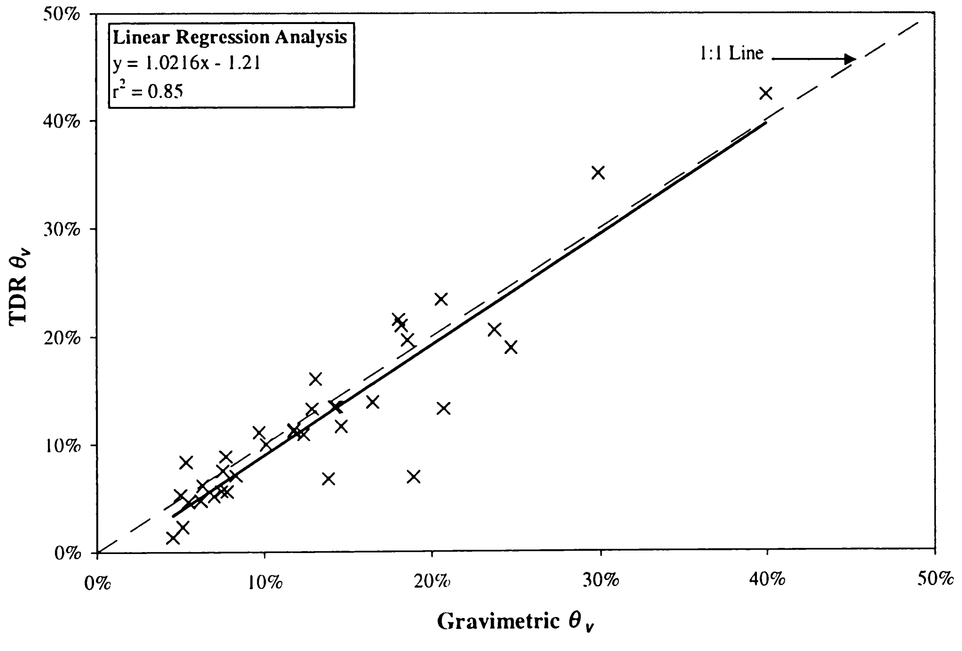

Figure 5.12: Field verification of TDR probes on soils near Scott Base.

The field experiments undertaken on the Scott Base soils show similar results to those that were found in the laboratory experiments, whereby the data points all plot near the 1:1 line. There was, however, more scatter in the field results. One reason for this scatter is likely to be the non-uniform dry bulk density observed in the soil, and consequently the use of an average dry bulk density in calculating the volumetric moisture content from the gravimetric moisture content determined. When the manufacturer's error is considered, approximately 80% of the data points collected fall within ± 3% of the 1:1 line.

5.3.2.2 Scott Base HC Soil

As with the Scott Base soils, the Scott Base HC soils were also classified as Typic Anhyorthels, but had been contaminated by hydrocarbons spilt on them. Because there are only small patches of hydrocarbon-contaminated soils located at Scott Base, the moisture content variability at the time of sampling was less than for the Scott Base soils. The soils sampled were all from an area where oil drums had previously been stored, and subsequently leaked, and/or spilt. An oiled crust was evident at the soil surface, but there was no liquid fuel remaining. Balks *et al.* (2002) previously sampled the site and reported a total petroleum hydrocarbon (TPH) value of 25 100 $\mu g\ g^{-1}$ for the 0-2 cm (surface) depth.

In the Scott Base HC soils the TDR θ_v underestimated the gravimetric θ_v by approximately 2.6% (Figure 5.13). However, an R-squared value of 0.84 suggests that there was a reasonable relationship between the two variables. The slope of the regression analysis is 1.00, suggesting the only difference between the TDR θ_v and gravimetric θ_v is the offset. The offset can be explained by the effect of the hydrocarbons on the gravimetric determination of θ_v. During the gravimetric moisture content analysis, hydrocarbons are also evaporated, thus giving mass differences between the wet and oven dry soil having both moisture and hydrocarbon components. Because the dielectric constant of hydrocarbons is small, they are not recorded as soil moisture by the TDR probes, and consequently only the liquid moisture content is recorded by the TDR probes.

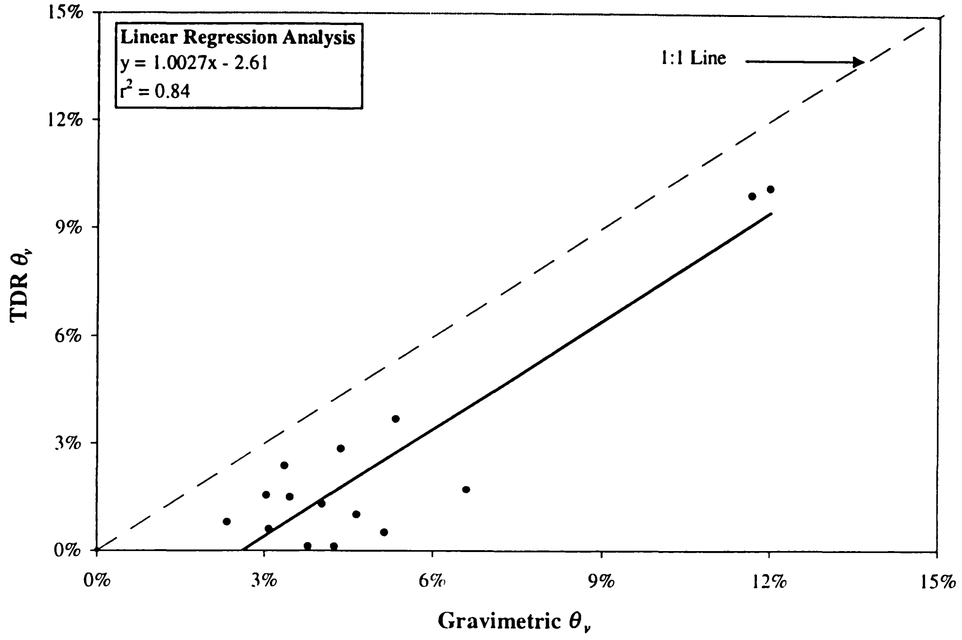

Figure 5.13: Field verification of TDR probes using Scott Base HC soil.

The moisture contents of the Scott Base HC soils were low, with only two sites sampled where the volumetric moisture content was >10%. However, at all sites, the TDR probes underestimated the volumetric moisture content relative to the gravimetric θ_v by an average of 2.6%. Total Petroleum Hydrocarbon (TPH) data from the site (Balks *et al.*, 2002) gave a hydrocarbon content of 25 100 µg g^{-1} (at the 0-2 cm depth). Therefore, the gravimetric hydrocarbon content is 2.5%, which accounts for the calculated average underestimate of the TDR probes determined from the Scott Base HC site. There is some scatter amongst the data points, which is likely to be due to the variability discussed for the Scott Base soils, and also the influence of hydrocarbons. Variability in the amount of hydrocarbon at any point in the soil can cause variability in the overestimate of the gravimetric moisture content. The TDR probes appear to accurately determine the volumetric moisture content of the Scott Base HC soils.

5.2.3 Sources of Measurement Error in Field Analysis

One source of error is the soil dry bulk density used to calculate θ_v from θ_g. The soil dry bulk density was determined at all sites where measurements were made, however there was a lot of variation between the results, and an average dry bulk density was used in the calculation of θ_v from θ_g. The variation in measured dry bulk density was due to the small sample size, and the variable gravel, rock and sand contents of the samples. Larger measurement errors (±15%) using the sand replacement technique occur due to the replacement of the sample material with sand, where replication of an exact volume using sand is difficult. Reproduction of the exact soil surface was also difficult adding to errors in determining the volume of material excavated. The composition of the sample has an effect where, for example, a basalt pebble was included in the sample, hence increasing the weight compared to a sample where all the material was of a finer grain size. The gravelly soil meant that the small sample sizes used to determine the soil dry bulk density had measurement errors that were relatively large (±15%). Therefore, an average dry bulk density was used as it provided a better indicator of the dry bulk density of the Scott Base soils.

Placement of the TDR probes into the ground can also lead to an error in measurement of the volumetric moisture content by not obtaining a smooth contact between the probe tines and soil. The gravelly texture of the Scott Base soils meant that often probe tines were in contact with larger particles rather than the smaller particles, and thus air voids may have been present between the soil and the TDR probe tines. Presence of coarser material meant that the probe couldn't be placed in the ground at some locations.

5.4 Discussion

The laboratory experiments varied parameters known to influence TDR measurements. There was variation in TDR θ_v of up to 2.5% between the probes when tested on the same soil sample. Two of the three probes tested showed a significant difference ($p<0.05$) from the expected (1:1 relationship between the TDR θ_v and the gravimetric θ_v). A temperature influence of up to 1% in TDR θ_v was observed, even for temperature changes as low as 4°C, with TDR recorded moisture content decreasing with decreasing soil temperature. The soil texture influenced the TDR θ_v with increased gravel content giving a TDR θ_v underestimate of up to 2% (at 37.5% gravel content). While the errors associated with each parameter tested were within the ±3% specified by the manufacturer, the effect of decreasing temperature and coarse soils are cumulative, however, these are offset by the overestimation of θ_v by high soil electrical conductivities. There were also limits to the accuracy of the laboratory determined gravimetric θ_v method, particularly in determining the bulk density of the sample (measurement error = ±5%).

The Antarctic field experimental results showed a strong relationship between the TDR θ_v and the gravimetric θ_v. Most of the results obtained from the field experiments showed the two measurement techniques to be within ±3% of the 1:1 relationship expected. As with the laboratory experiments, there were associated errors, particularly for the gravimetric θ_v determination, where the bulk density of the soil was difficult to accurately determine and had an estimated measurement error of ±15%.

One limitation of the field experiments was that they were all undertaken at Scott Base, while soil climate stations (and consequently Hydra probes) are located throughout the Ross Sea region, and on differing soils. However, in most instances the gravelly sand dominated textures prevailed, so results would be expected to have application to other sites in the Ross Sea region.

In hydrocarbon-contaminated soils the TDR probes were shown to determine only the soil moisture content, and not the soil moisture and hydrocarbon content, which is determined by gravimetric techniques. Both the laboratory and field experiments in soils contaminated by hydrocarbons showed similar results, with the gravimetric θ_v technique overestimating the soil moisture content (due to inclusion of hydrocarbons) compared to the TDR probes.

The laboratory and field experiments have shown that the accuracy of the Hydra (TDR) probes are affected by soil temperature, gravel content and salinity. However, the errors were shown to be within the error specified by the manufacturer of ±3%, and consequently interpretation of volumetric moisture content data obtained from the TDR probes can be undertaken on changes of greater than 3%. Data obtained from soil climate stations located at hydrocarbon contaminated sites are subject to the same errors, and consequently can be interpreted with the same limitations as data from the other soil climate stations.

5.5 Summary and Conclusions

- Sample volume had a minimal effect on the accuracy of the TDR probes, and only in circumstances where the constraining bounds of the sample were of the same size as the probe were any differences noted, in which case the result was an underestimate of θ_v of about 1% by the probe;
- Variation between individual Hydra probes was about 2.5% of θ_v;
- Increasing the gravel content of the sample led to an underestimate of the gravimetrically determined θ_v by the Hydra Probes, but was still within ±2% (up to 37.5% gravel by weight);
- The volumetric moisture content measured by the Hydra Probes was influenced by temperature with lower measurements of θ_v at lower temperatures (about 1% over the temperature change from 17°C to 4°C);
- Only liquid soil moisture was determined by the TDR probes;
- The TDR probes overestimated θ_v in soils with high electrical conductivities, however the θ_v overestimation for the range of electrical conductivities recorded at the soil climate stations is likely to be less than 5%;
- Hydrocarbons were not recorded by TDR probes as part of the soil moisture content and did not impact on the TDR probe measurements;
- Field results showed similar results to the laboratory experiments, except with more scatter within the data sets. The increased scatter is likely to be due to field variability in soil dry bulk density and limitations to the bulk density measurement method.

Each of the individual parameters considered had an influence on the θ_v recorded by the TDR probes. Except for the effect of salinity, the error of the TDR probes was shown to be within the limits of accuracy described by the manufacturers of ±3%. The effects of decreasing soil temperature (underestimated θ_v by about 1%)

and of coarse soil textures (underestimated θ_v by about 2%) are cumulative, while the overestimation of θ_v by high soil electrical conductivities (up to 5%) offsets the temperature and texture effects. In many cases the manufactures limit of accuracy of ±3% seem to be a sufficient margin of error for the Hydra probes in Antarctic soils. With the Hydra probe being accurate to ±3%, relative changes over time can be interpreted provided the changes are of a greater magnitude than 3%.

Knowing the limits of accuracy of the Hydra probes now allows data from soil climate stations located in the Ross Sea region of Antarctica to be interpreted with confidence, including data obtained from soils that are contaminated by hydrocarbons.

Chapter 6 – Antarctic Soil Moisture and Temperature Regimes

6.1 Introduction

Soil moisture and temperature data have been collected from three soil climate stations located in the Ross Sea region of Antarctica since 1999. Soil moisture (as liquid) and temperature influence the survival and diversity of micro-organisms and plants in the Antarctic ecosystem. The most important period for micro-organism and plant growth is likely to be the summer where soil surface temperatures warm to above 0°C, and subsequently the soil moisture changes phase from ice to liquid.

The soil moisture and temperature regimes discussed in this section are from the period between 1 November to 28 (or 29) February when the soils are potentially at or above 0°C. Three summer seasons (1999/2000, 2000/01 and 2001/02) are described for three sites (Scott Base, Wright Valley and Marble Point). All soil moisture contents are volumetric soil moisture contents unless otherwise specified. The probe depths specified are ± approximately 2 cm as the TDR probes are 3 cm in diameter. Consequently a probe depth described as 2 cm is providing results for approximately the 0.5-3.5 cm depth. At greater depth in the soil profile the effect of the probe diameter is unlikely to be important, but at the surface where the soil temperature and moisture have strong gradients, there may be differences between 0.5 cm and 3.5 cm.

Because the TDR moisture probes only measure the liquid moisture content of the soil, a large part of the soil moisture data for each year shows a moisture content of 0% when water is frozen. Changes of less than 3% are not generally discussed as they are outside the limits of accuracy of the TDR probes. Therefore, only the larger changes are considered, such as the soil-moistening events when the snow melts, and when the soil moisture in the active layer melts giving a liquid moisture content in the soil.

6.2 Scott Base

At the Scott Base soil climate station (Figure 6.1) 12 TDR probes were placed in the ground, with three replicates at each of 2 cm, 15 cm, 25 cm, and 40 cm depth. A summary of the key soil moisture and temperature properties (Table 6.1) indicates that the 0 C isotherm in the soil at Scott Base differs annually, where it was between 25 and 40 cm in 1999/2000, 15 and 25 cm in 2000/01, and deeper than 40 cm in 2001/02. This suggests that there is significant inter-annual variability in the soil temperature regime at Scott Base. The liquid moisture content also varies with the soil temperature, which dictates the phase that the soil water is in. The number of soil-moistening events at each depth shows that when the soil is unfrozen, the moistening events can penetrate to >40 cm.

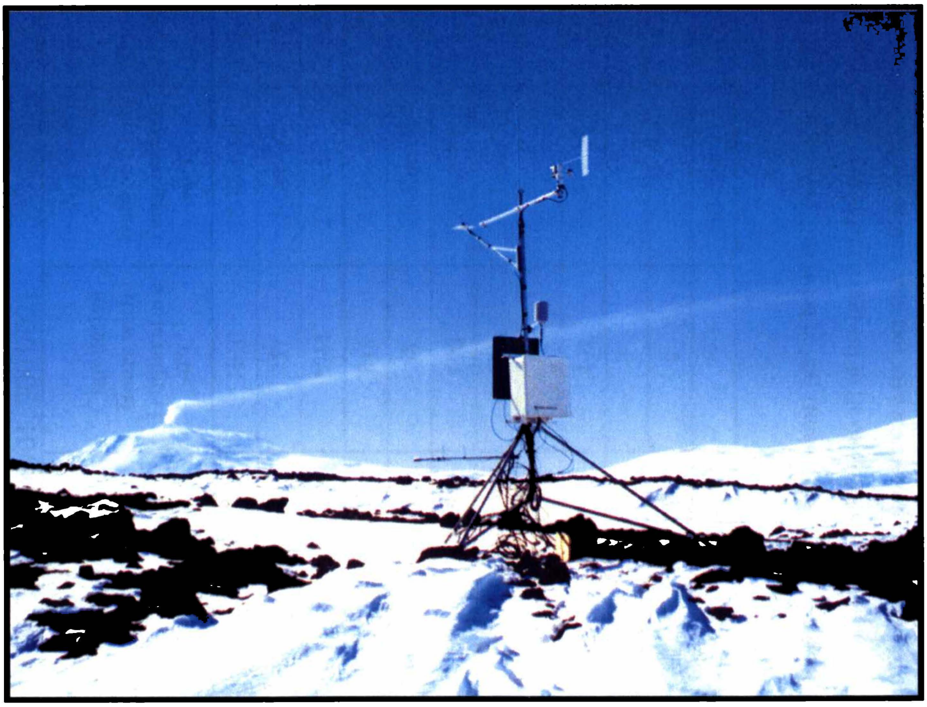

Figure 6.1: Soil climate station at Scott Base.
(Photo courtesy of Ron Paetzold)

Table 6.1: Key soil moisture and temperature properties for Scott Base at the 2, 15, 25 and 40 cm depths over three summers (1999/2000, 2000/01, 2001/02).

		Cumulative Hours with Temperature >0°C [1]	**Date of First Temperature >0°C**	**Date of Last Temperature >0°C**	**Maximum Soil Temperature (°C)** [2]	**Number of Freeze-Thaw Events** [3]	**Total Hours with liquid Moisture Content >5%** [1]	**Number of Soil-Moistening Events** [4]	**Maximum Soil Liquid Moisture Content** [2]
2 cm	1999/2000	1010	15-Nov-99	7-Feb-00	16.8	65	747	3	14.6%
	2000/01	457	2-Dec-00	15-Feb-01	8.0	49	751	3	22.5%
	2001/02	1011	23-Nov-01	9-Feb-02	16.0	36	1079	5	17.7%
15 cm	1999/2000	816	8-Dec-99	3-Feb-00	6.6	39	0	1	4.1%
	2000/01	58	18-Dec-00	7-Feb-01	1.7	8	225	1	14.3%
	2001/02	896	2-Dec-01	1-Feb-02	9.2	13	764	2	10.1%
25 cm	1999/2000	318	16-Dec-99	17-Jan-01	2.6	17	0	0	2.6%
	2000/01	0	–	–	-1.0	–	0	0	3.1%
	2001/02	631	21-Dec-01	22-Jan-02	4.7	4	328	1	8.3%
40 cm	1999/2000	0	–	–	-0.5	–	29	0	5.7%
	2000/01	0	–	–	-2.6	–	0	0	3.2%
	2001/02	79	30-Dec-01	18-Jan-02	0.6	4	586	2	24.0%

NOTES:

Data is based on the summer period between 1 November and 28 (or 29) February.

[1] Calculated by adding up all of the individual hours with temperature >0°C (or moisture content >5%) and dividing by the number of replicates.

[2] Maximum soil temperature (or moisture content) recorded by all replicates.

[3] Calculated by dividing the number of times the soil temperature crossed the 0°C line by 2.

[4] Determined by distinct, rapid rise in soil moisture content of at least 3%, which were not due to freeze-thaw cycles.

6.2.1 The 2 cm Depth

At the 2 cm depth, the soil temperature first rose to 0°C between late November and early December (Figure 6.2). Once the soil temperature had initially risen above 0°C, the soil was strongly affected by the diurnal air temperature trend, and consequently, freeze-thaw cycles began. In some summers the near-surface soil temperature remained above 0°C for consecutive periods of 1 week or greater. At the 2 cm depth, freeze-thaw cycles occurred frequently over the December-January period. The peak soil temperature at the 2 cm depth ranged between 5°C and 20°C, with the summer maximum soil temperature occurring between mid December and early January. By mid January the soil temperature began to drop, and the freeze-thaw cycles became more evident as the soil temperature fluctuated about 0°C until early to mid February. Throughout the summer period, climatic events often occurred where the air temperature cooled sufficiently for the soil temperature to drop below 0°C for a period of 2 or more consecutive days.

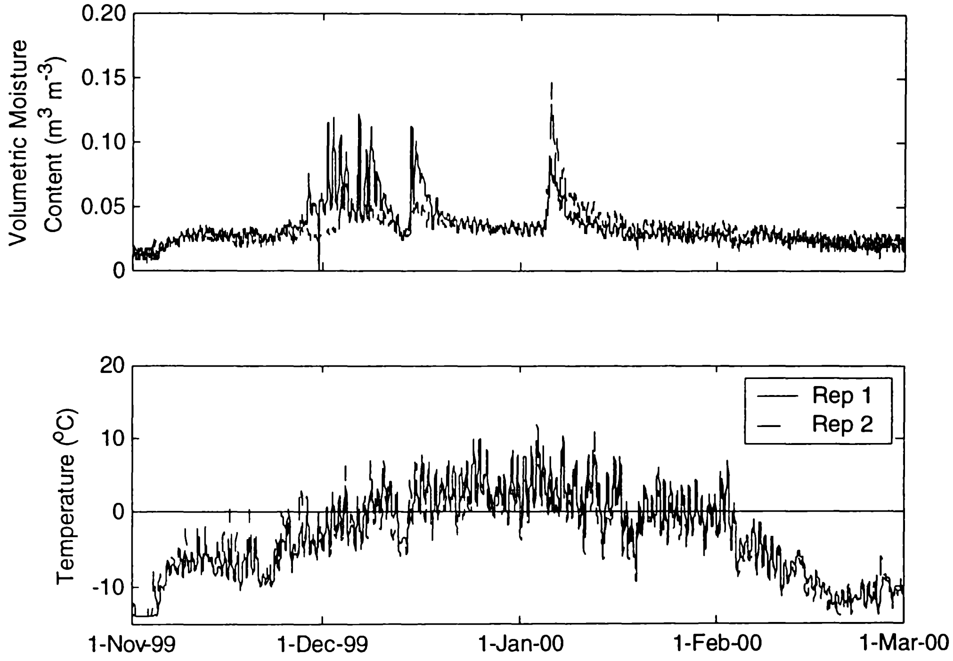

Figure 6.2: Soil moisture and temperature regime for Scott Base at the 2 cm depth for the 1999/2000 summer.

The liquid soil moisture content at the 2 cm depth generally ranged between 5 and 6% throughout the summer, with moistening events, where the liquid soil moisture content increased up to and above 15 to 20%, occurring intermittently (Figure 6.2). As the soil temperature increased to 0°C in late November to early December, the ice in the soil melted increasing the liquid soil moisture content to approximately 5%. The rise in soil temperature to 0°C often coincided with the first soil-moistening event, occurring due to the accumulated winter snow and ice at the surface melting. The soil moisture content increased to between 10 and 15%. Following the initial melting event, the soil dried out over the following 1-2 weeks (Figure 6.3). If freeze-thaw events occurred during the drying period, the drying period was prolonged. From mid December through to early February the soil moisture content remained in the range of 5 to 6%, with rises occurring as moistening events occurred.

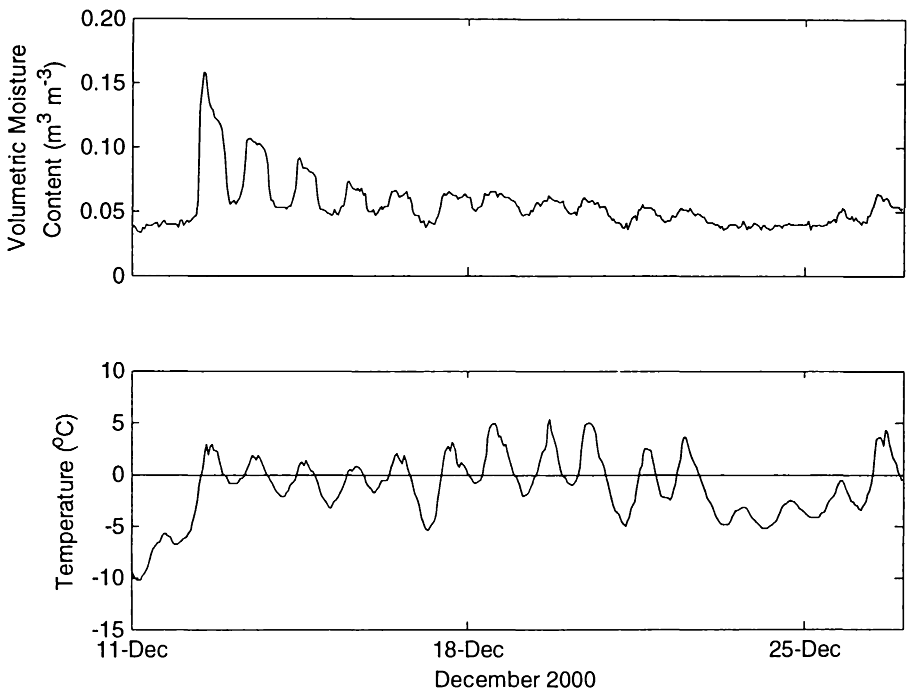

Figure 6.3: First melting and drying event recorded by one TDR probe at 2 cm depth at Scott Base in the 2000/01 summer

The moistening events are often a result of snow melting, and are dependent on snowfalls occurring. On one occasion during the 2001/02 summer, the soil moisture content was recorded as being constantly at 15% for a period of about 2 weeks suggesting a constant supply of moisture over that period (Figure 6.4). Ponding of melt water, and melt water flows down the Scott Base hillside have been observed, and are possible sources for constantly elevated liquid soil moisture contents. In mid February the liquid soil moisture record decreased towards 0% as the soil froze.

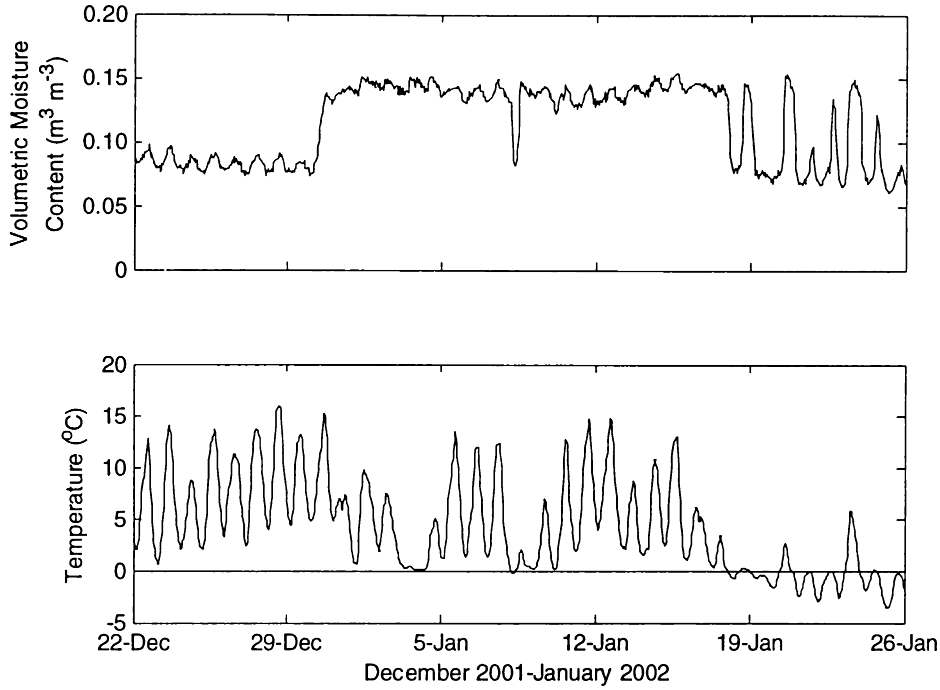

Figure 6.4: Constant elevation of liquid soil moisture recorded by one TDR probe over the January period of the 2001/02 summer at 2 cm near Scott Base.

6.2.2 The 15 cm Depth

At the 15 cm depth, the soil temperature didn't reach 0°C until early to mid December, and fluctuated about 0°C through until late January/early February (Figure 6.5). The soil temperature didn't fluctuate as much at the 15 cm depth compared to the 2 cm depth, but there were still up to 39 freeze-thaw events occurring over the summer period. In the cooler summer (2000/01), the soil temperature rarely rose above 0°C. The time of maximum soil temperature at 15 cm occurred in early January. The soil froze at the end of the summer between late January and early February (Table 6.1).

