AN INVESTIGATION INTO REPELLENCY-INDUCED RUNOFF AND ITS CONSEQUENCES IN A NEW ZEALAND HILL COUNTRY PASTURE SYSTEM

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ABSTRACT

Soil water repellency affects a wide range of soils within diverse environments. In agricultural systems, it has the potential to reduce infiltration of water into the soil and enhance surface runoff processes. Accordingly, soil water repellency may have significant consequences in hill country. In these landscapes, repellency-induced runoff has the potential to result in a marked reduction in the quantity of water available to pasture in summer and autumn, and to increase the impact of summer storm events on stream flow.

The objective of this thesis is to examine repellency-induced runoff and to study its consequences in New Zealand hill country pasture systems, with a particular focus on the East Coast of the North Island as represented by the research area at Alfredton and a catchment near Waipawa.

Detailed meteorological data, surface runoff measurements from small plots (1.0 x 2.0 m), and soil moisture values gathered over two years at the Alfredton catchment were used to determine the effect of soil water repellency on the infiltration rate of the soil and surface runoff, and to assess its importance as a hydrological process in that catchment. The persistence of repellency was further investigated on soil slabs in the laboratory. A soil water balance model, which incorporates the observed throttling effect of repellency in the top 50 mm of soil, was developed to help assess when this phenomenon was most likely to occur. Output from the model using 8 years of rainfall and stream flow data from the Waipawa catchment was used to help gauge the effect of repellency-induced runoff on peak stream flow and total stream flow. The effect of repellency on pasture production was also measured at the Alfredton site.

The Alfredton soils had high intrinsic infiltrability (at least 2 mm min^{-1}), but this property was compromised by water repellency under dry soil conditions. However, analysis of detailed meteorological, soil moisture, and surface runoff data at the Alfredton catchment indicated that plot-scale repellency-induced runoff events occurred less than 10 times a year and that over two years these events equated to less than 5 % of the mean annual rainfall of 1517 mm. Observations and modelling showed that repellency-induced runoff occurred whenever

both the rainfall intensity exceeded 0.1 mm min^{-1} and the soil water content in the 0-50 mm topsoil was less than 0.28 m^3 m^{-3}. Although repellency reduced the infiltration rate of the Alfredton soils by a factor of 10, it disappeared less than 44 hours after significant rainfall, and only reappeared once the soils had again become sufficiently dry. The rapid disappearance of water repellency was confirmed by the laboratory study using large soil slabs. The implication is that repellency-induced runoff is not a significant hydrological process.

The soil water balance model was used to predict repellency-induced runoff over 8 years in the Waipawa catchment. It predicted on average about 50 mm yr^{-1} of repellency-induced runoff from both the North catchment and South catchments over the 8 years, during which time the catchments received an average rainfall of 793 mm yr^{-1}. This suggests that even in this drier climate, repellency-induced runoff plays a relatively minor role in the soil water balance of these hill country catchments.

Examination of Waipawa stream flow data on those days when more than 10 mm of repellency-induced runoff was predicted, revealed a maximum stream flow of 1.1 mm and an average flow that was only 3.3 % of the modelled repellency-induced runoff. Additionally, on those days, peak stream flow was less than 3 % of peak rainfall intensity. These values suggest that at least 95 % of repellency-induced runoff infiltrated the soil before reaching the stream and thus contributed very little to both peak and total stream flow at Waipawa over the 8 years.

Repellency-induced runoff appears to have had little effect on pasture production at the Alfredton site. Employment of the refined soil water balance model in combination with a pasture production model suggested that repellency-induced runoff would be responsible for less than 1 % reduction in pasture production per annum. Statistical analysis of production data over the 2010 and 2011 years showed that shallower (20^o) slopes significantly out-produced steeper (30^o) slopes by 2.7 t ha yr^{-1}, with North and South aspect production being similar.

In summary, repellency-induced runoff does not appear to play a major role in the soil water balance of the study catchment at Alfredton. Furthermore, repellency-induced runoff does not seem to have a marked impact on stream flow under the drier Waipawa climate.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

New Zealand continues to rely strongly on its agricultural sector for export income. In the year ended December 2011, New Zealand's merchandise exports totalled $47.7 billion (Statistics, 2012). Of this total, agricultural exports contributed $27.1 billion, with significant increases from the previous year being recorded (amongst other products) for the dairy, meat, and meat products categories (Statistics, 2012).

Sheep and beef farms cover approximately 10 million of New Zealand's 13.5 million ha of pastoral land. A very significant fraction of sheep and beef farming occupies Class V, VI, VII, and VIII land (New Zealand Land Resource Inventory) with Grade D slopes ($\geq 15^{o}$) and above (Basher et al., 2008). This land is characterised by a large variability in both slope and aspect which influence microclimate, pasture growth rates, hydrology, stock grazing behaviour, and soil fertility (Gillingham, 1974; Lambert and Roberts, 1976; Rumball and Esler, 1968). As general rules, North aspect slopes are warmer and drier than South aspect slopes (Gillingham and Bell, 1977; Radcliffe and Lefever, 1981) and steeper slopes are less productive than shallow slopes (Gillingham and During, 1973; Radcliffe, 1968).

Soil hydrology is one of the fundamental disciplines underpinning agriculture. With hillslopes, hydrology is primarily concerned with flow processes within the soil and over the soil surface (Anderson and Burt, 1990). Studies concerning pastoral hillslope hydrology in New Zealand are very sparse with only one paper (Bircham and Gillingham, 1986) attempting to describe the main processes. In this paper, Bircham and Gillingham (1986) attempted to extend the successful soil water balance models for flat pastoral land (McAneney and Judd, 1983; Scotter et al., 1979b; Woodward et al., 2001) to hill country pasture. A particular feature of the model proposed by Bircham and Gillingham (1986) was the inclusion of a throttling mechanism for rainfall infiltrating the soil to account for soil water repellency often observed after prolonged dry periods.

Soil water repellency is a phenomenon that reduces the affinity of soils for water so that infiltration of rainfall/irrigation into the soil matrix is reduced. A review of soil water repellency by Doerr et al. (2000) suggested that there are a number of consequences associated with repellency. These include; a reduction in the soil's infiltration rate, the likelihood of enhanced overland flow, spatially localised infiltration, changes in the dynamics and distribution of soil moisture, enhanced responses of stream flow to rainstorms, and enhanced total stream flow. Repellency has a potentially detrimental (and perhaps costly) implication for plant growth given New Zealand's reliance on pastoral agriculture (Deurer et al., 2011; Müller et al., 2010). In addition, the resulting reduction in the soil's ability to store and filter water may compromise its ability to retain nutrients and contaminants, thus leading to increases of these pollutants in streams, rivers, and lakes (Aslam et al., 2009).

The implications of soil water repellency in New Zealand are not widely understood, particularly in summer-dry hill country. Dry soil surfaces and permanent pasture are conducive to the development of repellency (Doerr et al., 2006). The purpose of this thesis is to quantify repellency-induced runoff in New Zealand pastoral hill country and to examine a number of the implications of this phenomenon for pasture growth and its effect on peak and total stream flows.

The following chapter (Chapter 2, 'Literature Review') presents the current state of scientific knowledge regarding soil water repellency in New Zealand pastoral hill country, beginning with a short overview which includes a general description of the geology, geography, climate, and soils of these landscapes. A very brief discussion of pasture and environmental issues is also included. The main body of the review then follows, starting with a short discussion of the types of surface runoff on sloping land and then focussing on repellency-induced surface runoff. The reader is then familiarised with the nature of soil water repellency – this includes a general discussion of the chemistry of water repellency, the components responsible for its appearance in the soil, the methods by which it is characterised, and its spatial and temporal variability. The literature review then finishes with a discussion of the current state of knowledge regarding the distribution of soil water repellency in New Zealand and its impacts in hill country pasture systems.

Chapter 3 ('Site details and instrumentation') describes the characteristics of the research site located at Alfredton on the East Coast of the North Island, the analytical methodology, as well as the experimental design and the logistics of collecting the data that are analysed and discussed in the later chapters.

Chapter 4 ('Soil water availability in hill country') reports initial soil moisture observations and runoff volumes from the research area. Conclusions regarding pasture rooting depth are drawn. This information is then employed to modify and refine a sloping pasture land soil water balance model proposed by Bircham and Gillingham (1986).

The following chapter (Chapter 5 'Measurement of repellency-induced runoff in hill country') examines in more detail the meteorological, runoff, and soil moisture measurements subsequent to the installation of automated monitoring systems at the Alfredton research area. Specific conclusions are presented regarding the effect of soil water repellency on the amount of rainfall infiltrating the soil profile, the infiltration characteristics of the soils, and the transient nature of repellency-induced runoff.

Chapter 6 ('A laboratory study of runoff and water repellency using a hill country soil') describes a laboratory experiment which was undertaken to confirm the dynamics of the Alfredton field observations regarding repellency and surface runoff, specifically the ephemeral nature of repellency during and after rainfall events.

Chapter 7 ('Stream flow and water repellency in paired hill country catchments') describes a refined model which uses rainfall intensity to simulate repellency-induced runoff. Data gathered at the Alfredton research area is used to evaluate the model's parameters. The model was then applied to paired catchments at Waipawa, about 100 km north-east of the Alfredton research site. The model was used to simulate repellency-induced runoff at the Waipawa site using historical rainfall data provided by the National Institute of Water and Atmospheric Research (NIWA). The simulated runoff is then matched against stream flow data (again provided by NIWA) in order to help elucidate the role of repellency-induced runoff in stream flow responses to rainstorms as well as in enhanced total stream flow.

Lastly, Chapter 8 ('The effect of repellency-induced runoff on pasture production in hill country") examines pasture production data at the Alfredton research area and provides a statistical analysis of this data in terms of the effects of slope and aspect. The potential effect of repellency-induced runoff on pasture production at Alfredton is also explored using the refined daily soil water balance model (Chapter 7) in combination with a daily pasture production model proposed by Moir et al. (2000a).

The final chapter in this thesis (‘Conclusions’) integrates and summarises the conclusions drawn from each chapter and discusses how this research work has contributed to the pool of knowledge regarding the impacts of soil water repellency in New Zealand hill country pasture systems. The opportunities for further research in this area are also discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This literature review is intended to be tightly focussed and attempts to knit together the individual chapter reviews that follow in this thesis.

A general description of hill country pastoral farming in New Zealand is first presented so as to give the reader some of the context in which this study was conducted. The geology and climatic factors which dictate the nature of the soil encountered in this study as well as the type of farming practised in the area will be described.

The primary focus of the thesis is repellency-induced surface runoff. The processes controlling surface runoff on hill slopes are listed with attention being drawn specifically to surface runoff resulting from soil water repellency. The general principles of soil water repellency are then outlined including an examination of; its physical chemistry, current knowledge regarding the components that contribute to repellency, methods of measuring repellency, and the spatial and temporal nature of repellency.

The final part of the review examines the distribution of soil water repellency in New Zealand and focuses on the phenomenon and its consequences in hill country pasture systems.

2.2 New Zealand hill country pastoral farming

2.2.1 Geology, geography, and climate

Hill country in New Zealand is defined as including all Class V, VI, VII, and VIII land from the New Zealand Land Resource Inventory (NZLRI) with Grade D slopes and above. Furthermore, it includes land located below an altitude of 1000 m above sea level (Basher et al., 2008). With this definition, 37 % (10 million hectares) of New Zealand's total land area is classified as hill country, with the majority (6.6 million hectares) located in the North Island.

The majority of North Island hill country is located in the East Coast region (that area east of the main divide between northern Gisborne and southern Wairarapa). This region lies on the Hikurangi Subduction margin where the Pacific tectonic plate is subducting from the Hikurangi Trough beneath the Australian Plate, resulting in a convergent movement rate of 35 mm yr^{-1} and a transcurrent rate of 25 mm yr^{-1} (Kamp, 1982).

Parent rock materials are varied, with the higher axial ranges of the main divide consisting of older greywacke and argillite rocks. The plains immediately to the east of the main divide have been built up from aggradation gravels through the erosion of these ranges during the late Quaternary (Molloy, 1998). Most of the East Coast region however, consists of a complex mixture of softer rocks of Tertiary and late Cretaceous age, predominately marine sandstones and siltstones with bands of harder limestone. These softer rocks have been uplifted and compressed by the relative convergent movement and subduction of the Pacific plate underneath the Australian plate.

The East Coast region is also strongly faulted, the faults trending north-east/south-west and parallel with the main divide, inland valleys, and coastal hills. The combination of faulting and soft parent material has predisposed the region to widespread erosion and this has been exacerbated by the removal of indigenous forest. Erosion is dominated by mass movement through soil slip, earthflow, and gully erosion (Basher et al., 2008) and is driven by large storms or long wet periods.

Areas immediately east of the main divide have moderate rainfall (approximately 1400 mm per annum) but annual rainfall decreases to approximately 800 mm when travelling further east of the main divide (Kerr et al., 1986; Molloy, 1998). Most rain falls in winter with spring and summer rainfalls being unreliable. Summer temperatures often rise above 30 ^{o}C and high evapotranspiration rates combined with unreliable rainfall and dry, prevailing north-westerly winds dries out the landscape quickly. As a result, soils are often dry in summer (Coulter, 1973).

2.2.2 Soils

Soils of the East Coast hill country have not been mapped in detail and are not well understood. The most widespread soils are those developed in siltstone although there are significant areas of soils in mudstone which are fertile but suffer from deep-seated mass movement (Molloy, 1998). Generally, the development of soils from parent material in these hill country landscapes will be influenced by slope, aspect, and the microclimate variations associated with these topographic features (Molloy, 1998).

Slope affects soil development so that soil on the flatter land associated with ridge crests is usually deeper and water tends to infiltrate and pass vertically through the soil. These more stable areas allow the underlying parent material to weather without eroding. Where parent material and soil is eroded from steeper slopes, it accumulates as colluvium at the bottom of slopes, leaving the eroded steeper mid-slope areas with shallower soils. In addition, infiltrating water on the steeper slopes tends to move down-slope under the influence of gravity and concentrates both water and nutrients in the colluvium, resulting in fertile but poorly drained soils (Molloy, 1998). Both slope and aspect modify the general climate of the area to produce variations in microclimate, affecting the amount of solar radiation and wind received by different slope-aspect combinations. This in turn affects the amount of water in the soil so that the sunnier N and NW facing slopes have soils which are warmer and drier while the S and SE facing slopes are cooler and more moist (Gillingham, 1974).

The variability associated with hill country soils prompted an examination of hill soils across landscapes by Campbell (1973) and Campbell (1975) in the Wanganui region. The author (Campbell, 1973) identified four soil units on a single hill country slope – ridge (well developed), intermediate steep slope (less weathered and developed), eroded slope (weakly weathered and developed), and accumulation slope (accumulation of material from down-slope movement). When extending the study across a number of landscapes Campbell (1975), found that higher altitudes presented soil profiles which were subjected to greater chemical weathering and leaching and that, in combination with the identified soil units, large variations in hill country soil patterns result from the process of landform development.

The East Coast hill country region experiences significant erosion and this consequently affects the development of soil. Trustrum (1984) studied erosion scars in the Wairarapa hill country and showed that although eroded soils re-vegetated rapidly to within 70-80 % of un-eroded productivity, they may never regain the same potential for agricultural production under a pasture regime. Further supporting studies on soil slip erosion related to events in 1906, 1941, 1961, and 1977 in the Wairarapa (Lambert et al., 1984) indicated that pasture production on hill soils formed under pastoral agriculture was unlikely to return to the production levels supported by soils formed under the original forest vegetation. N and C contents of soils increased since erosion but were still much lower than un-eroded sites.

2.2.3 Pasture

Hill country pastures in New Zealand are highly variable, both in species composition and production. The primary reason for this is the dominant influence of slope and aspect, both of which determine microclimate, stock grazing behaviour, and soil fertility. Calculation of evapotranspiration values based on measured climatic variables at Ballantrae (Lambert and Roberts, 1976) indicated that evapotranspiration values were larger for the North than for the South aspect. Wind speed values were highest for the North aspect, and differences in net radiation between the North and South aspects were largest during the winter and smallest during the summer months. These studies indicate that different microclimates are experienced by different slopes and aspects in hill country, thereby encouraging or discouraging the establishment of different pasture species. Rumball and Esler (1968) studied small-scale distribution patterns of pasture species on tracked slopes in Taranaki and Manawatu and found that variations in the relative abundance of the majority of species at all sites were closely related to the ground surface configuration associated with track features – path, kerb, bank, and slope. These micro topographic differences further add to the spatial variation and potential diversity of pasture species in hill country.

Studies on a Waingaro steepland soil (Gillingham, 1974) showed that pasture on North aspects produced more dry matter than on South aspects owing to a higher growth rate during winter and early spring and that pasture species composition differed between aspects and changed during the year. The authors also found a highly significant negative relationship between slope and production which accounted for 22 % of the variability in pasture growth rate on both North and South aspects over the major part of the year. This negative relationship has also been observed by other workers (Gillingham et al., 1998; White, 1990) with Gillingham et al. (1980) observing nutrient transfer away from steeper slopes to easier slopes by grazing animals, resulting in a depletion of nutrients, particularly nitrogen, on steep slopes.

Most hill country soils are of low fertility, resulting in grass species of low quality with a subsequent limitation in pasture production (Gillingham, 1974; Lambert et al., 1982). The principal nutrient limit to pasture growth is nitrogen availability with most hill country farms relying on nitrogen fixation by pasture legumes. Unimproved hill country pastures in the southern North Island typically contain grass species such as browntop (*Agrostis capillaris),* yorkshire fog (*Holcus lanatus*), and sweet vernal (*Anthoxanthum odoratum*) (Grant et al., 1973). Also included are poorly productive legumes such as subterranean clover (*Trifolium subterraneum*) and a range of weeds. Once pastures are improved, there is an increasing incidence of ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). Generally however, poor phosphorus fertility and the dry nature of many hill country soils (particularly on the northern aspects) restrict clover growth and consequently ryegrass growth.

2.2.4 Land management and environmental issues

The dry nature and low productivity of East Coast hill country predisposes this area to sheep and beef farming with an average stocking rate of 8.8 su ha^{-1} (MAF, 2010). The steepness of hill country terrain precludes cultivation so that improvements in pasture species and production are achieved by oversowing, grazing management, and aerial topdressing.

The predominant form of fertiliser used is single superphosphate (SSP), the primary reason being that the addition of phosphate will encourage the development of legume based pasture which, in turn, will provide the nitrogen necessary for the growth of higher quality grass species such as ryegrass. The ready availability of urea since the 1980's has seen an increased application of this fertiliser with some reduction in the use of SSP (MacLeod and Moller, 2006). Since 1990 however, there has been increased use of both types of fertiliser.

Aerial topdressing of phosphatic and nitrogenous fertilisers combined with the topographic complexity of hill country landscape raises a number of potential environmental concerns. Phosphorus is often the limiting nutrient associated with the eutrophication of waterways (Sharpley and Rekolainen, 1997) and the aerial application of phosphate fertilisers has the potential, via surface runoff, to contaminate the multitude of ephemeral streams forming part of the New Zealand hill country landscape (Blennerhassett, 1998).

2.3 Soil water repellency

In their overview of hillslope hydrology studies, Anderson and Burt (1990) described hillslope hydrology as being primarily concerned with flow processes within the soil and over the soil surface. Hillslope hydrologists attempt to understand the interaction between precipitation input and hillslope discharge with respect to changes in soil moisture content. They also seek to elucidate the spatial and temporal aspects of surface runoff.

2.3.1 Surface runoff

The classical model of hillslope hydrology was first outlined by Horton (1933) who described surface runoff as “Neglecting interception by vegetation, surface runoff is that part of the rainfall that is not absorbed by the soil by infiltration”.

Runoff will occur when the amount of infiltration and surface detention is exceeded by the rainfall. In other words, excess water at the soil surface fills surface depressions and when these are filled, surface runoff starts to occur. This depression storage does not run off but eventually is evaporated and/or infiltrates into the soil (Chorley, 1978). Once surface runoff occurs, variations in micro-topography, vegetative cover, and soil surface properties will dictate flow directions so that down-slope movement will result in divided flow (Hjelmfelt (Jr) and Burwell, 1984).

Two mechanisms have been recognised that produce surface runoff from rainfall (Moore and Foster, 1990). The first is described as Hortonian surface runoff and occurs when rainfall intensity exceeds the surface infiltration rate of the soil. This mechanism often occurs when the soil surface is relatively impermeable and may be caused by a number of factors such as the development of water repellency (discussed later in this chapter) and the effect of surface sealing or compaction caused by animal or vehicle traffic or raindrop impact (Romkens et al., 1990). The second mechanism producing surface runoff is described as saturation surface runoff and occurs when a perched or a rising water table intersects the soil surface so that any rainfall, regardless of its intensity, will not infiltrate the soil surface.

These mechanisms may operate singularly or in combination and once surface depression storage has been exceeded, further rainfall will result in direct surface runoff. These runoff zones are likely to occupy only a portion of the catchment and will vary in size and location (Church and Woo, 1990).

2.3.2 Repellency-induced surface runoff

In the discussion above regarding surface runoff processes, soil water repellency was mentioned as one of the factors responsible for the potential reduction of the permeability of the soil surface layer. A reduction in infiltrability will lead to an increased incidence of Hortonian overland flow during rainfall events. Recent publications, e.g. Dekker et al. (2005), suggest that the phenomenon of water repellency is widespread and is gaining recognition as a process which has the potential to compromise the infiltration of water into the soil. It has been suggested that the possible consequences of this are enhanced runoff and potential flooding, and the reduction of soil water storage with a resulting decline in plant growth.

Prior to the 1960s, relatively few studies were concerned with water repellency. Subsequently, research into the phenomenon intensified, primarily associated with repellency that had been induced by fire and with mitigation techniques associated with water repellent soils. Much of this work was reviewed by DeBano (1981). Research into water repellency has since broadened significantly with a summary of this work presented by Wallis and Horne (1992) and with later reviews by Doerr et al. (2000) and Hallett (2008).

2.3.3 The chemistry of water repellency

In his description of the chemistry of water repellency, Doerr et al. (2000) described hydrophilic surfaces as those which allow water to spread over them in a continuous film while those that cause the water to form as droplets are termed hydrophobic surfaces (Adam, 1963). If the hydrophobic surface is a porous medium such as a soil, infiltration is thereby inhibited. The attraction (or otherwise) between water and solid surfaces is strongly influenced by the dipolar nature of the water molecule. Water molecules will adhere to most surfaces since they consist of both positively and negatively charged ions and the water molecules will orientate themselves on the surface accordingly. The dipole nature of water however, also causes it to form droplets because of the strong attraction between neighbouring water molecules, so that energy is required to overcome these attractive (cohesive) forces and increase its surface area. This energy is related to the surface tension of water (0.07275 N m^{-1}, Vargaftik (1983)) which is particularly high for a liquid. Since surface tensions for most solid surfaces range from 0.5 to 5.0 N m^{-1}, then nearly all soil minerals have surface tensions which are able to overcome that of water and enable the droplet to spread across the soil mineral surface as a film. Most soil minerals are therefore hydrophilic (Tschapek, 1984). Substances such as organic waxes or polymers on the other hand, have surface tensions below that of water (Zisman, 1964) and additional energy is required to overcome the cohesive forces causing the water to form as a droplet. These substances tend to be hydrophobic in nature.

From this discussion it can be seen that hydrophobicity is a surface phenomenon and that it is theoretically possible for a single layer of hydrophobic molecules to render a soil surface completely hydrophobic. Such uniformity however, is unlikely to present itself in a soil environment, and the amount of hydrophobic material required to render a soil water-repellent is likely to be greater than that indicated by a single layer of molecules. Work by Ma'shum et al. (1988) on the extraction of organic material from Australian sands suggested that the amount of material required to render the sands severely water repellent was quite small, of the order of 0.35 g per 1000 g of sand.