Because the soil temperature was closer to 0°C at the 15 cm depth, the soil moisture regime was variable from year to year depending on how warm or cool the summer was. At the 15 cm depth, the liquid soil moisture appeared in early to mid December (Figure 6.5). If soil-moistening events at the surface were large enough, they were observed at the 15 cm depth, usually with 1 or 2 events visible each summer. With the exception of moistening events, the liquid soil moisture content over the summer period was in the range of 4 to 7%. When the soil-moistening events penetrated to the 15 cm depth, the liquid soil moisture content reached as high as 15%.

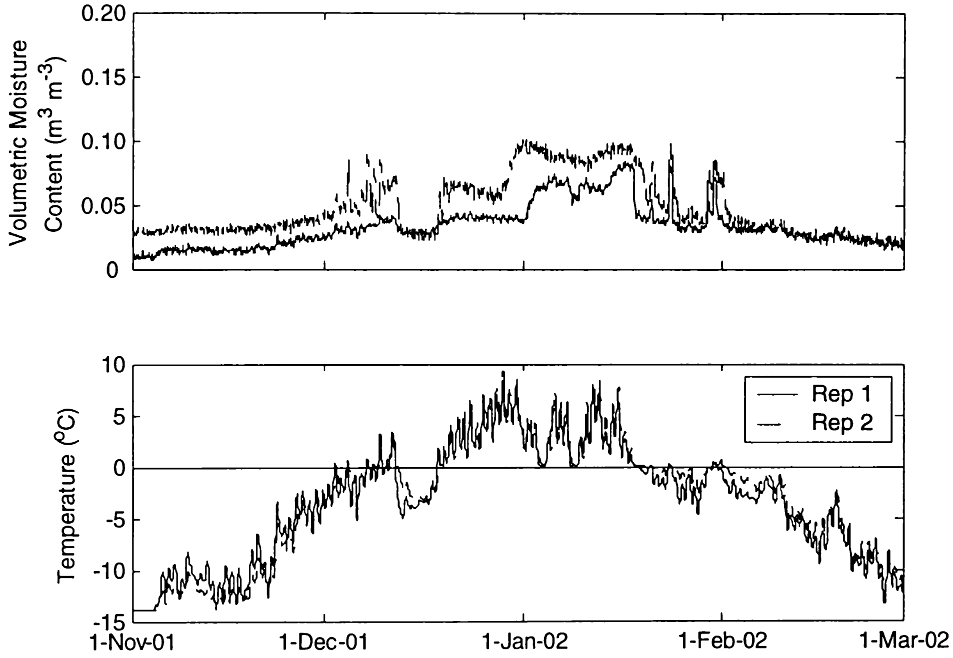

Figure 6.5: Soil moisture and temperature pattern at 15 cm depth for Scott Base (2001/02).

6.2.3 The 25 cm Depth

At the 25 cm depth, there were few distinct changes in temperature (Figure 6.6). The soil temperature at 25 cm depth rose to 0°C in the 1999/2000 and 2001/02 summers in mid to late December (Table 6.1) and reached a maximum of about 5°C. By mid January, the soil temperature again dropped below 0°C.

The soil moisture probes at 25 cm depth showed very little information, due to the soil frequently remaining frozen. When the soil warmed above 0°C between mid December and mid January, the liquid soil moisture rose up to as high as 8% (Figure 6.6). The soil-moistening events noted near the soil surface were not usually recorded at the 25 cm depth.

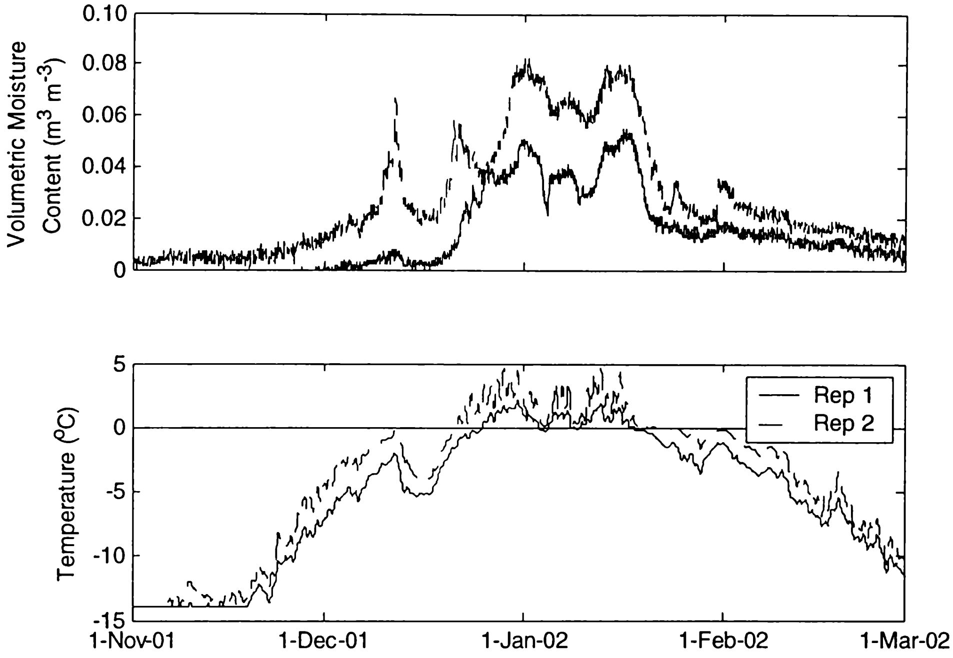

Figure 6.6: Soil moisture and temperature for the 2001/02 summer at the 25 cm depth (for Scott Base).

6.2.4 The 40 cm Depth

At the 40 cm depth, the soil temperature only occasionally rose to 0°C. The soil temperature warmed to a maximum summer temperature in late December and early January, and remained mostly constant between early January and late January/early February (Figure 6.7). There were very few short-term temperature fluctuations, with only the longer duration temperature changes recorded at 40 cm. By late January to early February, the soil temperature began decreasing.

The soil moisture trend at the 40 cm depth was strongly dependent on the soil temperature. There was an event in 2001/02 where the liquid moisture content rose to almost 25% (Figure 6.7). The high moisture content recorded in the 2001/02 summer was possibly due to either an ice lens melting, or liquid water perching above permafrost.

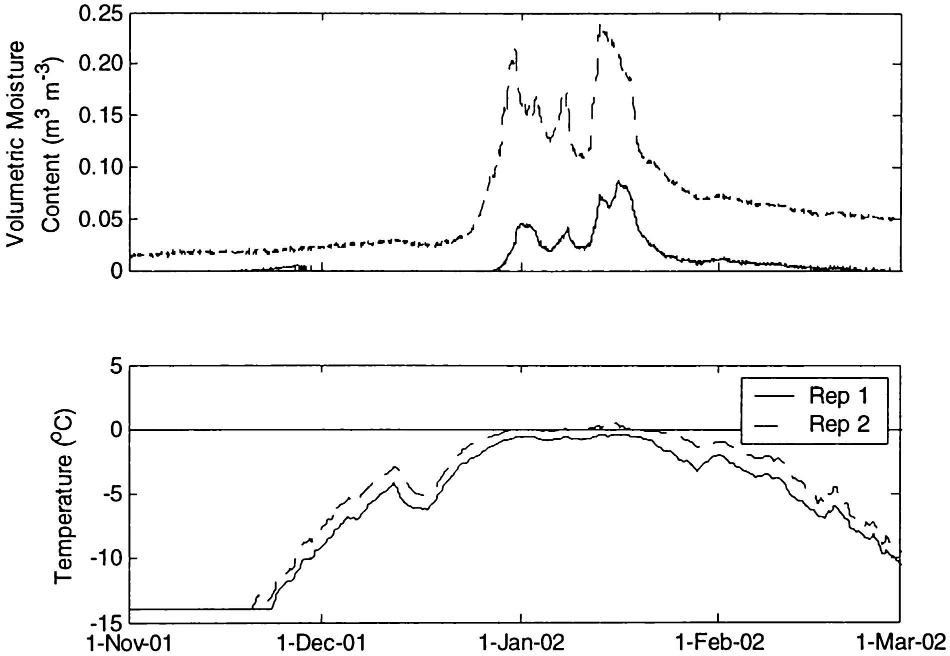

Figure 6.7: Soil moisture and temperature at 40 cm for Scott Base (2001/02).

6.3 Wright Valley

The soils of the Wright Valley are generally very dry, and consequently soil liquid moisture content changes were of small magnitude. Two probes were placed at each of five depths (2 cm, 20 cm, 30 cm, 50 cm, and 120 cm) in the soil at the Wright Valley soil climate station (Figure 6.8). A summary of the key soil moisture and temperature properties (Table 6.2) shows that the 0 C isotherm is generally between 30 and 50 cm depth during the warmest part of the summer. Although soil temperatures were above freezing the total hours with a moisture content >5% were low. Only one soil-moistening event recorded on one of the 2 replicated probes at 2 cm depth was identified in the Wright Valley over the 3 years of data.

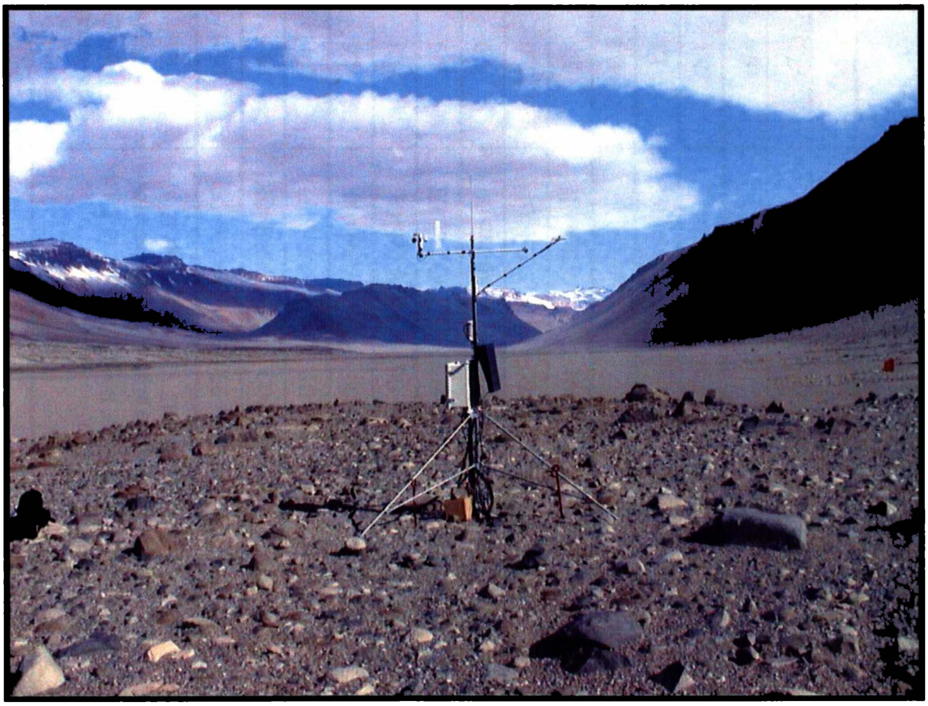

Figure 6.8: Wright Valley soil climate station.
(Photo courtesy of Ron Paetzold)

Table 6.2: Key soil moisture and temperature properties for the Wright Valley at the 2, 20, 30, 50 and 120 cm depths over three summers (1999/2000, 2000/01, 2001/02).

		Cumulative Hours with Temperature >0°C [1]	Date of First Temperature >0°C	Date of Last Temperature >0°C	Maximum Soil Temperature (°C) [2]	Number of Freeze-Thaw Events [3]	Total Hours with Liquid Moisture Content >5% [1]	Number of Soil-Moistening Events [4]	Maximum Liquid Soil Moisture Content [2]
2 cm	1999/2000	1663	6-Nov-99	14-Feb-99	16.6	74	3	1	5.4%
	2000/01	1573	6-Nov-00	23-Feb-01	15.3	102	0	0	3.0%
	2001/02	1789	5-Nov-01	20-Feb-02	19.8	61	0	0	3.5%
20 cm	1999/2000	1325	4-Dec-99	7-Feb-00	4.6	20	0	0	4.8%
	2000/01	1159	27-Nov-00	8-Feb-01	4.8	37	0	0	4.3%
	2001/02	1547	26-Nov-01	10-Feb-02	8.9	24	0	0	4.7%
30 cm	1999/2000	893	9-Dec-99	30-Jan-00	1.9	19	2	0	5.0%
	2000/01	265	10-Dec-00	8-Feb-01	2.0	19	2	0	5.0%
	2001/02	1101	10-Dec-01	9-Feb-02	5.8	17	73	0	5.3%
50 cm	1999/2000	0	–	–	-0.8	–	17	0	5.3%
	2000/01	0	–	–	-1.1	–	19	0	5.2%
	2001/02	593	28-Dec-01	24-Jan-02	2.1	2	281	0	5.9%
120 cm	1999/2000	0	–	–	-6.9	–	–	0	–
	2000/01	0	–	–	-7.0	–	–	0	–
	2001/02	0	–	–	-5.8	–	–	0	–

NOTES:

The same as for Table 6.1.

6.3.1 The 2 cm Depth

In the Wright Valley, the soil temperature at the 2 cm depth rose to 0°C in early November (Table 6.2), and continued to rise slowly until mid December to early January (Figure 6.9). The soil temperature showed a strong diurnal trend, where the diurnal temperature range was up to 20°C. Due to the large diurnal change, the soils frequently underwent freeze-thaw cycles, where the soil temperature was above or below 0°C for more than one week a maximum of twice during the summer period. The large diurnal soil temperature trend was due to the soils of the Wright Valley being shielded from direct sunlight by the Asgard Ranges during the 'night'. From mid January onwards the soil temperature began to drop. The soil temperature still diurnally rose to above 0°C until near the end of February.

The Wright Valley soils had a soil moisture content that averaged 2% throughout the summer. There was very little change to this moisture content, and only rare snowmelt events (one was recorded on one TDR probe in the 1999/2000 summer) had any effect on soil moisture content (Figure 6.9). In the one snow-melting event, the liquid soil moisture content rose to 5.4% (Table 6.2), and took approximately 1 week to dry and return to 2%.

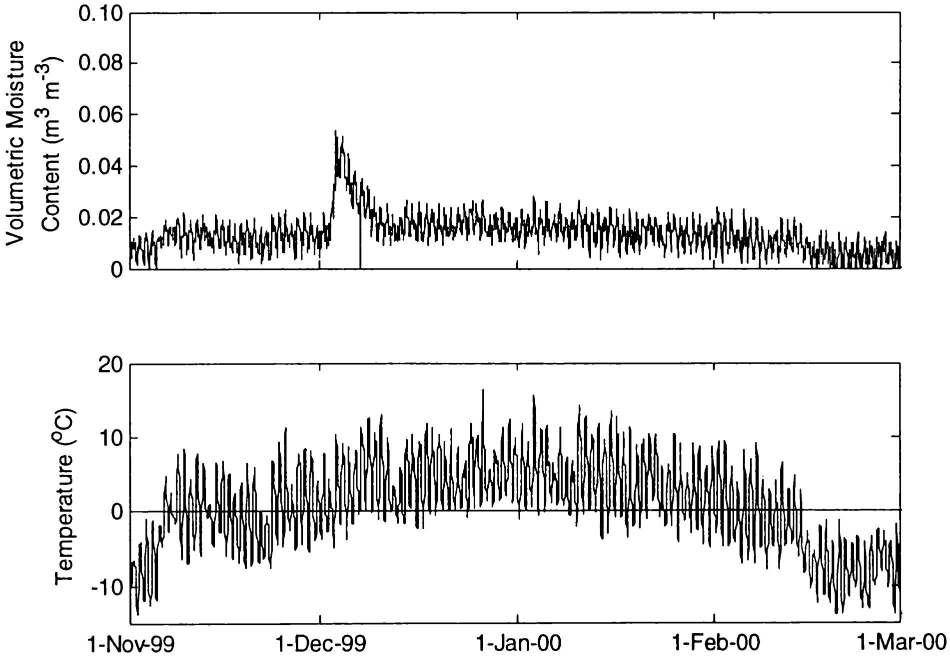

Figure 6.9: Soil moisture and temperature for the Wright Valley recorded by one TDR probe at the 2 cm depth (1999/2000).

6.3.2 The 20 cm Depth

The soil temperature at the 20 cm depth showed similar trends to temperatures at the 2 cm depth. The soil temperature rose above 0°C in late November or early December. Between early December and early February, the soil temperature remained above or slightly below 0°C, with diurnal temperature changes of approximately 2 to 3°C (Figure 6.10). Only on rare occasions when a cool event occurred did the soil temperature drop below 0°C for more than two or three consecutive days. Through December and January the soil temperature remained above 0°C for up to five consecutive days. By late January the soil temperature began to cool, and in early February rose above 0°C for the last time of the summer. As with the 2 cm depth, freeze-thaw cycles were evident in the soil temperature record, although there were fewer than at the surface.

When the soil was above 0°C, the soil liquid moisture content was approximately 4% (Figure 6.10). No changes in the moisture content were evident during the summer period.

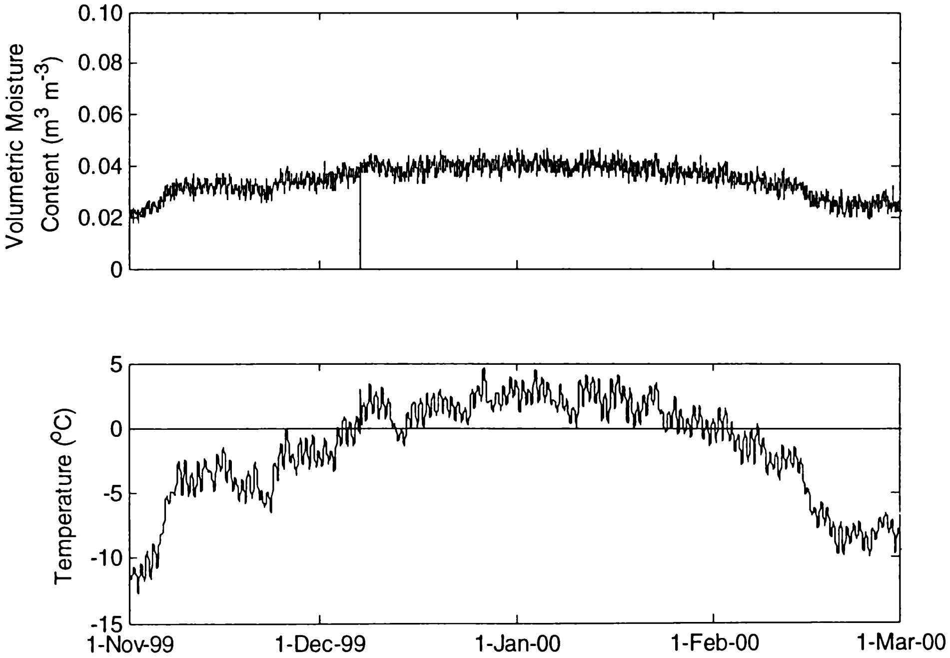

Figure 6.10: An example of the soil Moisture and temperature at the 20 cm depth in the Wright Valley (1999/2000).

6.3.3 The 30, 50 and 120 cm Depths

At the 30 cm depth in the Wright Valley, the soil temperature rose to 0°C in early to mid December, but didn't rise above 0°C until mid to late December (Figure 6.11). Diurnal variations in the soil temperature had a magnitude of less than 1°C. The soil temperature dropped below 0°C between late January and early February. In all years, the soil moisture data showed a trend which followed the soil temperature trend, and reached a maximum of about 5% when the soil temperature was above 0°C at 30 cm depth.

At the 50 cm depth, the soil temperature showed a smooth curve with no diurnal variability (Figure 6.11). The maximum soil temperature occurred in mid January, and the soil temperature only rose to 0°C during the 2001/02 summer (Table 6.2). The soil temperature began to drop by late January. When the soil moisture was in the liquid form, a maximum of about 5% was recorded.

The soil temperature at 120 cm remained below 0°C in all three summers studied (Figure 6.11). A maximum soil temperature (Table 6.2) of about -5 to -7°C was recorded in early to mid February. The soil moisture was frozen throughout the year at the 120 cm depth.

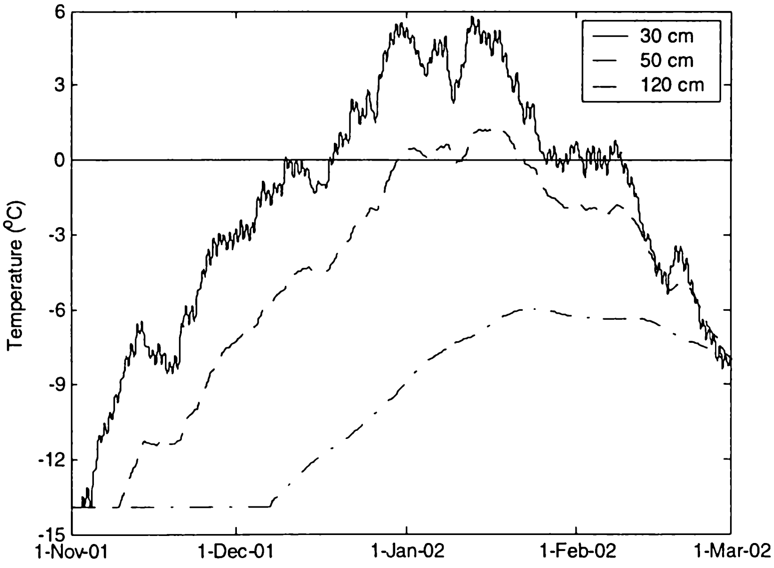

Figure 6.11: Soil temperatures at the 30, 50 and 120 cm depths for the Wright Valley as recorded by one TDR probe at each depth (2001-02).

6.4 Marble Point

Soil moisture probes were placed at four depths (2, 20, 50 and 80 cm) at the Marble Point soil climate station, with three replicates at each depth. Due to instrument malfunction, useful data was only available from early December 1999 onwards for the Marble Point soil climate station (Figure 6.12). The total hours with soil temperature >0 C is similar in both the 2 cm and 20 cm depths (Table 6.3) due to diurnal temperature variations near the surface leading to freeze-thaw cycles causing the soil temperature to fall below 0 C for up to half a day. The 20 cm depth has approximately half as many freeze-thaw cycles as the surface. The average total cumulative hours with a liquid moisture content >5% was 310 hours at 2 cm, 50 hours at 20 cm, and 360 hours at 50 cm. The increased time with soil moisture content >5% at the 50 cm depth compared to the 2 and 20 cm depths reflects the moister soil at depth even though there was a the longer period with soil temperatures >0 C near the soil surface.

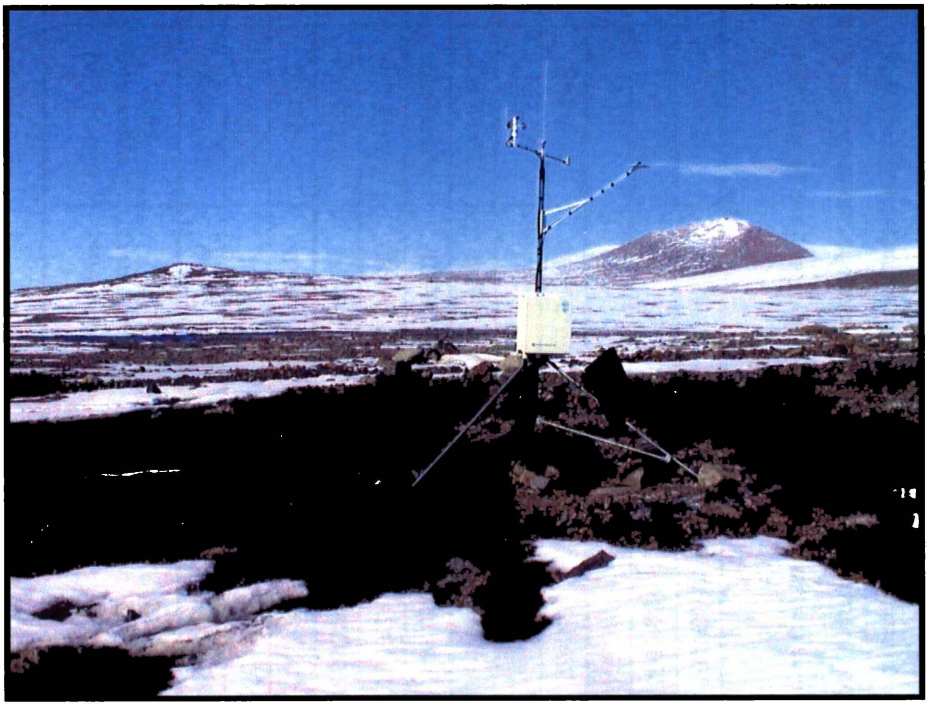

Figure 6.12: Marble Point soil climate station.
(Photo courtesy of Ron Paetzold)

Table 6.3: Key soil moisture and temperature properties for Marble Point at the 2, 20, 50 and 120 cm depths over three summers (1999/2000, 2000/01, 2001/02).

		Cumulative Hours with Temperature >0°C [1]	**Date of First Temperature >0°C**	**Date of Last Temperature >0°C**	**Maximum Soil Temperature (°C)** [2]	**Number of Freeze-Thaw Events** [3]	**Total Hours with moisture Content >5%** [1]	**Number of Soil-Moistening Events** [4]	**Maximum Soil Moisture Content** [2]
2 cm	1999/2000	1299	25-Nov-99	13-Feb-00	16.6	39	297	2	14.3%
	2000/01	742	7-Dec-00	20-Feb-01	11.0	69	324	1	31.8%
	2001/02	1288	26-Nov-01	18-Feb-02	19.8	48	318	2	8.5%
20 cm	1999/2000	1267	8-Dec-99	8-Feb-00	7.8	21	20	1	6.4%
	2000/01	173	18-Dec-00	7-Feb-01	5.6	29	71	1	9.1%
	2001/02	1109	9-Dec-01	10-Feb-02	10.6	23	54	1	6.4%
50 cm	1999/2000	234	3-Jan-99	19-Jan-99	1.5	5	326	1	8.7%
	2000/01	0	–	–	-1.7	–	122	0	6.1%
	2001/02	822	27-Dec-01	21-Jan-02	2.9	5	637	1	9.5%
80 cm	1999/2000	0	–	–	-1.8	–	354	1	18.3%
	2000/01	0	–	–	-2.0	–	1	0	5.1%
	2001/02	0	–	–	-0.6	–	422	1	21.1%

NOTES:

Data is based on the summer period between 1-November and 28-February.

[1] Calculated by adding up all of the individual hours with temperature >0°C (or moisture content >5%) and dividing by the number of replicates.

[2] Maximum soil temperature (or moisture content) recorded by all replicates.

[3] Calculated by dividing the number of times the soil temperature crossed the 0°C line by 2.

[4] Determined by distinct, rapid changes in soil moisture content of at least 3%, which are not due to freeze-thaw cycles.

6.4.1 The 2 cm Depth

The soil temperature at Marble Point reached 0°C in late November to early December, and exhibited a strong diurnal pattern (Figure 6.13). The diurnal soil temperature range was up to 15°C or greater, and led to many freeze-thaw cycles throughout the summer. A maximum soil temperature was reached between mid December and mid January, during which period the soil temperature was stable. Storms in the months of December and January led to extended periods (often 2 or 3 days) where the soil temperature was depressed – usually with the diurnal soil temperature change greatly reduced. In the warmer summers, the soil temperature sometimes remained above 0°C for a week or longer.

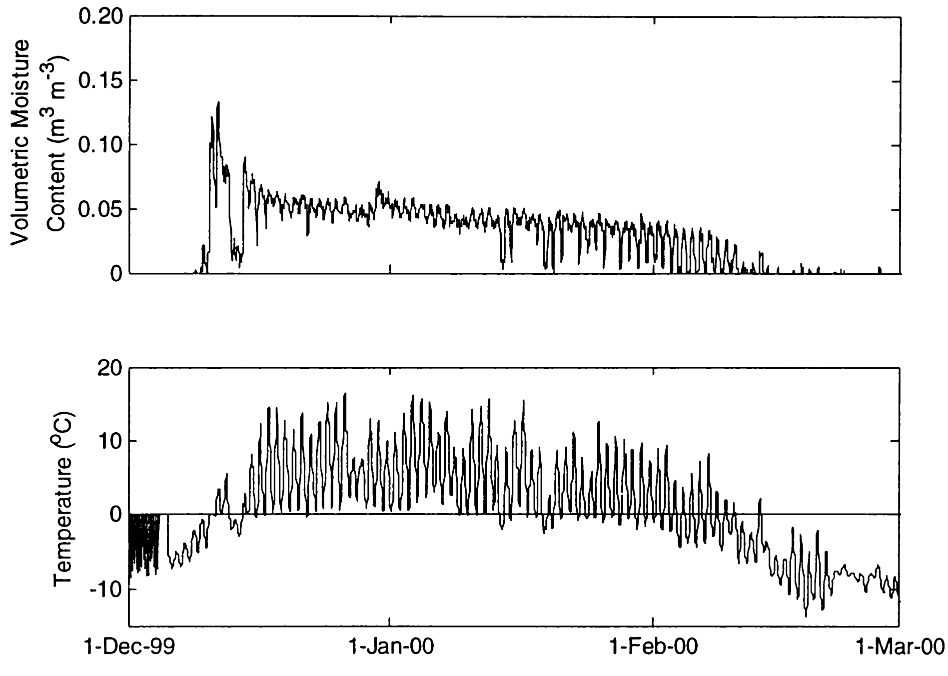

Figure 6.13: Soil moisture and temperature trends recorded by one TDR probe for Marble Point at 2 cm depth (1999/2000).

Distinct periods of soil moistening were observed in the Marble Point liquid soil moisture record (Figure 6.13). The soil moisture was liquid from early December through to late January/early February, during which time soil-moistening events and freeze-thaw cycles occurred. The soil-moistening events occurred initially as the soil warmed and snow cover melted causing an increase in the available soil moisture. Further soil-moistening events occurred later on in the summer season following melting of snowfall. The soil moisture at 2 cm depth at Marble Point averaged around 5% for most of the summer, while increasing up to 32% when soil-moistening events occurred. The drying period of the soil following a soil-moistening event took about 1 week, which was extended to approximately 2 weeks when freeze-thaw cycles occurred during the drying period.

Gradual moistening of the soil was observed by one of the TDR probes during the 2001/02 summer over the period of a week, while the soil then gradually dried over a 6-7 week period (Figure 6.14).

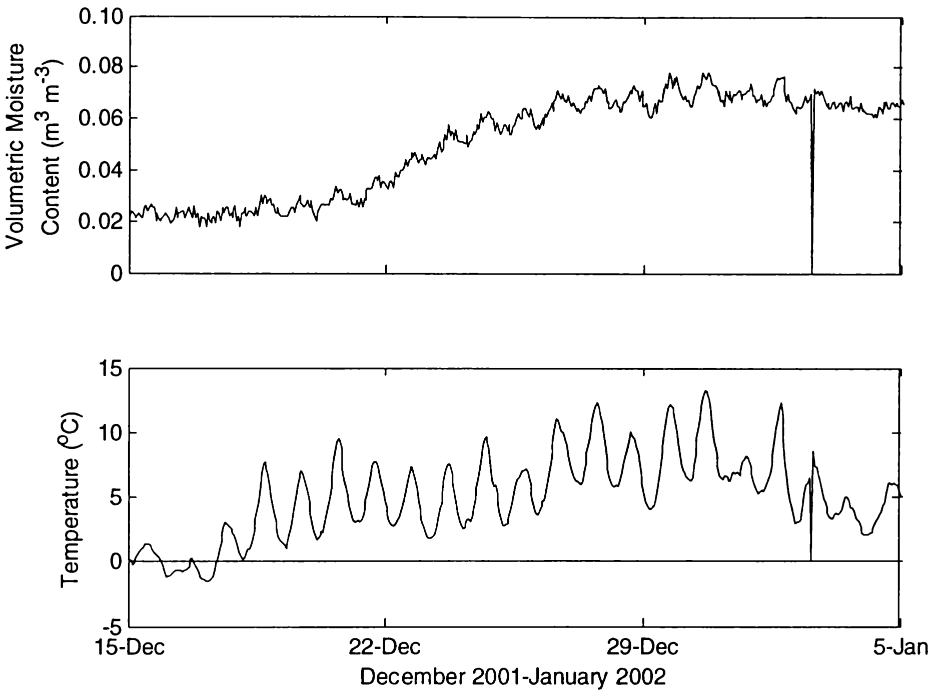

Figure 6.14: Gradual soil moistening recorded by one TDR probe at 2 cm depth at Marble Point (2001/02 summer).

6.4.2 The 20 cm Depth

At the 20 cm depth, the soil temperature increased to 0°C in mid December, and remained at or above 0°C throughout the summer (Figure 6.15). Diurnal temperature patterns were observed at 20 cm, with a smaller magnitude of temperature change (about 3 or 4°C) than the 2 cm depth. The soil temperature remained near 0°C throughout the summer, with freeze-thaw cycles occurring at the 20 cm depth, although not as frequently as at 2 cm (Table 6.3). Maximum soil temperature at the 20 cm depth occurred between mid December and mid January during which time the soil temperature remained stable. The soil temperature began to decrease from mid January onwards, and froze in early February.

The average liquid soil moisture content was about 5%. The few soil moistening events that penetrated to the 20 cm depth increased the liquid soil moisture content up to 8 to 10% (Figure 6.15).

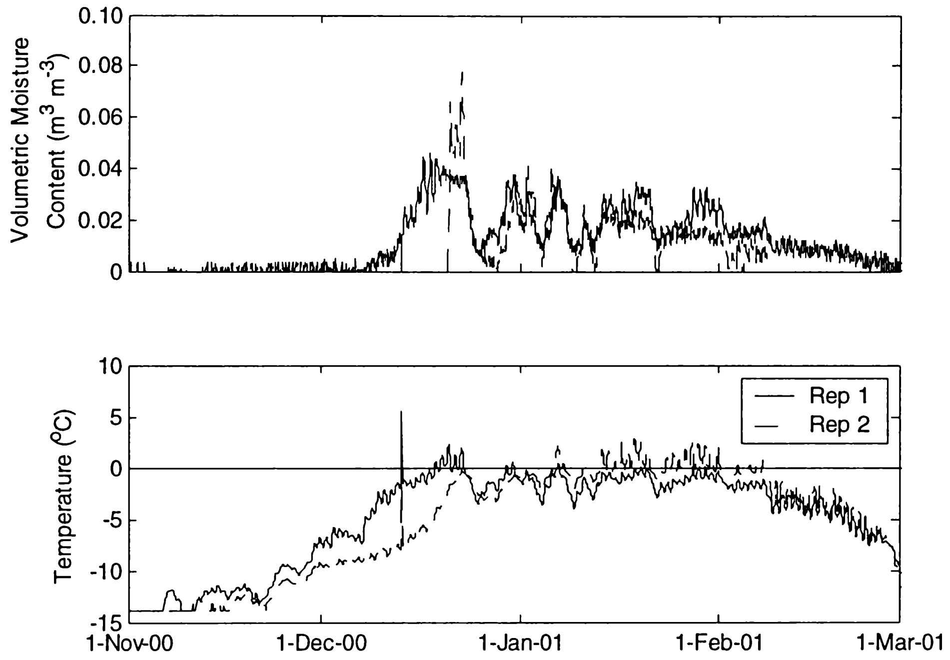

Figure 6.15: Soil moisture and temperature recorded by two TDR probes for Marble Point at the 20 cm depth (2000/01).

6.4.3 The 50 cm Depth

At the 50 cm depth, the soil temperature reached 0°C during the 1999/2000 and 2001/02 summers (Figure 6.16). The soil temperature reached a maximum temperature (Table 6.3) in late December and early January, then stabilised and only dropped minimally prior to early February. Few storm events experienced at the surface were recorded at 50 cm depth. Some of the diurnal cycles were recorded, with the magnitude of the diurnal change being <1 °C.

The liquid moisture content was between 3 and 7% (Figure 6.16). The liquid soil moisture content increased up to as high as 10% when the ice in the soil melted (also associated with surface snow melting and possibly penetrating into the soil). No distinct drying period was observed for the increased moisture content following ice melting, suggesting that it may freeze instead of dry.

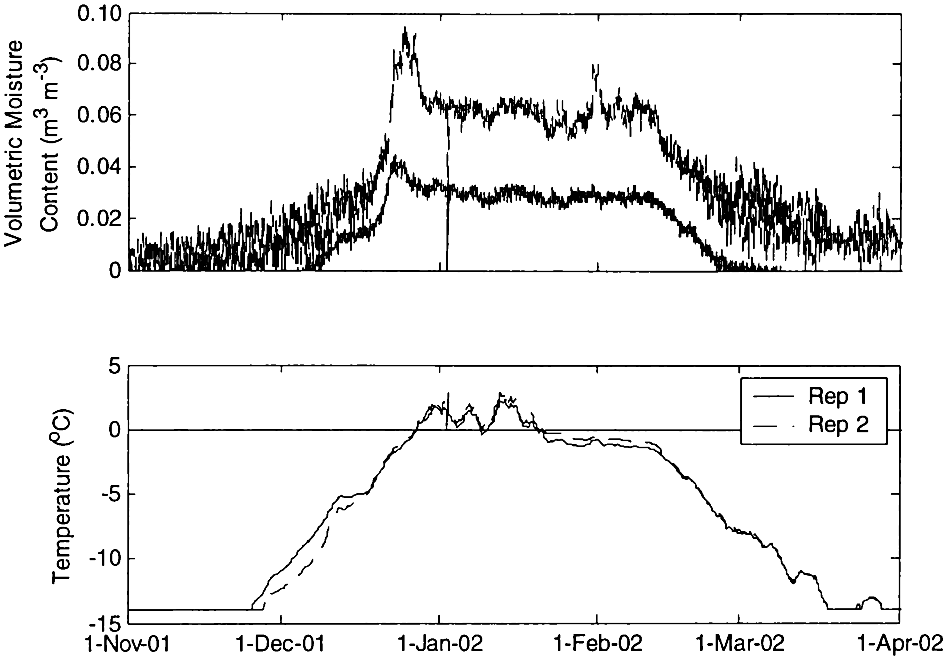

Figure 6.16: Soil moisture and temperature recorded by two TDR probes at 50 cm depth for Marble Point (2001/02).

6.4.4 The 80 cm Depth

The soil temperature at 80 cm did not reach 0°C during the summer period (Figure 6.17) of any of the three summers considered. The maximum soil temperature (Table 6.3) was recorded between mid January and early February. Throughout the January period, the soil temperature tended to plateau, and remain constant. By mid February the soil temperature began to drop quickly.

The liquid soil moisture data at Marble Point indicated the presence of an ice lens at the 80 cm depth (Figure 6.17). The liquid soil moisture content was seen to increase to 20% or greater in one of the TDR probes in late-December and early-January. While the soil temperature was below 0°C, the liquid soil moisture content may have increased because all the ice is required to be melted for the soil temperature to rise above 0°C. The presence of salts can cause the freezing point of the water to be depressed allowing liquid soil moisture to be present below 0°C (Anderson and Morgenstern, 1973). The liquid soil moisture content increased in late December and early January then decreased in mid January. Because the soil temperature was below 0°C, it is suggested that the drop in liquid moisture content was due to the soil freezing rather than drying.

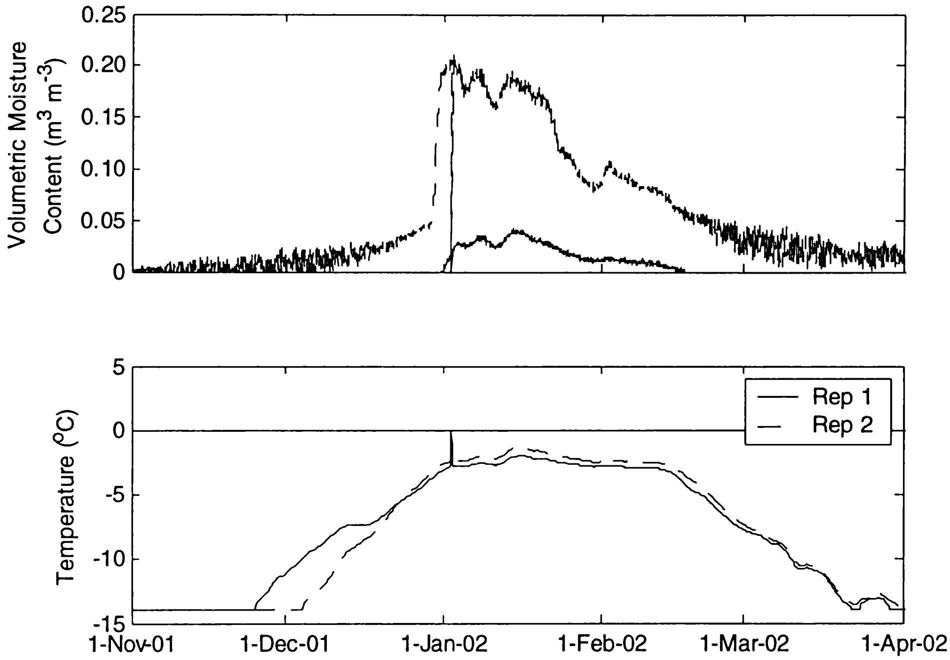

Figure 6.17: Soil moisture and temperature recorded by two TDR probes for Marble Point at 80 cm depth (2001/02).

6.5 Discussion

The three sites considered (Scott Base, Wright Valley, and Marble Point) show considerable differences in their moisture and temperature regimes. The differences between the three sites are not just spatial, but also inter-annual, with large differences between the three summer seasons analysed.

6.5.1 Differences in the Soil Moisture and Temperature Regimes Between Sites

The soil moisture and temperature regimes for Scott Base, Wright Valley and Marble Point show distinct differences between sites, similar to those observed by previous authors (e.g. Campbell and Claridge 1969; Campbell *et al.*, 1998b). While there were differences in soil temperature trends, there were larger differences in the soil moisture regimes between the coastal (Scott Base and Marble Point) and inland (Wright Valley) sites.

In all three summers the soil temperature first reached 0°C earlier (by up to or greater than one month) in the Wright Valley than in either of the two coastal sites. The timing difference between the three sites for the soil freezing for the winter was much smaller, where the greatest difference was 11 days over the three years considered. In all three years, the Wright Valley soil was also the last to freeze at the end of the summer. Consequently the period between when the soil first rose above 0°C to when it last fell below 0°C was greatest in all years for the Wright Valley. One reason may be due to less snow occurring in the Wright Valley compared to Scott Base and Marble Point. The presence of snow causes the solar radiation to be used to melt the snow prior to being able to warm the soil.

While the soil in the Wright Valley was unfrozen for a greater period of time, there was also a greater diurnal fluctuation of soil temperature in the Wright Valley. The diurnal fluctuation in the Wright Valley often caused the soil temperature to drop below 0°C when the sun was low in the sky and behind the Asgard Ranges leaving the soil climate station in shade. Consequently, the number of freeze-thaw cycles identified in the Wright Valley soils was always greater than in the Coastal sites (Figure 6.18).

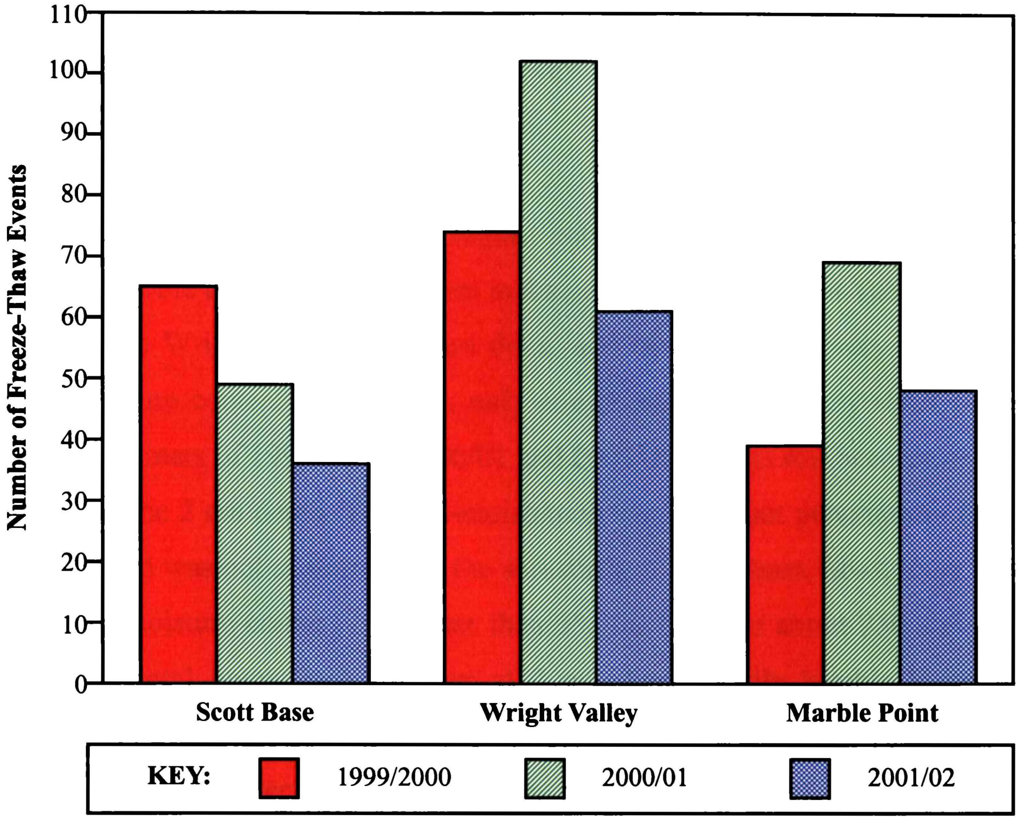

Figure 6.18: Number of freeze thaw cycles at Scott base, Wright Valley and Marble Point for 1999/2000, 2000/01 and 2001/02 summers.

One of the reasons for the differences observed in the summer soil temperature regimes of the Wright Valley, compared to the two coastal sites, is the impact of the short-period climatic events, such as storms and snowfall events. While the effects of storms were observed in the soil temperature regimes of Scott Base and Marble Point as decreases in the soil temperature, the Wright Valley soils didn't recorded any temperature decreases attributable to storms. As a result, the soil temperature was more stable in the Wright Valley, and changes in the soil temperature record were due to the longer-period climatic events, such as the change of seasons.

Because the Wright Valley is in a very dry environment with very low precipitation (45 mm per year (Bockheim, 1997)), the lack of precipitation, particularly snow, can have two effects. Firstly snow acts as an insulator, and consequently when snow is present on the soil surface, it can insulate the soil temperature from some of the effects of air temperature changes. Snow can therefore affect processes such as freeze-thaw cycles. The second important impact precipitation is as a source for soil moisture. In the coastal sites of Scott Base and Marble Point, the melting of snow led to the soil-moistening events being identified as the temperature warmed.

The differences in the soil moisture regime between the Wright Valley, and Scott Base and Marble Point are clearly seen in the properties outlined in Tables 6.1, 6.2 and 6.3. The Wright Valley soils are drier, and the soils were very rarely at a liquid moisture content of >5%. On only one occasion, for a very short period, over the summers of 1999/2000, 2000/01 and 2001/02 did the soil become moister than 5% at the 2 cm depth. The soil-moistening event did not penetrate to the 20 cm depth and was not uniform over the soil surface. In contrast, Scott Base had a liquid soil moisture content of greater than 5% for between about 750 and 1100 cumulative total hours each summer at 2 cm depth, while Marble Point had between about 295 and 325 cumulative total hours each year with the soil moisture content greater than 5% at the 2 cm depth (Figure 6.19).

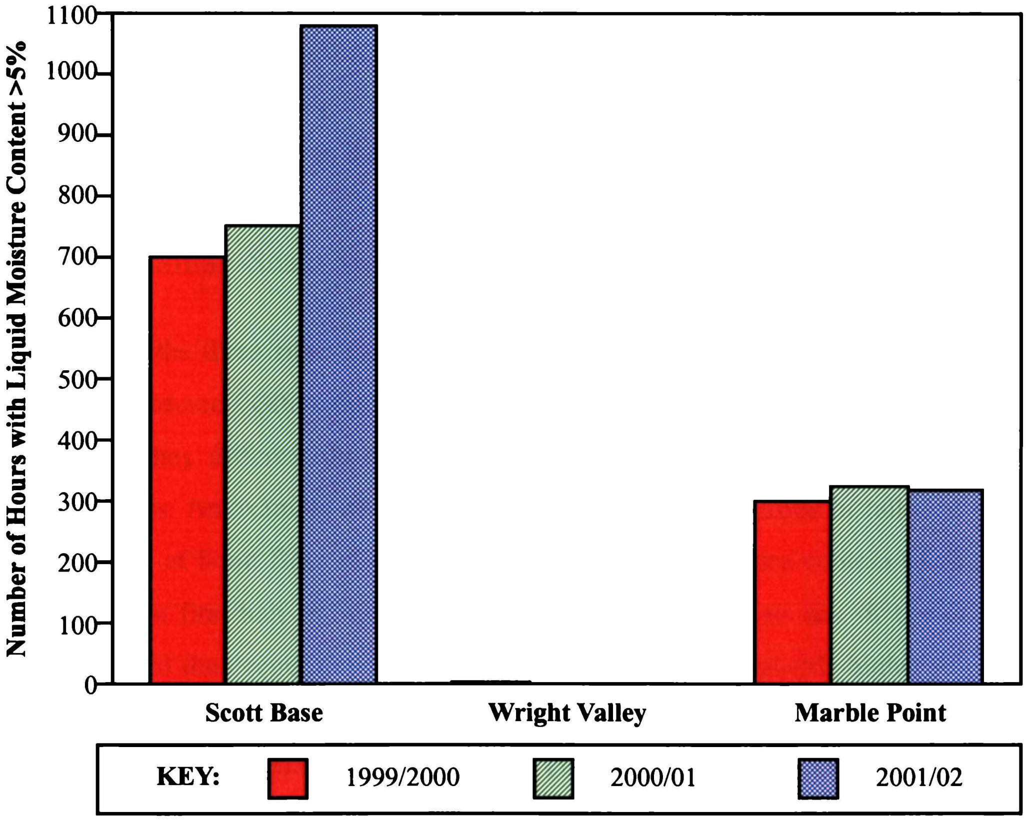

Figure 6.19: Number of hours with a liquid moisture content of >5% for Scott Base, Wright Valley and Marble Point.

Soil temperature differences between the two coastal sites, Scott Base and Marble Point were smaller than the differences between the Wright Valley and the coastal soils. The soil temperature at the surface reached 0°C earlier at Scott Base than Marble Point, but froze earlier at the end of the summer. The total number of hours with a soil temperature of >0°C was approximately 300 hours longer at Marble Point than at Scott Base. The maximum recorded soil temperature near the soil surface was cooler at Scott Base than at Marble Point in two of the three summers. Campbell *et al.* (1994) also suggested that Scott Base may be slightly cooler than Marble Point, and that the thawing isotherm may penetrate deeper at Marble Point than Scott Base.

The soils at Scott Base generally had a liquid moisture content of 5% or greater during the summer for three times as long as Marble Point. The maximum soil moisture content recorded at each site varied annually. In the first season both maximum soil moisture contents were similar (about 14.5%), while in the second summer Marble Point had a greater maximum moisture content (31.8% compared to 22.5%), and in the third season it was Scott Base (17.7% compared to 8.5%). The number of soil moistening events was consistently greater at Scott Base. Both Scott Base and Marble Point are considered to have annual precipitation of less than 200 mm water equivalent (N.Z. Met. Service, 1983). Not all of the precipitation is available to the soil as sublimation is prevalent.

6.5.2 Small-Scale Spatial Variability

At each of the three sites, the TDR probes were inserted with replicates at each depth considered. Often the replicated probes showed similar trends, but on occasions they differed showing small-scale variability over the distance of 1 metre or less. An example of small-scale variability was one probe installed at the 2 cm depth at Scott Base. This probe recorded a soil moisture content of about 15% for the first half of January 2002 – entirely different to any of the other replicates. At the deeper depths moisture contents were consistently higher for all probes than in any of the other summers. This suggests that a constant source of soil moisture was present where the TDR probe was installed. At times throughout the summer, parts of the Scott Base landscape may become saturated with water if the snow melts and then ponds. As Scott Base is on a hillside, water flows down the hillside on occasions following snowmelt. When processes such as snowmelt ponding and water flowing down the hillside occur, the soil moisture regimes can differ greatly from sites only a short distance away. Similar small-scale variability can be seen at Marble Point where one of the TDR probes at 80 cm depths is possibly installed just above an ice lens. Consequently the liquid soil moisture content during summer can increase significantly (gravimetric moisture content of ice lenses may be >140%, (Campbell *et al.*, 1997a)) compared to another probe placed less than 1 m away if the possible ice lens were to melt.

6.5.3 Inter-annual Differences in the Soil Moisture and Temperature Regimes

While spatial variability was evident in the soil moisture and temperature regimes in the Ross Sea region of Antarctica, inter-annual variations can also have a major effect. Even over the short three-year period considered here, there was considerable inter-annual variability, particularly in relation to the soil temperature regime.

At all three sites differences in the soil temperature regime were observed between the three years considered. In general, the 2000/01 summer was colder than either of the other two summers, while the 2001/02 was slightly warmer than the 1999/2000 summer. In the cooler 2000/01 summer, at all three sites, the number of days with the soil temperature above 0°C was less than either of the other two seasons (Tables 6.1, 6.2 and 6.3). At both Scott Base and Marble Point, the maximum summer temperature was lower (by about 8°C) in the 2000/01 summer than in the other two summers (Figure 6.20). In the Wright Valley, the effects of the cooler summer were not so 7evident in the soil temperature record. This may be associated with increased snowfall at Scott Base and Marble Point leading to more snow on the ground surface, which would have insulated the soil against temperature warming.

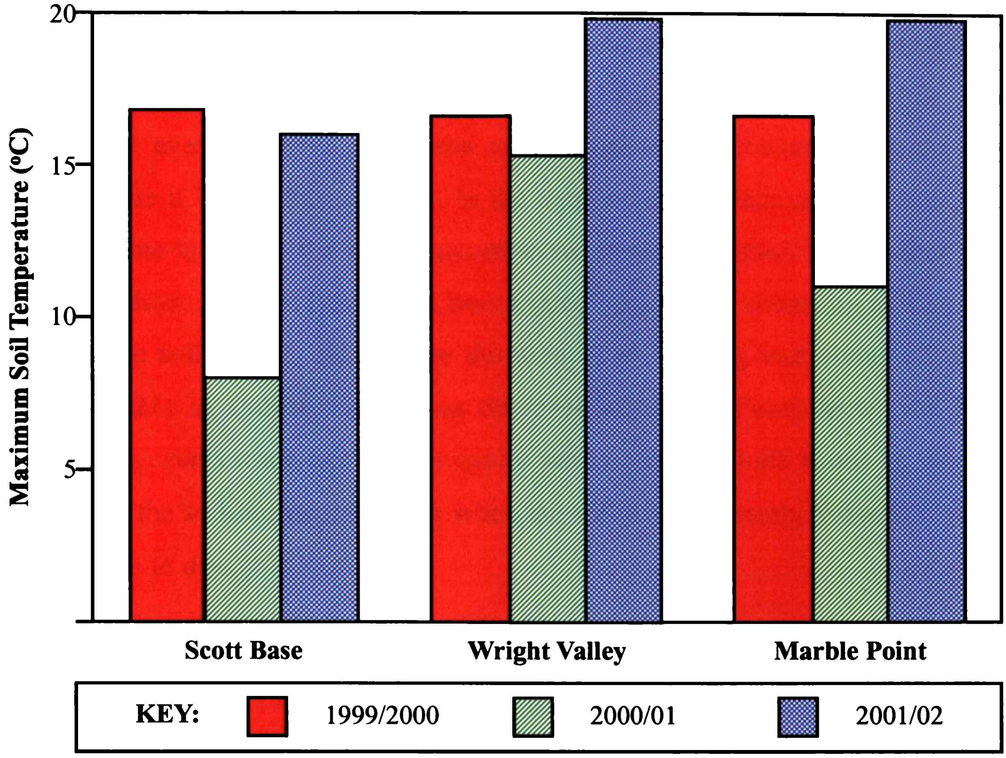

Figure 6.20: Maximum soil temperatures at the 2 cm depth for Scott Base, Wright Valley and Marble Point for three summers (1999/2000, 2000/01, 2001/02).