2.3.4 Water repellent compounds in soils

While a considerable amount of literature has appeared on the effects of water repellency, relatively little attention has been given to the organic chemistry of the compounds promoting hydrophobicity in soils. Ma'shum et al. (1988) identified long-chain fatty acids in Australian sands and concluded that hydrophobicity is caused by molecules with extensive polymethylene chains. Other Australian researchers (Franco et al., 1995) examined particulate organic matter in Australian sands and suggested that the larger particulates acted as reservoirs of waxes or hydrophobic materials which diffused onto the surface of sand grains during heating, particularly during the wetting, heating, and drying cycles occurring near the soil surface. A later study by the same authors (Franco et al., 2000) on water repellent sandy soils from South Australia indicated that the major component contributing to water repellency was a polar wax which was present on the sand grain surfaces and within particulate organic matter. The behaviour of this wax was mediated by low levels of a highly hydrophobic polar wax along with larger quantities of water soluble hydrophilic compounds. Both waxes were similar in composition to those associated with eucalyptus trees found in the region, and microbial activity was essential to the development and appearance of the polar wax materials.

Extracts of organic compounds from water repellent sands from the SW coast of the North Island of New Zealand (Horne and McIntosh, 2000) were partitioned into lipid and water-soluble fractions. The former fraction contained a mixture of neutral lipids (alkane hydrocarbons and triglycerides), acidic lipids (long-chain fatty acids), and polar lipids. The latter fraction exhibited amphipathic behaviour (containing both polar and non-polar functional groups). Repellency of the sands was able to be modified by the addition of either one of these fractions, with the lipid fraction increasing repellency and the water-soluble fraction decreasing repellency. The authors concluded that repellency was dictated by the functional groups present in the outermost layer of the organic material, particularly those of amphipathic compounds, rather than the composition of the bulk material.

Another study of organic compounds extracted from a range of water repellent sandy soils from Australia, Greece, Portugal, The Netherlands, and the United Kingdom (Doerr et al., 2005) found that none of the total organic carbon content, extent of aliphatic C-H, or quantity of material extracted provided any significant correlation with repellency. The extraction process however, completely removed repellency from most of the samples. The authors concluded that the compounds responsible for repellency represented a small fraction of the extracted material and that their presence did not always induce repellency. A similar study on wettable and water repellent sands from The Netherlands and the United Kingdom (Mainwaring et al., 2004) detected fatty acids (C_{16} – C_{24}), amides (C_{14} – C_{24}), alkanes (C_{25} – C_{33}), aldehydes/ketones (C_{23} – C_{31}), and complex ring structures in the organic extracts from all samples. The extracts from the water repellent samples contained greater quantities of high molecular weight polar compounds.

The above studies regarding the nature of water repellent compounds in soils suggest that the organic fraction is largely responsible for water repellency when it occurs. This fraction is derived from vegetative sources which then experiences microbial degradation, further increasing the complexity and variety of organic compounds available as potential sources of water repellency. Bulk analyses of the organic extracts indicate that the water-insoluble fractions consist of a variety of lipids of medium molecular weight which are primarily responsible for water repellency. The water-soluble fraction, which is amphipathic in behaviour, may act to mitigate the severity of water repellency by acting as an interface between an organic non-polar surface and the polar medium presented by the water molecules. Generally, there appears to be little correlation between quantities of organic material extracted and carbon chain lengths with repellency. The suggestion here (in light of the discussion on the chemistry of water repellency) is that the phenomenon is surface related and is sensitive to the presence (or otherwise) of polar/non-polar functional groups associated with the soil organic matter coating the surface of soil particles and directly interfacing with water molecules.

2.3.5 Measurement of soil water repellency

Most of the techniques associated with the measurement and classification of water repellency are largely covered in reviews by Tschapek (1984) and Wallis and Horne (1992). The discussion below is a synopsis of their work and discusses the techniques most commonly employed to measure water repellency.

A thorough review regarding the manner in which a liquid and a planar solid surface interact to produce a contact angle (*H*) was given by Zisman (1964). The interaction between the cohesive forces within a water droplet and the adhesive forces between the water droplet and the solid surface are directly indicated by the contact angle (*H*) between the water droplet and the solid surface. A number of authors (Bond and Hammond, 1970; Fink and Myers, 1969; Mallik and Rahman, 1985) have directly measured the apparent contact angle of water droplets in contact with soil surfaces. Their studies served to emphasise that the technique was only applicable to very repellent soils (otherwise water droplets on less repellent soil surfaces will infiltrate over time and make measurement of the contact angle impossible). Furthermore, surface roughness and pore shape and size distribution appeared to affect *H*.

An indirect measurement of *H* was suggested by Letey et al. (1962) who used a capillary rise and infiltration technique to determine *H*. A number of assumptions were made regarding the approximation of pore behaviour to that of cylindrical tubes in the soil and of Poiseuille flow through these tubes. The authors found that ethanol produced the same *H* for all soils tested and so *H* was assumed to be zero for ethanol. On this basis they were able to use Poiseuille's equation to calculate the pore radius which was then used in the calculation of *H* for other solutions. The method seemed to produce reasonable and consistent results. There were however, a number of drawbacks, notable of which was the time required to measure capillary rise and its unsuitability for use on intact soil cores.

In 1957, Philip (1957) developed the theory of intrinsic diffusivity and sorptivity which he later modified (Philip, 1969). Using this theory, Tillman et al. (1989) developed a method which determines the ratio of intrinsic sorptivity for ethanol to that of water for structurally stable soils, and argued that this ratio can be used as an index of water repellency. This repellency index was evaluated by Wallis et al. (1991) who measured the index on a range of

New Zealand soils. The index was compared with the 'water drop penetration time (WDPT)' and 'molarity of an ethanol droplet (MED)' techniques (described later in this section). The repellency index suggested that all soils were repellent to some extent at field moisture conditions and that the technique was more sensitive than either WDPT or MED, thus being of potential use for those soils exhibiting low levels of repellency. A number of other advantages were revealed whereby the index could be used to measure actual and potential short-term water infiltration which could be compared against rainfall and irrigation intensities. Additionally, the technique was able to be used *in situ* or on undisturbed field cores at field-moist or air-dry conditions.

Perhaps the simplest test for water repellency is the water drop penetration time (WDPT) method (Van't Woudt, 1959) which involves placing a drop of distilled water on the surface of a soil and measuring the time for the water to penetrate the sample. The soil surface is prepared beforehand to provide standard conditions since surface roughness and pore geometry affect WDPT. A number of techniques have been proposed to improve the repeatability of the method, but most researchers have opted for increased replication to improve their estimate of WDPT. Recent advances in the employment of this technique are provided by Doerr (1998). The relationship between WDPT and H has been considered by Letey (1969) and Letey et al. (2000) who suggested that WDPT classifies soils into two categories; those with an apparent H above 90^o, and those below. If the water forms a droplet on the soil surface then $H > 90^o$ and the soil is considered repellent. Since the droplet penetrates the soil surface over time, then H changes also, suggesting that the WDPT test is a better indicator of the persistence of repellency, rather than a measure of the initial contact angle. A study of South Australian sandy soils by King (1981) suggested that WDPT is limited in its ability to measure repellency and is relevant only for a few degrees span around $H = 90^o$. The study showed that WDPT is < 1 second for $H < 75^o$, thus imposing limitations on using the technique for low repellency soils. Other authors have measured WDPT times greater than an hour for severely repellent soils, making the technique time-consuming for these types of soils. Despite the limitations just described, the WDPT method has distinct advantages in terms of its speed (except for severely repellent soils), simplicity, and its application to both in-situ and disturbed samples, and as a result has been used in many studies associated with water repellent soils.

Another simple technique used in the measurement of soil water repellency is the molarity of an ethanol droplet test (MED) developed by King (1981). The test measures the molarity of ethanol in an aqueous droplet required to infiltrate the soil surface within 10 seconds. In his study of a large number of Australian sandy soils, King (1981) found that measured MED values correlated very well with observed apparent contact angles. Variability however, increased when $H > 92^{o}$ and the test was not useful in those soils where low repellency was observed ($H \leq 81^{o}$) since at this angle MED = 0. For such soils, King (1981) argued that the WDPT test was a useful extension of the MED test. As with the WDPT test, the most important advantages of the MED test are speed and simplicity and its applicability to field and disturbed samples. Furthermore, it can be used on highly repellent soils where WDPT values are in excess of 1 hour. Its main disadvantage lies with its unsuitability for use with low repellency soils.

While direct measurement of apparent contact angles (H) between the water droplet and the soil surface gives a definitive value for the degree of water repellency of very repellent soils, the duration of the procedure and the measurement of very small areas of the soil surface makes this technique prohibitive in terms of replication and time. This has prompted the development of further techniques such as capillary rise and intrinsic sorptivity which, although also time-consuming, produce H and repellency index values more representative of the bulk soil. The most popular techniques used for the measurement of water repellency are the WDPT and MED tests due to their speed and simplicity. The main disadvantages with these techniques lie with their measurement of point surfaces making large replication sets necessary, and the limited contact angle range of their respective measurements. The latter drawback may be mitigated somewhat by performing both tests in combination.

2.3.6 Spatial and temporal variations in soil water repellency

One of the characteristics associated with soil water repellency is its high spatial variability. Bond (1964) found that moisture in South Australian repellent sands after 25 mm of rainfall varied between 1 % to more than 8 % over a distance of 1 cm. Further observations by the same author indicated that water penetrated into these repellent sands through narrow channels and that the intervening soil remained dry. Studies of soils under burned Scottish heathlands (Mallik and Rahman, 1985) showed high variability in WDPT tests of undisturbed soils, and Dekker and Ritsema (1994) found high variability in water repellency within the top 50 cm of Dutch dunes. A number of authors (Bond, 1964; Dekker and Ritsema, 2000; Hendrickx et al., 1988; Ritsema and Dekker, 2000) have observed that uneven wetting of repellent soils through narrow channels was initiated on the soil surface where repellency was least. Once established, these channels acted as preferential pathways for water through to the subsoil. A model describing wetting front instability and the development of preferential flow pathways in repellent soil was first provided by Raats (1973).

While the causes of high spatial variability of water repellency in soils are not well understood, micro-scale variabilities (over a few mm to cm) in topographic, physical, and chemical properties are likely to be contributing factors (Mallik and Rahman, 1985; Wallis et al., 1990a).

Soil water repellency is generally regarded as a seasonal phenomenon and it is most severe during extended dry periods. Repellency is often minimal or absent during prolonged wet conditions (Ritsema and Dekker, 1994). Generally, water repellency re-establishes upon drying (Walsh et al., 1994) once a critical soil moisture content is reached (Carter et al., 1994). It is likely however, that the soil moisture/water repellency relationship is more complicated than indicated above since repellency has been found in a wide range of soil moisture contents in different soils (Dekker and Ritsema, 1994; Dekker and Ritsema, 1996; Doerr and Thomas, 2000). Furthermore, while a number of authors have reported an inverse relationship of soil moisture with water repellency (King, 1981; Witter et al., 1991), others have found an initial increase in repellency with soil moisture (de Jonge et al., 1999).

It is clear then, that soil water repellency is highly variable, both spatially and temporally. Spatial variability complicates the analysis of repellency, particularly when the commonly employed point-specific techniques of WDPT and MED are used to upscale processes that are variable at a micro level. Seasonal and diurnal changes in repellency may be associated with changes in soil moisture content, particularly in the top few millimetres of the soil profile, but the relationship is not straightforward and is likely to be very specific to the site being studied.

2.3.7 Distribution of soil water repellency in New Zealand

Early overseas studies of water repellency were largely restricted to areas that experienced semi-arid or Mediterranean climates. Towards the end of the 1980s however, studies began to suggest that wetter areas such as Portugal, Great Britain, and the Netherlands also experienced water repellency and that the phenomenon was not just confined to drier areas, although the probability of occurrence of repellency increased in areas with drier climates.

In New Zealand, soil water repellency has been increasingly reported with studies by Wallis et al. (1991) who used the intrinsic sorptivity, MED, and WDPT techniques to measure the repellency index of 14 soils from the Manawatu, Central Otago, and Canterbury regions. The repellency index values suggested that all the soils were water repellent at field moisture conditions and that repellency reduced the short term water infiltrability of all the soils by an order of magnitude. A later study (Wallis et al., 1993) investigated a series of five sandy soils from the west coast of the lower North Island using the MED technique, and found severe repellency in the younger Waitarere and Motuiti dune sands with low repellency observed in the older Foxton and Koputaroa dune sands. Dune sands were more repellent than sands associated with low lying areas. There appeared to be no apparent relationship between repellency and either soil pH or carbon content.

Other areas in New Zealand examined for water repellency were Hawke's Bay (Deurer et al., 2007; Slay, 2008) and a survey conducted in 2009/2010 of 50 soils under pastoral land use in the North Island (Deurer et al., 2011). The latter study examined the top 40 mm across 50 sites, with the sites representing ten soil orders. The soil orders appeared to have an influence on the degree (MED test) and persistence (WDPT test) of repellency with the greatest repellency values being observed in the Podzol, Organic, and Recent soils, and the least for Allophanic soils. Both actual (field moist samples) and potential (samples dried at 65 ^{o}C) repellency values were measured. On this basis, the authors surmised that 98 % of the sites become water repellent when the soils dry out and that 70 % of the sites were water repellent at the time (summer) of sampling. Correlations were also attempted against different classes of drought-proneness which were determined by integrating soil dryness (the annual water deficit) and the amount of plant available water. The degree of water repellency did not vary significantly between the classes, leaving the authors to suggest that the top 40 mm of soil regularly dries out during summer regardless of the annual water deficit and the amount of plant available water.

Although the number of water repellency studies on New Zealand soils is limited, it is clear that water repellency is ubiquitous but is only readily observed when the soils become highly repellent. Sandy soils are more susceptible than most to water repellency and accordingly these soils were the early subjects of repellency research in New Zealand, particularly those associated with dunes under pasture in the Manawatu. Summer dry areas such as the Hawke's Bay region promote the onset of readily observable water repellency during dry periods thereby prompting research into the phenomenon known locally as 'dry patch syndrome'. Soil order appears to play a role regarding both the degree and persistence of repellency, although Deurer et al. (2011) do not offer an explanation as to why this might be the case. The soil survey performed by these authors does not state if their sites were located on sloping pastoral land: their primary site selection being based on soil order and drought-proneness. It is likely however, that a number of their samples would have been derived from hill country pastoral systems. Since the probability of soil water repellency increases with permanently vegetated sites (Doerr et al., 2006), as is the case with New Zealand hill country pastoral systems, then it seems probable that these systems are a potential source of samples for the study of soil water repellency in New Zealand.

2.3.8 Impacts of soil water repellency in New Zealand hill country pastures

According to a review by Doerr et al. (2000), the main hydrological impacts of soil water repellency are reduced infiltration capacity, increased overland flow, spatially localised infiltration, a change in the three-dimensional distribution and dynamics of soil moisture, enhanced stream flow responses to rainstorms, and enhanced total stream flow.

A number of studies have confirmed that water repellency compromises the infiltration capacity of a soil (DeBano, 1971; Wallis et al., 1990b; Wallis et al., 1991) and that increased overland flow occurs (Crockford et al., 1991; Witter et al., 1991). There are a very limited number of papers which examine the consequences of soil water repellency in New Zealand hill country pastoral systems. Of note is a study connecting 'dry patch syndrome' and soil water repellency in Hawke's Bay hill country pastures (Deurer et al., 2007) which prompted an analysis by Müller et al. (2010) of the effects of water repellency on pasture growth at two permanent pasture sites at Whatawhata in the Waikato and six sites at Maraetotara in the Hawke's Bay. The former location was used to test the effect of repellency on water infiltration and solute transport using soils with high and low organic carbon contents, while the latter location was used to test the effect of repellency on pasture production by installing pasture cages on 3 hydrophobic and 3 control sites.

Using disc infiltrometers with ethanol and water at Whatawhata, the authors found that repellency appeared to reduce the permeability of the soil by a factor of 6 and 20 in the low and high organic carbon content soils, respectively. These values were consistent with other values for New Zealand soils reported in the literature (Wallis et al., 1990b), and suggest that repellency is likely to enhance both overland flow and localised infiltration. Intact Whatawhata soil columns were used in leaching experiments to measure transport of the herbicide 2,4-D with results indicating reduced sorptivity of this compound in the high organic carbon (and highly repellent) soil. The low organic carbon soil displayed significantly higher overall filtering efficiency. These results suggest that the enhanced localised infiltration caused by repellency reduces the opportunity for solutes to enter soil macro-aggregates where degradation would normally take place and that the soil's normal filtering efficiency is compromised by soil water repellency.

Experimental results from their Hawke's Bay sites (Müller et al., 2010) showed a 50 % reduction in pasture production over 4 months in the 'dry patches' compared to the wetter areas surrounding them, with the 'dry patches' making up about 30 % of the pasture area. The authors suggested that 'dry patch syndrome' may lead to an estimated 30-40 % loss in pasture production. These figures are not definitive however, since only three replicates were used, which is insufficient for a statistical analysis and may be the reason why the authors seemed not to have attempted this. The Müller et al. (2010) paper also implies that the positioning of cages at the Maraetotara site was by selection rather than being randomised, indicating the potential for bias. Other factors which may also influence pasture production appear not to have been measured, such as pasture species, density, and soil fertility.

While not specifically examining water repellency in hill country, there are a number of papers which allude to the possibility of water repellency having an effect on their research outcome. In an attempt to develop a pasture production model based on a daily soil water balance and where pasture growth was proportional to actual evapotranspiration, Moir et al. (2000a) suggested that the over prediction of pasture growth at their Whareama sites on hill country in the eastern Wairarapa, particularly during summer and autumn, may have been due to the soil surface becoming water repellent. While this may have been a factor, the authors acknowledge that other reasons would also have accounted for the slow recovery of dead or desiccated pasture after rainfall, such as the reliance of pasture growth on germination or re-growth from buried stolons.

In their study on the development of a soil water balance model for sloping land, Bircham and Gillingham (1986) acknowledged the role of repellency during the rewetting phase of the soil where " ... on a dry, steepland soil, often only the surface few millimetres of the profile will be re-wetted during a rainfall event, almost regardless of the intensity of rainfall." The authors accommodated this observation into their 4-layer model by controlling the rate of water entry into the top layer so that " ... duration rather than intensity of rainfall tends to control the rate of soil rewetting." This was achieved by imposing a minimum time of 3.3 days to allow the top layer to reach field capacity if the moisture content of that layer was less than 0.68 of field capacity. While it is highly likely that water repellency does compromise the infiltration rate at the surface layer, the authors do not justify the threshold soil moisture value at which the throttling takes place nor the period of time over which it occurs. The result of the imposition of their throttling process was an underestimation of soil moisture values during September and October because of the inability of the sub surface layer to be rewetted until the surface layer had reached or exceeded field capacity. During these months, high evapotranspiration rates often kept moisture contents of the surface layer below that of field capacity and prevented the rewetting of the layer below it.

A number of papers have described the interaction of lime application and soil moisture responses in hill country. During et al. (1984) observed a rapid increase in soil moisture in the top 25 mm of soil after an application of 3 t ha^{-1} of lime on over-sown pasture at Whatawhata. This effect was less marked on steep than on easy slopes during autumn.

Work by Jackson and Gillingham (1984) showed a soil moisture advantage to liming except at very low soil moisture levels. This advantage was most pronounced during late summer and early autumn and the mechanism proposed by these authors was that the application of lime relaxed hydrophobic conditions promoted by organic matter formed by herbage senescence in summer. Morton et al. (2005) however, reported only small increases in soil moisture in response to the application of lime at a site near Waipawa, suggesting that the lime-soil moisture-repellency relationship is complex and that more parameters need to be monitored in order to better understand the soil surface chemistry response to lime applications.

2.4 Conclusions

Although soil water repellency has been recognised as a phenomenon since the end of the nineteenth century, it was not until 1960 that worldwide research on this topic began to exponentially increase (Dekker et al., 2005).

New Zealand publications regarding soil water repellency however, are still limited – particularly regarding hill country pasture, the primary focus of this thesis. Initial studies focussed on sandy soils sited in the Manawatu in 1990 where repellency was most easily observed. A 2011 soil survey of numerous North Island soil orders has indicated that soil water repellency is ubiquitous in pastoral systems and is not readily observed in the field until the onset of extended dry conditions. The response of soils to these conditions varies from soil to soil but the onset of repellency is likely to be promoted by sandy soils and/or by soils under permanent pasture. As a consequence of the limited number of studies conducted on the phenomenon in New Zealand, the effects of repellency on hill country pastoral systems are poorly understood.

Studies to date have indicated that soil infiltration is compromised and that the filtering capacity of the soil is reduced when repellency is established. The inference here is that under these conditions there is the potential for an increase in overland flow as well as an increase in localised infiltration. The effects of an enhancement in these two flow paths in hill country pastures and the potential resulting effect on stream flow is not yet known.

The effect of repellency on hill country pasture production has been estimated by one author (Müller et al., 2010) to result in a loss of production of 30-40 %. However, the lack of supporting statistical analyses would suggest that these values should be treated with some circumspection. Other authors (Moir et al., 2000a) have hinted that repellency may have been a factor affecting unexpected production observations. While this may have been the case, there were a number of equally important factors that could also have been responsible for the observed deviance. These qualifications notwithstanding, this review suggests that repellency in the hill country landscape is a phenomenon which merits further study.

CHAPTER 3

SITE DETAILS AND INSTRUMENTATION

3.1 The research area

The research area was established on Pori Station, a sheep and beef hill country farm which lies 5.2 km NE of Alfredton and 16 km E of Eketahuna (Figure 3.1 and Plate 3.1). The research area is located at 40^{o} 38' S and 175^{o} 54' E and at an altitude of 200 m. Thirty year (1980-2009, NIWA CliFlo database) annual average rainfall for this area is 1224 mm while the average daily temperature over the same period is 12.6 ^{o}C. Winters are often cold and wet with summer rainfall being unreliable. Prevailing north-westerly winds are stronger during spring and are often dry, having shed their moisture on the Tararua Ranges. The consequence is that soils often dry out in late spring and summer, and farmers often face pronounced dry summer and autumn seasons. Occasional heavy storms from the south or south-east are also typical of the climatic pattern for this region and frequently result in enhanced erosion on slopes which have been cleared of native vegetation and replaced with pasture.

Molloy (1998) describes the geology of the region as strongly faulted, with splinter faults from the Alpine Fault running parallel to each other in a northeast-southwest direction. Subduction of the Pacific tectonic plate under that of the Indo-Australian plate off the east coast of the North Island has resulted in the scraping, compression, and uplift of soft marine sandstones, siltstones, and limestones of Tertiary and late Cretaceous age. These sedimentary rocks provide the parent material for soils in this region.

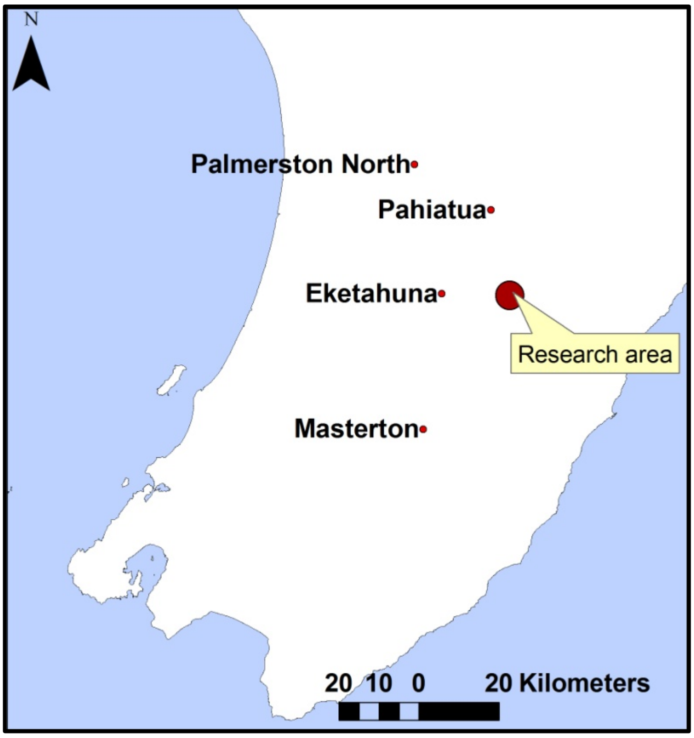

Figure 3.1 Location of the research area.

Plate 3.1 The primary catchment area – looking WNW.