The effect of the cooler summer isn't as evident in the soil moisture record. However, the soil moisture was in a liquid state for fewer hours. Campbell *et al.* (1998a) however, suggest that inter-annual differences can be identified in the soil moisture regime due to differences in the amount of snow melted or the amount of evaporation occurring differing on a year-by-year basis.

6.5.4 Fate of Soil Moisture and Length of Time Spent at Higher Moisture Contents

When the soil becomes moistened due to melting of snow or ice in the soil, the soil moisture contents rose above what appeared to be the equilibrium summer soil moisture content. Generally, within 2 weeks of the soil moisture content increasing, it had returned to its equilibrium moisture content. Campbell *et al.* (1998b) suggest the drying period to be 10-14 days. The rate of decrease in moisture content appeared to be affected by the soil temperature, as the sites that had freeze-thaw cycles occurring took longer for the soils to dry.

At Scott Base, a total of 10 soil-moistening events were recorded near the soil surface over the three summers considered. Six of the ten soil moistening events were affected by freeze-thaw cycles during the drying period, while one moistening event occurred at the end of the summer, and consequently the soil froze before it had a chance to dry. In the three other soil-moistening events, the average time taken for the soil to return to its equilibrium moisture content was about six days. At Scott Base when freeze-thaw cycles were occurring at the same time as the soil drying, the average duration of soil drying was about 12 days, (Figure 6.21). A similar pattern was observed at Marble Point, where the four moistening events when freeze-thaw cycles were occurring, took about 13 days to dry, while the soil-moistening event when the soil was constantly above 0°C took only 5 days to dry.

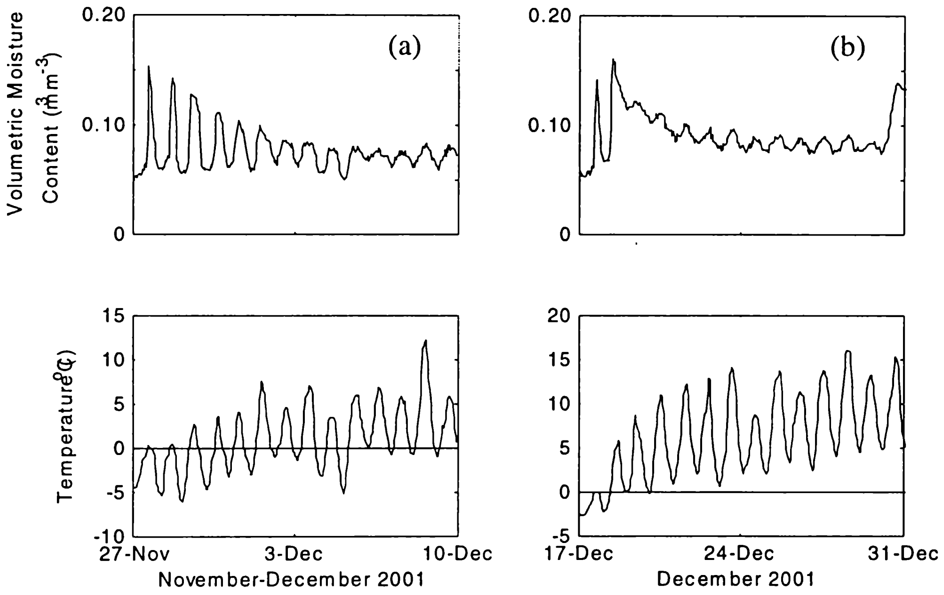

Figure 6.21: Drying period of soils with (a) freeze-thaw processes operating and (b) with soil temperatures constantly >0°C

When the soil moistening events penetrated to greater depths in the soil, the increased soil moisture content dried slowly throughout the summer period. No time frames for drying were determined at the depths >2 cm, as the soil temperature, particularly at Scott Base, was near freezing, so the soil moisture would have often changed phase throughout the summer. However, when the soils were constantly above 0°C at the greater depths, soil moisture contents decreased slowly over the remainder of the summer.

6.6 Summary and Conclusions

- This chapter has reported soil moisture and temperature data from 3 sites, Scott Base, the Wright Valley and Marble Point over the 1999/2000, 2000/01 and 2001/02 summers;
- There was considerable spatial and inter-annual variability in the soil moisture and temperature regimes;
- Soil-moistening events occurred up to five times a summer at Scott Base and Marble Point, but only once in three summers in the Wright Valley;
- Soil-moistening events caused the liquid soil moisture content to increase up to 23% at Scott Base, 32% at Marble Point, and 6% in the Wright Valley;
- The total cumulative of hours with a soil moisture content >5% averaged 860 at Scott Base, 1 in the Wright Valley, and 310 at Marble Point over the 1999/2000, 2000/01 and 2001/02 summers.
- The drying period for the soils took an average of about 6 days, which was extended to of about 12 days if freeze-thaw cycles occurred during drying;
- The soil temperature was >0°C for an average of 830 hours at Scott Base, 1680 hours in the Wright Valley, and 1100 hours at Marble Point over the 1999/2000, 2000/01 and 2001/02 summers;
- Freeze-thaw cycles occurred throughout the summer period at all three sites, with an average of 50 freeze-thaw cycles at Scott Base, 79 in the Wright Valley and 52 at Marble Point.

Chapter 7 – Soil Moisture and Temperature Regimes of Hydrocarbon Contaminated Sites

7.1 Introduction

Hydrocarbons (from fuel and lubricating oils) are known contaminants in a number of sites in Antarctica. In this chapter we seek to characterise the moisture and temperature regimes at two hydrocarbon-contaminated sites and compare them with other climate data in the area.

Bioremediation, which uses micro-organisms or microbial processes to degrade contaminants (Børrensen *et al.*, 2003), has been proposed as a possible process to remediate hydrocarbon-contaminated soil using microbes indigenous to Antarctic soils (Aislabie *et al.*, 2000). Effective bioremediation is dependent on factors including temperature, type of contaminant and micro-organisms present, pH, and the availability of nutrients and water (Børrensen *et al.*, 2003). Consequently an understanding of the soil moisture regimes provides information relevant to determining potential for bioremediation of hydrocarbon-contaminated soils.

Soil climate stations were installed at two hydrocarbon-contaminated sites (Scott Base and Marble Point). At each location soil climate stations were also installed (chapter 6) and used as a control, while several probes at each of the contaminated sites were also used for comparison in adjacent uncontaminated soil. The data from 1 November to 28 (or 29) February for two summers (1999/2000 and 2001/02), was considered in this thesis. All soil moisture contents are volumetric unless otherwise specified.

7.2 Scott Base and Marble Point Sites

7.2.1 Scott Base

Six TDR probes were installed in the Scott Base hydrocarbon-contaminated soil at three depths: 5, 15 and 25 cm. Two probes were installed at each of the three depths, where one was installed in the contaminated soil, and the second in a nearby uncontaminated site to act as a control (the adjacent control). Further measurements were made at a nearby soil climate station (section 6.2). The climate station and hydrocarbon-contaminated sites at Scott Base were located on different landforms, as the climate station is away from the human influences of Scott Base on an exposed southerly facing slope. The hydrocarbon-contaminated site (Figure 7.1) was a former drum storage site (Figure 7.2), with hydraulic and lubricating oils having been spilt intermittently from the drums from as early as 1960 until 1998 (Balks *et al.*, 2002). The hydrocarbon-contaminated soil was located next to a road (Figure 4.1) on ground that had been disturbed, and was sheltered from some winds and sometimes shaded by a nearby building.

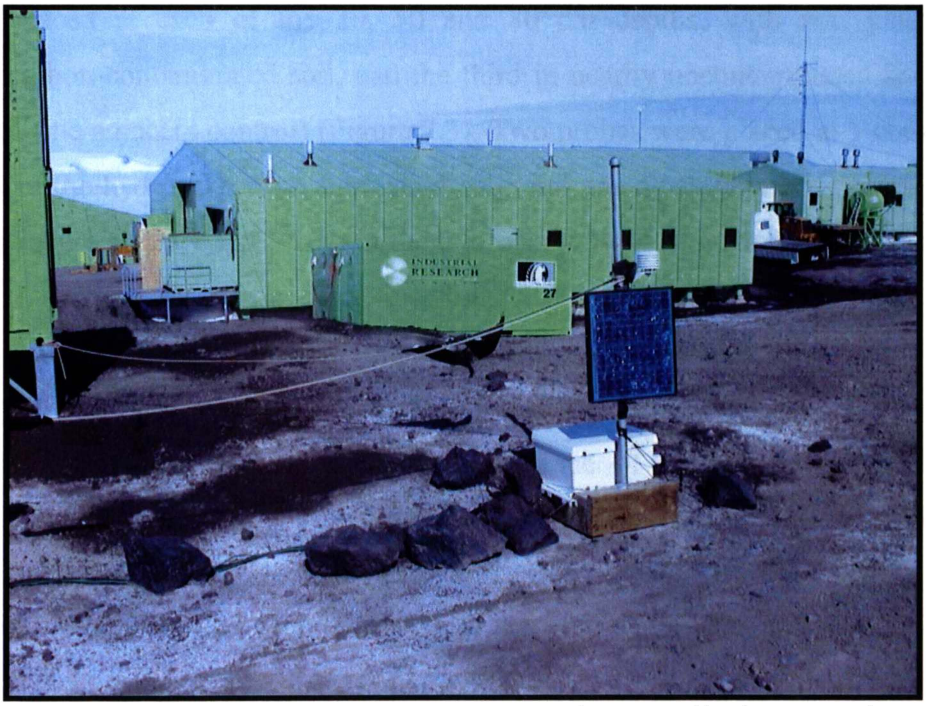

Figure 7.1: Scott Base hydrocarbon-contaminated soil climate station. (Photo courtesy of Ron Paetzold)

Figure 7.2: Drum storage rack at the site of the Scott Base hydrocarbon-contaminated soil climate station.
(Photo courtesy of Megan Balks)

7.2.2 Marble Point

Twelve TDR probes were installed at the Marble Point (Figure 4.7) hydrocarbon-contaminated site at five different depths (5, 10, 20, 50 and 80 cm). Three probes were placed at each of the 20, 50 and 80 cm depths, with two placed in hydrocarbon-contaminated soil, and the third in nearby uncontaminated soil as a control (the adjacent control) (Figure 7.3). Two probes were placed at 5 cm depth – one in the hydrocarbon-contaminated soil, and one as an adjacent control. The final probe was placed at 10 cm in the hydrocarbon-contaminated soil. A separate climate station site was also installed 200 m away (section 6.4). The characteristics of the climate station and hydrocarbon-contaminated sites were essentially similar, in terms of landform, aspect and parent material. However, at the hydrocarbon contaminated site the presence of the datalogger caused a snowdrift, which possibly affected the results in the 2000/01 summer due to extended snow cover on the site. The hydrocarbon-contamination (Figure 7.4) was possibly caused by heavy lubricating oils (M. Balks pers. comm.) when the old Marble Point camp nearby was inhibited between 1957 and about 1963 (Balks *et al.*, 2002). Site and soil description are located in Appendix 1.

Figure 7.3: Marble Point hydrocarbon-contaminated soil climate station. (Photo courtesy of Ron Paetzold)

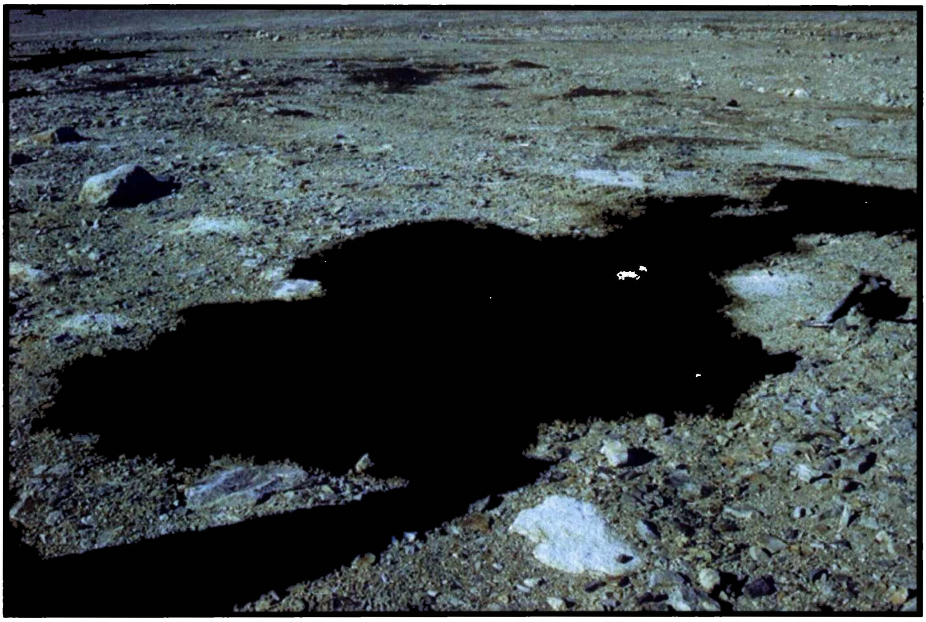

Figure 7.4: Hydrocarbon contamination of the soil at Marble Point, possibly caused by heavy lubricating oils. (Photo courtesy of Megan Balks)

7.3 Limitations to Interpreting Hydrocarbon Data

One limitation is the accuracy of the TDR probes. The TDR probe accuracy for determining soil moisture content of 3% suggests that many of the differences between the moisture contents of the hydrocarbon-contaminated and control soils were outside the limitation of probe accuracy. The effect of the probe accuracy on the soil temperature regime is likely to be minimal as the TDR probe temperature accuracy is ±0.6°C.

A second limitation is the spatial variability and differences between the soil climate stations and the hydrocarbon-contaminated sites. At Scott Base, the hydrocarbon-contaminated site was sheltered and sometimes shaded more than the climate station. While control probes were installed adjacent to the contaminated site, there was difficulty in identifying an exactly similar site due to small-scale spatial variability. The hydrocarbon-contaminated site at Scott Base was in an area that is strongly impacted by human influence with a dangerous goods store and road in close proximity to the site. The Scott Base site was also in an area where moisture accumulated from runoff upslope.

There was limited TDR replication due to cost and availablity of equipment. At Marble Point there were two replicates in the hydrocarbon-contaminated soil, but only one control probe at each depth once again affecting the replication of the results. At each of the climate station sites there were showing probes at each of the depths allowing moisture and temperature regimes to be described confidently.

As a result of these limitations, the soil moisture data can give a general characterisation of the moisture regime but are limited with regard to detecting differences between hydrocarbon-contaminated sites and controls. There was insufficient replication and sensitivity in the TDR probes to identify small changes to the soil moisture regime.

7.4 Scott Base

7.4.1 Soil Moisture and Temperature Summary

The maximum soil moisture content was between 27 and 46% for all depths over both summers, except in the 2000/01 summer at the 25 cm depth where the soil remained frozen all summer (Table 7.1). However, the total hours with a moisture content >5% increases with depth, suggesting that the near surface soils dry more quickly than soil at greater depths.

There is a strong temperature gradient with depth in Antarctica. For example the maximum soil temperature at 15 cm is 10°C lower than at the 5 cm depth (Table 7.1). The maximum soil temperature at the 25 cm depth was above 0°C in the 1999/2000 summer, but below 0°C the following summer. This suggests that the 0°C isotherm is near 25 cm depth but varies annually.

Notes For Table 7.1:

Data collected over the period of 1 November to 28 (or 29) February.

[1] Calculated by adding up all the individual hours with soil temperature >0°C and dividing by the number of replicates.

[2] Maximum soil temperature recorded by all replicates.

[3] Calculated by dividing the number of times the soil temperature crossed the 0°C line by 2.

[4] Calculated by adding up all the individual hours with soil moisture content >5% and dividing by the number of replicates.

[5] Determined by distinct, rapid changes in soil moisture content of at least 3% which are not due to freeze-thaw processes.

[6] Maximum soil moisture content recorded by all replicates.

[7] TDR probes placed in hydrocarbon-contaminated soil.

[8] TDR probes placed in uncontaminated soil adjacent to hydrocarbon-contaminated soil.

[9] Data collected from the nearby soil climates station (Section 6.2).

[10] Data collection period of 3 December to 29 February.

[11] Data collection period of 9 December to 28 February.

Table 7.1: Key soil moisture and temperature properties at Scott Base for hydrocarbon-contaminated and control soils at 5, 15 and 25 cm depths for two summers (1999/2000 and 2000/01). (Notes on previous page)

Site			Total Hours With Soil Temp. >0°C	Date of First Soil Temp. >0°C[1]	Date of Last Soil Temp. >0°C	Maximum Soil Temp. (°C)[2]	Number of Freeze-Thaw Events[3]	Total Hours with liquid moisture Content >5%[4]	Number of Soil Moistening Events[5]	Maximum Soil Moisture Content[6]
5 cm	1999/2000[10]	*HC Soil*[7]	1002	–	2-Feb-00	11.93	46	424	1	32.4%
		Adj. Cont.[8]	954	–	2-Feb-00	12.32	42	576	0	6.4%
		Clim. Stn.[9]	1010	15-Nov-99	7-Feb-00	16.80	65	747	3	14.6%
	2000/01[11]	*HC Soil*	473	–	15-Feb-01	4.51	32	252	1	32.0%
		Adj. Cont.	531	–	10-Feb-01	7.74	42	496	0	7.2%
		Clim. Stn.	457	2-Dec-00	15-Feb-01	8.00	49	751	3	2.3%
15 cm	1999/2000	*HC Soil*	537	–	17-Jan-00	2.01	8	854	1	46.3%
		Adj. Cont.	1025	–	3-Feb-00	4.15	7	854	1	19.8%
		Clim. Stn	816	8-Dec-99	3-Feb-00	6.62	39	0	1	4.1%
	2000/01	*HC Soil*	6	–	20-Dec-00	0.19	1	1707	1	27.0%
		Adj. Cont.	192	–	20-Jan-01	1.11	5	1739	1	39.6%
		Clim. Stn.	58	18-Dec-00	7-Feb-01	1.66	8	225	1	14.3%
25 cm	1999/2000	*HC Soil*	73	–	10-Jan-00	1.06	6	2000	1	34.6%
		Adj. Cont.	380	–	14-Jan-00	0.32	5	778	1	56.0%
		Clim. Stn.	318	16-Dec-99	17-Jan-00	2.59	17	0	0	2.6%
	2000/01	*HC Soil*	0	–	–	-0.86	–	1949	0	7.7%
		Adj. Cont.	0	–	–	-0.64	–	0	0	4.4%
		Clim. Stn.	0	–	–	-1.04	–	0	0	3.1%

7.4.2 Soil Moisture and Temperature Regimes

Near the surface (5 cm depth), the soil temperature showed diurnal variability of up to 10°C or more, with frequent freeze-thaw cycles (Figure 7.5). The soil temperature remained constantly above 0°C for periods of up to a week during the December-January period. There where also periods of 2-3 consecutive days when the soil temperature remained below 0°C over December-January. The soil moisture regime at the 5 cm depth at the Scott Base hydrocarbon-contaminated site showed periods of increased soil moisture in December. Only one soil-moistening event (where the moisture content increased to about 30%) occurred with the background liquid soil moisture content being between 3 and 5% (Figure 7.5). The soil took between 1 and 2 weeks to dry, depending on freeze-thaw cycles at 5 cm depth.

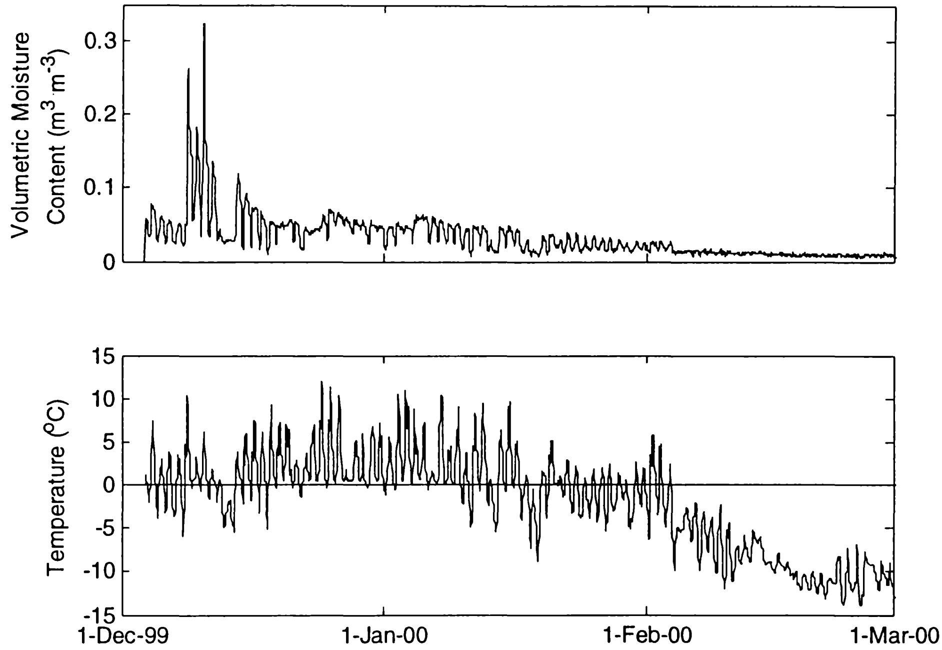

Figure 7.5: Near-surface (5 cm) soil moisture and temperature pattern for hydrocarbon-contaminated soil at Scott Base during the 1999/2000 summer.

The 15 cm depth had fewer freeze-thaw cycles, and smaller diurnal variability than near the surface. Diurnal variability at the 15 cm depth was no more than 5°C, and was often only 1 or 2°C (Figure 7.6). During the summer the soil temperature reached 0°C at 15 cm depth, but for a much shorter period than at the surface. The soil moisture regime was controlled almost exclusively by the soil temperature regime. During melting of ice in the soil, the liquid soil moisture content rose to between 20 and 30% at the 15 cm depth (Figure 7.6).

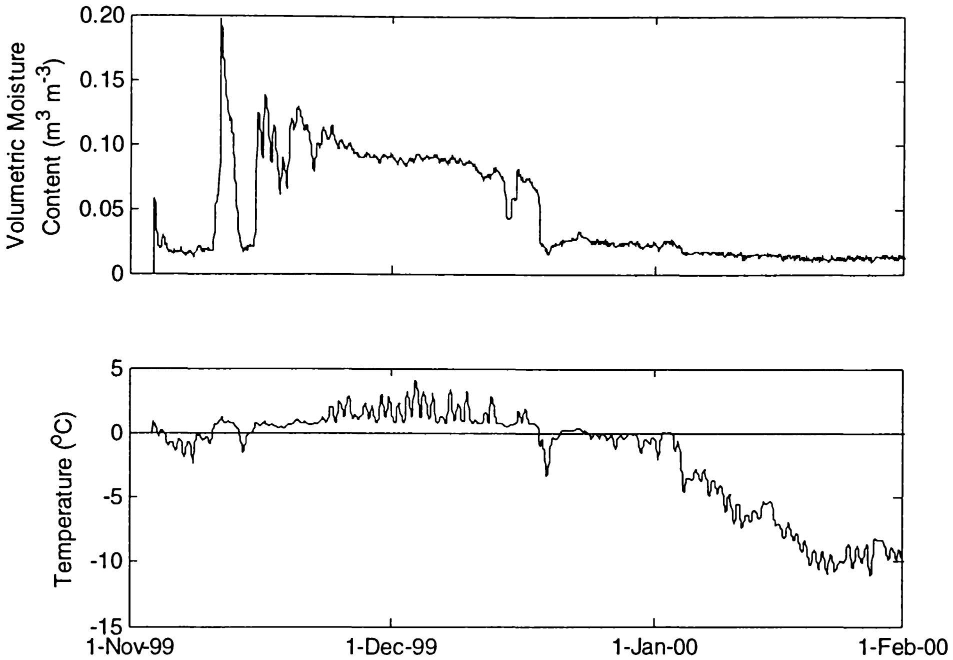

Figure 7.6: 15 cm depth soil moisture and temperature pattern for hydrocarbon-contaminated soil at Scott Base during the 1999/2000 summer.

At 25 cm depth, the soil temperature rarely rose to 0°C in 1999/2000 summer, and remained frozen for the entire 2000/01 summer period. The diurnal variability was never more than 1 or 2°C at 25 cm. Freeze-thaw cycles rarely occurred and didn't follow a diurnal pattern. During the 1999/2000 summer, as the ice melted in the soil, the liquid moisture content increased gradually to about 12%. The gradual increase suggests that no surface water penetrated to 25 cm depth. In 2000/01 the ice in the soil never melted. In the 2000/01 summer there was an anomaly in that the soil temperature reached a maximum of –0.9°C, however, the cumulative hours with a moisture content of >5% was 1949. The high hours with a moisture content >5% may be due to either salts depressing the thawing temperature of the ice, and consequently melting occurring, or probe malfunction.

7.5 Marble Point

7.5.1 Soil Moisture and Temperature Summary

The 0°C isotherm was located between 50 and 80 cm in 1999/2000, and between 20 and 50 cm in 2000/01 summer at the hydrocarbon-contaminated and control soils. The second summer was cooler than the 1999/2000 summer, and this is also seen in the lower maximum summer temperatures and hours with a soil temperature >0°C at all depths. The lower maximum summer temperatures are possibly due to snow accumulating next to the datalogger at the hydrocarbon-contaminated site instead of the colder summer, although the colder summer was also noted at the climate station site. The maximum soil liquid moisture content was higher in the hydrocarbon-contaminated soil than either the adjacent control or the climate station (Table 7.2). The number of cumulative hours with a liquid soil moisture content of greater than 5% was higher at the 20 cm depth than any of the other depths considered for the hydrocarbon contaminated soil. No differences with regard to the cumulative hours of soil moisture >5% were evident between any of the three sites measured at Marble Point.

<u>**Notes For Table 7.2**</u>:

Data collected over the period of 1 November to 28 (or 29) February.

[1] Calculated by adding up all the individual hours with soil temperature >0°C (or moisture content >5%) and dividing by the number of replicates.

[2] Maximum soil temperature recorded by all replicates.

[3] Calculated by dividing the number of times the soil temperature crossed the 0°C line by 2.

[4] Determined by distinct, rapid changes in soil moisture content of at least 3% which are not due to freeze-thaw processes.

[5] Maximum soil moisture content recorded by all replicates.

[6] TDR probes placed in hydrocarbon-contaminated soil.

[7] TDR probes placed in uncontaminated soil adjacent to hydrocarbon-contaminated soil.

[8] Data collected from the nearby soil climates station (Section 6.4).

[9] Data collection period of 5 December to 29 February.

Table 7.2: Key soil moisture and temperature properties at Marble Point for hydrocarbon-contaminated and control soils at 2, 20, 50 and 80 cm depths, and for hydrocarbon-contaminated soils at 10 cm depth for two summers (1999/2000 and 2000/01)

			Total Hours with Soil Temp. >0°C[1]	**Date of First Soil Temp. >0°C**	**Date of Last Soil Temp. >0°C**	**Maximum Soil Temp (°C)[2]**	**Number of Freeze-Thaw Events[3]**	**Total Hours with Liquid Moisture Content >5%[1]**	**Number of Soil-Moistening Events[4]**	**Maximum Soil Moisture Content[5]**
2 cm	1999/2000[9]	*HC Soil*[6]	1329	8-Dec-99	13-Feb-00	18.80	23	506	1	14.4%
		Adj. Cont.[7]	1235	10-Dec-99	13-Feb-00	14.34	31	1735	1	15.3%
		Clim. Stn.[8]	1299	25-Nov-99	13-Feb-00	16.62	39	297	2	14.3%
	2000/01	*HC Soil*	565	6-Jan-01	19-Feb-01	12.37	29	278	1	12.0%
		Adj. Cont.	781	12-Dec-00	19-Feb-01	9.80	61	2030	1	17.3%
		Clim. Stn.	742	7-Dec-00	20-Feb-01	10.98	69	324	1	31.8%
10 cm	1999/2000	*HC Soil*	1334	11-Dec-99	11-Feb-00	13.81	11	1448	1	31.3%
	2000/01		529	13-Jan-01	16-Feb-01	7.05	10	779	1	36.1%
20 cm	1999/2000	*HC Soil*	1285	11-Dec-99	12-Feb-00	7.96	1	1522	1	27.4%
		Adj. Cont.	1212	12-Dec-99	11-Feb-00	8.82	14	1318	0	9.1%
		Clim. Stn.	1207	8-Dec-99	8-Feb-00	7.82	21	20	1	6.4%
	2000/01	*HC Soil*	294	15-Jan01	8-Feb-01	2.38	2	623	1	19.2%
		Adj. Cont.	264	19-Jan-01	8-Feb-01	3.26	25	427	0	8.0%
		Clim. Stn.	173	18-Dec-00	7-Feb-01	5.62	29	71	1	9.1%

Table 7.2 Continued over page...

Table 7.2 Cont…

			Total Hours with Soil Temp. >0°C[1]	**Date of First Soil Temp. >>0°C**	**Date of Last Soil Temp. >>0°C**	**Maximum Soil Temp (°C)** [2]	**Number of Freeze-Thaw Events** [3]	**Total Hours with Liquid Moisture Content >5%** [1]	**Number of Soil-Moistening Events** [4]	**Maximum Soil Moisture Content** [5]
50 cm	1999/2000 [9]	*HC Soil* [6]	605	4-Jan-00	4-Feb-00	1.60	5	1058	1	16.0%
		Adj. Cont.[7]	942	26-Dec-99	8-Feb-00	3.08	6	1054	0	7.0%
		Clim. Stn.[8]	234	3-Jan-00	19-Jan-00	1.48	5	326	1	8.7%
	2000/01	*HC Soil*	0	–	–	-1.65	–	326	0	7.0%
		Adj. Cont.	0	–	–	-0.96	–	0	0	4.0%
		Clim. Stn.	0	–	–	-1.68	–	122	0	6.1%
80 cm	1999/2000	*HC Soil*	0	–	–	-0.44	–	6	0	5.2%
		Adj. Cont.	0	–	–	-1.01	–	265	0	5.3%
		Clim. Stn.	0	–	–	-1.84	–	354	1	18.3%
	2000/01	*HC Soil*	0	–	–	-2.89	–	0	0	3.6%
		Adj. Cont.	0	–	–	-3.15	–	0	0	3.9%
		Clim. Stn.	0	–	–	-2.01	–	0	0	5.1%

(Notes for Table 7.2 located prior to the table)

7.5.2 Soil Moisture and Temperature Regime

At the 5 cm depth, the soil temperature reached 0°C in early to mid December, and then fluctuated about 0°C with freeze-thaw cycles occurring in the hydrocarbon-contaminated and adjacent control soils. Diurnal temperature variations of between 10 and 15°C occurred throughout the summer. In the 1999/2000 summer (Figure 7.7), the soil temperature remained above 0°C for up to approximately 2 to 3 weeks consecutively. The background liquid soil moisture content at 5 cm and 10 cm was between 5 and 15% during the summer. When a soil-moistening event occurred the soil moisture content increased to a maximum of about 15% at 5 cm depth (Figure 7.7) and over 30% at 10 cm depth. The drying period was approximately 2 weeks.

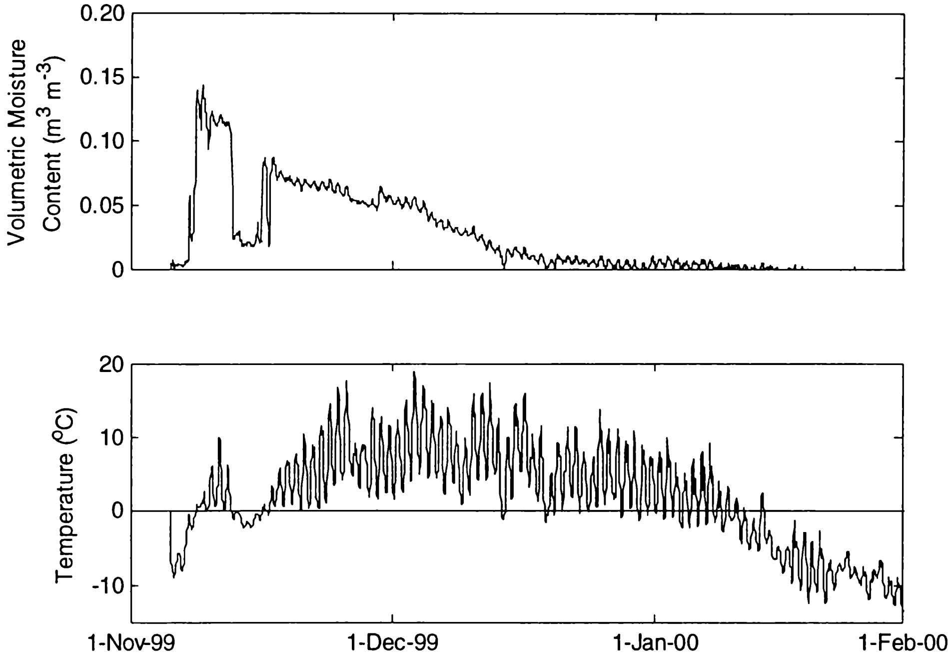

Figure 7.7: 5 cm depth soil moisture and temperature patterns for hydrocarbon-contaminated soil at Marble Point during the 1999/2000 summer.

At the 20 cm depth, the diurnal temperature change was less than 5°C, and the soil temperature sometimes remained above 0°C for periods of 1 week or longer. The liquid soil moisture content rose up to between 20 and 30%, possibly due to surface soil-moistening events. The background soil moisture content was between 10 and 20%. The drying period at 20 cm appeared to be very slow – possibly taking the entire summer.

The soil temperature rose above 0°C at 50 cm during the 1999/2000 summer, but only reached a maximum of -1.6°C in 2000/01, suggesting that the 0°C isotherm was near 50 cm depth. Diurnal variations at 50 cm were only about 1°C, while freeze-thaw cycles were rare. The liquid soil moisture content rose to between 10 and 15% at the beginning of the summer, and then slowly decreased over the remainder of the summer at 50 cm depth.

The soil temperature remained below 0°C at the 80 cm depth, with no diurnal variations evident. The moisture in the soil remained as ice throughout the summer at 80 cm depth.

7.6 Discussion

The soil moisture and temperature regimes described for the hydrocarbon-contaminated soils (sections 7.4 and 7.5) were similar to those characterised for the climate stations at Scott Base and Marble Point in chapter 6. However, some differences were noted between the hydrocarbon-contaminated and control soils.

7.6.1 Comparison of Soil Temperature Properties Between Hydrocarbon-Contaminated and Uncontaminated Soils

Previous work by Balks *et al.* (2002) suggested that hydrocarbon-contaminated soils, which had a darkened soil surface and decreased soil albedo, had higher weekly maximum soil temperatures than the controls during sunny periods with no snow cover. The study undertaken by Balks *et al.* (2002) was based on the data collected from Marble Point and Scott Base from the climate stations used in this study, and included both the TDR temperature data and also data from a number of additional temperature probes. However, similar results were expected.

The Marble Point hydrocarbon-contaminated soils had warmer summer maximum temperatures than the control soils, by about 2°C. The number of freeze-thaw events at Marble Point was significantly fewer at the hydrocarbon-contaminated site than the adjacent control or the climate station ($p<0.05$). This may be because the hydrocarbon-contaminated soils were consistently warmer than the control, consequently may not freeze when the soil cools during the night period. At Scott Base the number of freeze-thaw cycles in the hydrocarbon-contaminated soils were similar to the control soils. At both Marble Point and Scott Base the total number of hours with the soil temperature greater than 0°C was similar for both the hydrocarbon-contaminated and control soils.

The results obtained by this study, while only being indicative, show differences between the soil temperature regime of hydrocarbon-contaminated soils and control soils using temperatures measured only by the TDR probes for the 1999/2000 and 2000/01 summers. At Marble Point, the results indicated warmer soils in the hydrocarbon-contaminated soils compared to the adjacent control and the climate station soil, while at Scott Base, the results were inconclusive.

7.6.2 Comparison of Soil Moisture Properties Between Hydrocarbon-Contaminated and Uncontaminated Soils

At Scott Base the maximum liquid soil moisture content was significantly greater in the hydrocarbon-contaminated soil compared to the climate station ($p<0.01$), but only significantly higher at the 5 cm depth of the hydrocarbon-contaminated soil compared to the adjacent control ($p<0.05$). At Marble Point, the maximum liquid soil moisture content was significantly higher in the hydrocarbon-contaminated soil compared to the adjacent control ($p<0.10$), but not compared to the climate station. The differences in maximum soil moisture contents recorded at each site are likely to be due to spatial variation. At Scott Base the hydrocarbon-contaminated site was subject to surface water runoff and ponding, while the Marble Point hydrocarbon-contaminated site was located lower down the slope than the climate station and consequently was more prone to water runoff. The location of the datalogger at Marble Point hydrocarbon-contaminated site caused a snowdrift, which may have increased the moisture available at the site. Both Scott Base and Marble Point had fewer ($p<0.15$) hours with a liquid moisture content >5% in the adjacent control soil than in the hydrocarbon-contaminated soils in the near-surface soils (5 cm depth). Therefore, it is suggested that the hydrocarbon-contaminated soils near the surface dried faster than the adjacent control soil. This may be due to the warmer soil maximum temperatures leading to increased evaporation of the soil moisture and consequently quicker drying, or lower background moisture contents (spatial variability). The weak hydrophobicity of the hydrocarbon-contaminated soils (Balks *et al.*, 2002) may have also influenced soil drying.

7.6.3 Effects of Soil Moisture and Temperature on Micro-organisms

Microbial growth, and consequently bioremediation of hydrocarbon-contaminated sites in Antarctica, has been suggested to be limited by several factors including soil temperature, moisture and nutrient availability, and soil pH (Balks *et al.*, 1998). Biodegradation of hydrocarbons by micro-organisms has been noted to occur in temperatures as low as –1.1°C, although at very low rates (Walworth *et al.*, 2001). Optimal rates for biodegradation of hydrocarbons have been suggested to be in the range of 15 to 30°C (Mohn and Stewart, 2000). However, hydrocarbon degrading microbes have been shown to be active in temperatures less than the optimal range (Mohn and Stewart, 2000). The soils considered at Scott Base and Marble Point reached temperatures within the optimal range of hydrocarbon degradation, although often for short periods due to diurnal temperature fluctuations. However, the soils of Scott Base and Marble Point do spend a considerable period of time each summer with soil temperatures greater than 0°C – over 1200 hours in the 1999/2000 summer, and just over 550 hours during the 2000/01 summer. These could be considered periods where the soil temperature was in a range suitable for hydrocarbon degradation in Antarctic soils.

Soil moisture availability is also considered to be another limiting factor for microbial growth and biodegradation of hydrocarbons, with 10-20% moisture content considered optimal (King *et al.*, 1992). Soil moisture contents at Scott Base and Marble Point rose to and above 10-20% during the summer for short periods (generally no more than a few hours). Higher moisture levels were not maintained for long periods as the soil dried out or froze. Background soil moisture contents in the coastal Scott Base and Marble Point environments were between 5 and 10% – lower than conditions considered optimal.

The optimal limits for hydrocarbon biodegradation (soil temperature of 15-30°C, and moisture content of 10-20%) didn't occur simultaneously at any point at either Scott Base or Marble Point in any of the three years considered (Table 7.3). However, there were a few hours per year at each site where at least one of the parameters for optimal microbial growth and biodegradation did occur. If soil moisture and temperature conditions are considered in which microbial growth is possible, but not optimal (i.e. soil temperature >0°C and soil moisture content >5%), there were a few hundred hours each summer for microbial growth and hydrocarbon biodegradation (Table 7.3).

Table 7.3: Near-surface (2-5 cm) cumulative total hours with soil moisture and temperature set to different limits at Scott Base and Marble Point for three summers (1999/2000, 2000/01 and 2001/02). Data are averages from the replicated TDR probes at each climate stations site.

Soil Moisture Content		**Soil Temperature**			
		>0°C	>5°C	>10°C	>15°C
Scott Base					
>5%	**1999/2000**	349	115	6	0
	2000/01	341	7	0	0
	2001/02	765	336	86	0
>10%	**1999/2000**	11	6	0	0
	2000/01	61	3	0	0
	2001/02	9	0	0	0
Marble Point					
>5%	**1999/2000**	125	58	4	0
	2000/01	135	11	0	0
	2001/02	347	276	114	4
>10%	**1999/2000**	0	0	0	0
	2000/01	35	0	0	0
	2001/02	0	0	0	0

7.7 Conclusions

- The general soil moisture and temperature regimes in hydrocarbon contaminated soils were similar to the nearby climate stations (Chapter 6);
- The maximum soil temperatures recorded in the hydrocarbon-contaminated soil at Marble Point were approximately 2°C warmer than the climate station soil;
- At both Scott Base and Marble Point the total number of hours with a moisture content of >5% was higher in the adjacent control soil than the hydrocarbon-contaminated soil at the surface;
- Maximum liquid soil moisture contents were often higher in the hydrocarbon-contaminated soils, which is likely to be due to spatial variability.
- Limitations to data interpretation at the hydrocarbon-contaminated sites include lack of replication, probe accuracy limitations, and spatial variability between the hydrocarbon-contaminated sites and the nearby control sites. Therefore only general comparisons between hydrocarbon-contaminated sites and controls can be made from the data presented here;
- No conditions of optimal soil temperature (suggested to be 15-30°C) and concurrent optimal moisture content (suggested to be 10-20%) for microbial growth and hydrocarbon biodegradation occurred over the monitoring period at either Scott Base or Marble Point.
- There were periods up to about 760 hours at Scott Base and about 350 hours at Marble Point, each summer at the 2-5 cm soil depth when the soil temperature was >0°C and concurrently the soil moisture was >5%, and would be expected to support some microbial activity.

Chapter 8 –Discussion and Conclusions

8.1 Discussion

The installation of soil climate stations in the Ross Sea region of Antarctica has allowed investigation of the soil moisture and temperature regimes of three sites. The Hydra (TDR) probes have been shown to be effective in determining the volumetric liquid soil moisture content of Antarctic soils to an accuracy of ±3%, thus allowing changes in liquid soil moisture content (>3%) of the soils during the summer periods to be identified. The changes in soil moisture content (>3%) throughout the summer are associated, firstly with the initial thaw where the surface snow and ice and sub-surface ice melts, and secondly melting of snowfalls throughout the summer. Many of the smaller snowfalls were subject to sublimation, and consequently were not registered in the soil moisture record. There were differences in the moisture and temperature regimes between the coastal Scott Base and Marble Point soils, and the inland Wright Valley soils.

Hydrocarbon-contamination of soils has occurred in Antarctica for many years, with the soil climate stations set up partly to monitor and determine the effect that the hydrocarbons can have on the physical environment at Scott Base and Marble Point. The Hydra (TDR) probes have been shown to be effective tools for monitoring the moisture content of hydrocarbon-contaminated soils because the measurement technique is only minimally affected by presence of hydrocarbons. While there are several differences between the contaminated and uncontaminated soils, too many limitations remain for the differences, particularly in regards to the soil moisture regime, to be confidently interpreted as being the result of hydrocarbon-contamination, rather than spatial variability.

8.2 Summary and Conclusions

8.2.1 Soil Properties

- Soil pH was higher in the coastal Scott Base soils (median pH = 8.1) than the inland Wright Valley and Bull Pass soils (median pH = 6.7);
- Soil electrical conductivities were higher in the Wright Valley and Bull Pass soils (median EC = 2 970 μS cm^{-1}) than the Scott Base soils (median EC = 354 μS cm^{-1});
- The soil moisture content was lower in the Wright Valley and Bull Pass soils than the Scott Base soils;
- Soil dry bulk density was more variable in the Wright Valley and Bull Pass soils compared to the Scott Base soils, but mean dry bulk densities were similar (Scott Base ρ_b = 1.8 g cm^{-3}, Wright Valley and Bull Pass ρ_b = 1.7 g cm^{-3}).

8.2.2 Verification of Hydra (TDR) Probes

- Variations in volumetric moisture content (θ_v) between individual Hydra probes was about 1%;
- The Hydra probes underestimated the volumetric moisture content, compared to the gravimetric θ_v in soils that had a texture coarser than sand, by up to 2% for 37.5% gravel (by weight);
- The volumetric moisture content, as determined by the Hydra probes, was influenced by the soil temperature (at soil temperatures >0°C), with lower θ_v measurements at lower temperatures. Volumetric soil moisture content as recorded by the Hydra probes decreased by about 1% over the temperature change from 17°C to 4°C);
- The Hydra probe only measured the liquid moisture content of soils;
- The Hydra probe overestimated θ_v in soils that had high electrical conductivities. The θ_v overestimation was deemed to be caused by the high electrical conductivity of the soil solution, and when the soil solution electrical conductivity was within the range specified (0-20 000 μS cm^{-1})

by the manufacturers for effective operation, the overestimation was up to 5%;

- Hydrocarbons were not recorded by the Hydra probe as liquid soil moisture;
- The manufacturers suggested Hydra probe error of ±3% was concluded to be appropriate for use in Antarctic soils.

8.2.3 Moisture and Temperature Regimes of Three Antarctic Soils

- Soil-moistening events occurred up to five times each summer at Scott Base and Marble Point, but only occurred once in three summers in the Wright Valley;
- Soil moistening events increased the liquid soil moisture content up to 23% at Scott Base, 32% at Marble Point, and 6% in the Wright Valley;
- The soil had a moisture content >5% for an mean cumulative total hours of 860 at Scott Base, 1 in the Wright Valley and 310 at Marble Point over the 1999/2000, 2000/01 and 2001/02 summers;
- Following a snow-melt event, the soil took an average of 6 days to dry and return to background soil moisture contents, but was extended to about 12 days when freeze-thaw cycles occurred during drying;
- Freeze-thaw cycles were frequent in all three soils at 2-5 cm depth during the summer, with an average of 50 freeze-thaw cycles per summer at Scott Base, 79 in the Wright Valley, and 52 at Marble Point;
- The 2 cm depth soil temperature was >0°C for an mean cumulative total of 830 hours at Scott Base, 1680 hours in the Wright Valley, and 1100 hours at Marble Point during the 1999/2000, 2000/01 and 2001/02 summers;
- There was spatial and inter-annual variability in the soil moisture and temperature regimes of the Scott Base, Marble Point and Wright Valley soils.

8.2.4 Influences of Hydrocarbons on the Moisture and Temperature Regimes of Two Antarctic Soils

- The general soil moisture and temperature regimes in hydrocarbon contaminated soils were similar to the nearby climate stations (Chapter 6);
- The maximum soil temperatures recorded in the hydrocarbon-contaminated soil at Marble Point were approximately 2°C warmer than the climate station soil;
- At both Scott Base and Marble Point the total number of hours with a moisture content of >5% was higher in the adjacent control soil than the hydrocarbon-contaminated soil at the 2-5 cm depth;
- Maximum liquid soil moisture contents were often higher in the hydrocarbon-contaminated soils, which is likely to be due to spatial variability.
- Limitations to data interpretation at the hydrocarbon-contaminated sites include lack of replication, probe accuracy limitations, and spatial variability between the hydrocarbon-contaminated sites and the nearby control sites. Therefore only general comparisons between hydrocarbon-contaminated sites and controls can be made from the data presented here;
- No conditions of optimal soil temperature (suggested to be 15-30°C) and concurrent optimal moisture content (suggested to be 10-20%) for microbial growth and hydrocarbon biodegradation occurred over the monitoring period at either Scott Base or Marble Point.
- There were periods up to about 760 hours at Scott Base and about 350 hours at Marble Point, each summer at the 2-5 cm soil depth when the soil temperature was >0°C and concurrently the soil moisture was >5%, and would be expected to support some microbial activity.

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Appendix 1 – Soil Profile and Site Descriptions

1. Introduction

This Appendix provides the soil profile and site descriptions for all of the soil climate stations in the Ross Sea region (Paetzold, unpublished data), including Scott Base, Wright Valley, Marble Point, Mt Fleming, Victoria Valley, Minna Bluff, and Granite Harbour. Soil profile and site descriptions for the three hydrocarbon-contaminated soil climate stations at Scott Base, the Wright Valley and Marble Point are also included. Locations of each site described are indicated on Figure 4.7. The soil and site descriptions of all of the soil climate stations in the Ross Sea region are included in this thesis is so that they are all reported in one place.

Soil profile and site descriptions from Scott Base, the Wright Valley and Bull Pass for the sites that were sampled for the purpose of this thesis are also included in this Appendix.

2. Soil Profile and Site Descriptions for the Ross Sea Region Soil Climate Stations

2.1 Scott Base

Described By:	John Kimble and Iain Campbell
Date:	1999
Location:	
Southing:	77° 50' 53.9'' S
Easting:	166° 45' 40.7'' E
Elevation:	60 m
	Immediately uphill of Hatherton Lab, about 200 m from Scott Base
Site Description:	
Slope Characteristics:	
Slope:	6%
Aspect:	135°
Physiography:	
Local:	Mountainside
Major:	Glaciated upland
Geomorphic Position:	back slope, of a side slope
Moisture Regime:	Aridic (torric) moisture regime
Landuse:	Tundra
Natural Drainage Class:	Well drained
USDA Classification:	Loamy-skeletal, mixed, superactive, hypergellic Typic Anhyorthel
Parent Material:	Scoriaceous Basalt with minor inputs of glacially derived gravel and sand fragments of mixed lithology
Climate:	Moist coastal
Weathering Stage:	I
Depth to Ice-Cemented Ground:	30 cm

Depth to Permafrost: 30 cm

Soil Description:

Depth (cm)	*Description*
0–1	Grayish brown (10 YR 5/2) gravelly sandy loam, very dark grayish brown (10 YR 3/2) moist; moderate fine and medium lenticular platy and single grain; soft, very friable, non-sticky and non-plastic; non-effervescent (HCl, 1 normal); 30% angular basaltic-ash gravel; abrupt smooth boundary.
1–7	Pale brown (10 YR 6/3) gravelly sandy loam, very dark grayish brown (10 YR 3/2) moist; moderate very fine and fine single grain; loose, loose, non-sticky and non-plastic; non-effervescent (HCl, 1 normal); 30% angular basaltic-ash gravel; clear smooth boundary.
7–15	Brown (10 YR 5/3) gravelly sandy loam, dark grayish brown (10 YR 4/2) moist; moderate very fine and fine single grain; loose, loose, non-sticky and non-plastic; non-effervescent (HCl, 1 normal); 35% angular basaltic-ash gravel; clear smooth boundary.
15–30	Brown (10 YR 5/3) gravelly sandy loam, brown (10 YR 4/3) moist; moderate very fine and fine single grain; loose, loose, non-sticky and non-plastic; non-effervescent (HCl, 1 normal); 35% angular basaltic-ash gravel; abrupt smooth boundary.

2.2 Wright Valley

Described By: John Kimble and Iain Campbell
Date: 1999

Location:
Southing: 77° 31' 05.7'' S
Easting: 161° 51' 57.3'' E
Elevation: 152 m
In Wright Valley on Moraine / fan 400 m E of Bull Pass camp and approximately 500 m SW of bottom of Bull Pass

Site Description: On convex shoulder of low angle fan (slope 4° to south), many large rocks/boulders on surface, distinct desert pavement with approximately 20% rock cover.

Slope Characteristics:
Slope: 3%
Aspect: 180°
Physiography:
Local: Outwash terrace
Major: Glaciofluvial Landform
Geomorphic Position: Foot slope, of a side slope
Moisture Regime: Aridic (torric) moisture regime
Landuse: Barren land
Natural Drainage Class: Well drained
Erosion: Class 3 wind erosion

USDA Classification: Fine-silty, mixed, subactive hygergillic Typic Anhyorthel
Coarse-loamy, mixed, superactive, hygergillic Nitric Anhyorthel (Paetzold, unpublished data)

Parent Material: Strongly weathered glacial till from igneous-intermediate (e.g. diorite) over strongly weathered glacial till from igneous-granite.

Climate: Dry inland (precipitation 13 mm)

Weathering Stage[1]: III

Depth to Ice-Cemented Ground: not encountered

Depth to Permafrost: approximately 70 cm

Soil Description:

Depth (cm)	*Description*
0–3	Light brownish gray (10 YR 6/2) very gravelly sand, very dark grayish brown (10 YR 3/2) moist; single grained; loose, loose, non-cemented, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); abrupt smooth boundary.
3–12	Brown (10 YR 5/3) silt loam, brown (10 YR 4/3) moist; slightly hard, very friable, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCl , 1 normal); abrupt irregular boundary.
12–18	Light gray (10 YR 7/2) silt loam, brown (10 YR 5/3) moist; massive and single grain; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); clear smooth boundary
18–28	Light gray (10 YR 7/2) silt loam, dark grayish brown (10 YR 4/2) moist; massive and single grain; slightly hard, loose, non-cemented, brittle. Non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); clear smooth boundary.
28–38	Very pale brown (10 YR 7/3) silt loam, brown (10 YR 4/3) moist; massive and single grain; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); clear smooth boundary.
38–51	Light brownish gray (10 YR 6/2) silt loam, brown (10 YR 5/3) moist; massive and single grain; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); clear smooth boundary.

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[1] According to weathering stages as outlined by Campbell and Claridge (1987)

51–78	Light brownish gray (10 YR 6/2) silt loam, brown (10 YR 5/3) moist; massive and single grain; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); clear smooth boundary.
78–109	Very pale brown (10 YR 7/3) gravelly silt loam, brown (10 YR 4/3) moist; massive; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; slightly effervescent throughout (HCL, 1 normal); clear smooth boundary.
109–130	Light gray (10 YR 7/2) gravelly silt loam, grayish brown (10 YR 5/2) moist; massive and single grain; slightly hard, loose, non-cemented, brittle, non-sticky and non-plastic; strongly effervescent throughout (HCl, 1 normal).