The research area was located in a well-defined primary catchment (Figure 3.2) which consists of a number of sub-catchments. Five experimental sites were established in one of these sub-catchments (C1) and one site was established in an adjacent sub-catchment (C2). The sites were labelled using slope and aspect abbreviations, e.g. C1 30 N to denote a north-facing site on a 30^{o} slope in sub-catchment 1. Each of these sites contained paired, side-by-side runoff plots, giving a total of 12 runoff research plots. Table 3.1 summarises the layout of these sites.

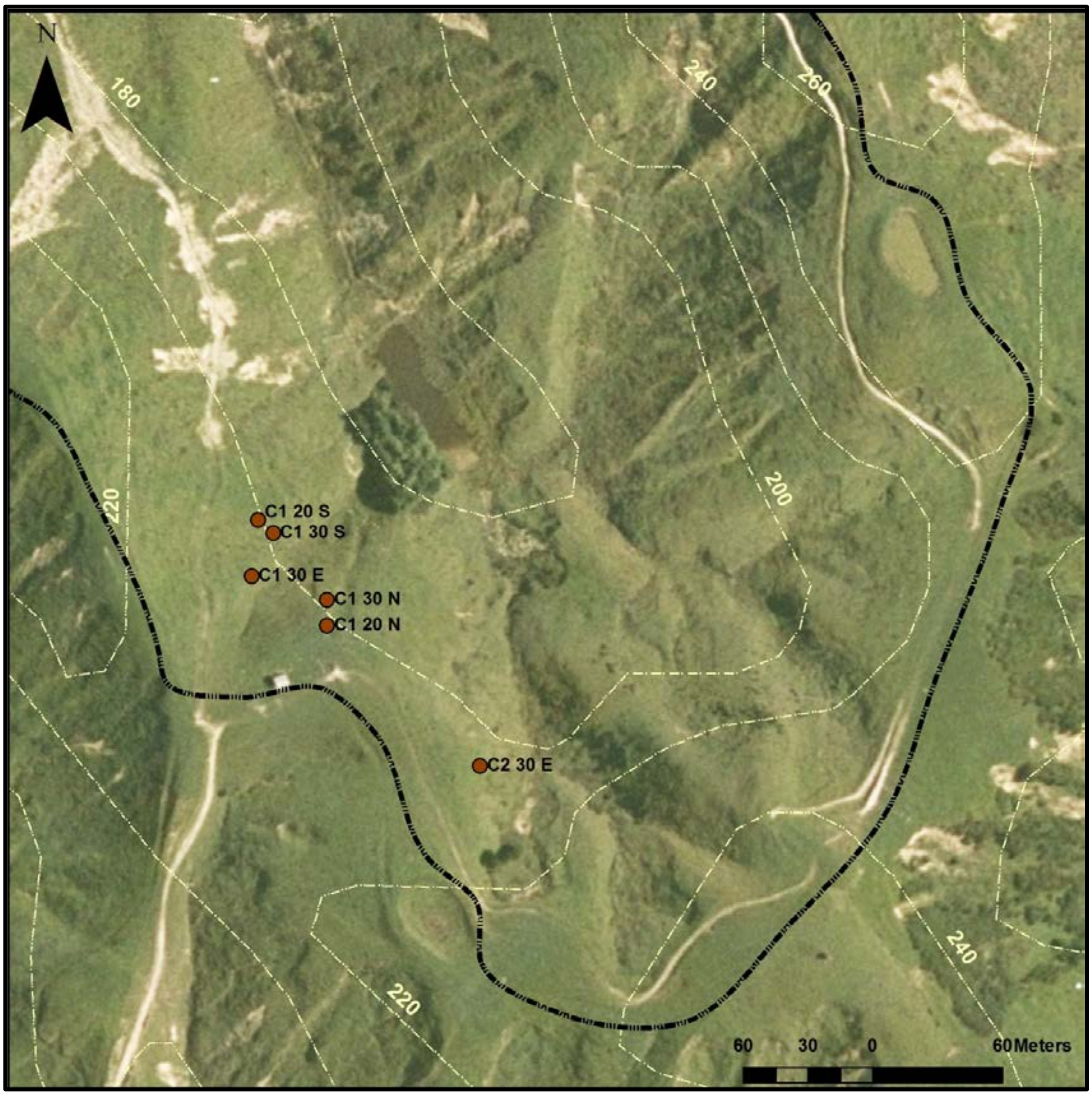

Figure 3.2 Location of the research sites at Alfredton. The primary catchment boundary is shown by the black dotted line; yellow dotted lines denote contours at 20 m intervals.

Table 3.1 Summary of site layout at the research area.

Site Code	Sub-catchment	Slope	Aspect	Date established
C1 20 S	1	20^o	South	02-05-2006
C1 30 S	1	30^o	South	02-05-2006
C1 20 N	1	20^o	North	27-04-2006
C1 30 N	1	30^o	North	20-04-2006
C1 30 E	1	30^o	East	02-05-2006
C2 30 E	2	30^o	East	09-05-2006

3.2 Soils

Soil on the slopes is primarily Atua silty clay loam (Plates 3.2 and 3.3), which is a mottled orthic recent soil (Hewitt, 1998) with a land use capability classification of VII. Detailed soil profile descriptions for a C1 North aspect and a C1South aspect are given in Table 3.2 with bulk density data given in Table 3.6. Appearances and descriptions for both aspects suggest that the soils are visually and physically similar and would be expected to have similar infiltration responses. Of particular note is the depth at which pasture roots were observed – down to 70 cm for the C1North aspect and down to 85 cm for the C1South aspect.

Table 3.2 Soil profile descriptions for the C1North aspect (Plate 3.2) and the C1South aspect (Plate 3.3).

Aspect	Depth (cm) [Horizon]	Colour	Soil Type	Texture	Structure
C1North	0 – 27 [Ap]	Dark (10YR 4/2) to very dark (10YR 3/2) greyish brown	Silty clay loam	Friable; slightly sticky; plastic	Moderately developed fine nut and granular structure; many fine roots; diffuse even boundary
	27 – 35 [ABw]	60 % dark greyish brown (10YR 4/2), 40 % yellowish brown (10YR 5/4). Coarse distinct worm mottles	Silty clay loam	Brittle; sticky; plastic	Moderately developed fine block structure with coarse crumbs around roots; common fine roots; diffuse even boundary
	35 – 48 [Bg1]	70 % yellowish brown (10YR 5/4), 20 % yellowish brown (10YR 5/8), 10 % dark greyish brown (10YR 4/2) from worm mottles. Vertical worm burrows up to 5 mm diameter filled with topsoil. Medium distinct mottles	Silty clay loam	Brittle; very sticky; plastic	Moderate fine block structure; few fine roots; diffuse even boundary
	48 – 69 [Bg2]	60 % pale brown (10YR 6/3), 40 % strong brown (7.5YR 5/7)	Silty clay loam	Brittle; very sticky; plastic	Weak fine blocky structure; few fine roots; wavy indistinct boundary
	69 – 140 [Bg3]	30 % light brownish grey (10YR 6/2) arranged in a net gammate structure, 30	Silty clay loam	Brittle; very sticky; very plastic	Weak coarse blocky structure; no roots

		% strong brown (7.5YR 5/7), 40 % yellowish brown (10YR 5/5) occurring as large (> 5 cm) irregular shaped zones with thin clay coatings on exterior and interior surfaces. Coarse distinct mottles			
	140 – 170 [Bg4]	80 % yellowish brown (10YR 5/5), 10 % light brownish grey (2.5Y 6/2), 10 % strong brown (7.5YR 5/7). A few thin clay coatings	Silty clay loam	Firm; sticky; plastic	Weak coarse block structure; no roots
C1South	0 – 23 [Ap]	Dark greyish brown (10YR 4/2) with a few light yellowish brown (10YR 6/4) worm mottles near the base	Silty clay loam	Friable; slightly sticky; plastic	Moderately developed medium nut and granule structure; common fine roots; diffuse even boundary
	23 – 30 [ABw]	70 % dark greyish brown (10YR 4/2), 30 % yellowish brown (10YR 5/5) mottled by worms	Silty clay loam	Friable; sticky; plastic	Moderately developed medium nut and granule structure (granules due to earthworm casts); common fine roots; diffuse even boundary
	30 – 65 [Bw]	90 % brownish yellow (10YR 6/5), 10 % dark greyish brown (10YR 4/2) due to vertical and sub vertical earthworm burrows up to 10 mm diameter filled with topsoil	Silty clay loam	Brittle; very sticky; plastic	Moderately developed fine block structure; few fine roots; diffuse even boundary

	65 – 87 [Bg1]	70 % brownish yellow (10YR 6/5), 15 % light brownish grey (2.5Y 6/2), 15 % strong brown (7.5YR 5/7). Coarse distinct mottles. Thin brown (7.5YR 5/3) to strong brown (7.5YR 5/6) clay coatings on peds	Silty clay loam	Firm; very sticky; plastic	Weak medium blocky structure; very few fine roots; indistinct even boundary
	87 – 100 [Bg2]	50 % light grey (2.5Y 7/2), 50 % strong brown (7.5 YR 5/8) as a net gammate structure. Thin brown (7.5YR 5/3) to strong brown (7.5YR 5/6) clay coatings on peds	Silty clay loam	Firm; very sticky; plastic	Weak block structure; no roots
	100 – 114 [Bg3]	50 % light grey (2.5Y 7/2), 50 % strong brown (7.5 YR 5/8) as a net gammate structure. Thin brown (7.5YR 5/3) to strong brown (7.5YR 5/6) clay coatings on peds. Increasing number of pale brown (10YR 6/3) angular bedrock fragments	Silt stone	Some brittle, some soft	No roots

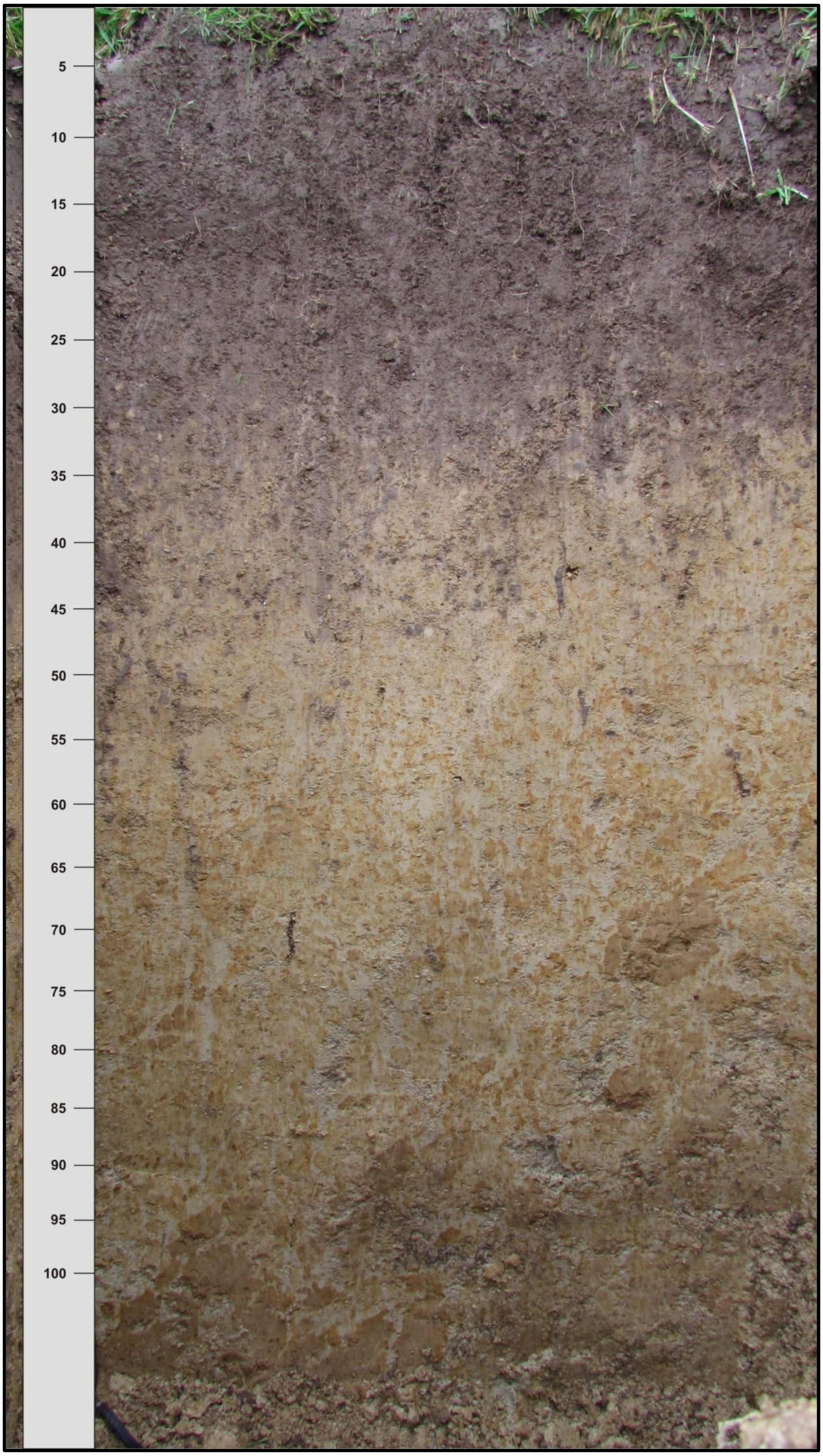

Plate 3.2 **The soil profile at the C1North aspect (scale units are in cm).**

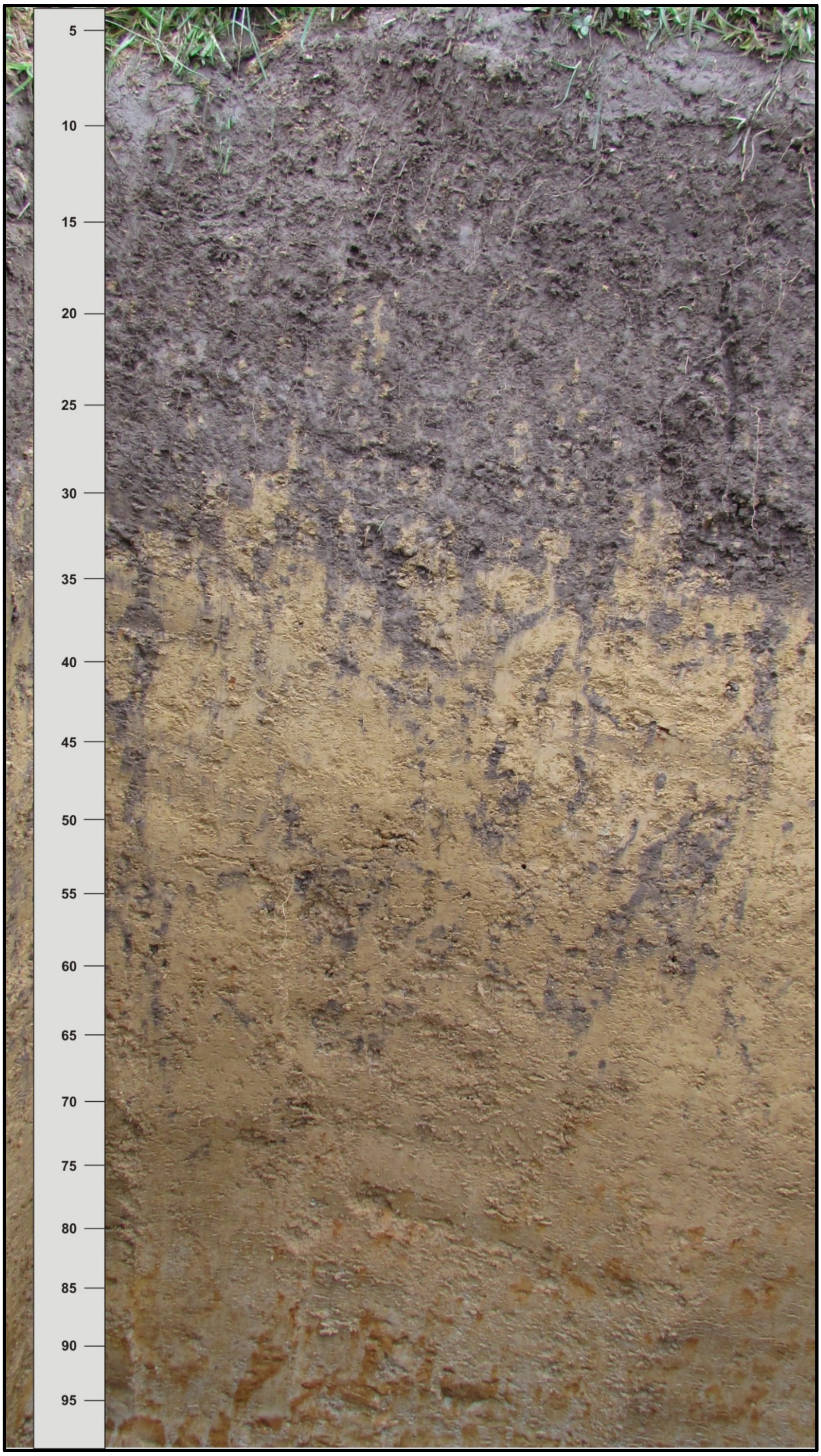

Plate 3.3 **The soil profile at the C1South aspect (scale units are in cm).**

Soil fertility analyses were performed on 0-75 mm depth soil core samples taken from the research area at the beginning and at the end of the research project. Table 3.3 presents these analyses for all aspects at both times.

Table 3.3 **Nutrient status of the soils for all sites on 23-11-2006 (first row) and 12-06-2012 (second row). The additional C2, C3, C4 and C5 sites (which have only one analysis on 12-06-2012) are associated with pasture sampling sites that are described in detail in Chapter 8.**

Aspect	pH	Olsen P (μg P g^{-1})	SO_4 (μg S g^{-1})	K (me 100 g^{-1})	Ca (me 100 g^{-1})	Mg (me 100 g^{-1})	Na (me 100 g^{-1})	CEC (me 100 g^{-1})
C1NSh	5.4	27.4	12.3	0.70	6.6	1.52	0.11	19
	5.4	31.1	16.0	0.50	5.5	1.35	0.21	18
C1NSt	5.1	21.8	14.0	0.40	5.9	1.23	0.25	20
	5.3	31.1	17.0	0.39	6.1	1.29	0.25	18
C1SSh	5.2	34.5	13.8	0.35	5.6	1.29	0.09	22
	5.2	28.7	19.5	0.78	5.0	1.44	0.32	20
C1SSt	5.1	23.6	11.5	0.23	5.3	1.21	0.11	19
	5.2	22.6	18.3	0.35	5.2	1.31	0.24	21
C1ESt	5.1	27.9	13.0	0.30	6.7	1.56	0.12	21
	5.2	21.2	17.0	0.54	6.4	1.86	0.21	22
C2ESt	5.1	18.4	11.0	0.49	5.6	1.78	0.20	23
	5.2	17.4	16.1	0.59	5.9	1.75	0.20	23
C2NSh								

	5.2	32.0	16.7	0.69	7.8	1.93	0.17	23
C2NSt								
	5.2	35.8	13.8	0.45	7.5	1.76	0.19	22
C3NSh								
	5.2	26.4	16.4	0.99	6.3	1.96	0.18	22
C3NSt								
	5.2	31.5	12.8	0.78	5.5	1.80	0.19	22
C4SSh								
	5.4	23.1	17.9	0.50	6.2	1.34	0.20	22
C4SSt								
	5.4	20.7	16.0	0.41	5.3	1.03	0.14	19
C5SSh								
	5.3	17.4	13.9	0.58	5.6	1.32	0.17	19
C5SSt								
	5.4	16.0	11.4	0.32	5.8	1.33	0.15	18

Soils at all sites and at both times exhibit low but consistent pH values ranging from 5.1 to 5.4. There was very little change in pH between the sampling dates.

Olsen P values demonstrate a wider range from 16.0 (C5SSt) up to 35.8 (C2NSt) µg P g^{-1} with no consistent trend in plant-available P between the two sampling dates. Overall P status for the soils is high for hill country pastures. For routine soil testing, Olsen P is expressed on a volumetric basis, so for the purposes of comparison, the gravimetric values stated in this thesis should be multiplied by 0.8 g ml^{-1} (the average topsoil bulk density at the site).

Sulphate levels range from 11.0 (C2ESt) through to 19.5 (C1SSh) µg S g^{-1} with increases in readily plant-available sulphur between the two sampling dates for all (relevant) sites. The observed range of values is adequate for hill country pastures.

For the plant-essential cations, K values range from 0.23 (C1SSt) through to 0.99 (C3NSh), Ca values range from 5.0 (C1SSh) through to 7.8 (C2NSh), Mg values range from 1.03 (C4SSt) through to 1.96 (C3NSh), and Na values range from 0.09 (C1SSh) through to 0.32 (C1SSh) me 100 g^{-1}. Trends between the two sampling dates varied between cations and sites, but the resultant ranges observed are acceptable for hill country pasture growth. CEC values ranged from 18 - 23 me 100 g^{-1} with rises and falls for different sites between the sampling dates.

3.3 Pasture

The range of pasture plants at the Alfredton research area was diverse with browntop (*Agrostis capillaris*) being the dominant grass species (grass averaged 83 % of pasture composition (Sanches, 2009)), followed by crested dogstail (*Cynosurus cristatus*) and perennial ryegrass (*Lolium perenne*). Legumes averaged 9 % of pasture composition with subterranean clover (*Trifolium subterraneum*) being the dominant legume, followed by white clover (*Trifolium repens*). Weed species averaged 8 % of pasture composition and were dominated by californian thistle (*Cirsium arvense*), narrow-leaved plantain (*Plantago lanceolata*), and catsear (*Hypochaeris radicata*).

3.4 Instrumentation and sampling

3.4.1 General

The first phase of the research project involved manual measurements of rainfall, runoff volumes, and soil moisture. This phase continued while automated measurement systems were being developed and tested. The project moved to the second phase when most of the manual sampling procedures were supplanted with automated systems.

The purpose of the second phase was to increase the frequency of rainfall, air temperature, wind speed, relative humidity, solar radiation, runoff volumes, and soil water content measurements so that detailed site-specific data would be available to observe runoff responses to a range of rainfall intensities and soil moisture contents. It was planned to use this more detailed data to refine a daily soil water balance model described in Chapter 4 and developed using the manual data gathered in phase one.

The necessary automation for the collection of high resolution data was provided by the installation of solar-powered weather stations, one each at C1 North, C1 South, C1 East, and C2 East aspects. Each of these stations recorded the previously mentioned meteorological variables as well as soil moisture and runoff volumes. All dates and times related to data gathered at the research area are in New Zealand Standard Time (NZST).

Each station was protected from stock by an electric fence powered by a 12V car battery which was, in turn, recharged by the solar radiation panel supplying power to the weather station. Sensor data was accumulated within the logger memory and downloaded either by directly connecting a laptop computer to the logger or by using a modem which connected to the logger via a cellular network. Due to the remote location of the research area, connection via the latter method often proved to be unreliable and, as a result, was rarely employed. Table 3.4 summarises the sensor layout for each weather station.

Table 3.4 Summary of the logger and sensor inventory for each of the weather stations.

Station Name	Installation Date	Logger Type[1] (replacement date)	Sensors
C1 North	30-10-2007	Campbell Scientific CR800 (17-12-2009)	- Hydrological Services TB5 0.2 mm tipping bucket rainfall gauge - Apogee PYR-S Pyranometer - Vaisala HMP50Y temperature/humidity sensor - Maximum Hall Effect Anemometer - Campbell Scientific CS616 300 mm TDR probes - Custom-built 145 mL runoff tipping buckets
C1 South	20-11-2007	Campbell Scientific CR800 (06-01-2010)	
C1 East	04-12-2007	Campbell Scientific CR211 (14-01-2010)	
C2 East	05-12-2007	Campbell Scientific CR211 (11-03-2010)	

[1] – All loggers were later replaced with Campbell Scientific CR1000 units

There were two major problems involving data capture using the loggers associated with the weather stations. The first problem quickly manifested itself in the form of a large number of spurious data signals arriving at the loggers from the runoff tipping buckets for each plot. After testing it was discovered that the pulsed output from the electric fence surrounding each weather station was interfering with the data cables between the logger and the runoff tipping buckets. Considerable time was expended in attempting to resolve this problem: installation of shielded data cables and re-arrangement of the electric fences resulted in minor improvements. A solution to this first issue was finally achieved with the design and construction of optical pulse filters at Massey University. These were inserted between the tipping bucket data cable and the logger and were installed on 12-11-2009 at the C1North and C2East aspects and on 19-11-2009 at the C1South and C1East aspects.