2.3 Marble Point

Described By:	John Kimble and Iain Campbell
Date:	1999
Location:	
Southing:	77° 25’ 9.9’’ S
Easting:	163° 40’ 55.1’’ E
Elevation:	60 m
	Marble Point Old Camp, approximately 60 m east of lake edge, approximately 25 m north of bulldozed “track” 120 m west of oil spill area
Site Description:	Very gently sloping (3°) area of glacial till material, easterly aspect, surface relatively undisturbed (never been bulldozed). Surface comprised about 30% surface rocks, rest is gravel/sand pavement material.
Slope Characteristics:	
Slope:	3%
Aspect:	180°
Physiography:	
Local:	fluvial terrace
Major:	glaciofluvial landform
Geomorphic Position:	back slope, of a nose slope
Moisture Regime:	Aridic (torric) moisture regime
Landuse:	Tundra
Natural Drainage Class:	Well drained
Erosion:	–
USDA Classification:	Sandy-skeletal, Mixed, Superactive Calcic Haplorthel Sandy-skeletal, mixed, superactive Hypergellic Calcic Anhyorthel at main site; Loamy-skeletal, mixed, Hypergellic Typic Haplorthel at remote site
Parent Material:	slightly weathered glacial till from marble over slightly weathered glacial till from gneiss over slightly weathered glacial till from igneous-granite

Climate: Moist coastal (precipitation 200 mm)

Weathering Stage: I

Depth to Ice-Cemented Ground: 70 cm

Depth to Permafrost: 70 cm

Soil Description:

Depth (cm)	*Description*
0–3	Dark grayish brown (10 YR 4/2) very gravelly sand, very dark grayish brown (10 YR 3/2) moist; single grain; loose, non-cemented, non-smeary, low toughness, non-sticky and non-plastic; strongly effervescent throughout (HCl, 1 normal); 1% marble cobbles and 1% gneiss cobbles and 1% igneous-granite cobbles; clear smooth boundary.
3–15	Brown (10 YR 4/2) very gravelly sand, dark brown (10 YR 3/3) moist; strong single grain; loose, loose, non-cemented, non-smeary, low toughness, non-sticky, and non-plastic; very slightly effervescent throughout (HCl, 1 normal); 1% marble cobbles and 1% gneiss cobbles; clear smooth boundary.
15–32	Brown (10 YR 5/3) very gravelly sand, dark brown (10 YR 3/3) moist; strong single grain; loose, loose, non-cemented, non-smeary, low toughness, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); 1% marble cobbles and 1% gneiss cobbles and 1% igneous-granite cobbles; clear smooth boundary.
32–45	Grayish brown (10 YR 5/2) very gravelly sand, dark brown (10 YR 3/3) moist; strong single grain; loose, loose, non-cemented, non-smeary, low toughness, non-sticky and non-plastic; strongly effervescent throughout (HCL, 1 normal); 1% marble cobbles and 1% gneiss cobbles and 1% igneous-granite cobbles; clear smooth boundary.
45–69	Pale brown (10 YR 6/3) very gravelly sand, brown (10 YR 4/3) moist; strong single grain; loose, loose, non-cemented, non-smeary, low toughness, non-sticky and non-plastic; violently effervescent (HCl, 1 normal); 1% marble cobbles 1% gneiss cobbles and 1% igneous-granite cobbles; clear smooth boundary.
69–100	1% marble cobbles

2.4 Mt. Fleming

Described By:	Megan Balks
Date:	5 Jan 2002
Location:	
Southing:	77° 32' 42.7'' S
Easting:	166° 17' 24.6'' E
Elevation:	1698 m
	Cirque on north side of Mt. Fleming, above cliff next to VXE6 ice fall at head of Upper Wright glacier, in area of coarse patterned ground, in middle of patterned ground polygon
Site Description:	On a gently sloping, wide shouldered, ridge which slopes to the south (although the overall slope of the area is to the north). On coarse patterned ground with many large dolerite boulders on polygons and patterned ground cracks about 1 m wide dominated by sandy material. Polygons were high-centred, about 10 to 15 m across with a vertical relief of about 1 m. Surface generally snow-free though blowing snow did accumulate on the surface for short periods
USDA Classification:	–
Parent Material:	Mixed lithology with dolerite dominant and sandstone and granite common. Glacial till, possibly with ground ice beneath

Soil Description:

Depth (cm)	*Description*
0–2	Desert pavement, very strongly weathered, polished and pitted boulders and gravels with (10 YR 6/3 dry, 10 YR 5/4 moist) coarse sand, surface boulders cover about 60% of surface, are up to 1 m in diameter, and have strong desert varnish and ventifaction. Dolerite is dominant with sandstone and granite also present; gravels are sub-angular, desert varnished, many ventifacted, dolerite and quartz dominate, sands are coarse, loose and weathered to FeO colours, about 2% moisture, distinct irregular boundary;

2–8	Strongly weathered bouldery gravelly, (10 YR 6/6 dry, 10 YR 5/4 moist) coarse sand (estimate 98% sand, 2% silt), common 0.5-0.8 cm thick, white, salt crusts under larger stones. About 20% 10-40 cm diameter boulders, angular, some strongly weathered (so fall apart when disturbed), dolerite dominant, but granite and sandstone also present. About 30% gravels, angular (rocks split to gravel size), weakly to strongly weathered, dolerite dominant with granite, sandstone and some rounded quartz pebbles, about 7% moisture (following recent snow), distinct, irregular boundary;
8–20	Weakly weathered gravelly (2.5 Y 7/2 dry, 2.5 Y 5/2 moist) silty sand (estimate 70% fine sand, 30% silt), no salts visible, about 10% unweathered angular gravel, with an occasional (10%) up to 20 cm diameter, non to weakly weathered, angular boulder, about 5% moisture, diffuse, smooth boundary;
20–45	Relatively unweathered gravelly (2.5 Y 6/2 dry, 2.5 Y 4/2 moist) silty sand. About 10% unweathered, angular gravel and rocks, about 2% moisture, sharp distinct boundary;
45–70+	Ice cemented ground, similar material to the horizon above, but with sufficient water to cement (16% moisture, sample appeared to be saturated when thawed) (2.5 Y 5/1 wet)

Soil Description (2): Patterned ground crack about 1 m from foot of climate station on Wright Valley side was also described. Soil was similar to that above but no large stones on surface, though plenty in subsurface, sand/gravel layer was up to 8 cm thick compared to 2 cm in mid-polygon.

Depth (cm)	*Description*
0–8	Strongly weathered (7.5 YR 5/2 dry, 7.5 YR 3/3 wet) sandy fine gravel, only occasionally stone, <1% moisture, distinct irregular boundary;
8–13	Weathered (10 YR 7/3 dry, 10 YR 5/3 wet) gravelly coarse sand, similar to 2–8 cm horizon in polygon site above, common angular rocks, 2% moisture, distinct irregular boundary;
13–30+	Relatively unweathered (2.5 Y 7/2 dry, 2.5 Y 6/2 wet) silty sand, 2% moisture.

2.5 Victoria Valley

Described By: Megan Balks and Ron Sletten
Date: 10 Jan 2002

Location:
Southing: 77° 19' 51.3'' S
Easting: 161° 36' 02.2'' E
Elevation: 411 m

Victoria Valley on true right bank of river/lake at lower end of Lake Victoria. About 20 m down valley from a dolerite dominated recessional moraine, on coarse low-centred patterned ground polygons, approximately 300 m from lake edge

Site Description: Large (15-35 m diameter) low-centred, fairly flat (<1 m vertical relief), patterned ground polygons formed from gravel and sand materials, very few rocks evident. Surface considered to be about 10 000 years old and a former lake bed (by Ron Sletten)

USDA Classification: –

Parent Material: Dominated by granite with marble and sandstone

Depth to Ice-Cemented Ground: 40 cm

Soil Description:

Depth (cm)	*Description*
0–2	Desert pavement, weakly weathered (10 YR 7/2 dry, 10 YR 5/2 wet), gravelly sand, (estimate 70% gravel, 30% sand), colours of individual grains are evident, occasional thin (<0.5 mm) intermittent salt accumulations on base of stones, <1% moisture, distinct smooth boundary;
2–8	Weakly cemented (10 YR 7/2 dry, 10 YR 5/2 wet) gravelly sand (estimate 20% gravel, 77% sand, 3% silt), gravels are

	predominantly 1-50 mm in diameter, weakly weathered, sub-angular, cementation is sufficient to hold an overhang of up to 20 cm, 2% moisture, distinct smooth boundary;
8–40	Unweathered, stratified gravelly sand (estimate 20% gravel, 77% sand, 3% silt), gravels are predominantly 10-50 mm in diameter, weakly weathered, sub-angular. Colours are those of individual sand grains and range from dark grey to white, occasional pebble layer is evidence of former surface horizon, 2% moisture, sharp smooth boundary;
40–120+	Ice cemented material essentially similar to the horizon above as evidence by drill holes to install MRC probe.

2.6 Minna Bluff

Described By:	Megan Balks
Date:	January 2003

Location:

Southing:	78° 30.691' S
Easting:	166° 45.971' E
Elevation:	130 m
	North side of Minna Bluff, 45.91 miles directly south (bearing 180°) from Scott Base, on a line between Black and White Islands.

Site Description: Situated in rectangular patterned ground about 2/3 of the way from the Ross Ice Shelf edge to the steep side of Minna Bluff and about 50 m north of a long E-W oriented snow-filled depression

Geomorphic Position: Rectangular patterned ground – with patterns approximately 30 m × 15 m. The longer sides of the patterns generally ran north-south and were more pronounced than the cross-pattern cracks. The profile site was situated near the centre of a polygon. The vertical relief in the polygons was about ±0.5 m. The overall area had a gentle (<5°) slope towards the north. The patterned ground area was relatively flat overall but was bounded to the north and east by areas of strongly hummocky material (relief of up to about 10 m) which showed evidence of ice melt-out still occurring and numerous "kettle" lakes.

USDA Classification: –

Parent Material: Ablation till with basalt and granite dominated rock materials

Depth to Ice-Cemented Ground: 34 cm

Soil Description:

Depth (cm)	*Description*
0-4 cm	Desert pavement. Gravelly coarse sand, colours are those of individual mineral grains, dry, salt accumulation beneath some

	rocks (1 sample). The desert pavement comprised dominantly basalts and dolerites, including scoreacious and porphoritic basalts. Granites (pink, red, grey and white dominated) were common with a range of other rock types seen occasionally including Beacon sandstone, weathered marble, angular conglomerates and shale. The pavement materials were generally moderately rounded and smooth, a few with desert varnishing. (Generally more weathered than Marble point). The pavement comprised about 5% large boulders (>30 cm diameter), 10% medium boulders (20-30 cm diameter), 20% stones (5-20 cm diameter) and remainder gravel and coarse sand. Distinct, smooth boundary;
4-10 cm	Brown (10 YR 4/4) gravelly loamy sand (estimate 2% silt and clay in <2 mm fraction), moisture content of <2 mm fraction was 15% , loose, gravel content variable – ranging from about 30 to 70%, no salts seen, diffuse boundary;
10-30 cm	Dark brown (10 YR 3/3) gravelly loamy sand (estimate 2% silt and clay in <2 mm fraction), slightly moist (<2 mm fraction was 10%), very loose, gravel content variable – ranging from about 30 to 70%, measured as 64% by weight >5.6 mm, 17% by weight 2.6 – 2 mm and 19% <2 mm, no salts seen, sharp smooth boundary;
30-60 cm	Dull yellowish brown (10 YR 4/3) gravelly icy sandy silt loam (estimate 60% silt and 10% clay in <2 mm fraction), ice saturated (>50% ice), ice-cemented, very sticky when melted, gravel content about 30%, boulders about 1%, no salts seen, diffuse smooth boundary;
60-80+ cm	Grayish yellow brown (10 YR 4/2) gravelly icy sandy silt loam (estimate 60% silt and 10% clay in <2 mm fraction), ice saturated (>50% ice), ice-cemented, very sticky when melted, gravel content about 10%, boulders about 1%, no salts seen.

2.7 Granite Harbour

Described By: Megan Balks
Date: January 2003

Location:
Southing: 77° 23.6’ S
Easting: 162° 32.4’ E
Elevation: 5 m
West end camping area adjacent to the Botony Bay SSSI between Cape Geology and New Glacier

Site Description: Situated on small (5 m wide) terrace (marine bench?) about half way between edge of ice sea and base of cliff

Geomorphic Position: Narrow (approximately 100 m wide) fan/lateral moraine between cliff-face and edge of sea ice in Granite Harbour. Overall slope of about 10° towards the sea (north west). Upper half of the slope composes predominantly angular granite blocks and boulders and has a colluvial fan form (with water flowing beneath the fan surface in some areas). The finer soil material shows evidence of some weathering. The lower half of the slope comprises predominantly rounded granite boulders in a matrix of well-sorted unweathered sand reminiscent of beach sand. Our site was located just up-hill of the interface between the two areas. The half of the slope is dominated by the colluvial fan processes and material falling from the adjacent rock-face. The lower half may be, in part lateral moraine material but it is likely that it represents a raised beach surface

USDA Classification: –

Parent Material: Granite dominated rock materials, possibly some sand reworked by marine and glacial processes.

Depth to Ice-Cemented Ground: 80 cm

Vegetation: Abundant mosses and lichens occur in moist and sheltered areas among the rocks uphill of the site, no obvious vegetation downhill of the site. Site was just below a smaller moss patch where there is evidence of surface moisture flow having occurred during the melt.

Soil Description:

Depth (cm)	*Description*
0-2 cm	Desert pavement comprises about 50% granite boulders greater than 80 cm diameter, some up to 5 m in diameter, 30% granite boulders and stones of less than 80 cm diameter, 10% sand and 10% granite gravel. Boulders are rounded and weathering by grains falling off. A small amount of iron oxidation is visible on some boulders. The matrix is gravelly coarse sand which comprises angular mineral grains from the granite, colours are those of individual minerals, minimal chemical weathering, dry, loose, distinct smooth boundary;
2-10 cm	Dull yellowish brown (10 YR 5/4 dry, 10 YR 4/4 moist) gravelly coarse sand which comprises rounded mineral grains from granite, moderately weathered with a trace (<1%) of silt and clay and some iron oxides, dry loose, no salts seen, diffuse smooth boundary;
10-20 cm	gravelly coarse angular sand, minimal chemical weathering, colours are those of granite minerals (pink, white, grey, black), loose, dry, no salts seen, distinct wavy (±10 cm) boundary;
30-70 cm	Dull yellowish brown (10 YR 4/3) loamy fine sand, sand is very uniform and well sorted, and does not have the individual granite minerals obvious (maybe a beach deposit?) moist, firm in-situ (holds vertical walls in pit), few angular stones (about 10%), few granite gravels (about 5%), occasional lenses of coarse granite sand (ghosts of boulders), irregular distinct boundary;
70-80 cm	Gravelly coarse sand, 70% strongly interlocking stones and boulders, sand is unweathered granite mineral grains in granite mineral colours, this horizon is interpreted as a buried former desert pavement, indistinct irregular boundary;
80-90+ cm	Ice-cemented sands with many rocks.

3. Soil Profile and Site Descriptions for the Hydrocarbon-Contaminated Soil Climate Stations

3.1 Scott Base Hydrocarbon-Contaminated Soil

No soil profile and site descriptions were reported for the Scott Base hydrocarbon-contaminated soil

3.2 Wright Valley Hydrocarbon-Contaminated Soil

Described By:	John Kimble and Iain Campbell
Date:	1999
Location:	
Southing:	77° 31' 01.8'' S
Easting:	161° 51' 09.5'' E
Elevation:	–
	At Bull Pass camp in the Wright Valley, 10 m downhill from seismic hole in till-filled gully between granite bedrock outcrops
Site Description:	On margin of sloping plain that reaches from base of steep valley-side to Onyx River (about 1 km) and makes up floor of Wright Valley in the Bull Pass vicinity. Plain has gravel desert pavement but no boulder/rock till material present on it. Site is on outer edge of plain, marginal to granite bedrock outcrop. Diesel was not obviously evident at the soil surface – a new desert pavement had formed that was indistinguishable from the surrounding landscape. Diesel smell / presence was stronger at bedrock interface, suggesting that flow was perching on the bedrock base. Site has slope of 7° to south.
USDA Classification:	Typic Anhyorthel

Parent Material:	Silt dominated glacial till material – with a few large, predominantly granite rocks. Granite bedrock at about 70 cm
Climate:	Dry inland
Weathering Stage:	III
Depth to Ice-Cemented Ground:	Not encountered

Soil Description:

Depth (cm)	*Description*
0–2	Dry desert pavement comprising pebbly sand. Rounded pebbles, granite dominated, distinct smooth boundary;
2–8	Dry sand, distinct smooth boundary;
8–16	Dry consolidated sand / silt, distinct smooth boundary;
16–35	Gravelly sandy silt, many moderately weathered rounded gravels with FeO coatings on surfaces, white salt efflorescence's formed following exposure to air, distinct convoluted boundary;
35–50	Dry sand, distinct discontinuous boundary;
50–60	Slightly moist, weathered bedrock with iron-stained sandy silt in joints, very strong diesel smell, distinct irregular boundary;
60–65	Dull grey silty clay material directly above bedrock, moist, very strong diesel odour, sharp boundary to granite bedrock.

3.3 Marble Point Hydrocarbon-Contaminated Soil

Described By:	John Kimble and Iain Campbell
Date:	1999
Location:	
Southing:	77° 25' 11.9'' S
Easting:	163° 41' 12.7'' E
Elevation:	55 m
	Marble Point Oil Spill site at Old Marble Point Camp, approximately 200 m from source of stream, approximately 100 m from stream on left bank.
Site Description:	Relatively flat area of glacial till material, micro-topography gently concave area. A series of oil spills are evident with dark coloured hydrocarbon material exposed at the soil surface. Soil surface in the wider area has been bulldozed but no obvious movement of material has occurred at the sample site. Surface comprised about 10% surface rocks, rest is hydrocarbon coated gravel/sand material.
Slope Characteristics:	
Slope:	0%
Aspect:	–
Geomorphic Position:	in a depression, toe slope, of an interfluve
Landuse:	Waste disposal land
USDA Classification:	Loamy-Skeletal, Mixed, Hygerillic Typic Haplorthel Loamy-skeletal, mixed, superactive, Hypergellic Calcic Anhyorthel
Parent Material:	slightly weathered glacial till from marble over slightly weathered glacial till from gneiss over slightly weathered glacial till from igneous-granite

Climate:	Moist coastal (precipitation 200 mm)
Weathering Stage:	I
Depth to Ice-Cemented Ground:	65 cm
Depth To Permafrost:	65 cm

Soil Description:

Depth (cm)	*Description*
0–15	Dark brown (10 YR 3/3) gravelly sand, brown (10 YR 5/3) dry; strong fine and medium single grain; loose, loose, low toughness, non-sticky and non-plastic; slightly effervescent throughout (HCl, 1 normal); 15% subangular marble gravel and 15% subangular gneiss gravel and 5% angular marble stones.
15– 30	Dark brown (10 YR 3/3) very gravelly sand, pale brown (10 YR 6/3) dry; strong fine and medium single grain; loose, loose, low toughness, non-sticky and non-plastic; strongly effervescent throughout (HCl, 1 normal); 10% subangular marble gravel and 10% subangular gneiss gravel and 30% angular marble stones.
30–50	Dark grayish brown (10 YR 4/2) very gravelly clay loam, pale brown (10 YR 6/3) dry, strong very fine angular blocky structure; hard, high toughness, slightly sticky and slightly plastic; strongly effervescent throughout (HCl, 1 normal); 10% subangular marble gravel and 10% subangular gneiss gravel and 30% angular marble stones.
50–82	Dark yellowish brown (10 YR 4/4) very gravelly clay loam, pale brown (10 YR 6/3) dry; strong very fine angular blocky structure; hard, high toughness, slightly sticky and slightly plastic; violently effervescent throughout (HCl, 1 normal); 20% subangular marble gravel and 20% subangular gneiss gravel and 30% angular marble stones.

4. Soil profile and Site Descriptions of Soils sampled for the Purpose of This Thesis

4.1 Scott Base Site 2

Described By: Aaron Wall
Date: 12 Dec 2002

Location:
Southing: 77° 50.914' S
Easting: 166° 45.281' E
Elevation: 42 m
On spur facing south, on the flanks of Crater Hill, ~200 m from Scott Base

Site Description: 0% rock outcrops. 50% boulder outcrops
Slope Characteristics:
  Slope: 4°
  Aspect: 180°
Geomorphic Position: mid slope of flank of hill

USDA Classification: Lithic(?) Anhyorthel

Parent Material: Basalt

Depth to Ice-Cemented Ground: 25 cm

Soil Description:

Depth (cm)	*Description*
0–11	Colour: grayish yellow brown (5 Y 3/2). 2% salts of 1 mm size in a random pattern. 30% sand, 10% silt, 50% gravel, 10% boulders. Gravel – 2-6 mm sub-rounded basalt, boulders – <10 cm sub-angular basalt. Boundary – distinct (2-5 cm), irregular.
11–25	Colour: brownish gray (5 Y 3/1). 40% sand, 15% silt, 40% gravel, 5% boulders. Gravel – 2-6 mm, rounded basalt, boulders - <10 cm sub-angular basalt. Boundary – indistinct (5-10 cm), convolute.
>25	Colour: yellowish brown (10 YR 3/2). 50% sand, 15% silt, 30% gravel, 5% boulders. Gravel – 2-6 mm, rounded basalt, boulders - <10 cm, subangular basalt.

4.2 Wright Valley Site 1

Described By:	Aaron Wall
Date:	1 Dec 2002
Location:	
Southing:	77° 31.073' S
Easting:	161° 51.616' E
Elevation:	178 m
	Base of Bull Pass in the Wright Valley
Site Description:	On a slope facing south, bouldery, pebbly and sandy surface. In the Wright Valley, below Bull Pass near existing climate station. Half way between climate station and Bull Pass hut. Slopes towards Onyx River. 1% rock outcrops, 10% boulder outcrops
Slope Characteristics:	
Slope:	5°
Aspect:	180°
Geomorphic Position:	convex toe slope
Erosion:	Wind erosion of fine surface material
USDA Classification:	Typic Anhyorthel
Parent Material:	Dolerite and granite weathered material. Possibly aeolian sands and silts in the lower horizons also

Soil Description:

Depth (cm)	*Description*
0–4	Colour of sands and pebbles: yellow orange (10YR 8/6), bluish gray (10 BG 5/1), pale reddish orange (2.5 YR 7/4), light gray (10Y 8/1); 50% sand, <1% silt, 50% gravel; gravel – ~10 mm size, well rounded, of dolerite / granite lithology; smooth, sharp boundary.
4–26	Colour: silt – pale yellow (2.5 Y 8/3), sand – light gray (10 YR 8/2). Possible salt layers(?): colour – yellow orange (10 YR 7/8),

	5% abundance, layered pattern; 40% sand, 60% silt; indistinct, irregular boundary.
26–44	Colour: same as second horizon, including salts; 30% sand, 70% silt; indistinct, irregular boundary.
>44	Colour: same as second horizon, including salts; 20% sand, 80% silt.

4.3 Wright Valley Site 2

Described By:	Aaron Wall
Date:	2 Dec 2002
Location:	
Southing:	77° 31.456' S
Easting:	161° 52.930' E
Elevation:	147 m
	Base of Bull Pass in the Wright Valley, near the Onyx River
Site Description:	On patterned ground at base of fan / terrace from Bull Pass. On river terrace, one up from active flood plain of the Onyx River (~1 m). No rock outcrops. 2% boulder outcrops
Slope Characteristics:	
Slope:	<1°
Aspect:	90°
Geomorphic Position:	Flat terrace
Erosion:	Wind erosion of fine surface materials, possibly alluvial erosion at times
USDA Classification:	Typic Anhyorthel
Parent Material:	Dolerite and granite weathered material

Depth to Ice-Cemented Ground: 29 cm

Soil Description:

Depth (cm)	*Description*
0–8	Colour: sands – grayish brown (5YR 5/2), gravels: yellow orange (10YR 8/6), bluish gray (10 BG 5/1), pale reddish orange (2.5 YR 7/4), light gray (10Y 8/1); 80% sand, <2% silt, 20% gravel; gravel – <40 mm size, sub-angular, of dolerite -/ granite lithology; boulders – ~50 cm size, angular, of dolerite composition; distinct, wavy boundary.

8–18	Colour: brown (7.5 YR 4/3); 95% sand, <2% silt, <5% gravel; gravel – <10 mm size, sub-angular, of dolerite / granite lithology; distinct, occluded boundary.
18–29	Colour: sand – grayish brown (5 YR 4/2), gravel – same as 1st horizon; 50% sand, <2% silt 50% gravel; gravel – 10 – 40 mm size, sub-angular, of dolerite and granite lithology; abrupt, irregular boundary.
>29	Ice cemented 3rd horizon.

4.4 Wright Valley Site 3

Described By: Aaron Wall
Date: 2 Dec 2002

Location:
Southing: 77° 31.048' S
Easting: 161° 50.077' E
Elevation: 159 m
Wright Valley floor, at the foot of Mt Jason

Site Description: On the Wright Valley floor, about 500 m towards Lake Vanda from the Bull Pass hut site. At the foot of Mt Jason. No rock outcrops. 2% boulder outcrops

Slope Characteristics:
Slope: 2-3°
Aspect: 0°
Geomorphic Position: flat toe slope
Erosion: Wind erosion of fine surface materials

USDA Classification: Typic Anhyorthel

Parent Material: Dolerite and granite weathered material. Possibly aeolian sands and silts in the lower horizons also

Depth to Ice-Cemented Ground: Not encountered

4.5 Bull Pass Site 1

Described By:	Aaron Wall
Date:	3 Dec 2002

Location:

Southing:	77° 29.389' S
Easting:	161° 49.834' E
Elevation:	580 m On a sloping valley towards the east from Mt Jason, up in Bull Pass itself. <1% rock outcrops. 5% boulder outcrops

Site Description:

Slope Characteristics:	
Slope:	2°
Aspect:	90°
Geomorphic Position:	concave toe slope
Erosion:	Wind erosion of fine surface materials

USDA Classification:	Typic Anhyorthel
Parent Material:	Dolerite and granite eroded and weathered material. Possibly some sandstone origin also

Depth to Ice-Cemented Ground: 20 cm

Soil Description:

Depth (cm)	*Description*
0–7	Colour: sands – dull brown (7.5 YR 5/3), pebbles: bluish gray (10 BG 5/1), light gray (10Y 8/1); 90% sand, <1% silt, 5% gravel, 5% boulders; gravel – 10-50 mm size, sub-angular, of dolerite, granite and sandstone lithology; boulders – ~2 m, sub-angular shape, dolerite and granite lithology; distinct, irregular boundary.
7–18	Colour: dull brown (7.5 YR 5/3); 97% sand, <1% silt, 2% gravel; gravel – 2-4 mm size, sub-rounded shape, granite and dolerite lithology; sharp, irregular boundary.
>18	Colour: dull brown (7.5. YR 5/3); 95% sand, <1% silt, 5% gravel; gravel – 2-6 mm size, granite and dolerite boundary.