The second problem manifested itself some time after the installation of the TDR probes and proved to be more difficult to identify and resolve. The following symptoms were observed:

1) The C1 North and C1 South loggers experienced random lockups (a failure to respond to communications and a failure to log data).

2) The internal software monitoring system of the C1 North and C1 South loggers began to record errors.

3) The C1 South logger in particular was severely affected with complete loss of accumulated data occurring at times.

4) The symptoms were more prevalent when the soil was very moist and/or during significant rainfall events.

5) The C1 East and C2 East loggers were completely unaffected.

A number of attempts were made to try and isolate the cause of the problem. These involved:

1) Stepwise removal of the various sensors attached to the logger.

2) Switching off the temporary electric fence surrounding the relevant logger.

3) Consultation with the suppliers of the loggers (Scott Technical Instruments Limited).

Trouble-shooting was a time-consuming process due to the random appearance of the symptoms and the isolation of the research site. Following recommendations from Scott Technical, all temporary electric fences surrounding the logger stations were replaced with conventional fences. This resulted in a significantly decreased incidence of lockups and internal logging errors, and there were no further instances of data loss. Those errors that did continue to occur were attributed to permanent electric fences 25 m from the C1 North aspect. It is suspected that the more substantial network of underground cabling associated with the C1 North and C1 South loggers (installation of the TDR probes and a greater number of runoff tipping buckets) served to act as antennas and attenuators for sub-surface current flows generated from the combination of temporary and permanent electric fence installations. These current flows would be more active during wetter conditions and induce electrical spiking (probably via the TDR power and data cables) in the logger and hence the observed lockups and loss of accumulated data.

3.4.2 Runoff plots and the measurement of runoff volumes

A number of small plots were constructed to measure runoff. Each plot was 2 m long down the slope and 1 m across. The borders were defined by 25 mm thick wooden boards, dug in so that 40 mm remained above ground and 200 mm below. These wooden boards were placed at the top and sides of the plot, with runoff being captured by a 55 mm diameter PVC pipe buried at the bottom of the plot (Figure 3.3 and Plate 3.4). A PVC delivery plate (1 m long) was inserted a short distance into the soil face at the bottom of the plot to ensure that runoff was not lost between the pipe and the soil face. This plate, coupled with the split geometry of the PCV pipe, allowed captured surface runoff to be channelled, via tubing, to 45 litre plastic collection bins which were installed further down the slope during phase one of the research project.

The volume of the collected runoff in the bins was measured periodically and the bins then emptied, but there were occasions when overflow occurred (when the runoff depth exceeded 22 mm since the last measurement).

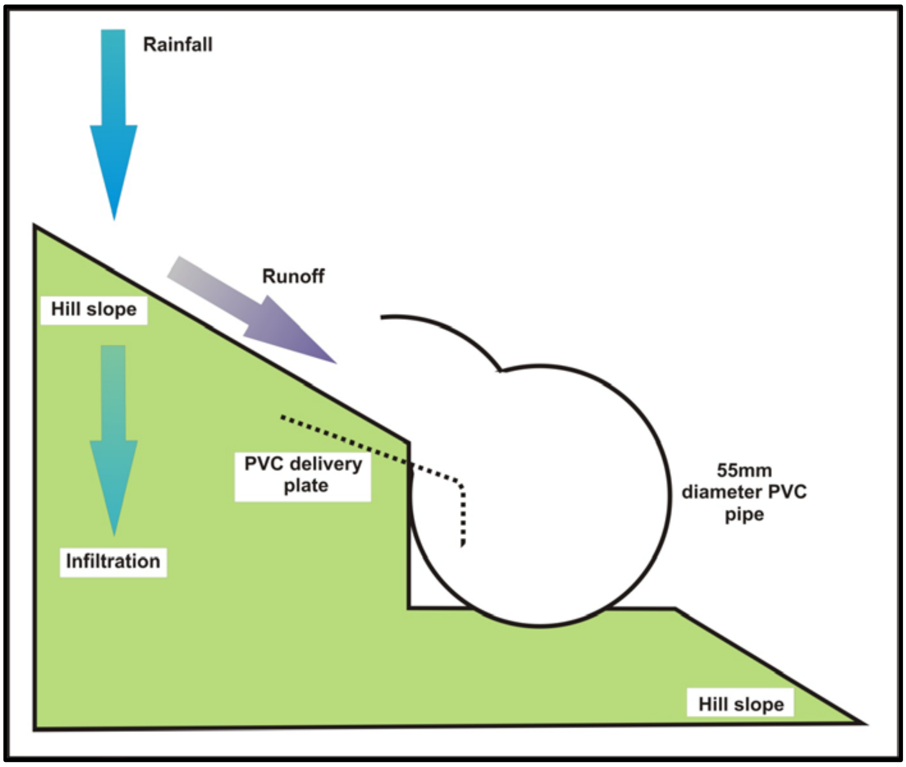

Figure 3.3 **The setup for the collection of surface runoff.**

Plate 3.4 **One of the C1 30 N plots showing the split PVC pipe and collection bin.**

The second phase of the project necessitated the automated measurement of surface runoff. This required the design and manufacture of small tipping bucket units to be housed inside 50 L chilly bins for protection from stock and the weather. These units were manufactured at Massey University (Plate 3.5) and were sized so that each tip delivered approximately 145 mL (or approximately 0.08 mm for a 1 m x 2 m runoff plot).

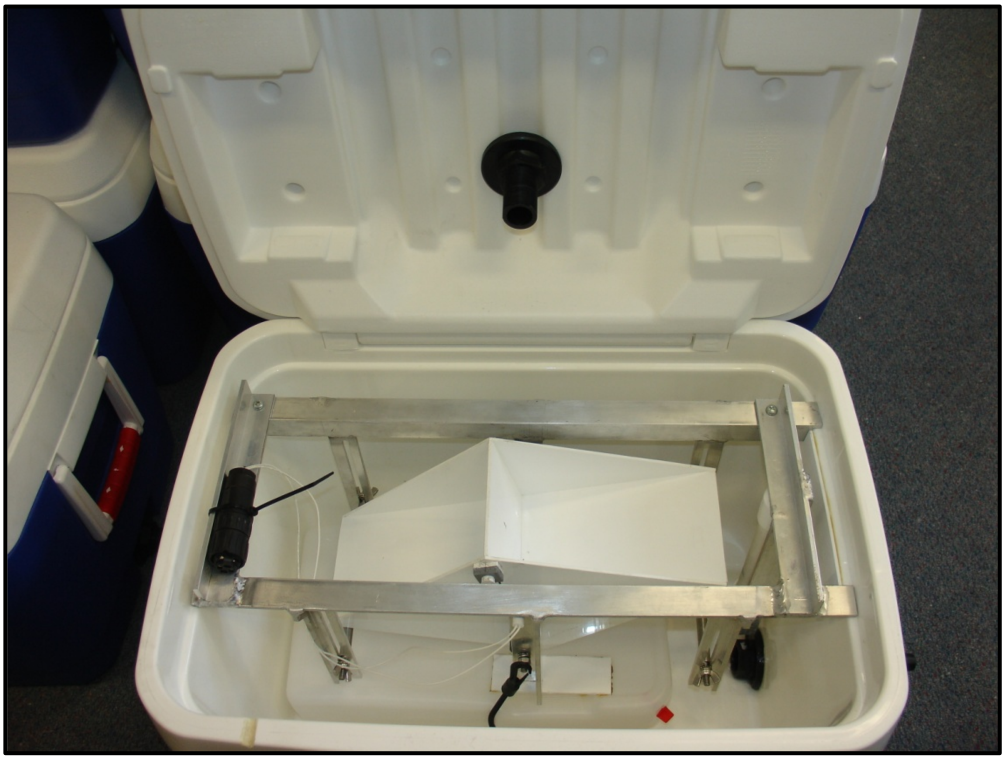

Plate 3.5 Custom designed and manufactured runoff tipping bucket housed inside a chilly bin.

Figures 3.4 and 3.5 clearly show that tip volumes increase as tip rates increase. Consequently, each bin was individually calibrated i.e. the tip volume as a function of tip rate was determined. All tipping bucket units showed similar tip volume responses to tip rates and a least squares curve-fitting procedure was employed to provide calibration curves with the following general formula:

$$Y = A - BC^{x}$$

where *Y* is the tip volume (mL); *A*, *B*, and *C* are parameters found by least squares iteration and *x* is the tip rate (tips per minute). Plate 3.6 shows one of the units installed in the field.

The initial static collection bins (employed during phase 1 and shown in Plate 3.4) were replaced with these new systems over a period of time (Table 3.5).

Plate 3.6 **Surface runoff measurement system installed in the field.**

Table 3.5 **Installation dates of surface runoff tipping buckets for the research plots.**

Plot Name	Installation Date	Plot Name	Installation Date
C1 20 N L	06-03-2008	C1 30 S L	21-04-2008
C1 20 N R	14-03-2008	C1 30 S R	21-04-2008
C1 30 N L	14-03-2008	C1 30 E L	20-05-2008
C1 30 N R	17-03-2008	C1 30 E R	20-05-2008
C1 20 S L	10-04-2008	C2 30 E L	25-06-2009
C1 20 S R	11-04-2008	C2 30 E R	25-06-2009

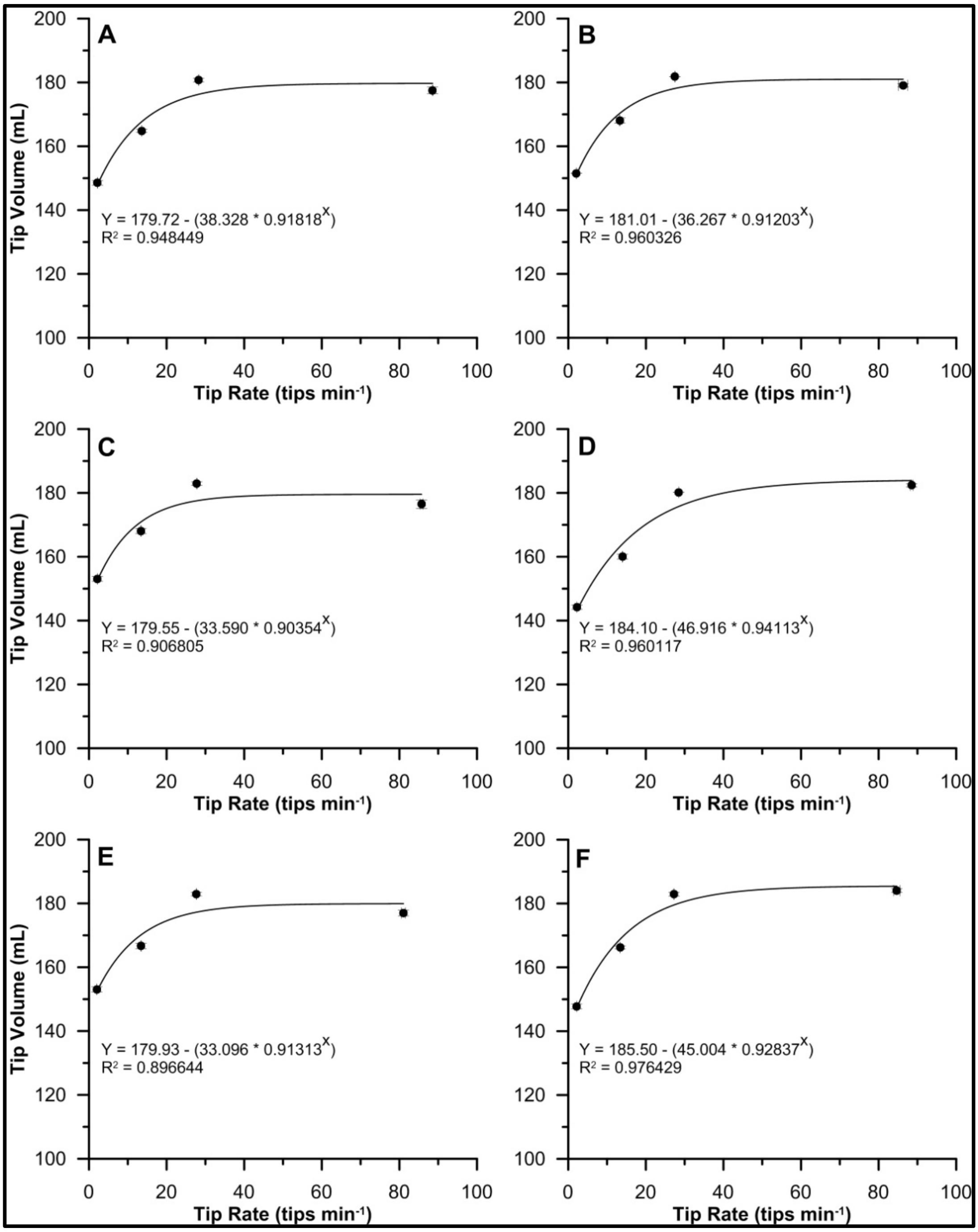

Figure 3.4 Tip volume as a function of tip rate. Calibration plots for runoff tipping buckets C1 20 N L (A), C1 20 N R (B), C1 30 N L (C), C1 30 N R (D), C1 20 S L (E), and C1 20 S R (F). Data points are the means of 3 replicates; solid lines are least squares fitted curves.

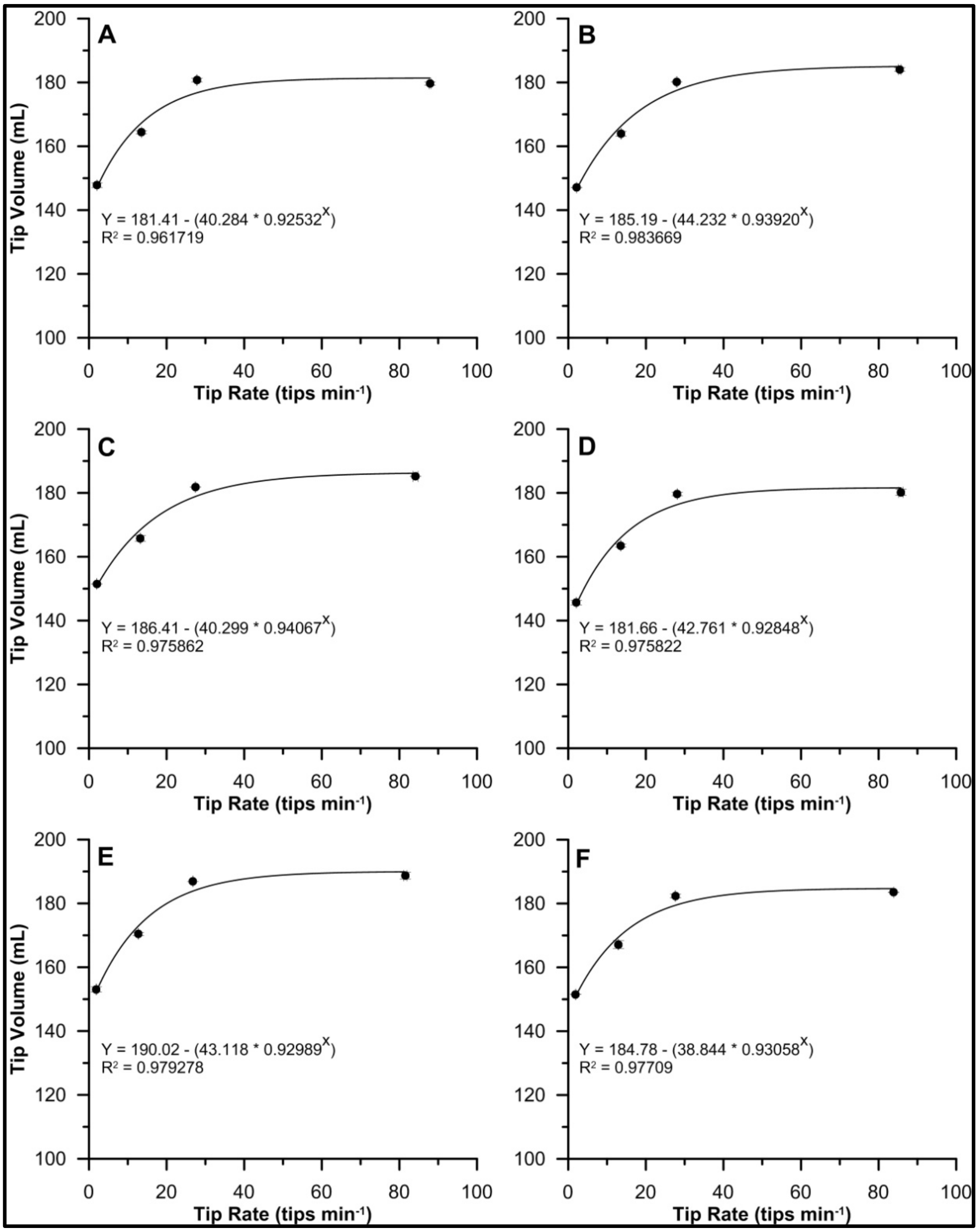

Figure 3.5 Tip volume as a function of tip rate. Calibration plots for runoff tipping buckets C1 30 S L (A), C1 30 S R (B), C1 30 E L (C), C1 30 E R (D), C2 30 E L (E), and C2 30 E R (F). Data points are the means of 3 replicates; solid lines are least squares fitted curves.

3.4.3 Rainfall

A manual rainfall gauge was installed at the top of the hill near the C1 North aspect. Rainfall depth was recorded whenever the research area was visited and, during phase 1 of the project, the accumulated data was compared with that measured at NIWA's automated weather station (5.2 km SW distant) at Alfredton. Manual readings continued to be recorded throughout phase 2 of the research project. Later, automated rainfall gauges were installed on each of the four aspects (Table 3.4) and were set to record the time of every 0.2 mm of accumulated rainfall. The amount of cumulative rainfall recorded varied with each aspect with the highest values being measured at the C1 South aspect. This coincided with this aspect having the lowest recorded wind run values (Figure 3.10). A detailed examination of the rainfall data is provided in Chapter 5.

3.4.4 Soil moisture

During the first phase of the project, soil samples were taken at each site and at regular intervals to determine gravimetric water contents. A 25 mm diameter soil corer was used to extract 3 vertical cores to a depth of 350 mm in close proximity to the paired plots at each site. These cores were cut into 50 mm lengths; the three replicates bulked for each interval, and the bulked samples stored in sealed polyethylene bags until they were weighed the following day. They were then oven-dried, reweighed, and the gravimetric water content calculated. Bulk density values were then used to convert the gravimetric soil water contents to their volumetric equivalents. During phase two, only the top 0-50 mm of topsoil continued to be analysed in this manner.

Phase two of the research project saw the installation of 300 mm long TDR probes in the paired runoff plots at the C1 20 N and C1 30 N sites on 06-05-2010 and at the C1 20 S and C1 30 S sites on 19-05-2010. These sensors were installed vertically in the middle of the relevant plot and a single reading was taken once a day at midnight. The raw output from a TDR probe gives the travel time (µs) of an attenuated signal from a generated wave-front within the probe. The attenuation time is a function of the volumetric water content (VWC) of the soil around the probe and so the probes require calibration. VWC values to relate to attenuation times were provided by manually removing 300 mm depth soil cores from the sites when low, mid, and high range TDR values were recorded. Gravimetric soil water contents were calculated from the dried cores and then converted to volumetric values using previously measured bulk densities for the sites. The resulting calibration curve is shown in Figure 3.6. Physical limitations imposed by TDR technology prevented its use in the measurement of VWC in just the topsoil (0-50 mm) and therefore manual sampling was continued for this depth.

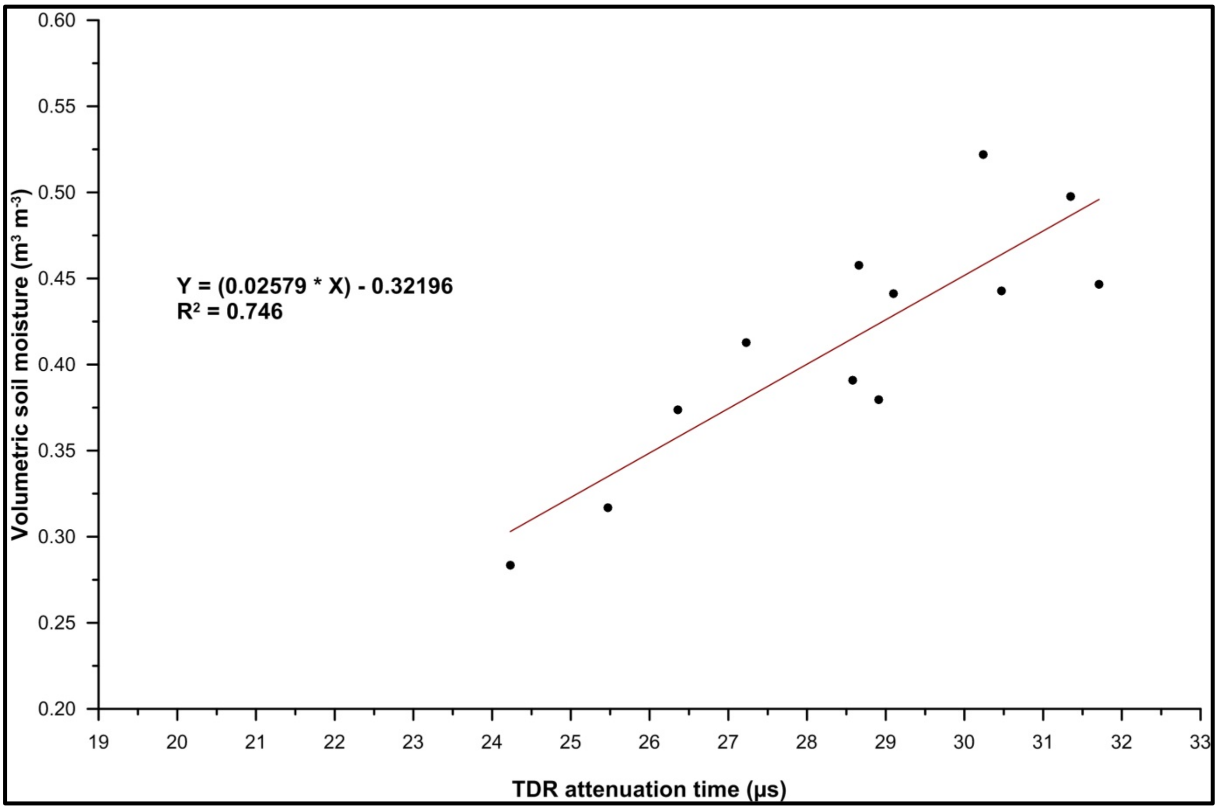

Figure 3.6 Calibration plot for 300 mm depth TDR probes; the red line is a least squares fitted linear curve.

A more detailed examination of the soil moisture data is provided in Chapter 5.

3.4.5 Bulk density

On 22 July 2009, duplicate cylindrical soil samples (exactly 48 mm in diameter and 50 mm long) at alternate 50 mm depth intervals were taken for bulk density measurement. These were dried at 105 ^{o}C, weighed, and the bulk density calculated. Values for the top 50 mm depth were highly variable, prompting a further sampling (this time with 5 replicates) at this depth on 7 September 2011. A summary of bulk density values is given in Table 3.6.

Table 3.6 **Bulk density statistics for each of the research sites.**

Site	Depth (mm)	Range (kg m^{-3})	Mean (kg m^{-3})
C1 20 N	0 - 50	780 - 956	873
	100 - 150	1129 - 1161	1145
	200 - 250	1322 - 1335	1329
	300 - 350	1469 - 1532	1501
C1 30 N	0 - 50	710 - 1014	859
	100 - 150	1120 - 1121	1121
	200 - 250	1218 - 1256	1237
	300 - 350	1454 - 1563	1509
C1 20 S	0 - 50	568 - 860	686
	100 - 150	1092 - 1118	1105
	200 - 250	1161 - 1243	1202
	300 - 350	1298 - 1357	1328
C1 30 S	0 - 50	743 - 1095	897
	100 - 150	1233 - 1269	1251
	200 - 250	1324 - 1450	1387
	300 - 350	1454 - 1467	1461

C1 30 E	0 - 50	714 - 822	764
	100 - 150	1056 - 1097	1076
	200 - 250	1185 - 1234	1210
	300 - 350	1274 - 1364	1319
C2 30 E	0 - 50	628 - 868	761
	100 - 150	1061 - 1084	1072
	200 - 250	1204 - 1284	1244
	300 - 350	1351 - 1402	1376

Bulk density values for the top 0-50 mm depth are (as would be expected for hill country pastures) highly variable, ranging from 568 – 1095 kg m^{-3} for the C1South aspect and 710 – 1014 kg m^{-3} for the C1North aspect. These values increased with depth so that at 300-350 mm, ranges of 1298 – 1467 kg m^{-3} for the C1South aspect and 1454 – 1563 kg m^{-3} for the C1North aspect were observed. For the purposes of the conversion of 0-50 mm gravimetric water contents to their volumetric equivalents, the 0-50 mm depth bulk density values were treated as a single data set, giving a mean value of 807 kg m^{-3}. Values for each of the other depths were also treated as a single data set. For the TDR calibration data, the mean 0-300 mm bulk density at each site was used to convert 0-300 mm gravimetric soil water contents to VWC values.

3.4.6 Water repellency

The water drop penetration time (WDPT) and molarity of ethanol droplet (MED) tests were not used routinely to measure water repellency, due to their small spatial resolution and the potentially high spatial variability of these measurements across the dimensions of the runoff plots, not to mention the variability across entire slope/aspect categories. However, one measurement set was undertaken using the WDPT and MED tests on 16-11-2010 in order to assess the potential repellency of the 0-40 mm surface soils at each of the runoff sites. The sampling and measurement techniques were adopted from Deurer et al. (2011), with specific reference to the potential degree and persistence of soil water repellency. Specifically, bulk 0-50 mm depth soil samples were taken around each site, sealed in plastic bags, and transported to Massey University where they were passed through a 5 mm sieve and then dried at 65 ^{o}C for 48 hours. Both WDPT and MED measurements were performed on the cooled samples. The results of these analyses are given in Table 3.7.

Table 3.7 **Potential degree and persistence of water repellency for 0-40 mm top soils at each of the research sites on 16-11-2010.**

Site	WDPT (s)	Persistence Class*	MED# (mol L^{-1})	Contact Angle+ (degree)
C1 20 N	1644	3 (severe)	1.71	100.2
C1 30 N	237	2 (strong)	1.03	97.6
C1 20 S	804	3 (severe)	1.71	100.2
C1 30 S	81	2 (strong)	0.86	96.8
C1 30 E	91	2 (strong)	0.68	95.9
C2 30 E	392	2 (strong)	1.37	99.0

* - Dekker and Jungerius (1990)
# – ethanol concentration required for droplet adsorption in less than 10 s
+ – Roy and McGill (2002)

The 0-40 mm surface soils at all sites exhibit potential for water repellency (as shown by contact angles greater than 90^{o}). The shallow slopes (C1 20 N and C1 20 S) are capable of expressing severe persistence and the greatest degree of repellency (100.2^{o}) once these soils become sufficiently dry.

3.4.7 Solar radiation

Solar radiation was not measured at the research area until phase two was established with the installation of weather stations at the four aspects (C1 North, C1 South, C1 East, and C2 East). Until then, radiation data was sourced from a NIWA site, East Taratahi, about 30 km S of the research area: the assumption being that incoming shortwave radiation and the subsequent calculation of reference crop evapotranspiration is much less spatially variable than rainfall.

For the second phase of the research project, solar radiation sensors (Table 3.4) were mounted on top of 2 m high masts and, except for one, were angled at 30^{o} in order to simulate the amount of short wave radiation intercepting the slope at that particular aspect. The exception was for C2 East where the sensor was fixed in a horizontal position. Short wave radiation was recorded and accumulated over a 24 hour period then stored at midnight. Unfortunately, failure rates were high and suspect data was frequently encountered for all of the sloping sensors, so that any calculations requiring solar radiation input used data gathered only from the horizontal sensor at C2 East. Revfeim's (1982) equations were used to estimate the incoming solar radiation for the various slopes and aspects. Missing values (resulting from sensor or power failures) were obtained from the nearest virtual climate site located within NIWA's CliFlo database.

The resulting dataset is shown in Figure 3.7. The annual pattern is roughly sinusoidal with maximum values of about 35 MJ m^{-2} day^{-1} occurring in December and minimum values of about 2 MJ m^{-2} day^{-1} occurring during June. Day to day variation due to cloudiness is quite considerable, particularly during the summer months.

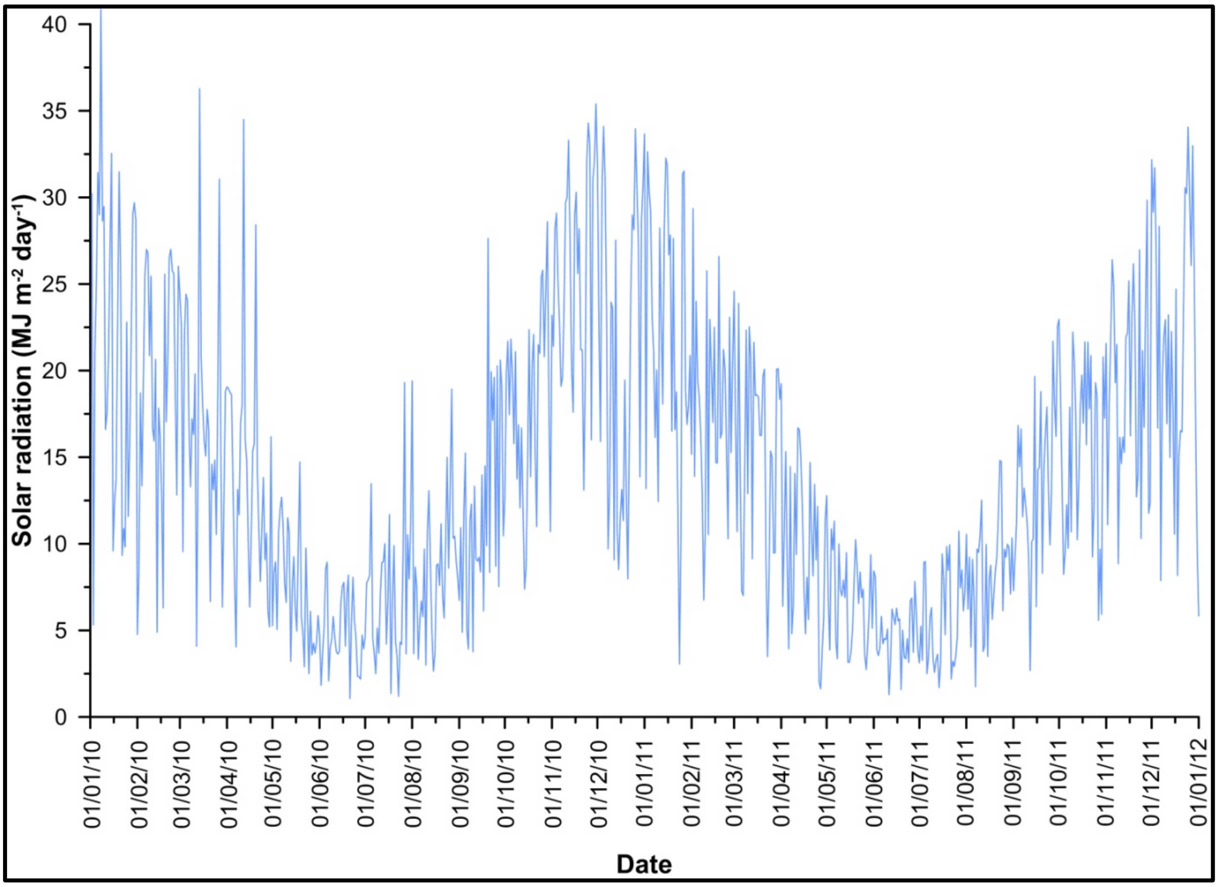

Figure 3.7 **Incoming daily short wave solar radiation measured on a horizontal surface at the C2East site.**

3.4.8 Air temperature and relative humidity

As with solar radiation, no air temperature measurements were made at the research site until the establishment of phase two of the project. Prior to this, data was obtained from the NIWA East Taratahi site. With the onset of phase two, shielded air temperature and relative humidity (RH) sensors (Table 3.4, one sensor performs both measurements) were fixed at 1.5 m above ground level at all aspects and were set to monitor maximum and minimum values for both relative humidity and air temperature over a 24 hour period and to store these values at midnight.

The means for both maximum and minimum relative humidity were calculated across all aspects and used as input for the calculation of reference crop evapotranspiration. Loss of data at any one aspect was adequately covered by the very high likelihood that data was present in at least one of the other three aspects. The resultant dataset is shown in Figure

3.8. Maximum RH values showed considerably less variation than minimum RH values, with values ranging from 80 - 100 %. Minimum RH values appear to follow an annual sinusoidal pattern with maximum values of about 90 % occurring during June-August, with minimum values of about 35 - 40 % occurring during November-March.

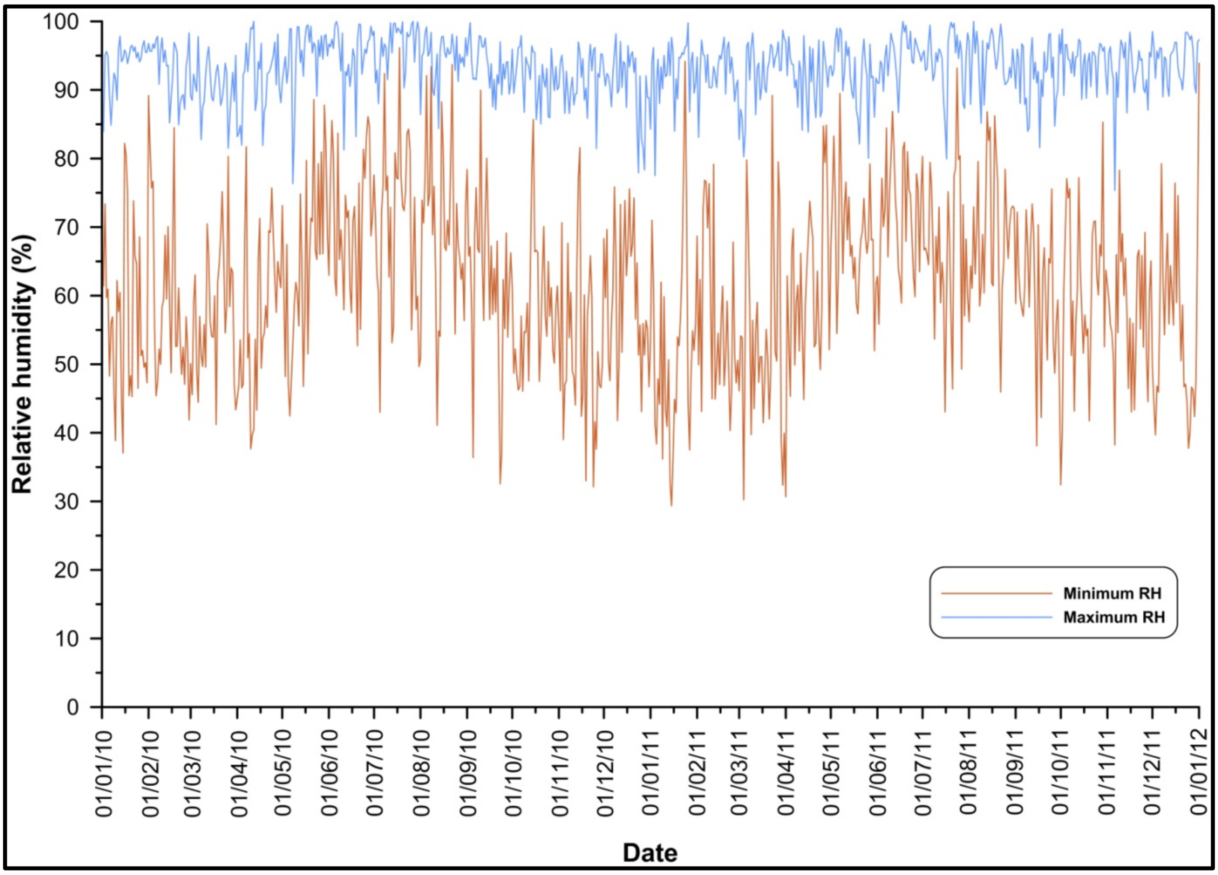

Figure 3.8 Mean daily maximum and minimum relative humidity values for the research sites.

Individual C1North and C1South maximum and minimum air temperature data sets were quite well correlated, giving slopes of 0.95 and 0.99 and offsets of 1.7 and -0.5 respectively. The means for both maximum and minimum air temperatures were thus calculated across all aspects and used as input for the calculation of reference crop evapotranspiration. The resultant dataset is shown in Figure 3.9. The annual patterns for both minimum and maximum air temperatures are both strongly sinusoidal, with maximum temperatures reaching 25 - 30 ^{o}C during November-December and falling to 2 - 10 ^{o}C during June-July. Minimum temperatures reached 15 - 20 ^{o}C and fell to -2 - 2 ^{o}C during the same months.

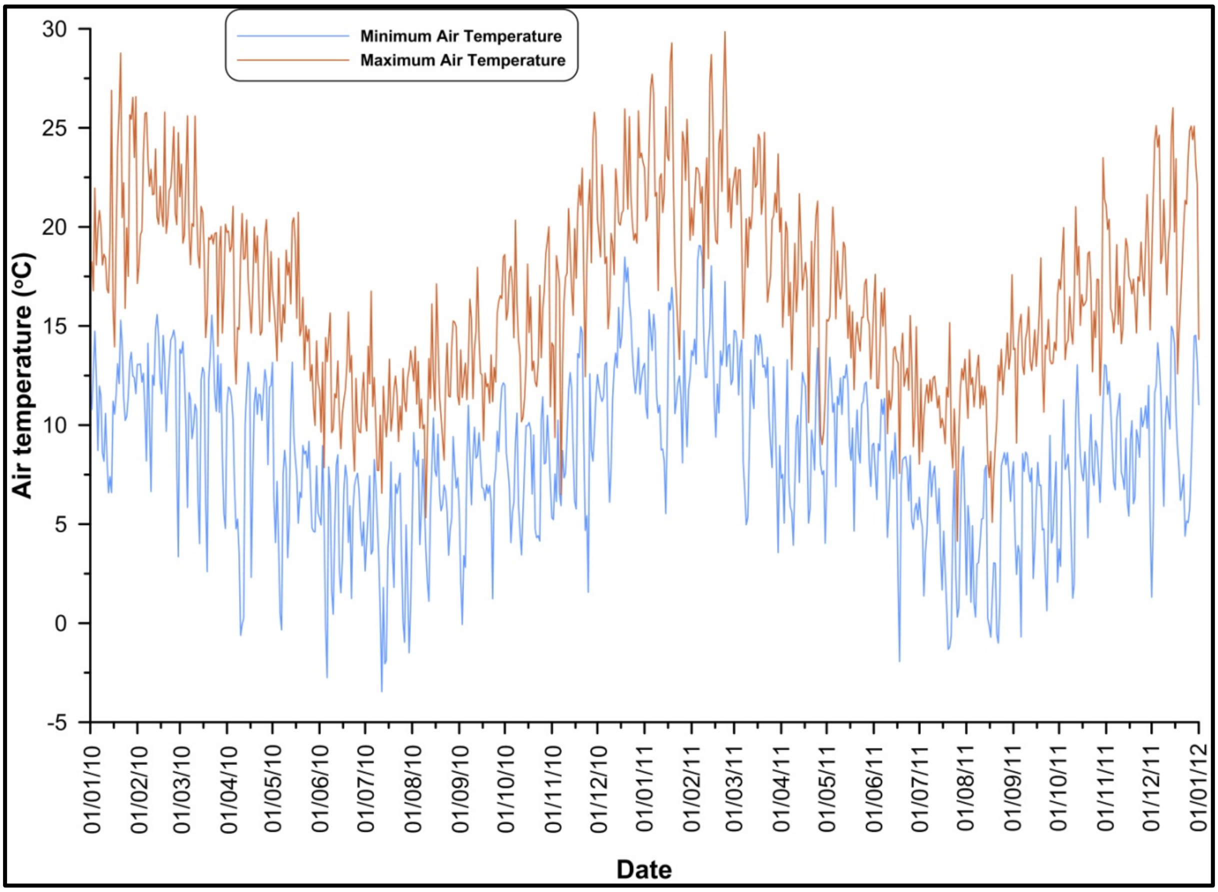

Figure 3.9 Mean daily maximum and minimum air temperature values for the research sites.

3.4.9 Wind

Once again this parameter was not measured at any of the aspects until the onset of phase two of the research project. Up until this point, data from NIWA's East Taratahi climate station was used to provide input information for the initial daily soil water balance model proposed in Chapter 4.

With the commencement of phase two, anemometers (Table 3.4) were installed on masts 2 m above ground level at each of the aspects and were set to record wind run over a 24 hour period and store this data at midnight. As might be expected, wind run data was highly spatially variable with patterns being strongly dependent on the location of the aspect with respect to landscape features and the prevailing wind direction (N). The C1 North aspect experienced high wind run values (a mean of 233 with a maximum of 670 km day^{-1}) with C1 South displaying the lowest values (a mean of 119 with a maximum of 330 km day^{-1}). Additionally, both C1 East and C2 East experienced maximum wind runs of 670 km day^{-1}, with mean values of 206 and 272 km day^{-1} respectively. Because of the frequent lapses in data collection due to power or sensor failures or electric fence interference, it was decided to divide the data into two groups; one with high wind run data (mean of C1 North, C1 East, and C2 East), and the other with (relatively) low wind run data (C1 South). For the low wind data, missing days were filled in by scaling the high run data by 0.4. The resulting two wind run data sets (Figure 3.10) were then applied to the relevant aspects (High = C1North, C1 East, and C2East, Low = C1 South) to help contribute to the calculation of daily reference crop evapotranspiration.

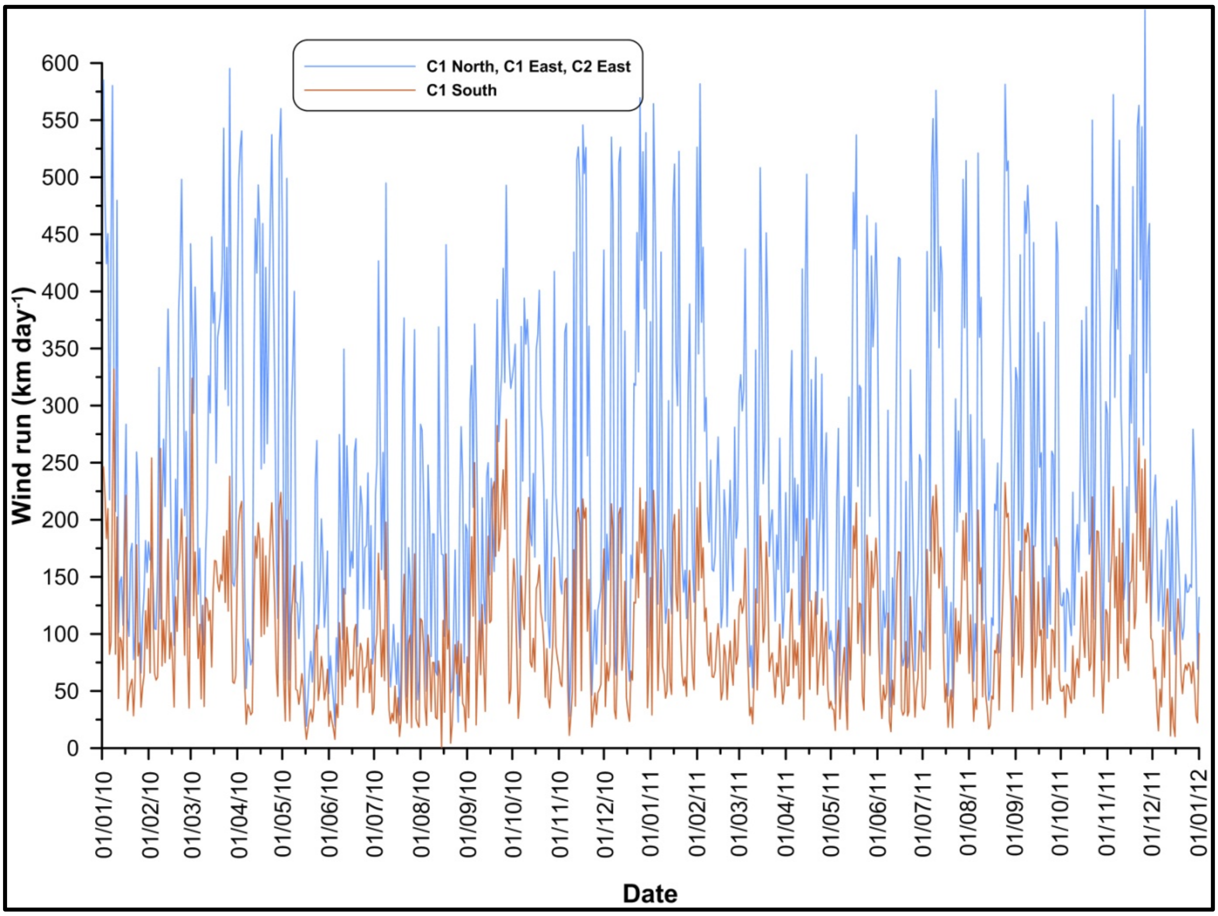

Figure 3.10 High and low wind run datasets for the research sites.

CHAPTER 4

SOIL WATER AVAILABILITY IN HILL COUNTRY

4.1 Introduction

The previous chapter described the establishment of the runoff plots at the research site and the procedure employed in the first experimental phase where surface runoff volumes and gravimetric soil moisture contents were collected manually. A second experimental phase, involving the design, manufacture, purchasing, and commissioning of equipment for real-time monitoring of surface runoff, soil moisture content and meteorological variables, is also described. Implementation of this second phase of development of the research site took some considerable time, thus a substantial body of data was accumulated prior to it coming into operation. Although this data had poor time resolution and other deficiencies (due to manual sampling and the remote location of the research site), it contained enough information to begin modelling the soil water balance of the research site, in particular, the surface soil moisture content. Subsequently (Chapter 7), this initial model is refined to better account for repellency-induced runoff.

The remainder of this chapter is reprinted from volume 53 of the New Zealand Journal of Agricultural Research (pages 175-185) by M. R. Bretherton, D. R. Scotter, D. J. Horne, and M.J. Hedley in 2010. It is entitled 'Towards an improved understanding of the soil water balance of sloping land under pasture'.

4.2 Towards an improved understanding of the soil water balance of sloping land under pasture

The soil water balance for relatively flat pasture land in New Zealand has been extensively studied and is quite well understood. Woodward et al. (2001) provide an analysis of previous work, leading to a daily time-step, two-soil-zone model, that they validate using 11 historical datasets. In contrast, relatively few studies have been published on the water balance in hill country, despite it constituting over 75% of New Zealand pastoral land. Both Radcliffe (1968) on Banks Peninsula in Canterbury and Gillingham (1974) at Whatawhata in Waikato used soil sampling to show that the top 75 mm of soils on North (N) facing slopes were significantly drier than those on South (S) facing slopes. Lambert and Roberts (1976) using gypsum blocks found that the soil on an N facing slope was often at a lower matric potential (and so drier) than the soil on a S facing slope in hill country near Palmerston North.