4.6 Bull Pass Site 2

Described By: Aaron Wall
Date: 2 Dec 2002

Location:
Southing: 77° 29.543' S
Easting: 161° 49.934' E
Elevation: 571 m
On the footslope of Mt Jason sloping into Bull Pass Valley

Site Description: On an east facing slope, sloping down towards Bull Pass valley from the west side of the range, about 2 km up from the Wright Valley. No rock outcrops. 10% boulder outcrops

Slope Characteristics:
Slope: 5°
Aspect: 90°
Geomorphic Position: convex footslope
Erosion: Wind erosion of fine surface materials

USDA Classification: Typic Anhyorthel

Parent Material: Unknown

Depth to Ice-Cemented Ground: 15 cm

4.7 Bull Pass Site 3

Described By:	Aaron Wall
Date:	2 Dec 2002
Location:	
Southing:	77° 30.090' S
Easting:	161° 52.418' E
Elevation:	491 m
	Top of the Wright Valley, where Bull Pass joins the Valley
Site Description:	In a hollow formed by dolerite rock, just before the drop from Bull Pass into the Wright Valley, on the western side of the Pass. 50% rock outcrops. 5% boulder outcrops
Geomorphic Position:	base of hollow
USDA Classification:	Lithic Anyhorthel
Parent Material:	Dolerite
Depth to Ice-Cemented Ground:	Not encountered

Appendix 2 – Soil Properties Summary and Raw Data

1. Summary of Soil Properties

1.1 Scott Base

Sample Number	Depth (cm)	Site Name	Bulk Density (g cm^{-3})	Gravimetric Moisture Content (θ_g) (g g^{-1})	Volumetric Moisture content [1] (θ_v) (cm^3 cm^{-3})	pH	Electrical Conductivity (µS cm^{-1})	Volumteric Moisture Content [2] (θ_v) (cm^3 cm^{-3})	Hydra Probe θ_v (cm^3 cm^{-3})
121	0-5 cm	SB Site 2	1.98	0.019	0.039	6.73	93	0.034	-
122	5-10 cm	SB Site 2	2.28	0.042	0.095	7.02	43	0.074	-
123	10-15 cm	SB Site 2	2.16	0.036	0.078	7.10	42	0.064	-
124	15-20 cm	SB Site 2	-	0.037	-	7.48	45	0.065	-
125	15-20 cm	SB Site 2	1.84	0.044	0.080	7.84	49	0.077	-
126	21-25 cm	SB Site 2	2.09	0.044	0.092	7.71	49	0.078	-
127	27-33 cm	SB Site 2	1.82	0.093	0.168	-	-	0.164	-
131	0-7 cm	-	1.70	0.083	0.140	7.51	101	0.146	0.117
132	0-8 cm	-	1.94	0.117	0.227	8.04	681	0.207	0.133
133	0-6 cm	-	1.80	0.078	0.141	7.49	86	0.138	0.068
134	0-6 cm	-	1.71	0.044	0.075	7.59	55	0.078	0.056
135	0-7 cm	-	1.62	0.093	0.150	6.76	1874	0.165	0.139
141	0-7 cm	-	1.81	0.029	0.052	7.27	332	0.051	0.024
142	0-7 cm	-	2.01	0.134	0.269	8.50	126	0.237	0.206
143	0-7 cm	-	1.98	0.031	0.061	8.55	261	0.054	0.047
144	0-8 cm	-	1.84	0.067	0.122	7.79	2710	0.118	0.114
145	0-7 cm	-	1.86	0.116	0.216	8.31	83	0.206	0.234
146	0-8 cm	-	2.03	0.043	0.088	9.01	1358	0.077	0.089
147	0-8 cm	-	1.83	0.042	0.077	7.77	1790	0.074	0.057
148	0-6 cm	-	1.96	0.226	0.444	8.08	180	0.400	0.424
151	0-5 cm	-	1.48	0.074	0.109	7.48	3273	0.131	0.161
152	0-5 cm	-	1.67	0.057	0.095	7.18	1690	0.101	0.100
153	0-5 cm	-	1.81	0.055	0.099	7.13	1942	0.097	0.111
154	0-5 cm	-	1.69	0.139	0.236	9.12	387	0.247	0.190
155	0-5 cm	-	1.17	0.107	0.125	9.19	459	0.189	0.070
156	0-5 cm	-	1.43	0.073	0.104	9.28	339	0.129	0.133
161	0-7 cm		1.62	0.042	0.069	9.42	1474	0.075	0.076
162	0-7 cm		1.89	0.066	0.126	8.94	118	0.117	0.113
163	0-8 cm		1.65	0.080	0.132	8.52	96	0.142	0.135
164	0-6 cm		1.43	0.103	0.147	8.36	138	0.182	0.210
171	0-6 cm	-	1.90	0.028	0.054	9.02	450	0.050	0.053
172	0-6 cm	-	1.97	0.039	0.078	9.17	381	0.070	0.052
173	0-7 cm	-	1.87	0.036	0.066	8.01	543	0.063	0.062
174	0-6 cm	-	2.52	0.081	0.204	9.15	317	0.143	0.135
175	0-6 cm	-	1.66	0.070	0.116	9.19	1617	0.123	0.109
176	0-8 cm	-	1.86	0.035	0.065	9.02	457	0.062	0.048
177	0-7 cm	-	1.97	0.030	0.059	8.10	426	0.053	0.084
178	0-9 cm	-	1.89	0.102	0.193	8.29	50	0.180	0.216
179	0-7 cm	-	2.07	0.105	0.217	8.23	73	0.186	0.197
180	0-7 cm	-	2.56	0.169	0.432	8.08	57	0.299	0.351
181	0-6 cm	-	1.83	0.025	0.047	7.54	46	0.045	0.014
182	0-8 cm	-	1.76	0.047	0.082	8.82	1210	0.083	0.071

[1] Calculated using the bulk density for that particular sample

[2] Calculated using an average bulk denisty for the site

1.2 Wright Valley

Sample Number	Depth (cm)	Site Name	Bulk Density ($g\ cm^{-3}$)	Gravimetric Moisture Content (θ_g) ($g\ g^{-1}$)	Volumetric Moisture content [1] (θ_v) ($cm^3\ cm^{-3}$)	pH	Electrical Conductivity ($\mu S\ cm^{-1}$)	Volumteric Moisture Content [2] (θ_v) ($cm^3\ cm^{-3}$)	Hydra Probe θ_v ($cm^3\ cm^{-3}$)
311	0-3 cm	WV Site 1	1.83	0.003	0.005	6.55	893	0.005	-
312	5-8 cm	WV Site 1	1.43	0.026	0.039	6.68	17130	0.043	-
313	8-12 cm	WV Site 1	1.35	0.020	0.028	6.32	2473	0.033	-
314	16-20 cm	WV Site 1	1.70	0.015	0.026	6.53	35067	0.025	-
315	24-28 cm	WV Site 1	1.67	0.018	0.030	6.54	12273	0.029	-
316	32-36 cm	WV Site 1	1.86	0.026	0.045	6.35	9093	0.043	-
321	0-4 cm	WV Site 2	2.08	0.007	0.014	6.59	2423	0.016	-
322	0-4 cm	WV Site 2	2.08	0.007	0.014	6.60	2270	0.015	-
323	0-1 cm	WV Site 2	2.30	0.005	0.013	6.61	2677	0.012	-
324	1-5 cm	WV Site 2	1.97	0.009	0.017	6.68	1456	0.020	-
325	5-10 cm	WV Site 2	2.07	0.014	0.029	6.06	666	0.030	-
326	10-15 cm	WV Site 2	2.35	0.012	0.027	6.09	668	0.027	-
327	5-10 cm	WV Site 2	-	0.005	-	6.55	532	0.011	-
331	0-5 cm	BP Site 1	1.36	0.042	0.059	6.60	3033	0.073	-
332	5-10 cm	BP Site 1	1.83	0.014	0.027	6.68	3617	0.025	-
333	10-15 cm	BP Site 1	1.81	0.008	0.014	6.76	2340	0.013	-
334	15-20 cm	BP Site 1	1.79	0.008	0.014	6.82	4680	0.014	-
335	20-25 cm	BP Site 1	1.83	0.008	0.015	6.86	6247	0.014	-
336	27-34 cm	BP Site 1	1.72	0.008	0.014	6.95	5060	0.014	-
341	0-3 cm	BP Site 2	0.69	0.072	0.053	6.74	14550	0.071	-
342	3-7 cm	BP Site 2	0.76	0.097	0.081	6.71	18223	0.096	-
343	7-11 cm	BP Site 2	0.78	0.100	0.085	6.72	17250	0.099	-
344	11-15 cm	BP Site 2	0.99	0.095	0.104	6.63	17360	0.095	-
345	15-20 cm	BP Site 2	1.31	0.113	0.165	6.63	17663	0.112	-
351	0-3 cm	BP Site 3	1.30	0.007	0.009	6.85	3003	0.011	-
352	3-7 cm	BP Site 3	1.70	0.011	0.018	7.14	809	0.017	-
353	7-8.5 cm	BP Site 3	1.80	0.016	0.030	7.31	528	0.027	-
354	0-5 cm	BP Site 3	-	0.013	-	7.14	3253	0.022	-
355	0-5 cm	BP Site 3	-	0.007	-	7.14	2393	0.011	-
356	0-5 cm	BP Site 3	-	0.004	-	7.37	1563	0.007	-
357	0-5 cm	BP Site 3	-	0.003	-	7.41	700	0.004	-
361	0-3 cm	WV Site 3	1.91	0.009	0.017	6.99	406	0.018	-
362	3-7 cm	WV Site 3	2.05	0.014	0.029	6.97	677	0.029	-
363	7-14 cm	WV Site 3	2.25	0.018	0.041	6.86	3683	0.037	-
364	16-22 cm	WV Site 3	1.91	0.006	0.012	7.00	3813	0.013	-
365	0-5 cm	WV Site 3	-	0.003	-	7.19	512	0.007	-
366	0-5 cm	WV Site 3	-	0.006	-	7.00	2107	0.011	-
367	0-5 cm	WV Site 3	-	0.004	-	7.06	1897	0.009	-
368	0-5 cm	WV Site 3	-	0.005	-	7.10	2657	0.011	-

[1] Calculated using the bulk density for that particular sample

[2] Calculated using an average bulk denisty for the site

1.3 Scott Base Hydrocarbon Contaminated Soil

Sample Number	Depth (cm)	Site Name	Bulk Density (g cm^{-3})	Gravimetric Moisture Content (θ_g) (g g^{-1})	Volumetric Moisture content [1] (θ_v) (cm^3 cm^{-3})	pH	Electrical Conductivity (µS cm^{-1})	Volumteric Moisture Content [2] (θ_v) (cm^3 cm^{-3})	Hydra Probe θ_v (cm^3 cm^{-3})
411	0-6 cm	-	1.55	0.018	0.028	8.19	68	0.030	0.016
412	0-6 cm	-	2.27	0.020	0.046	7.91	61	0.034	0.024
413	0-7 cm	-	2.11	0.023	0.048	7.71	91	0.038	0.001
414	0-7 cm	-	1.81	0.026	0.047	7.83	61	0.044	0.029
415	0-7 cm	-	1.85	0.028	0.052	7.59	62	0.047	0.010
416	0-6 cm	-	1.79	0.032	0.057	7.37	68	0.053	0.037
417	0-6 cm	-	1.53	0.014	0.021	7.60	149	0.023	0.008
418	0-7 cm	-	1.50	0.025	0.038	7.49	82	0.043	0.001
419	0-6 cm	-	1.70	0.031	0.052	7.78	148	0.051	0.005
421	0-7 cm	-	1.59	0.072	0.115	7.68	1945	0.120	0.101
422	0-8 cm	-	1.49	0.070	0.104	7.75	3350	0.117	0.099
431	0-9 cm		1.70	0.091	0.154	7.76	1260	0.151	-
441	0-7 cm	-	1.72	0.077	0.134	8.81	391	0.129	-
442	0-7 cm	-	1.77	0.073	0.129	8.24	243	0.122	-
443	0-7 cm	-	1.45	0.061	0.089	8.11	459	0.102	-
444	5-12 cm	-	1.43	0.072	0.104	8.13	423	0.121	-
451	0-6 cm	-	1.61	0.024	0.039	8.44	128	0.040	0.013
461	0-7 cm	-	1.58	0.021	0.033	7.90	414	0.035	0.015
462	0-5 cm	-	1.66	0.018	0.031	7.81	150	0.031	0.006
463	5-12 cm	-	1.99	0.040	0.078	8.08	144	0.066	0.017

[1] Calculated using the bulk density for that particular sample

[2] Calculated using an average bulk denisty for the site

2. Soil pH

2.1 Scott Base

Sample Number	Soil pH 1	2	3	Average	S.D.
121	6.73	-	-	6.73	-
122	7.10	6.96	6.99	7.02	0.07
123	7.10	7.13	7.07	7.10	0.03
124	7.52	7.47	7.45	7.48	0.04
125	7.87	7.81	-	7.84	0.04
126	7.72	7.70	-	7.71	0.01
131	7.43	7.50	7.61	7.51	0.09
132	7.90	8.17	-	8.04	0.19
133	7.41	7.50	7.57	7.49	0.08
134	7.52	7.66	7.60	7.59	0.07
135	6.73	6.78	-	6.76	0.04
141	7.25	7.30	7.27	7.27	0.03
142	8.49	8.53	8.49	8.50	0.02
143	8.58	8.61	8.46	8.55	0.08
144	7.72	7.80	7.86	7.79	0.07
145	8.38	8.29	8.26	8.31	0.06
146	8.95	9.01	9.08	9.01	0.07
147	7.68	7.86	7.78	7.77	0.09
148	8.12	8.06	8.06	8.08	0.03
151	7.49	7.48	7.48	7.48	0.01
152	7.15	7.22	7.17	7.18	0.04
153	7.12	-	7.14	7.13	0.01
154	9.12	9.12	9.12	9.12	0.00
155	9.15	9.22	-	9.19	0.05
156	9.27	9.28	-	9.28	0.01

Sample Number	Soil pH 1	2	3	Average	S.D.
161	9.50	9.42	9.35	9.42	0.08
162	9.02	8.84	8.97	8.94	0.09
163	8.64	8.43	8.49	8.52	0.11
164	8.27	8.44	-	8.36	0.12
171	9.13	9.05	8.88	9.02	0.13
172	9.23	9.13	9.16	9.17	0.05
173	8.08	7.97	7.98	8.01	0.06
174	9.18	9.10	9.17	9.15	0.04
175	9.16	9.23	9.17	9.19	0.04
176	9.06	8.92	9.07	9.02	0.08
177	8.22	8.06	8.01	8.10	0.11
178	8.29	8.31	8.27	8.29	0.02
179	8.39	8.18	8.12	8.23	0.14
180	8.07	8.08	8.08	8.08	0.01
181	7.62	7.49	7.50	7.54	0.07
182	8.67	8.90	8.88	8.82	0.13
Average				8.14	
Maximum				9.42	
Minimum				6.73	
Median				8.08	
Standard Deviation				0.77	

2.2 Wright Valley and Bull Pass

Sample	Soil pH				
Number	1	2	3	Average	S.D.
311	6.47	6.54	6.63	6.55	0.08
312	6.58	6.69	6.78	6.68	0.10
313	6.33	6.34	6.29	6.32	0.03
314	6.42	6.54	6.62	6.53	0.10
315	6.45	6.61	6.55	6.54	0.08
316	6.30	6.31	6.44	6.35	0.08
Site Average				**6.49**	
321	6.61	6.59	6.57	6.59	0.02
322	6.60	6.59	6.61	6.60	0.01
323	6.61	-	-	6.61	-
324	6.65	6.68	6.72	6.68	0.04
325	6.10	5.96	6.12	6.06	0.09
326	6.15	6.05	6.06	6.09	0.06
327	6.50	6.58	6.57	6.55	0.04
Site Average				**6.45**	
331	6.56	6.59	6.64	6.60	0.04
332	6.65	6.68	6.70	6.68	0.03
333	6.72	6.78	6.77	6.76	0.03
334	6.78	6.82	6.87	6.82	0.05
335	6.86	6.84	6.88	6.86	0.02
336	6.92	6.95	6.98	6.95	0.03
Site Average				**6.78**	
341	6.73	6.75	-	6.74	0.01
342	6.69	6.73	-	6.71	0.03
343	6.73	6.71	-	6.72	0.01
344	6.64	6.62	-	6.63	0.01
345	6.59	6.61	6.68	6.63	0.05
Site Average				**6.69**	

Sample	Soil pH				
Number	1	2	3	Average	S.D.
351.00	6.86	6.81	6.87	6.85	0.03
352.00	7.16	7.13	7.14	7.14	0.02
353.00	7.25	7.33	7.34	7.31	0.05
354.00	7.17	7.14	7.10	7.14	0.04
355.00	7.13	7.14	7.14	7.14	0.01
356.00	7.33	7.37	7.40	7.37	0.04
357.00	7.45	7.39	7.39	7.41	0.03
Site Average				**7.19**	
361.00	7.05	6.92	7.00	6.99	0.07
362.00	6.94	6.99	6.99	6.97	0.03
363.00	6.84	6.87	6.88	6.86	0.02
364.00	6.96	7.01	7.04	7.00	0.04
365.00	7.26	7.17	7.15	7.19	0.06
366.00	7.02	6.99	6.99	7.00	0.02
367.00	7.03	7.08	7.08	7.06	0.03
368.00	7.11	7.12	7.08	7.10	0.02
Site Average				**7.02**	
Average				6.79	
Maximum				7.41	
Minimum				6.06	
Median				6.74	
Standard Deviation				0.32	

2.3 Scott Base Hydrocarbon-Contaminated Soil

Sample	Soil pH				
Number	1	2	3	Average	S.D.
411	8.36	8.20	8.02	8.19	0.17
412	7.98	7.98	7.77	7.91	0.12
413	7.68	7.82	7.63	7.71	0.10
414	7.85	7.70	7.93	7.83	0.12
415	7.68	7.57	7.51	7.59	0.09
416	7.38	7.36	-	7.37	0.01
417	7.48	7.68	7.63	7.60	0.10
418	7.57	7.46	7.44	7.49	0.07
419	7.77	7.67	7.91	7.78	0.12
421	7.67	7.69	-	7.68	0.01
422	7.57	7.79	7.90	7.75	0.17
431	7.71	7.80	-	7.76	0.06
441	8.71	8.90	-	8.81	0.13
442	8.20	8.28	-	8.24	0.06
443	8.09	8.13	-	8.11	0.03
444	8.03	8.10	8.25	8.13	0.11

Sample	Soil pH				
Number	1	2	3	Average	S.D.
451	8.47	8.42	8.42	8.44	0.03
461	7.90	7.89	-	7.90	0.01
462	7.79	7.80	7.85	7.81	0.03
463	7.99	8.16	-	8.08	0.12
Average				7.91	
Maximum				8.81	
Minimum				7.37	
Median				7.82	
Standard Deviation				0.34	

3. Soil Electrical Conductivity

3.1 Scott Base

Sample Number	EC (μS cm^{-1}) ($K_{25°}$)			Average	S.D.
	1	2	3		
121	108	114	89	104	13
122	44	48	53	48	4
123	37	47	57	47	10
124	51	51	47	50	3
125	58	55	53	55	3
126	55	57	54	55	2
131	116	113	111	113	3
132	737	804	745	762	37
133	96	96	97	97	1
134	67	63	55	61	6
135	1983	2201	2101	2095	109
141	382	353	378	371	16
142	143	144	136	141	4
143	337	273	265	291	39
144	3086	2952	3052	3030	70
145	97	93	89	93	4
146	1573	1494	1489	1519	47
147	2035	2037	1932	2001	60
148	203	203	197	201	4
151	3801	3790	3388	3660	236
152	1907	1855	1906	1889	30
153	2213	2178	2124	2172	45
154	436	433	429	433	3
155	505	511	524	514	10
156	376	382	378	379	3

Sample Number	EC (μS cm^{-1}) ($K_{25°}$)			Average	S.D.
	1	2	3		
161	1656	1624	1665	1648	21
162	124	127	143	132	10
163	107	102	114	108	6
164	152	152	160	155	5
171	525	502	483	503	21
172	434	428	416	426	9
173	613	598	610	607	8
174	349	364	350	354	9
175	1855	1826	1742	1807	59
176	531	510	492	511	20
177	446	471	513	477	34
178	54	57	58	56	2
179	89	76	80	82	7
180	66	65	61	64	2
181	50	51	51	51	1
182	1392	1328	1337	1352	35
Average				695	
Maximum				3660	
Minimum				47	
Median				354	
Standard Deviation				902	

3.2 Wright Valley and Bull Pass

Sample Number	EC (μS cm^{-1}) ($K_{25°}$)			Average	S.D.
	1	2	3		
311	979	970	1046	999	42
312	18838	19263	19353	19151	275
313	2739	2761	2795	2765	28
314	37788	39913	39913	39205	1226
315	14333	12790	14042	13722	820
316	11158	9727	9615	10166	860
Site Average				**14335**	
321	2761	2683	2683	2709	45
322	2571	2549	2493	2538	40
323	3063	2918	2996	2993	73
324	1668	1595	1619	1627	37
325	752	718	765	745	24
326	707	740	795	747	45
327	612	601	570	594	22
Site Average				**1708**	
331	3410	3388	3376	3391	17
332	4148	4014	3969	4043	93
333	2672	2594	2583	2616	49
334	5411	5109	5176	5232	159
335	7043	6909	6999	6984	68
336	4964	6149	5858	5657	618
Site Average				**4654**	
341	16222	16200	16379	16267	97
342	20415	20504	20202	20374	155
343	19263	19319	19274	19286	30
344	18917	18872	20437	19408	891
345	19777	19710	19755	19748	34
Site Average				**19016**	

Sample Number	EC (μS cm^{-1}) ($K_{25°}$)			Average	S.D.
	1	2	3		
351	3365	3343	3365	3358	13
352	901	904	908	904	3
353	600	599	571	590	16
354	3645	3622	3645	3637	13
355	2706	2672	2650	2676	28
356	1756	1732	1753	1747	13
357	778	786	784	783	4
Site Average				**1956**	
361	444	453	464	454	10
362	774	755	742	757	16
363	4103	4103	4148	4118	26
364	4181	4304	4304	4263	71
365	578	563	576	572	8
366	2415	2325	2325	2355	52
367	2151	2110	2101	2120	27
368	3097	2907	2907	2970	110
Site Average				**2201**	
Average				6469	
Maximum				39205	
Minimum				454	
Median				2970	
Standard Deviation				8354	

3.3 Scott Base Hydrocarbon-Contaminated Soil

Sample	EC (μS cm^{-1}) ($K_{25°}$)				
Number	1	2	3	Average	S.D.
411	79	74	76	76	3
412	68	69	68	69	1
413	103	103	101	102	1
414	68	68	69	69	1
415	70	69	69	70	1
416	82	73	73	76	5
417	168	167	167	167	1
418	91	94	92	92	2
419	170	162	165	166	4
421	2205	2071	2247	2174	92
422	3768	3589	3879	3745	147
431	1419	1428	1381	1409	25
441	443	433	435	437	5
442	273	268	273	271	3
443	524	511	504	513	10
444	470	455	495	473	20

Sample	EC (μS cm^{-1}) ($K_{25°}$)				
Number	1	2	3	Average	S.D.
451	145	140	143	143	3
461	455	464	468	462	7
462	169	164	171	168	3
463	157	162	163	161	4
Average				542	
Maximum				3745	
Minimum				69	
Median				166	
Standard Deviation				918	

4. Gravimetric Moisture Contents (θ_g)

4.1 Scott Base

Sample	Moisture Content (θ_g)				
Number	1	2	3	Average	S.D.
121	0.020	0.019	0.019	0.019	0.001
122	0.040	0.047	0.038	0.042	0.005
123	0.033	0.040	0.035	0.036	0.004
124	0.037	0.039	0.034	0.037	0.002
125	0.047	0.045	0.039	0.044	0.004
126	0.043	0.046	0.043	0.044	0.001
131	0.090	0.057	0.100	0.083	0.023
132	0.112	0.138	0.101	0.117	0.019
133	0.071	0.086	0.078	0.078	0.008
134	0.043	0.043	0.045	0.044	0.001
135	0.092	0.097	0.090	0.093	0.004
141	0.029	0.028	0.030	0.029	0.001
142	0.144	0.136	0.121	0.134	0.012
143	0.032	0.030	0.030	0.031	0.001
144	0.067	0.066	0.067	0.067	0.000
145	0.099	0.118	0.131	0.116	0.016
146	0.045	0.046	0.039	0.043	0.004
147	0.043	0.037	0.046	0.042	0.005
148	0.215	0.232	0.231	0.226	0.009
151	0.074	0.081	0.067	0.074	0.007
152	0.062	0.050	0.059	0.057	0.006
153	0.054	0.056	0.054	0.055	0.001
154	0.138	0.137	0.144	0.139	0.004
155	0.108	0.116	0.097	0.107	0.009
156	0.077	0.069	0.071	0.073	0.004

Sample	Moisture Content (θ_g)				
Number	1	2	3	Average	S.D.
161	0.044	0.047	0.037	0.042	0.005
162	0.070	0.064	0.065	0.066	0.003
163	0.073	0.086	0.081	0.080	0.006
164	0.097	0.100	0.112	0.103	0.008
171	0.029	0.028	0.028	0.028	0.001
172	0.040	0.037	0.042	0.039	0.003
173	0.038	0.032	0.037	0.036	0.004
174	0.075	0.084	0.084	0.081	0.005
175	0.061	0.071	0.078	0.070	0.009
176	0.034	0.038	0.033	0.035	0.002
177	0.029	0.035	0.026	0.030	0.004
178	0.095	0.113	0.097	0.102	0.010
179	0.111	0.105	0.098	0.105	0.006
180	0.158	0.153	0.196	0.169	0.023
181	0.025	0.028	0.024	0.025	0.002
182	0.048	0.044	0.048	0.047	0.002
Average				0.070	
Maximum				0.226	
Minimum				0.019	
Median				0.057	
Standard Deviation				0.044	

4.2 Wright Valley and Bull Pass

Sample Number	Moisture Content (θ_g)			Average	S.D.
	1	2	3		
311	0.003	0.003	0.003	0.003	0.000
312	0.026	0.027	0.025	0.026	0.001
313	0.020	0.020	0.020	0.020	0.000
314	0.014	0.016	0.015	0.015	0.001
315	0.017	0.018	0.018	0.018	0.001
316	-	0.026	0.026	0.026	0.000
Site Average				**0.018**	
321	0.006	0.008	0.008	0.007	0.001
322	0.007	0.007	0.006	0.007	0.000
323	0.006	0.005	0.006	0.005	0.000
324	0.009	0.010	0.009	0.009	0.001
325	0.014	0.014	0.014	0.014	0.000
326	0.012	0.014	0.012	0.012	0.001
327	0.006	0.005	0.005	0.005	0.001
Site Average				**0.009**	
331	0.042	0.042	0.041	0.042	0.000
332	0.015	0.014	0.015	0.014	0.000
333	0.007	0.008	0.008	0.008	0.000
334	0.007	0.008	0.008	0.008	0.000
335	0.008	0.008	0.009	0.008	0.000
336	0.007	0.008	0.008	0.008	0.001
Site Average				**0.015**	
341	0.072	0.077	0.067	0.072	0.005
342	0.093	0.100	0.099	0.097	0.003
343	0.094	0.114	0.094	0.100	0.011
344	0.096	0.093	0.098	0.095	0.003
345	0.114	0.111	0.114	0.113	0.001
Site Average				**0.096**	

Sample Number	Moisture Content (θ_g)			Average	S.D.
	1	2	3		
351	0.007	0.006	0.006	0.007	0.000
352	0.011	0.011	0.010	0.011	0.000
353	0.017	0.017	0.016	0.016	0.000
354	0.012	0.013	0.015	0.013	0.001
355	0.007	0.007	0.006	0.007	0.000
356	0.005	0.004	0.004	0.004	0.000
357	0.003	0.002	0.003	0.003	0.000
Site Average				**0.009**	
361	0.009	0.008	0.009	0.009	0.001
362	0.013	0.015	0.014	0.014	0.001
363	0.019	0.017	0.018	0.018	0.001
364	0.006	0.006	0.007	0.006	0.000
365	0.003	0.003	0.004	0.003	0.000
366	0.006	0.005	0.006	0.006	0.000
367	0.004	0.004	0.004	0.004	0.000
368	0.005	0.005	0.005	0.005	0.000
Site Average				**0.008**	
Average				0.022	
Maximum				0.113	
Minimum				0.003	
Median				0.009	
Standard Deviation				0.030	

4.3 Scott Base Hydrocarbon-Contaminated Soil

Sample Number	Moisture Content (θ_g)			Average	S.D.
	1	2	3		
411	0.019	0.018	0.018	0.018	0.001
412	0.020	0.022	0.019	0.020	0.001
413	0.020	0.023	0.025	0.023	0.003
414	0.024	0.028	0.026	0.026	0.002
415	0.028	0.029	0.027	0.028	0.001
416	0.033	0.032	0.031	0.032	0.001
417	0.014	0.014	0.014	0.014	0.000
418	0.026	0.026	0.025	0.025	0.001
419	0.032	0.030	0.030	0.031	0.001
421	0.078	0.068	0.070	0.072	0.005
422	0.069	0.068	0.073	0.070	0.003
431	0.089	0.090	0.093	0.091	0.002
441	0.076	0.081	0.075	0.077	0.003
442	0.072	0.076	0.071	0.073	0.003
443	0.061	0.065	0.057	0.061	0.004
444	0.075	0.071	0.071	0.072	0.002

Sample Number	Moisture Content (θ_g)			Average	S.D.
	1	2	3		
451	0.022	0.025	0.025	0.024	0.002
461	0.020	0.021	0.022	0.021	0.001
462	0.016	0.019	0.020	0.018	0.002
463	0.038	0.039	0.041	0.040	0.002
Average				0.042	
Maximum				0.091	
Minimum				0.014	
Median				0.029	
Standard Deviation				0.025	

5. Soil Bulk Density (ρ_b)

5.1 Scott Base

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
121	1.98	1.94
122	2.28	2.20
123	2.16	2.09
124	-	-
125	1.84	1.75
126	2.09	2.00
131	1.85	1.70
132	2.16	1.94
133	1.92	1.80
134	1.78	1.71
135	1.77	1.62
141	1.81	1.76
142	2.01	1.76
143	1.98	1.91
144	1.84	1.72
145	1.86	1.69

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
146	2.03	1.94
147	1.83	1.76
148	1.96	2.39
151	1.48	1.38
152	1.67	1.57
153	1.81	1.72
154	1.69	1.49
155	1.17	1.06
156	1.43	1.32
161	1.62	1.55
162	1.89	1.77
163	1.65	1.53
164	1.43	1.31
171	1.90	1.85
172	1.97	1.89

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
173	1.87	1.80
174	2.52	2.34
175	1.66	1.56
176	1.86	1.79
177	1.97	1.92
178	1.89	1.73
179	2.07	1.86
180	2.56	2.21
181	1.83	1.79
182	1.76	1.84
Average	1.87	1.77
Maximum	2.56	2.39
Minimum	1.17	1.06
Median	1.86	1.77
Standard Deviation	0.26	0.27

5.2 Wright Valley and Bull Pass

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
311	1.84	1.83
312	1.47	1.43
313	1.37	1.35
314	1.72	1.70
315	1.70	1.67
316	1.74	1.86
Site Ave	**1.64**	**1.64**
321	2.09	2.08
322	2.09	2.08
323	2.31	2.30
324	1.99	1.97
325	2.10	2.07
326	2.37	2.35
327	-	-
Site Ave	**2.16**	**2.14**
331	1.41	1.36
332	1.86	1.83
333	1.82	1.81