Jackson (1967) used the Penman equation to estimate the effect on reference crop evaporation (or what was referred to then as the potential evapotranspiration) of the varying amounts of solar radiation falling on slopes of differing aspect and steepness. For land under pasture at Taita near Wellington, Jackson (1967) obtained evaporation estimates of 904 mm and 584 mm for 308 N and S facing slopes respectively, for the year 1966. Lambert and Roberts (1976) obtained similar differences for 148 N and S facing slopes near Palmerston North, suggesting that different evaporation rates were the reason for the often different moisture conditions they observed in N and S aspect topsoil.

However, only one in-depth study of the water balance of New Zealand hill country pasture soils has been published (Bircham and Gillingham, 1986); this work therefore mainly concentrates on this important paper. The experimental data presented by Bircham and Gillingham (1986) (B&G) are three years' of weekly or bi-weekly, 0-75 mm depth soil water content measurements at two Waikato hill country sites, one with a YellowBrown Earth and the other a YellowBrown Loam. A pair of 20^{o} or 30^{o} N and S facing slopes was studied at each site.

The conceptual side of B&G's paper presents a detailed model of the soil water balance for sloping land; they used the first year's gravimetric water content data to evaluate some of the model parameters and the remaining two years' data to validate the model. The most innovative feature of their model is the 'soil rewetting function', which limits infiltration when the surface soil is dry to take into account soil water repellency often observed under dry conditions in hill country (see Morton et al. (2005) and references therein). B&G drew two major and not previously apparent conclusions about pasture on hill country from their study:

1) Pasture growth was much more dependent on rainfall frequency than total rainfall
2) Actual evaporation (and so effective rainfall) was probably between 400 and 600 mm/yr, or only about 50% of the reference crop evaporation, which they estimated to be about 1050 mm/yr. This was despite the fact that annual rainfall at the two sites for the years studied was 1378-1935 mm.

Although B&G's paper was published over 20 years ago, it is still of interest. For example, Dodd et al. (2008) use the conclusions in it to justify the statement that in hill country under pasture 'effective rainfall can be below 30% of actual'. The primary reason for the above conclusions is B&G's assumption that the pasture rooting depth was only 150 mm, an assumption for which no justification was provided. Having made that assumption about the rooting depth, it had to be further assumed that the evaporation rate was soil-limited most of the time; otherwise the top 75 mm would have dried out a lot more rapidly than they observed. Thus the unrealistic assumption had to be made that only when the available water storage was above 90% of capacity did evaporation occur at the reference crop rate.

This paper presents data from the first phase of a study of a hill country site near Pahiatua. The data are then used to discuss the main strengths and weaknesses of the B&G study (Bircham and Gillingham, 1986). Next, the paper describes modifications to simplify and (we believe) improve the B&G model and compares the outputs with measured data from this study. Lastly, the paper reconsiders the validity of the conclusions about hill country pasture reached by those authors.

4.3 Methodology

The trial site (at 40°38'S and 175°54'E) was on a sheep and beef hill country farm 22 km SSE of Pahiatua at an altitude of about 230 m. The soil on the slopes was mainly Atua silt loam (mottled orthic recent soil (Hewitt, 1998)) and the land use capability classification is class VII (McLaren and Cameron, 1996). The slopes were vegetated by typical hill country pastures consisting of browntop (Agrostis tenuis), crested dogstail (Cynosurus cristatus), subterranean clover (Trifolium subterraneum), white clover (Trifolium repens) and various weed species. Annual pasture production measured by the exclusion cage (0.5 m x 1.0 m) technique ranged from 5 to 9 t dry matter (DM) per ha on 30° and 20° N facing slopes, respectively (MR Bretherton, unpublished data). Six locations were selected for installation of paired side-by-side runoff plots; five pairs were in one sub-catchment (I) and the remaining pair was in an adjacent sub-catchment (II) about 80 m away. In sub-catchment I, there were paired plots on 30° and 20° slopes on both N and S facing slopes, along with a pair of plots on a 30° slope with an east (E) facing aspect. In sub-catchment II, there was another pair of 30° slope E aspect plots. Each plot was 2 m long down the slope and 1 m wide across the slope. This paper uses the abbreviation of the slope and aspect to identify the plots, for example 20°N. The plots were defined by thin wooden borders (40 mm above ground and 200 mm below) that were inserted around the top and sides of each plot. The surface runoff from each plot was caught through a slot in a 55 mm diameter PVC pipe buried at the lower edge of the plot, from where it flowed into a 45 l collection vessel set in a hole dug down slope from the plot. Plate 4.1 shows the location of the plots. Between 2 May 2006 and 30 October 2007, the collection vessels were emptied whenever the site was visited (about 30 occasions).

Between 2 May 2006 and 4 May 2007, a 25 mm diameter soil corer was used to collect samples for gravimetric water content determination at approximately monthly intervals. These were collected from near the paired plots at each of the six locations. At each sampling location, three cores were taken vertically to a depth of 350 mm, cut into seven 50 mm depth increments, and the three replicate soil samples from each depth were bulked into one sample. In July 2009, duplicate cores (48 mm diameter and 50 mm long) were collected for bulk density determination at 0-50, 100-150, 200-250 and 300-350 mm depths from all six locations. The bulk density data were used to convert the gravimetric water contents to volumetric water contents. A manual rain gauge at the site was read whenever the site was visited.

Following Jackson (1967), all results involving or implying unit area (e.g. evaporation, rainfall, runoff, drainage and DM yield) are expressed on a horizontal projection basis, as that is the way land area is mapped and rainfall measured. Lambert and Roberts (1976) and Bircham and Gillingham (1986) do not specify whether the values they give are per unit slope area or per unit horizontal projection. For a 30^o slope there is a 15 % difference between the two values.

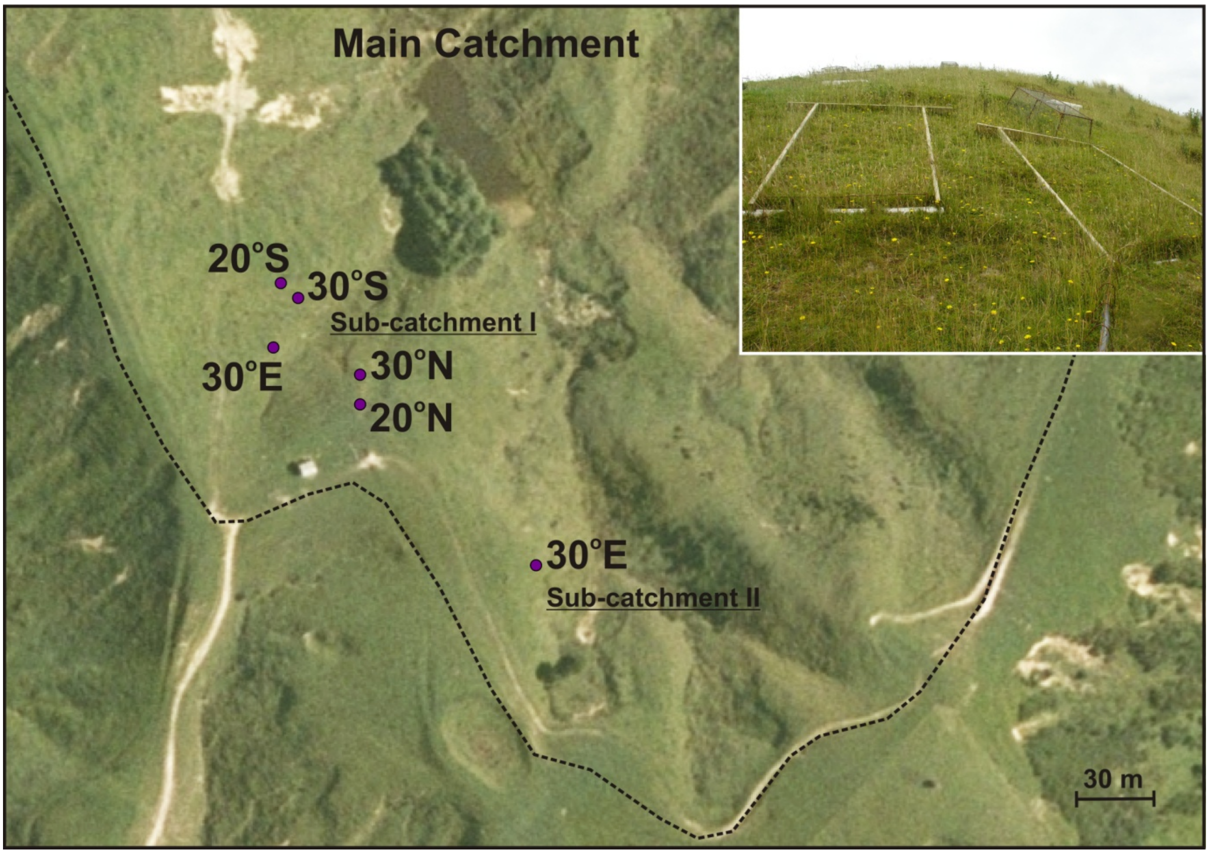

Plate 4.1 Aerial photograph (sourced from Terralink NZ Limited) showing the location of the runoff plots. Each point represents a replicate pair of plots and the dotted line denotes the main catchment boundary. The top of the photograph is true North. Inset shows the 30^{o}N (left) and 30^{o}N (right) runoff plots.

4.4 Results

The bulk density in the top 50 mm was highly variable, ranging from 568 to 1095 kg/m^3 with an average of 853 kg/m^3. Bulk density increased with depth to an average of 1415 kg/m^3 (ranging from 1274 to 1563 kg/m^3) at 300-350 mm. The values from each depth at the six sites did not appear to correlate well with location and were therefore treated as a single dataset. The fine texture and relatively high bulk density values at 300-350 mm depth, and the observed mottling and gleying below about 200 mm depth, suggest imperfect drainage and the presence of a perched water table at times.

The difference between the water stored in the top 350 mm of soil at its wettest and driest varied with location, ranging from 69 mm for the 30^{o}S location to 87 mm at the 20^{o}N location. Figure 4.1 shows the soil water content data for these two locations (the graphs for the other four locations showed similar behaviour). In all cases the data indicate water uptake by pasture roots at 300-350 mm soil depth, suggesting that there was also uptake from below 350 mm. Roots were observed down to at least 450 mm soil depth.

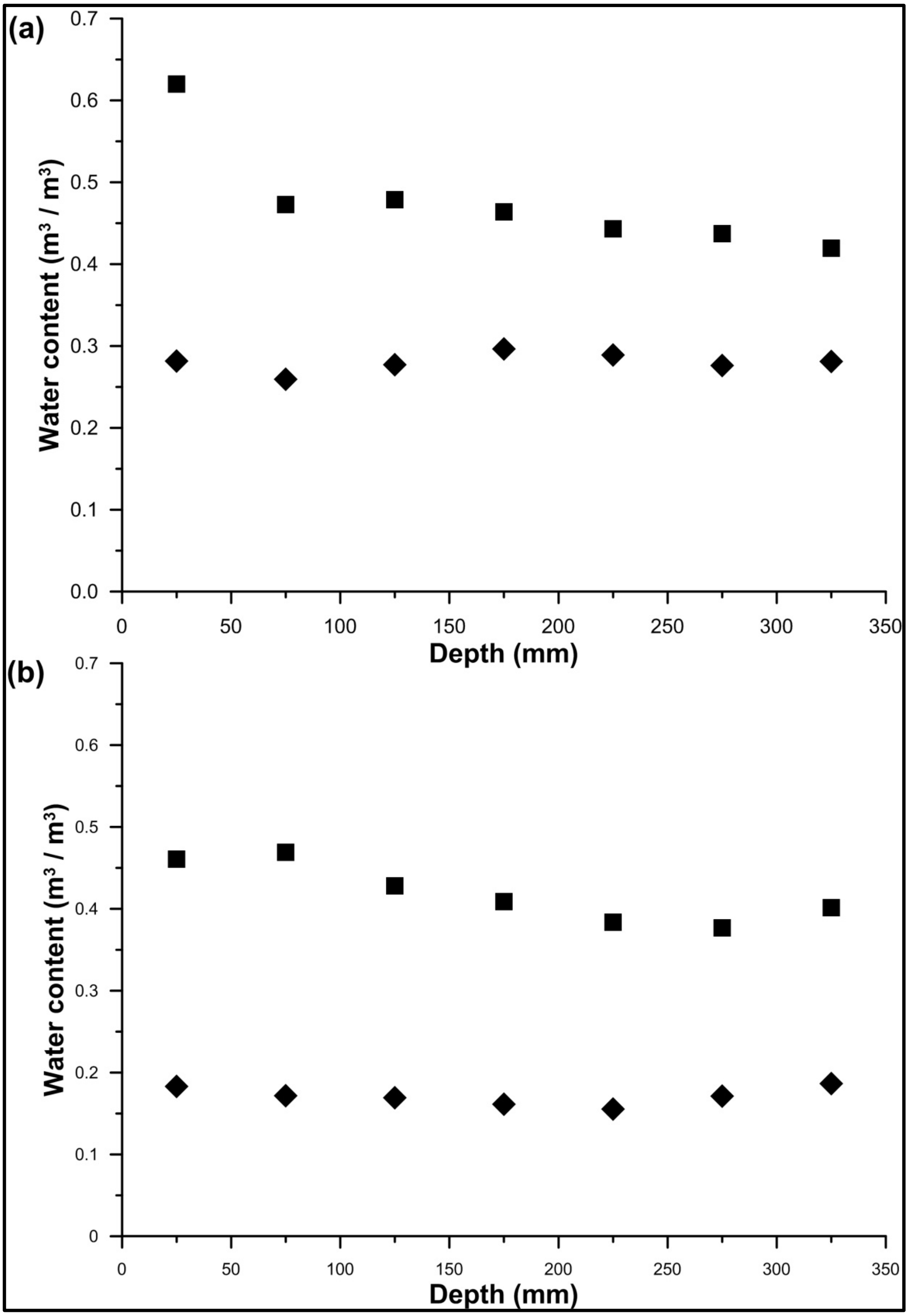

Figure 4.1 Driest (♦) and wettest (■) water content profiles measured at (a) 30°S and (b) 20°N locations.

The available water (*W*) stored in the top 350 mm depth of soil on the various sampling dates at the six locations is shown in Figure 4.2. To calculate these values it was assumed that 55 mm of the stored water is unavailable, as this was the minimum amount of water present in the driest (N facing) plots. A simple daily water balance calculation assuming infinite available water-holding capacity indicates the soil water deficit would have been about 150 mm at the time, so it is reasonable to assume the remaining water was not available to pasture then. Volumetric water contents measured at 0-50 mm soil depth on the same dates at the six locations are shown in Figure 4.3.

The runoff data are presented in Figure 4.4. The date associated with each amount of runoff is the date on which the collection container was emptied. The runoff will have occurred sometime between that date and the date of the preceding data point. The 45 l storage containers could only hold just over 22 mm of runoff and at times they were filled to overflowing at the time of sampling. Thus, all the runoff values of 22 mm are lower bounds of the runoff for the period rather than actual values. The only plots for which no such overflow occurred were the two 20^{o}N plots and the two 30^{o}E plots in sub-catchment II. The runoff collected from the two 20^{o}N plots over the study period (5 April 2006 to 30 October 2007) was equivalent to 4 and 5% of the 1761 mm of rainfall. The runoff from both 30^{o}E sub-catchment II plots was only 2% of the rainfall. In contrast, the runoff flows from the two 30^{o}E plots in sub-catchment I were greater than 5 and 11% of rainfall, with some overflow from both. This difference highlights the variability in runoff from hill country and the limitations of insufficiently replicated small-plot runoff experiments. The plots producing the most runoff (24 and 23% of rainfall) were those on 30^{o}S slopes. However, the actual runoff would have been considerably greater than that, due to overflow occurring on 11 occasions.

4.4.1 A modified model

The B&G model treats the pasture root zone as four separate layers, each of which is 37.5 mm thick, and then uses the simulated water content of the top 37.5 mm of soil to decide whether or not repellency limits infiltration. Infiltrating water has to cascade through all four layers before any excess drains into the deeper subsoil. Unverified assumptions had to be made about the cascade process and the relative amounts of water uptake from the four layers.

To obtain a simpler model while preserving the feature of limited infiltration when the topsoil is dry, we calculated two daily water balances in parallel, as advocated by Scotter et al. (1979b) and Woodward et al. (2001) in order to obtain more realistic evaporation estimates during rewetting. The main (first) water balance is similar to that employed by Coulter (1973). It assumes an available water-holding capacity (W_a) for the root zone and when this is exceeded, surplus water is lost immediately as drainage (D) or surface runoff. Evaporation (E) proceeds at the reference crop rate (E_0) if available water is present, and drops to zero once it is used up. The available water in the root zone at the start of the next day (W_{n+1}) is found in the usual way as

$$W_{n+1} = W_n + I - D - E \quad (1)$$

where I is the daily infiltration from rainfall on day n. Figure 4.2 suggests a value between 80 and 110 mm for the available water-holding capacity of the root zone. A value of 87 mm was chosen for W_a, as this was the difference between the two curves in Figure 4.1(b) and the largest measured change with time in water storage in the top 350 mm of soil. Figure 4.1 indicates that there was uptake from below the 350 mm measurement depth, so this value will almost certainly be an underestimate of the total available water-holding capacity.

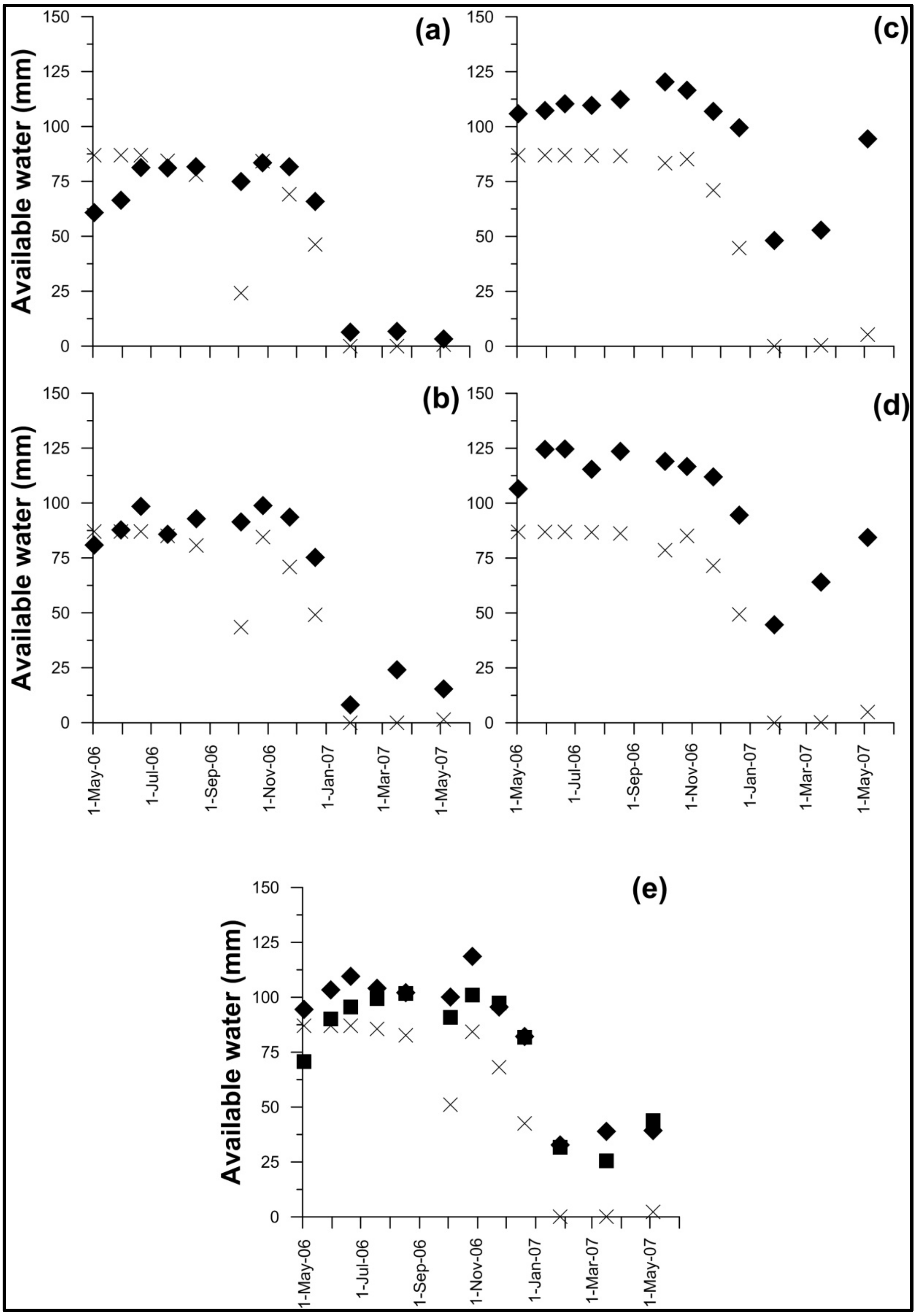

Figure 4.2 Modelled (×) and measured (♦) available water in the top 350 mm of soil at locations (a) 30°N (30° slope N aspect site), (b) 20°N (c) 30°S, (d) 20°S and (e) 30°E (♦ for sub-catchment I and ■ for sub-catchment II) on various sampling dates.

The second water balance is specifically associated with the top 50 mm of soil and is calculated in parallel in much the same way, but a smaller available water-holding capacity ($W_{s,a}$) is assumed and the evaporation from the topsoil (E_s) is estimated as some fraction of E. The soil water content in the top 50 mm of the two N facing slopes ranged from approximately 0.2 to 0.5 m^3/m^3 (Figure 4.3); therefore the available water storage capacity in the top 50 mm ($W_{s,a}$) was taken as 50 x (0.5 - 0.2) = 15 mm and the unavailable water as 0.2 x 50 = 10 mm.

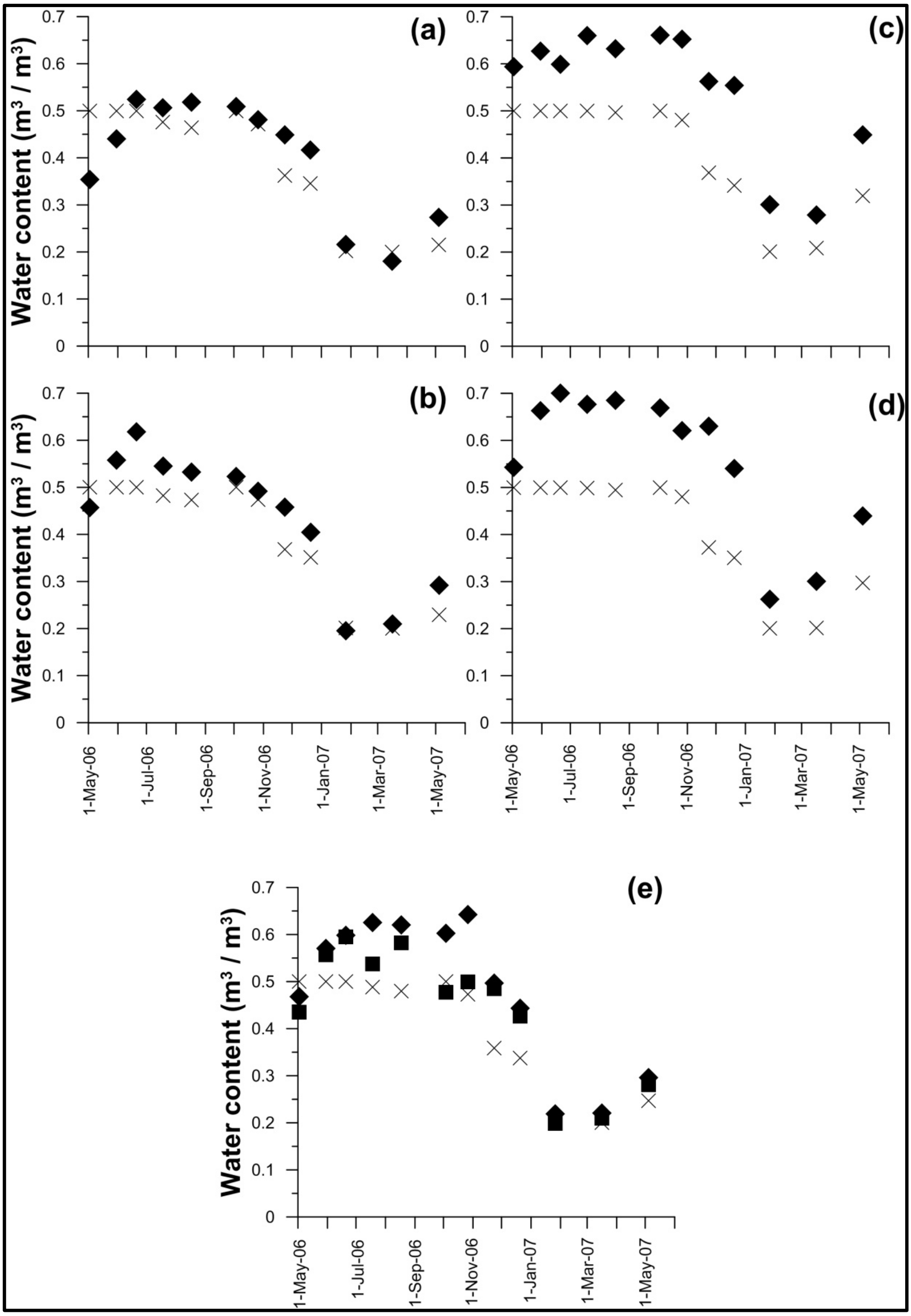

Figure 4.3 Modelled (×) and measured (♦) water content in the top 50 mm of soil at locations (a) 30°N (30° slope N aspect site), (b) 20°N (c) 30°S, (d) 20°S and (e) 30°E (♦ for sub-catchment I and ■ for sub-catchment II) on various sampling dates.