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
334	1.81	1.79
335	1.85	1.83
336	1.74	1.72
Site Ave	**1.73**	**1.71**
341	0.74	0.69
342	0.83	0.76
343	0.85	0.78
344	1.09	0.99
345	1.46	1.31
Site Ave	**0.99**	**0.91**
351	1.31	1.30
352	1.72	1.70
353	1.83	1.80
354	-	-
355	-	-
356	-	-
357	-	-
Site Ave	**1.62**	**1.60**

Sample Number	Field Bulk Density (g cm^{-1})	Oven-dry Bulk Density (g cm^{-1})
361	1.92	1.91
362	2.07	2.05
363	2.30	2.25
364	1.92	1.91
365	-	-
366	-	-
367	-	-
368	-	-
Site Ave	**2.05**	**2.03**
Average	1.71	1.68
Maximum	2.37	2.35
Minimum	0.74	0.69
Median	1.81	1.81
Standard Deviation	0.42	0.44

Appendix 3 – Laboratory Experimental Data

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1. Experiment 1 – Homogeneity of Mixing

1.1 Mix 1

Replicate	Container Weight (g)	Wet Weight (g)	Dry Weight (g)	Gravimetric Moisture Content (θ_g)
1	2.961	12.947	12.586	0.038
2	3.010	12.917	12.554	0.038
3	3.006	13.002	12.654	0.036
4	3.010	12.588	12.323	0.028
5	2.995	14.232	13.850	0.035
6	2.974	13.070	12.756	0.032
7	2.906	12.966	12.629	0.035
8	2.970	13.037	12.723	0.032
9	2.973	14.766	14.345	0.037
10	3.009	13.317	12.958	0.036
		Number of Samples		10
		Average		0.035
		Standard Deviation		0.003
		Standard Error		0.001
		95% Confidence Limit		0.002

1.2 Mix 2

Replicate	Container Weight (g)	Wet Weight (g)	Dry Weight (g)	Gravimetric Moisture Content (θ_g)
1	3.013	13.508	12.950	0.056
2	2.970	13.913	13.317	0.058
3	2.974	14.599	13.966	0.058
4	2.961	14.751	14.132	0.055
5	2.944	14.442	13.821	0.057
6	2.976	12.450	11.963	0.054
7	2.965	13.030	12.495	0.056
8	2.927	12.349	11.842	0.057
9	2.970	13.230	12.674	0.057
10	2.936	13.063	12.525	0.056
		Number of Samples		10
		Average		0.056
		Standard Deviation		0.001
		Standard Error		0.000
		95% Confidence Limit		0.001

1.3 Mix 3

Replicate	Container Weight (g)	Wet Weight (g)	Dry Weight (g)	Gravimetric Moisture Content (θ_g)
1	3.007	12.742	12.012	0.081
2	2.989	14.578	13.714	0.081
3	2.931	13.629	12.834	0.080
4	2.975	13.469	12.684	0.081
5	2.949	13.432	12.657	0.080
6	2.926	13.772	12.972	0.080
7	2.961	13.147	12.387	0.081
8	2.960	13.432	12.663	0.079
9	2.968	14.343	13.509	0.079
10	2.962	13.972	13.171	0.078
		Number of Samples		10
		Average		0.080
		Standard Deviation		0.001
		Standard Error		0.000
		95% Confidence Limit		0.001

1.4 Mix 4

Replicate	Container Weight (g)	Wet Weight (g)	Dry Weight (g)	Gravimetric Moisture Content (θ_g)
1	2.974	13.620	12.634	0.102
2	2.957	13.647	12.650	0.103
3	2.932	12.462	11.586	0.101
4	2.983	13.743	12.783	0.098
5	2.933	14.258	13.225	0.100
6	2.997	12.453	11.605	0.099
7	3.012	14.300	13.088	0.120
8	2.914	13.016	12.099	0.100
9	2.969	13.804	12.797	0.102
10	2.951	13.004	12.088	0.100
		Number of Samples		10
		Average		0.103
		Standard Deviation		0.006
		Standard Error		0.002
		95% Confidence Limit		0.004

2. Experiment 2 – Effect of Sample Size

	Gravimetric θ_v				
Container Size	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Small	5	0.035	0.003	0.001	0.003
	5	0.063	0.002	0.001	0.001
	5	0.092	0.001	0.001	0.001
	5	0.118	0.004	0.002	0.004
Medium	5	0.025	0.001	0.000	0.000
	5	0.053	0.001	0.000	0.001
	5	0.087	0.001	0.000	0.001
	5	0.125	0.002	0.001	0.002
Large	5	0.036	0.004	0.002	0.003
	5	0.068	0.007	0.003	0.006
	5	0.093	0.010	0.005	0.009
	5	0.121	0.003	0.001	0.002

	TDR θ_v				
Container Size	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Small	5	0.025	0.000	0.000	0.000
	5	0.044	0.001	0.001	0.001
	5	0.075	0.000	0.000	0.000
	5	0.103	0.000	0.000	0.000
Medium	5	0.030	0.001	0.001	0.001
	5	0.054	0.001	0.000	0.001
	5	0.083	0.000	0.000	0.000
	5	0.130	0.001	0.000	0.001
Large	5	0.024	0.001	0.000	0.000
	5	0.064	0.001	0.000	0.000
	5	0.086	0.001	0.000	0.000
	5	0.124	0.000	0.000	0.000

NOTE: Each line on the Gravimetric θ_v table corresponds with the same line on the TDR θ_v table

3. Experiment 3 – Consistency of Results between Different Probes

	Gravimetric θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Probe 1	5	0.025	0.001	0.000	0.000
	5	0.054	0.001	0.000	0.001
	5	0.087	0.002	0.001	0.001
	5	0.090	0.001	0.000	0.001
	5	0.126	0.003	0.001	0.002
	5	0.168	0.006	0.003	0.005
Probe 2	5	0.023	0.000	0.000	0.000
	5	0.053	0.001	0.000	0.001
	5	0.087	0.001	0.000	0.001
	5	0.125	0.002	0.001	0.002
	5	0.133	0.010	0.004	0.009
	5	0.168	0.008	0.004	0.007
Probe 3	5	0.022	0.000	0.000	0.000
	5	0.046	0.000	0.000	0.000
	5	0.052	0.000	0.000	0.000
	5	0.086	0.001	0.000	0.000
	5	0.125	0.002	0.001	0.002
	5	0.166	0.009	0.004	0.007
	5	0.177	0.019	0.008	0.016

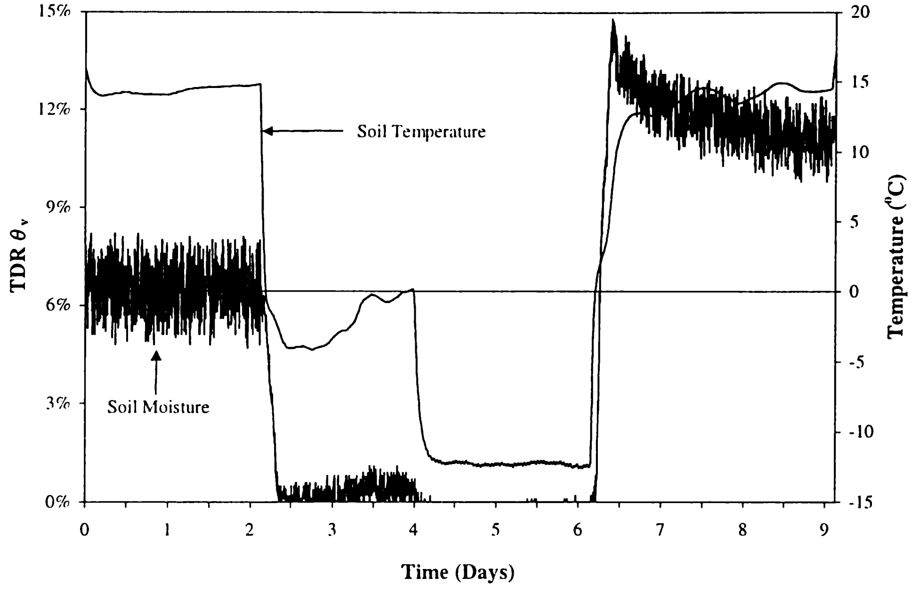
	TDR θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Probe 1	5	0.030	0.001	0.001	0.001
	5	0.065	0.003	0.001	0.003
	5	0.110	0.001	0.000	0.001
	5	0.097	0.001	0.000	0.001
	5	0.143	0.001	0.000	0.001
	5	0.192	0.001	0.000	0.000
Probe 2	5	0.020	0.001	0.000	0.001
	5	0.054	0.001	0.000	0.001
	5	0.083	0.000	0.000	0.000
	5	0.130	0.001	0.000	0.001
	5	0.130	0.001	0.000	0.001
	5	0.179	0.001	0.001	0.001
Probe 3	5	0.024	0.001	0.001	0.001
	5	0.042	0.001	0.001	0.001
	5	0.050	0.001	0.000	0.000
	5	0.066	0.001	0.000	0.001
	5	0.174	0.001	0.000	0.001
	5	0.192	0.000	0.000	0.000
	5	0.192	0.002	0.001	0.002

NOTE: Each line on the Gravimetric θ_v table corresponds with the same line on the TDR θ_v table

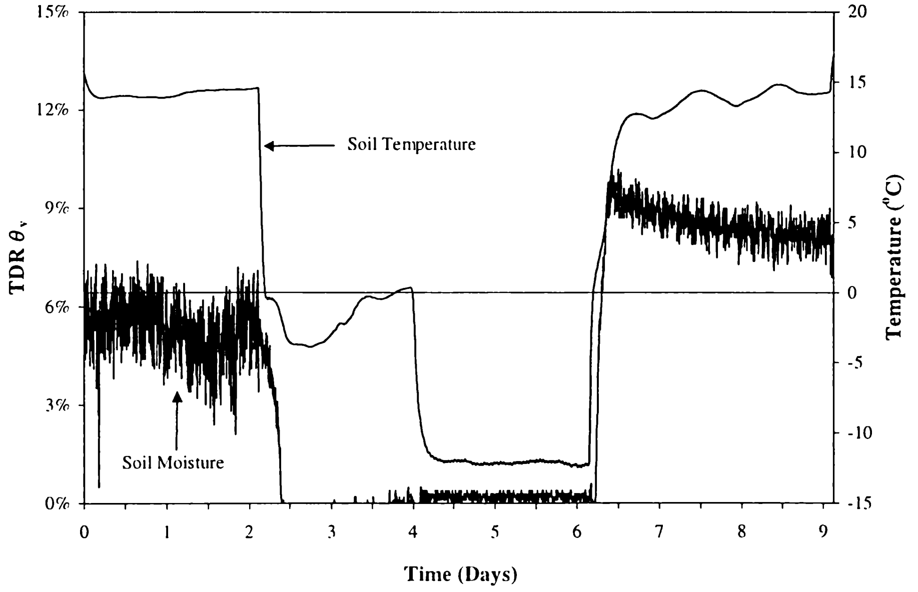
4. Experiment 4 – Accuracy of Hydra Probes at Different Temperatures

4.1 Soil Freezing

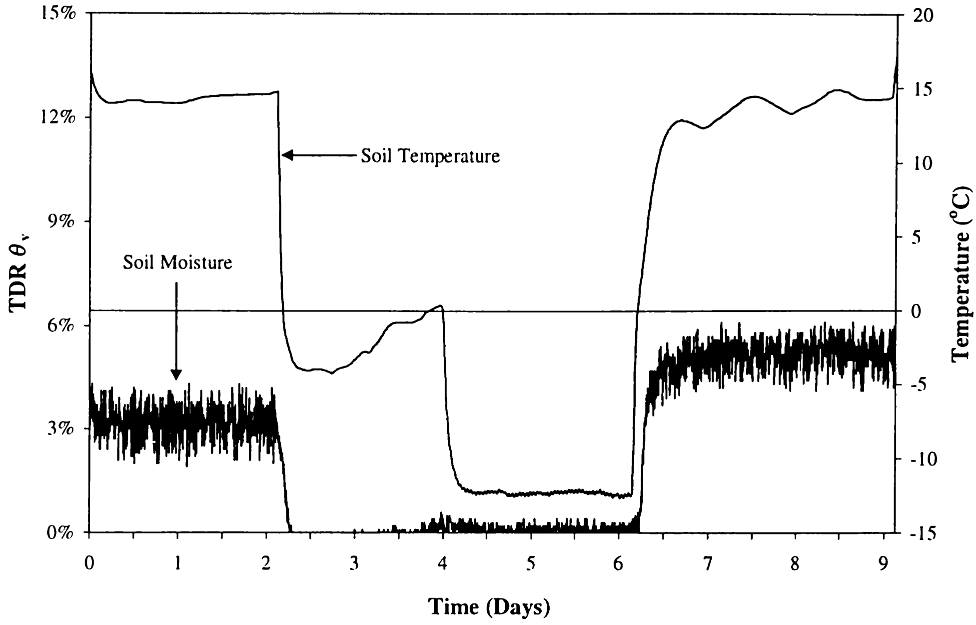
TDR Probe 1



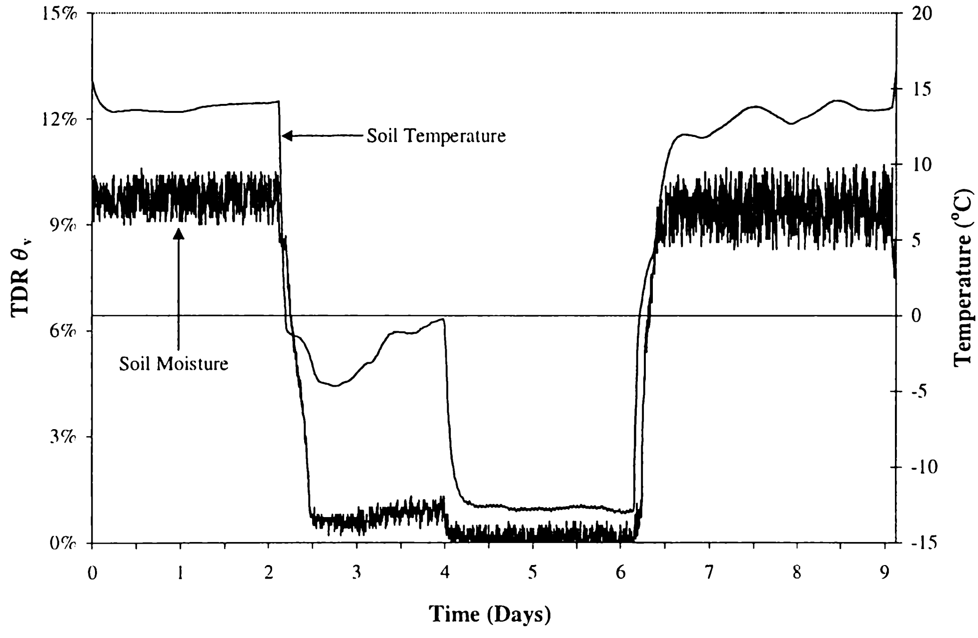
TDR Probe 2



TDR Probe 3

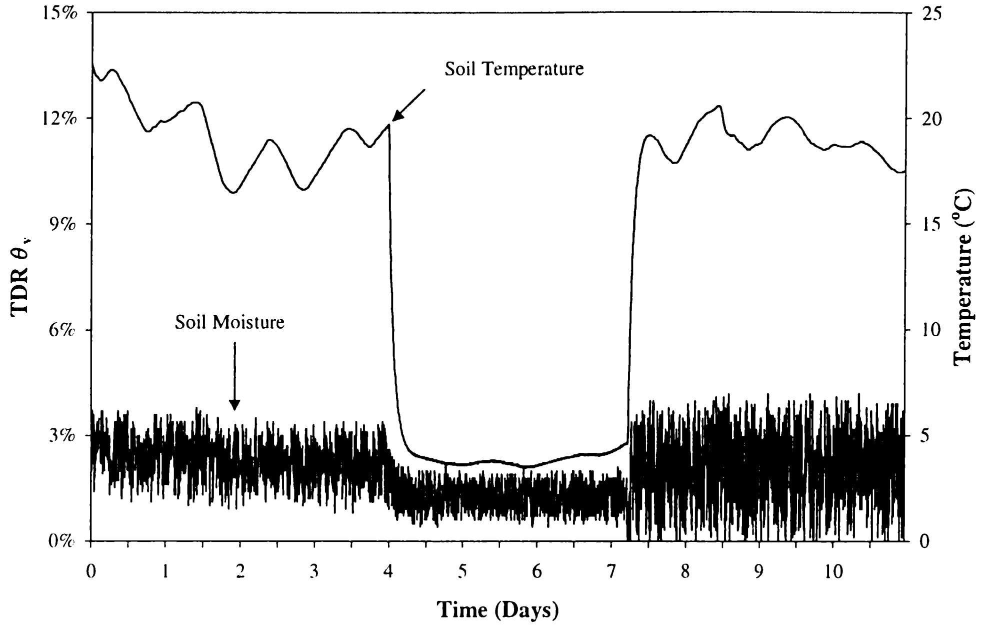


TDR Probe 4

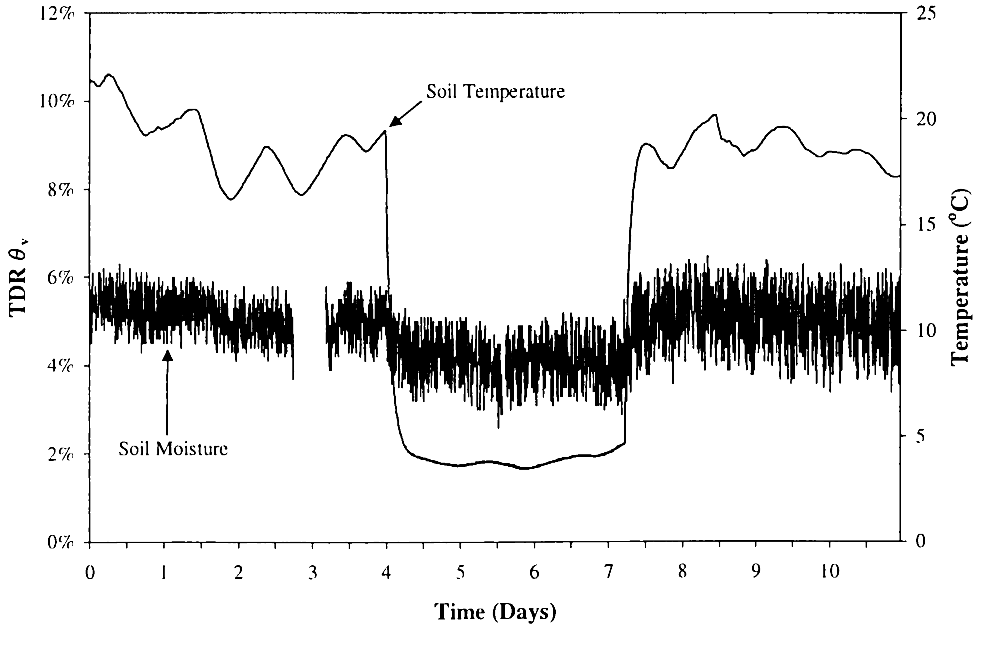


4.2 Soil Cooling

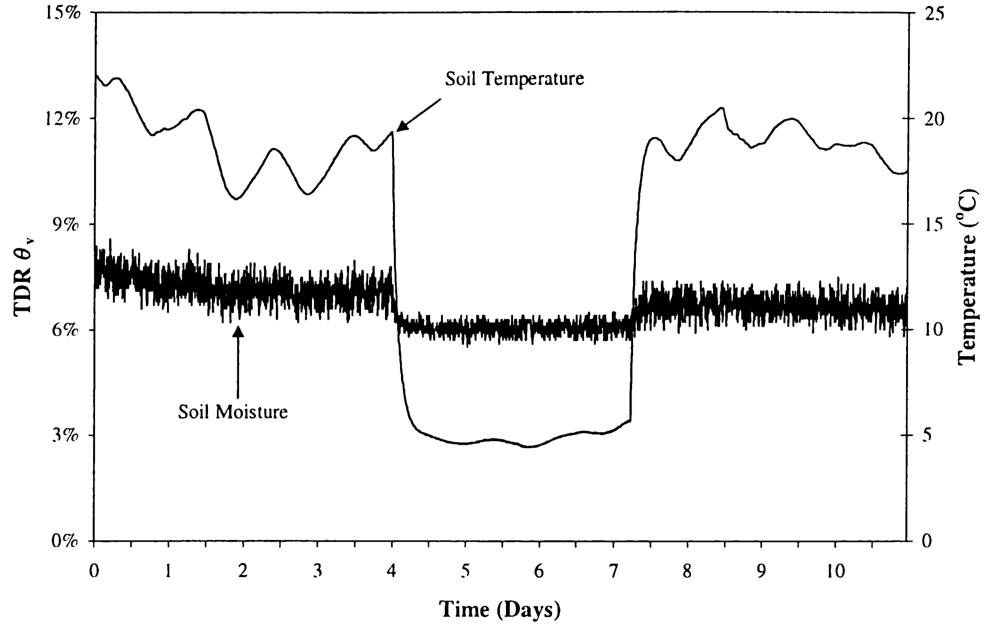
TDR Probe 1



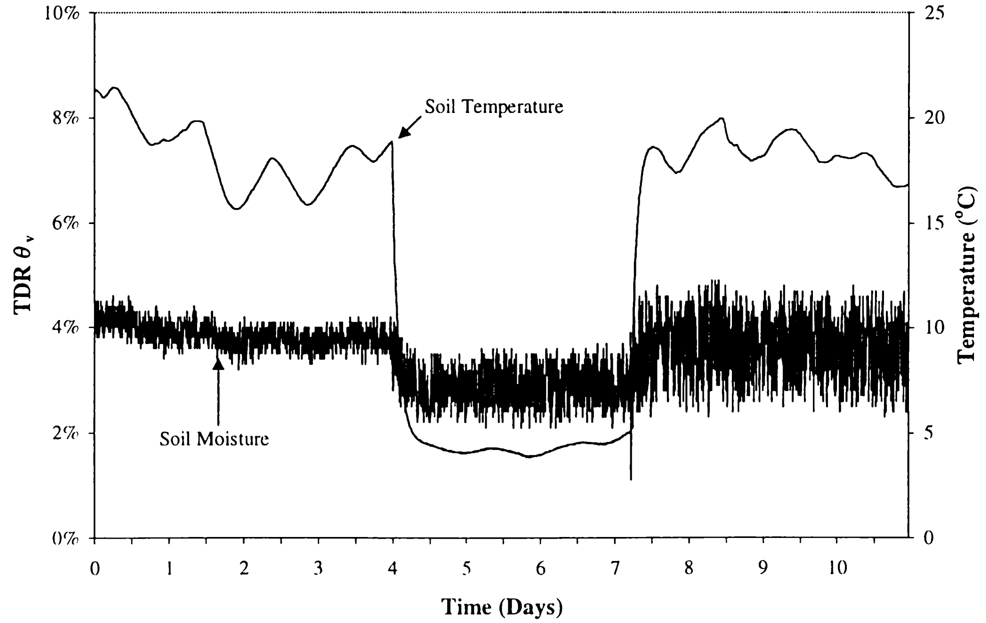
TDR Probe 2



TDR Probe 3



TDR Probe 4



5. Experiment 5 – Effect of Soil Texture on the Accuracy of the Hydra (TDR) Probes

	Gravimetric θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
0% Gravel	5	0.023	0.000	0.000	0.000
	5	0.053	0.001	0.000	0.001
	5	0.087	0.001	0.000	0.001
	5	0.133	0.010	0.004	0.009
	5	0.168	0.008	0.004	0.007
12.5% Gravel	5	0.039	0.001	0.001	0.001
	5	0.080	0.002	0.001	0.001
	5	0.113	0.005	0.002	0.005
	5	0.150	0.013	0.006	0.011
	5	0.200	0.015	0.007	0.013
25% Gravel	5	0.041	0.001	0.001	0.001
	5	0.081	0.004	0.002	0.003
	5	0.118	0.002	0.001	0.002
	5	0.159	0.015	0.007	0.013
	5	0.207	0.019	0.009	0.017
37.5% Gravel	5	0.042	0.002	0.001	0.002
	5	0.083	0.006	0.003	0.005
	5	0.124	0.009	0.004	0.008
	5	0.167	0.011	0.005	0.010
	5	0.204	0.015	0.007	0.013

	TDR θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
0% Gravel	5	0.020	0.001	0.000	0.001
	5	0.054	0.001	0.000	0.001
	5	0.083	0.000	0.000	0.000
	5	0.130	0.001	0.000	0.001
	5	0.179	0.001	0.001	0.001
12.5% Gravel	5	0.032	0.001	0.000	0.001
	5	0.064	0.000	0.000	0.000
	5	0.110	0.001	0.000	0.001
	5	0.134	0.000	0.000	0.000
	5	0.193	0.001	0.000	0.000
25% Gravel	5	0.033	0.000	0.000	0.000
	5	0.063	0.000	0.000	0.000
	5	0.103	0.001	0.000	0.001
	5	0.087	0.001	0.001	0.001
	5	0.195	0.001	0.000	0.000
37.5% Gravel	5	0.029	0.000	0.000	0.000
	5	0.061	0.001	0.000	0.001
	5	0.097	0.001	0.000	0.001
	5	0.163	0.001	0.000	0.000
	5	0.180	0.001	0.000	0.000

NOTE: Each line on the Gravimetric θ_v table corresponds with the same line on the TDR θ_v table

6. Experiment 6 – Effect of Salts on Hydra Probe Soil Moisture Determination

6.1 1% NaCl Solution

Gravimetric θ_v	TDR θ_v	TDR θ_v - Grav. θ_v	Lab EC (µS cm^{-1})
2.7%	2.6%	-0.1%	144
3.7%	5.3%	1.6%	183
4.8%	7.5%	2.7%	217
6.0%	7.6%	1.6%	250
7.0%	10.7%	3.8%	285
8.5%	13.2%	4.7%	338
9.8%	14.1%	4.3%	365
10.8%	16.1%	5.2%	398
12.0%	14.1%	2.1%	424
13.0%	13.7%	0.7%	461

6.2 2.5% NaCl Solution

Gravimetric θ_v	TDR θ_v	TDR θ_v - Grav. θ_v	Lab EC (µS cm^{-1})
4.8%	10.7%	5.9%	392
7.1%	15.1%	8.0%	542
9.2%	18.5%	9.3%	695
11.3%	19.8%	8.5%	836
13.3%	21.4%	8.1%	962
15.2%	20.1%	4.9%	1095
16.9%	16.2%	-0.7%	1160
18.1%	21.5%	3.4%	1250
19.1%	29.0%	9.9%	1345
21.0%	33.6%	12.6%	1408

6.3 5% NaCl Solution

Gravimetric θ_v	TDR θ_v	TDR θ_v - Grav. θ_v	Lab EC (μS cm^{-1})
2.7%	5.6%	2.9%	421
3.8%	9.1%	5.3%	600
4.7%	11.8%	7.1%	778
5.8%	14.2%	8.4%	946
6.9%	12.3%	5.4%	1110
8.0%	12.6%	4.6%	1286
9.2%	11.8%	2.6%	1419
10.3%	5.5%	-4.8%	1591
11.2%	19.2%	8.0%	1757
12.1%	32.5%	20.4%	1859

7. Experiment 7 – Influence of Hydrocarbons on the Hydra Probe Soil Moisture Determination

	Gravimetric θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Control (Sand)	5	0.001	0.000	0.000	0.000
Fuel Only	5	0.039	0.001	0.001	0.001
Fuel + Distilled Water (1)	5	0.073	0.004	0.002	0.004
Fuel + Distilled Water (2)	5	0.111	0.001	0.001	0.001
Fuel + Distilled Water (3)	5	0.149	0.002	0.001	0.001

	TDR θ_v				
	Number of Samples	Average θ_v	Standard Deviation	Standard Error	95% Confidence Interval
Control (Sand)	5	0.001	0.001	0.000	0.001
Fuel Only	5	0.004	0.001	0.000	0.001
Fuel + Distilled Water (1)	5	0.047	0.001	0.000	0.000
Fuel + Distilled Water (2)	5	0.085	0.001	0.000	0.001
Fuel + Distilled Water (3)	5	0.133	0.000	0.000	0.000

NOTE: Each line on the Gravimetric θ_v table corresponds with the same line on the TDR θ_v table

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