The amount of water uptake from the top 50 mm of soil depends on the root distribution and the dryness of the topsoil relative to the rest of the root zone. When the whole root zone is at field capacity, uptake will be largely dependent on the root density, so a large fraction of this uptake will be from the topsoil where the root density is the highest. Consequently, the topsoil initially dries out faster than the soil underneath, leading to a decreasing fraction of the uptake being tapped from the topsoil as the remaining water there becomes less available to plants. Trial and error suggested that E_s (the uptake from the top 50 mm) is reasonably well described by the equation

$$E_s = E_0 W_s / (2 W_{s,a}) \qquad (2)$$

Thus, at field capacity, half the water uptake by pasture is from the top 50 mm, with the fractional uptake decreasing in proportion to the available water remaining as the top 50 mm dries out.

Bircham and Gillingham (1986) used the Priestly and Taylor (1972) equation to estimate E_0, with Revfeim (1982) equations to estimate the effects of slope and aspect on solar radiation. However, rather than using actual solar radiation and air temperature data in the Priestley-Taylor equation, they used crude estimates of these variables obtained from empirical equations with only the latitude and Julian day as inputs, and not calibrated for New Zealand conditions. We also used Revfeim (1982) equations to correct the incoming radiation for slope and aspect, but used the version of the Penman-Monteith equation described by Allen et al. (1998) to estimate E_0. The nearest NIWA site with solar radiation data for the period of the study was at East Taratahi, about 30 km S of the site. Solar radiation, air temperature, dew point and wind run data from there were used to obtain daily estimates of the reference crop evaporation (E_0). E_0 is considerably less spatially variable than rainfall, so obtaining proximal meteorological data was not as critical to its calculation.

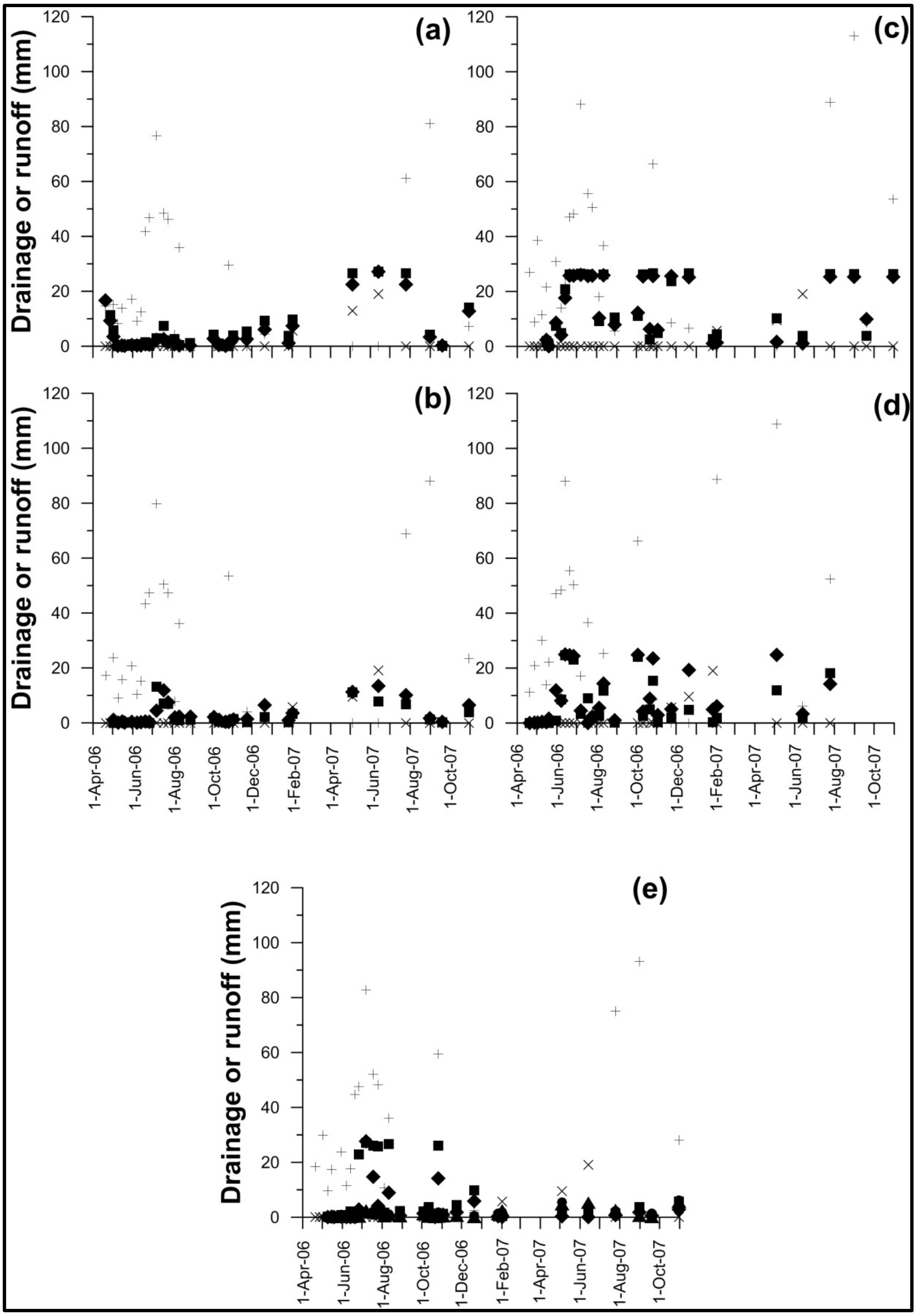

Figure 4.4 **Modelled drainage (+), repellency-induced runoff (×) and measured surface runoff (♦ for left- and ■ for right-paired plots) for (a) 30°N (30° slope N aspect site), (b) 20°N (c) 30°S, (d) 20°S and (e) 30°E (♦ and ■ for sub-catchment I; ▲ and ● for sub-catchment II) on various sampling dates.**

It is acknowledged that using any estimate of E_0 in hill country is, to some extent, problematic as the assumptions implicit in its definition are not met. These assumptions include strictly vertical transfer of heat and water vapour with no advection in the air immediately above the pasture. Thus it only applies to 'an extensive surface of green grass of uniform height' (Allen et al. (1998), p. 23) which hill country, by definition, is not. Furthermore, hill country induces local updrafts and downdrafts, violating the neutral stability conditions implied in estimates of the aerodynamic resistance in the Penman-Monteith equation and its equivalent empirical factor in the Penman equation. Therefore, it remains to be shown that the above violations are minor enough to make conventional E_0 estimates sufficiently accurate for use in water balance calculations in hill country.

The only meteorological measurement at the site was the cumulative rainfall between relatively infrequent site visits. However, daily rainfall and E_0 values were needed for the model. To derive daily rainfall estimates, data from Eastry Station (about 5 km away) were used in conjunction with the cumulative data from the trial site. Over the study period, the total rain at the site was only 75 % of that at Eastry Station, but a plot of the rainfall at the site and at Eastry for each of the sampling periods showed a strong correlation between them (R^2 = 0.82). So, to obtain daily rainfall estimates, the daily rainfall at Eastry was multiplied by the total rainfall at the trial site for each period and divided by the corresponding rainfall for the equivalent period at Eastry.

Bircham and Gillingham (1986) assumed a critical moisture content of 68 % of field capacity. At moisture contents greater than this, they assumed that repellency effects (and therefore reduced infiltration) did not occur. At moisture contents smaller than the critical value, they use an exponential recharge function to relate the reduced infiltration rate to the topsoil water content. Given the lack of detailed data on repellency behaviour and the use of crude daily rainfall totals rather than detailed rainfall intensity data, we believe that a simpler, if somewhat similar, infiltration rate model is warranted. Trial and error led us to assume that when the water content in the top 50 mm of soil (W_s) is less than 0.25 m^3/m^3, and thus the available water there (W_s) is less than 2.5 mm, the daily infiltration is limited to a set maximum (I_r) of 5 mm. Otherwise, all the rainfall infiltrates and I = P where P is precipitation. Daily repellency-induced surface runoff (R) is thus P - I_r.

4.4.2 Model outputs and discussion

The observed water uptake patterns in Figure 4.1 are at variance with the B&G key assumption that the effective root zone is only 150 mm deep with available water storage capacities of just 40 and 46 mm for their two soils. Of course, hill soils are highly variable and in some places the 150 mm value may well apply, for example at some recent slip sites. However, we suggest deeper effective rooting depths are probably more typical of hill country. At the site of this study, both the effective rooting depth and available water storage capacity are at least twice the values assumed by B&G, who did recognise that their assumption of a 150 mm deep rooting zone may not have been valid. After giving evaporation estimates of 400-600 mm/yr for their sites, B&G state

> Annual AE (actual evapotranspiration) may be higher if . . . deeper rooting of plants enables significant utilisation of . . . moisture from depths greater than 150 mm (McAneney and Judd, 1983; Scotter et al., 1979a; Scotter et al., 1979b).

The papers referred to show that pasture on flat land can extract significant amounts of water from a depth of 1 m or more.

Figure 4.2 shows the measured and modelled values for the available water in the root zone at our trial site. As expected for the N aspect locations, the maximum and minimum values are in quite good agreement, as the model parameters were chosen so that this would be so. The values for the S and E locations are nearly all higher than the model values by between 20 and 40 mm. Pressure plate measurements at a matric potential of -1.5 MPa, converted to estimate the water stored in the top 350 mm at that potential, were on average 20 mm higher for the S and E locations than for the N locations. Soil variation can explain much of this difference. The observed and modelled time trends of W are closely synchronised, with three exceptions. The first was that in most cases the first three data points show the soil was still rewetting, whereas the model indicates the soil had reached field capacity. This could be due to soil cracks and repellency in autumn delaying rewetting somewhat in a way not modelled. The second is for the N and E facing locations on 3 October 2006, when the modelled values were much lower than the measured values. The reason for this discrepancy is not obvious. The third exception was that the two S facing locations ‘wet up’ towards the end of the observation period while the model predicted that

W would remain small. A possible explanation for this is the addition of interflow from higher up the slope, as the S facing locations had much more land above them to provide this than did the N and E locations. To quote O'Loughlin (1990) 'It can be shown that wherever topographical gradients exist, more often than not there is a significant component of subsurface flow that moves laterally'. Bircham and Gillingham (1986) also comment that subsurface flow in spring may contribute to plant-available water down slope.

Despite the discrepancies discussed above, the simple water balance with its embedded E_0 values seems accurate enough to be useful.

The modelled and measured values in Figure 4.3 for the water content in the top 50 mm are in quite close agreement, with the exception of the S and E locations where, again, the measured values tend to be higher than the modelled values, particularly when the soil was around field capacity. Despite this discrepancy, this particular aspect of the model seems to be accurate enough to be useful in predicting when repellency is likely to limit infiltration.

To interpret the runoff data in Figure 4.4, the processes involved need to be considered. There are two mechanisms that produce overland flow from rainstorms:

1) saturation-induced overland flow that occurs when rising water tables intersect the soil surface, generating exfiltration and/or preventing infiltration of rainfall

2) Hortonian overland flow that occurs when the rainfall intensity exceeds the infiltration rate of the soil (Moore and Foster, 1990).

In New Zealand hill country under pasture, runoff induced by a rising water table, perched or otherwise, occurs when the moisture content in the root zone is greater than field capacity and low-permeability subsoil does not allow all the surplus water to escape. Hortonian flow is less common due to the usually high permeability of the topsoil, but can occur in a number of situations, one of which is the development of repellency in dry surface soil. Thus the two mechanisms often produce surface runoff under contrasting hydrological conditions.

While the presented simple one-dimensional model includes a crude attempt to simulate repellency-induced Hortonian overland flow, it makes no attempt to describe how much of the drainage (*D*) term in the water balance appears as saturated overland flow. Such flow is highly variable in space and time over a catchment, and is strongly dependent on the hydraulic properties of the soil as well as the morphology of the catchment. The results presented here for the S sites suggest interflow occurred, so that in order to simulate the runoff, a detailed multi-dimensional model of water movement in the land up slope of the location of interest would be needed (O'Loughlin, 1990).

Figure 4.4 shows that for nearly all periods, the modelled drainage (*D*) at all six locations was usually much greater than the measured surface runoff, suggesting that the soil was often wetter than field capacity and that the measured surface runoff was mainly due to saturated overland flow. However, there are three contiguous collection dates (covering the period from 26 January 2007 to 13 June 2007) on which surface runoff was measured but for which no drainage was predicted. It is only for these three collection dates that the model simulates any repellency-induced surface runoff. The amount of repellency-induced surface runoff is under-predicted for the 30^{o}N plots (it is not known by how much as the collection vessels overflowed on two of the three collection periods), but over-predicted for the four 30^{o}E plots, and on 13/6/2007 for the 20^{o} and 30^{o} S plots. Given the coarseness of the rainfall data, and the simplicity of the infiltration restriction in the model, this lack of agreement is not surprising. However, the ability to model when repellency-induced runoff is most likely to occur suggests that further work along these lines is worthwhile, provided it involves the collection of more detailed rainfall intensity and runoff data and leads to a more sophisticated description of the effect of repellency on infiltration in the water balance model and the production of more realistic repellency-induced runoff volumes.

Table 4.1 Summary of model output for all aspect and slope combinations for the year 31/10/2006 to 30/10/2007 when total rainfall was 840 mm. All numbers are mm.

Aspect and slope	Modelled reference evaporation	Modelled actual evaporation	Modelled drainage + runoff
N 30^o	1154	671	191
N 20^o	1054	635	226
S 30^o	843	545	313
S 20^o	850	550	309
E 30^o	1051	629	233

The relative size of the components of the water balance generated with the modified model for our site (see Table 4.1) are markedly different to those generated by B&G for their sites using their model. For the 12 months from 31 October 2006 to 30 October 2007, the estimated reference crop evaporation (E_0) at our site ranged from 843 mm for the 30^{o}S location to 1154 mm for the 30^{o}N location (Table 4.1). The estimated actual evaporation (E) ranged from 545 mm for the 30^{o}S location to 671 mm for the 30^{o}N location, while the rainfall was 840 mm, i.e. evaporation was between 65 and 80 % of incident rainfall. These actual evaporation values are higher than the values estimated by B&G's model for their sites, despite the rainfall at their site being about twice the rainfall at our site. Estimated losses from drainage and runoff (D + R) ranged from 191 mm for the 30^{o}N location to 313 mm for the 30^{o}S location, or between 23 and 37 % of rainfall. B&G's model, with a 150 mm rooting depth, would have provided much higher estimates of drainage and runoff.

If most of the drainage and runoff in B&G's model had ended up as drainage from their catchments, about 1000 mm/yr would have been lost. However, this value is about twice the reported average over six years of 450 mm/yr of outflow from a Waikato catchment with a similar average annual rainfall of 1660 mm (Gillingham and Gray, 2006). This provides further, if circumstantial, evidence that they underestimated the rooting depth and associated evaporation losses from pasture in their model.

While we have no outflow data for our catchment, data for similar catchments are given by Gillingham and Gray (2006). They describe a 3-year study of two 13 ha hill country catchments near Waipawa during which the annual rainfall was slightly lower than in our study, ranging from 664 to 828 mm/yr. They measured, using V-notch weirs at the bottom of the catchments, annual outflows of between 126 and 202 mm, similar to (but somewhat smaller than) the values we simulated for drainage plus runoff at our sites. This comparison provides further indirect support for our claim that the modification and simplification proposed here provide an improvement to the B&G model.

4.5 Conclusions

While hill country soils are usually shallower than lowland soils (Molloy, 1998), the data presented here suggest that the assumption (Bircham and Gillingham, 1986) of a typical rooting depth of 150 mm is much too shallow. We observed significant water extraction down to at least 350 mm depth. Because the rooting depth assumption is central to the B&G model, this throws into question their major conclusions that the availability of moisture to pasture in hill country soils was 'highly dependent on rewetting frequency rather than the total rainfall and (that) probably less than 50 % of the total annual rainfall was involved in replenishing soil moisture at plant-available depths'. The modified model presented here suggests that between 65 and 80 % of the 840 mm of rainfall over a 12-month period was evaporated by the pasture at the site studied.

On occasions, surface runoff occurred when the topsoil was quite dry, suggesting it was induced by repellency. We show that a simplified version of the innovative way in which Bircham and Gillingham (1986) modelled repellency-induced surface runoff has merit and warrants further development in conjunction with a more detailed experimental study of the phenomenon.

4.6 Acknowledgements

We thank Clem and Joy Smith for allowing their farm to be used for the experimental site and for their hospitality. We thank NIWA for providing access to meteorological data from nearby sites and Ian Furkert for his competent assistance collecting bulk density samples. Two referees and the editor provided valuable comments.

4.7 References

The references in this paper have been included in the references on page 187.

4.8 Summary

The paper presented in this chapter concluded that a more detailed study of repellency-induced surface runoff was warranted. The primary purpose of the second phase of experimental work at Alfredton was to conduct just such a study and this is described in the next chapter. The results are then used to further develop the model, as described in Chapter 7.

CHAPTER 5

MEASUREMENT OF REPELLENCY-INDUCED RUNOFF IN HILL COUNTRY

5.1 Introduction

The classical model of hillslope hydrology was first outlined by Horton (1933) who described surface runoff as: "Neglecting interception by vegetation, surface runoff is that part of the rainfall that is not absorbed by the soil by infiltration".

The production of runoff will occur during a rainfall event when the infiltrability of the soil is exceeded and the excess water that has ponded in surface indentations (depression storage) starts to overflow. Infiltration therefore, is a key process governing the runoff response to rainfall and describes the manner in which water enters the soil. It is one of the most important stages in the hydrological cycle since it controls the partitioning of incident rainfall into surface runoff, subsurface runoff and soil water, some of which may, in turn, become either subsurface runoff or groundwater recharge (Gregory and Walling, 1973). Once surface runoff occurs, it is unlikely to behave uniformly, and will move down the slope as divided flow due to variations in micro-topography, vegetative cover, and soil surface properties (Hjelmfelt (Jr) and Burwell, 1984).

There are two mechanisms that produce surface runoff from rainfall (Anderson and Burt, 1990):

1) Hortonian surface runoff which occurs when rainfall intensity exceeds the infiltration rate of the soil surface.

2) Saturation surface runoff which occurs when the soil profile is saturated (often from a perched or rising water table), so that some rainfall, regardless of its intensity, is forced to flow over the surface.

Both these mechanisms produce saturated zones at the surface and once surface detention has been filled, any further rainfall produces some direct surface runoff. These mechanisms may operate singularly or in combination. Furthermore, these runoff zones may only occupy a portion of the catchment and will vary in size depending on a number of the following factors (Anderson and Burt, 1990):

1) Elevation – increasing altitude favours greater rainfall in terms of frequency and duration.

2) Aspect – in the southern hemisphere, N-NW facing slopes receive more solar radiation so that evaporation is enhanced and soils are often drier.

3) Slope configuration – combinations of slope, convexity, and concavity determine patterns of subsurface flow so that local saturation occurs in hollows and at the toes of slopes.

4) Soils and geology – primarily determines the rate of infiltration, drainage rate, and the soil water holding capacity.

5) Surface cover – intercepts rainfall which may evaporate before reaching the surface.

An additional complexity associated with hillslope hydrology is that infiltrated water (through the soil matrix or via macropores) may well intercept less permeable zones at depth and then move downslope for some distance before returning to the surface and contributing to surface runoff and/or stream flow (Mosley, 1979).

It is clear that hillslopes are very likely to be comprised of a large number of complex areas, each of which may have a unique response to rainfall in terms of overland flow. The complexity of hillslope hydrology suggests that small scale surface runoff plots (as employed in this study) will have very limited use in determining runoff/stream flow responses on a catchment scale.

Little research has been carried out in New Zealand concerning the soil water hydrology of hill country pasture (Bircham and Gillingham, 1986; Bretherton et al., 2010) despite the fact that these systems make up more than 75 % of New Zealand's pastoral surface area (Statistics, 2002). The phenomenon of surface runoff from hill country pastoral systems in

New Zealand is of interest because of its potential impacts on soil moisture status, nutrient losses and erosion and the effects that these have on pasture production and environmental degradation. Of particular note is the loss of phosphorus via surface runoff (Gillingham and Thorrold, 2000; Gillingham and Gray, 2006). A number of papers relating erosion patterns to slope and aspect have been published (Crozier et al., 1980; Owen, 1981). The two examples given specifically discuss erosion patterns arising from Wairarapa storm events in 1977 and found that the sunny north, north-east, and north-west quadrants were much more susceptible to failure than the shadier south, south-east, and south-west quadrants. Erosion was shallow (0.6 m) and occurred on slope angles greater than 24^{o}. The study by Owen (1981) attempted to relate these erosion events to low soil strength on the northern aspects. Saturated soil on northern aspects exceeded the “liquid limit water content” whereas this was not the case for the soil on the southern aspects.

Overseas studies in Portugal ((Shakesby et al., 2000; Shakesby et al., 2003)) referred to enhanced runoff resulting from the development of a phenomenon referred to as soil water repellency, despite classical infiltration theory (Philip, 1969) suggesting that runoff volumes should be low due to the high sorptivity of the dry (and therefore hydrophilic) soil. Generally, the phenomenon of hydrophobicity, or soil water repellency, is increasingly being recognised in the scientific literature (Abadi Ghadim, 2000; DeBano, 2000; Deurer et al., 2011; Doerr et al., 2003; Harper et al., 2000; Jaramillo et al., 2000) with the resulting consensus that soil water repellency can play an important part in soil water hydrology.

In New Zealand, Bircham and Gillingham (1986) infer repellency by noting that for a dry steepland soil, only the top few millimetres of the soil profile will be re-wetted during a rainfall event, regardless of the intensity of the rain. They then describe this observation as hydrophobicity, and adopted a layer model “with the surface layer controlling the rate of entry of water to the profile”. Gillingham and Thorrold (2000), in their review of New Zealand research on phosphorus in runoff from pasture, state that “hydrophobicity and seasonal variability in soil conductivity due to cracking have also emerged as significant factors in the modelling of surface runoff responses in New Zealand ...”. However, no justification was provided for this statement.

Gillingham and Gray (2006) make several statements implying the importance of hydrophobicity although the term is not specifically mentioned. Their work on runoff and phosphate movement from seasonally dry hill country pastures showed that statistically, the "highest runoff volumes were associated with low soil moisture conditions". Gillingham and Gray (2006) also make the additional statements that their studies "pointed to surface runoff occurring predominantly in the drier seasons of the year from soils that were previously dry, and typically on slopes well away from streams, with little surface runoff occurring in the wetter months when soil moisture levels were relatively high", and that "areas within a catchment where surface runoff totally infiltrates after travelling overland for some distance does not contribute surface runoff to catchment output". The latter statement further emphasises the localised effect of surface runoff and the challenge surrounding the use of small surface runoff plots in the modelling of catchment runoff.

Finally, two papers (Moir et al., 2000a; Moir et al., 2000b) which attempted to model pasture production based on trials in the Wairarapa, mention that "the behaviour of pasture and soil following a prolonged dry spell is also of interest, and is one of the most under-researched topics in the soil-water-plant area" and "during prolonged dry periods soil fertility status is likely to affect plant survival and, perhaps (indirectly), the development of surface hydrophobicity".

Provided that instrumentation is in place to measure input rainfall and soil moisture and surface runoff responses in real time, it would seem that small scale runoff plots have the potential to measure the throttling effect that soil water repellency has on infiltration.

The objective of this chapter is to quantify the magnitude of repellency-induced runoff in a hill country catchment in northern Wairarapa. Surface runoff events observed on a number of aspects and slopes are described and those events which are associated with soil water repellency are identified and analysed. For each of these events, rainfall intensities, runoff volumes, and soil moisture values gathered at the site will be reviewed in order to help understand the conditions and processes associated with the development and abatement of soil water repellency.

5.2 Results

5.2.1 Rainfall

Rainfall was measured at all four logger sites. However, logger failure prevented complete capture of rainfall data at all sites over the study period (see Chapter 3). In order to determine the total amount of rainfall on all of the runoff plots, two time periods were examined during which the rainfall data sets for all sites were complete. These are shown in Figures 5.1a and 5.1b. In both figures, the pattern of rainfall for all the logger sites is very similar. The size of the events, however, varied somewhat, with the C1North site (both the manual and automatic gauges) consistently receiving less rainfall than the other three sites. This effect was more marked in Figure 5.1b where there was a 54 mm difference in rainfall between the sites as measured by automatic gauges on the North and South aspects.

The C1North and C1South sites represent extremes in terms of wind exposure with the C1South logger located in the more sheltered position (Chapter 3). The more exposed C1North site is more likely to experience induced 'rain blow past' and will thus be less representative of incident rainfall on the runoff plots. Frei and Schar's (1998) commentary on errors associated with rain gauges in the European Alps indicate that wind-induced under catches are the most significant source of bias and may be as high as "several 10 percents", the magnitude being dependent upon the ambient wind speed, the drop size distribution, and the type of precipitation (rain or snow). Relative to C1South (the most sheltered site), cumulative rainfall for C1North suggests 4 and 11 % under-catch for the periods in 2010 and 2011, respectively. Under-catch is particularly noticeable for the manual rainfall gauge – the C1North rainfall gauge was located on a fence post at a height of 1200 mm above ground level (where the wind speed would have been greater) while the automatic rainfall gauges were 300 mm above the ground. In addition, the manual gauge was emptied infrequently and a fraction of the captured rainfall would have been lost through evaporation.

Given this pattern of behaviour, the decision was made to use (where possible) the C1South rainfall data for each logger site, and to fill in its missing days with data from C1East after a small adjustment using a scaling factor based on the average rainfall rate.

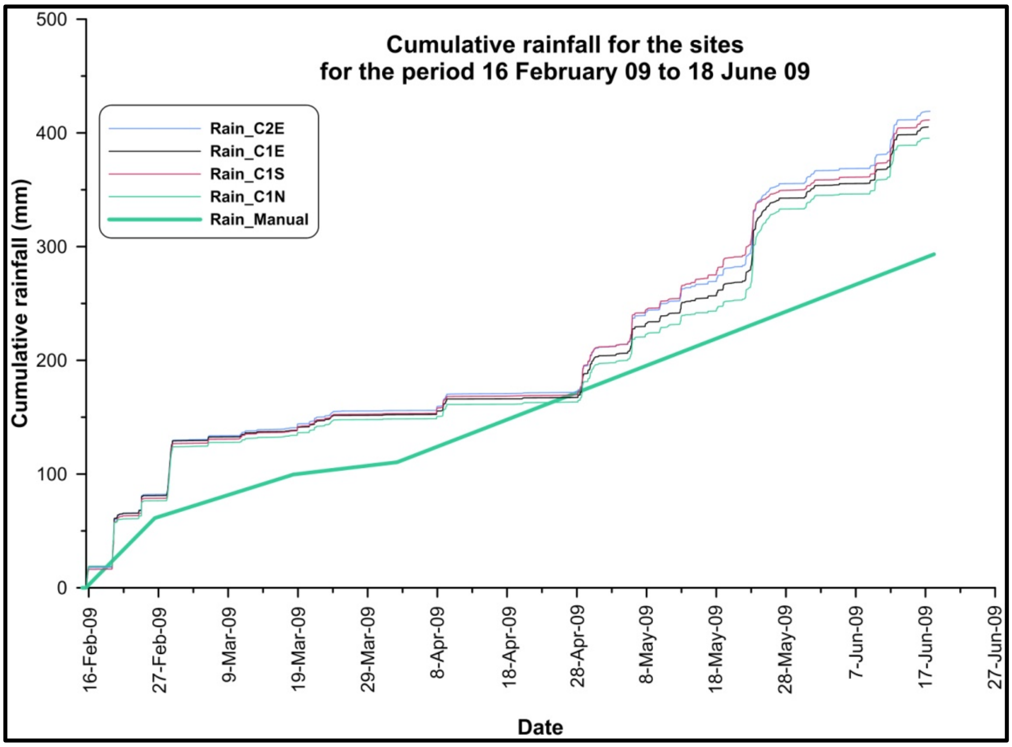

Figure 5.1a **Cumulative rainfall for all rainfall gauges during the period February 2009 through to June 2009.**

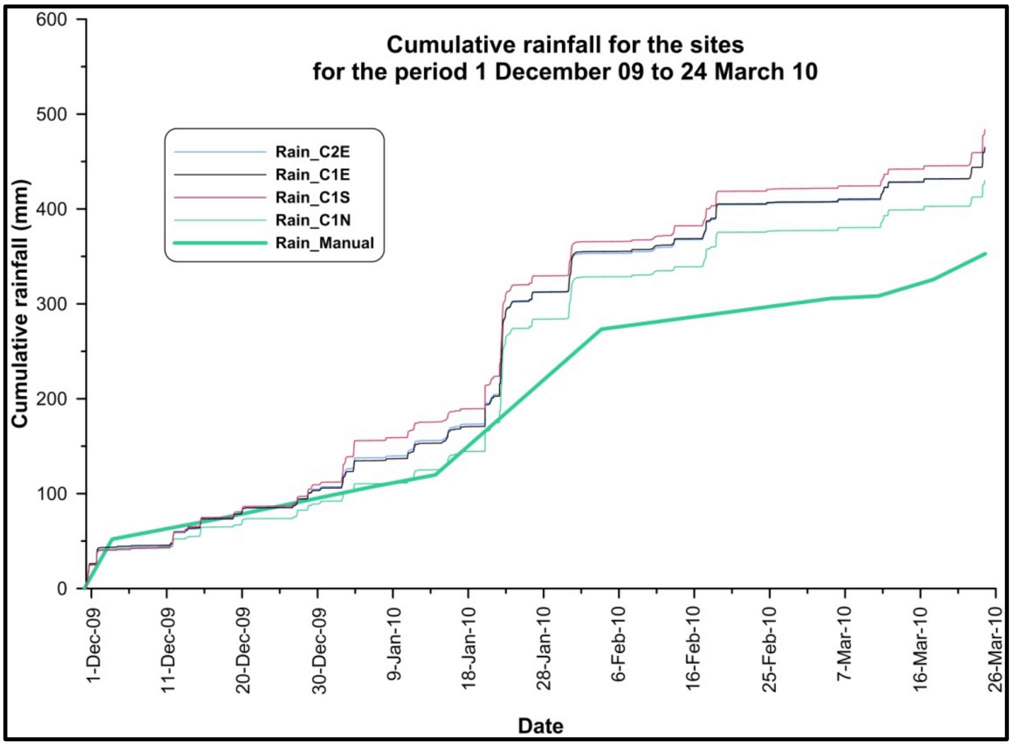

Figure 5.1b **Cumulative rainfall for all rainfall gauges during the period December 2009 through to March 2010.**

5.2.2 Runoff and volumetric soil water content

Runoff and volumetric water content (VWC) data was gathered from all four logger sites in the manner described in Chapter 3. As with the rainfall data, logger failures prevented full capture of the runoff data during 2010 and 2011. Rainfall, runoff, and VWC data for the sites are shown in Figures 5.2 through to 5.9.

Daily rainfall as well as rainfall intensities for the two years using the corrected C1South data set is included in Figures 5.2-5.9 below. Since a small amount of heavy rainfall will not cause repellency-induced runoff due to temporary storage in macropores and surface indentations, the data was smoothed to 1.0 mm increments before intensities were calculated (the raw data is logged in 0.2 mm increments).

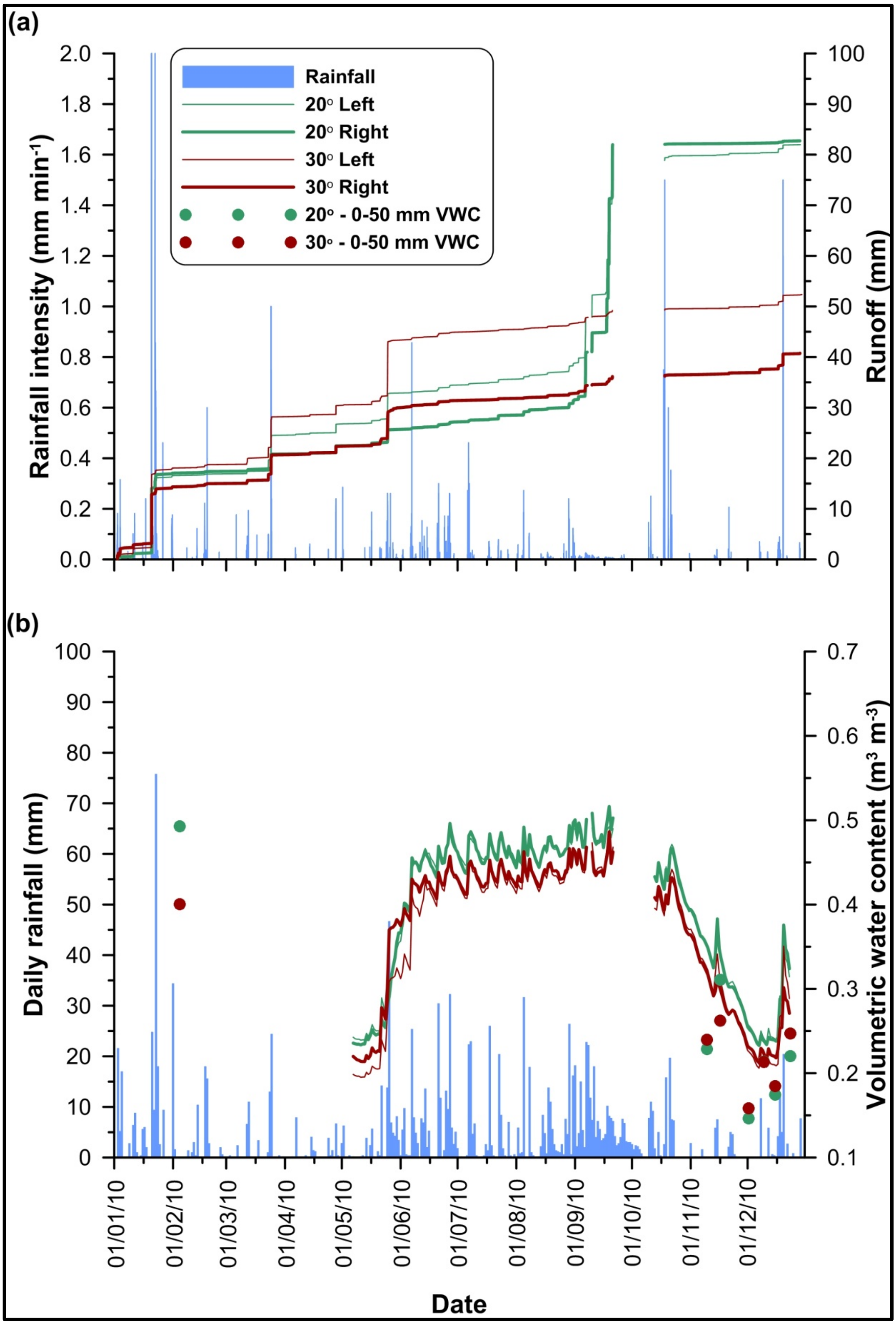

Figure 5.2 Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1North site during 2010. Solid lines in (b) denote VWC for 0-300 mm soil depth.

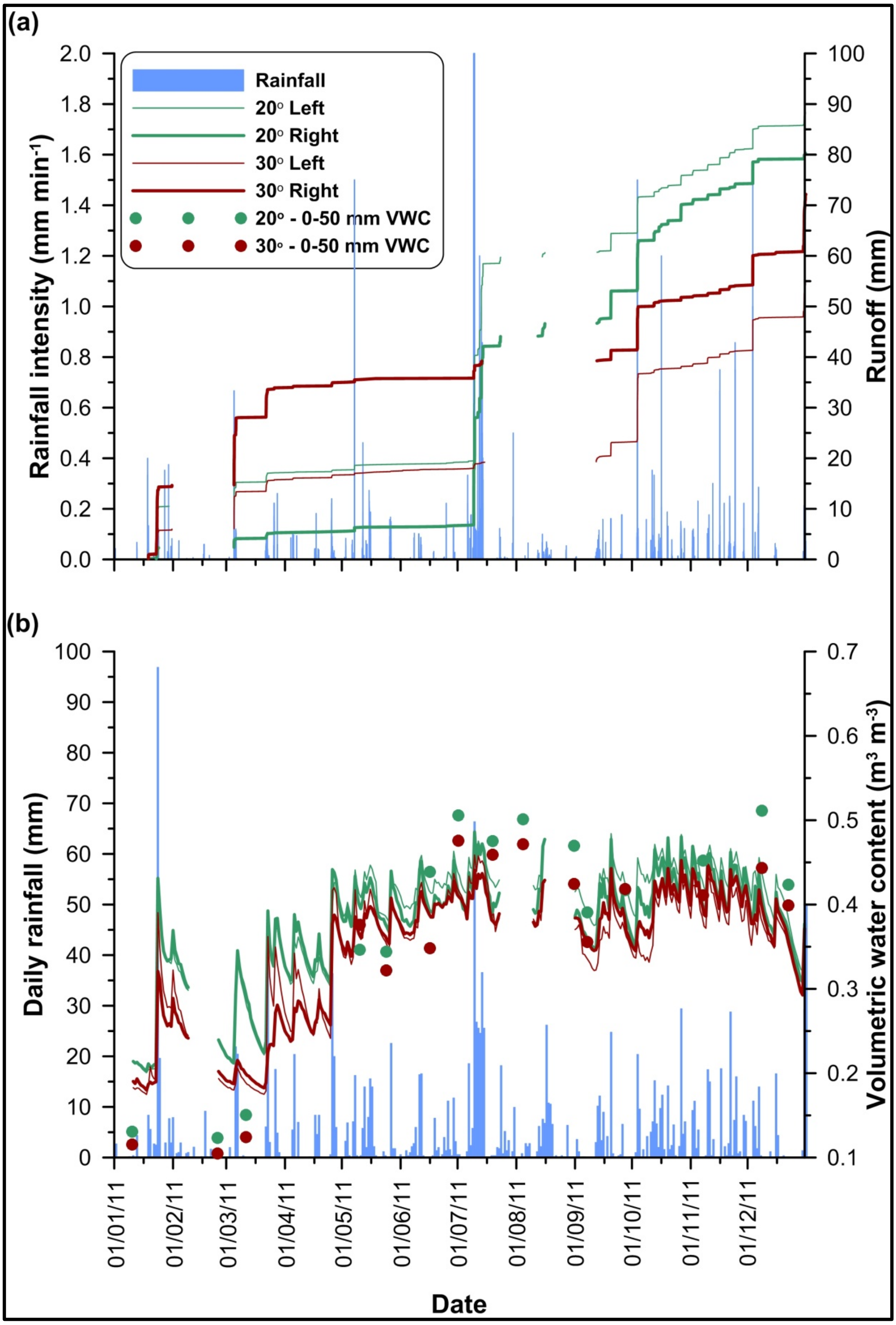

Figure 5.3 **Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1North site during 2011. Solid lines in (b) denote VWC for 0-300 mm soil depth.**

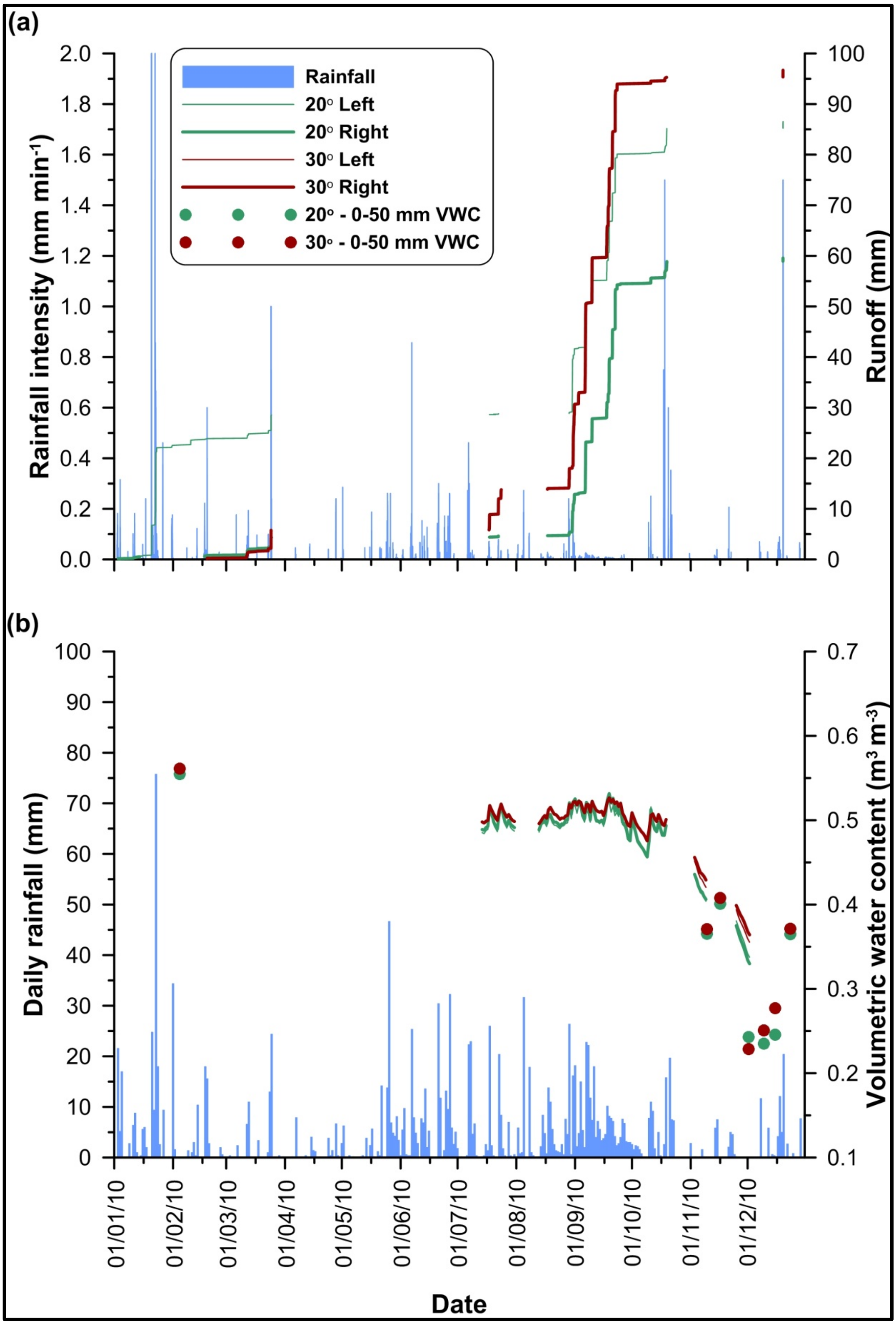

Figure 5.4 **Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1South site during 2010. Solid lines in (b) denote VWC for 0-300 mm soil depth.**

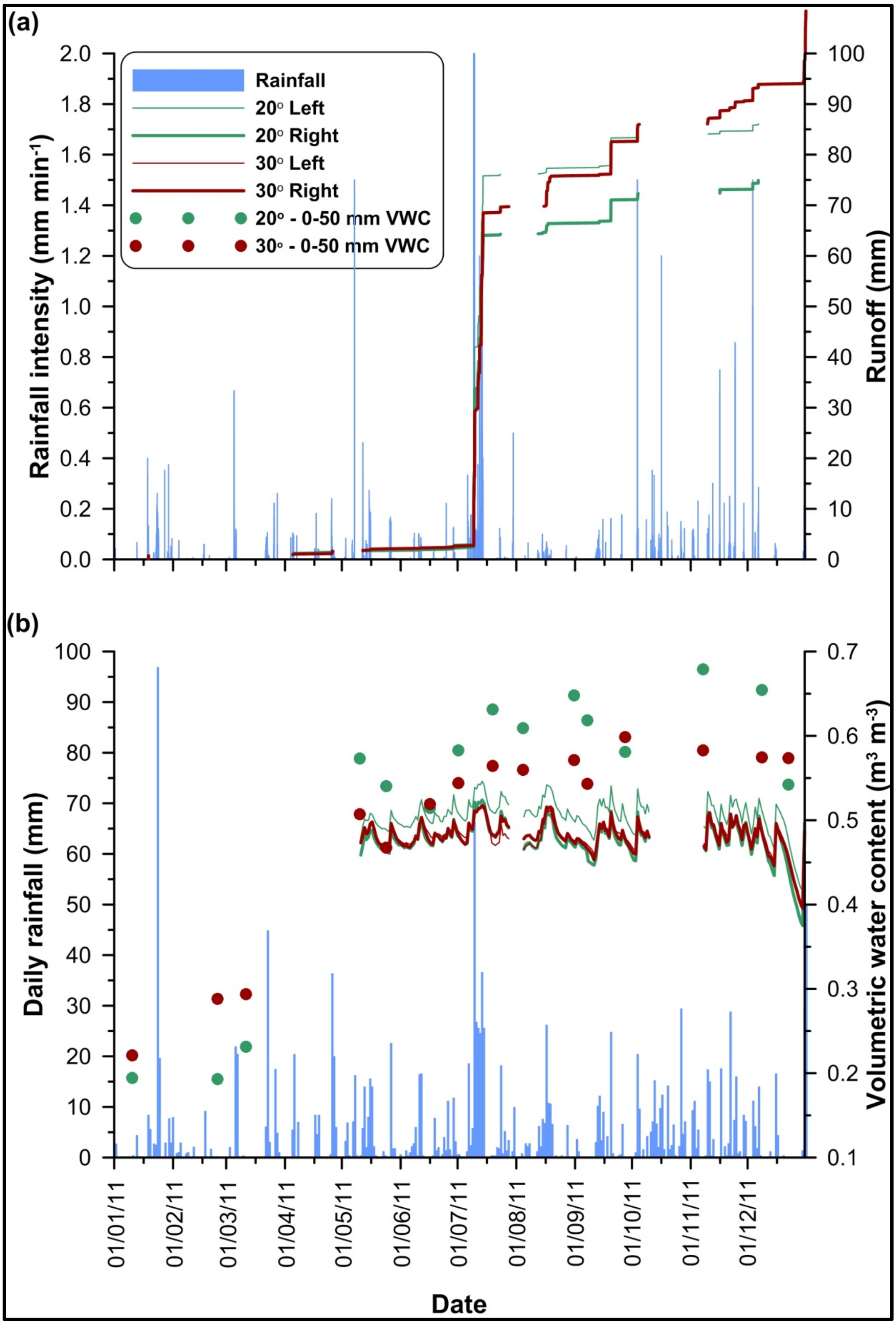

Figure 5.5 **Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1South site during 2011. Solid lines in (b) denote VWC for 0-300 mm soil depth.**

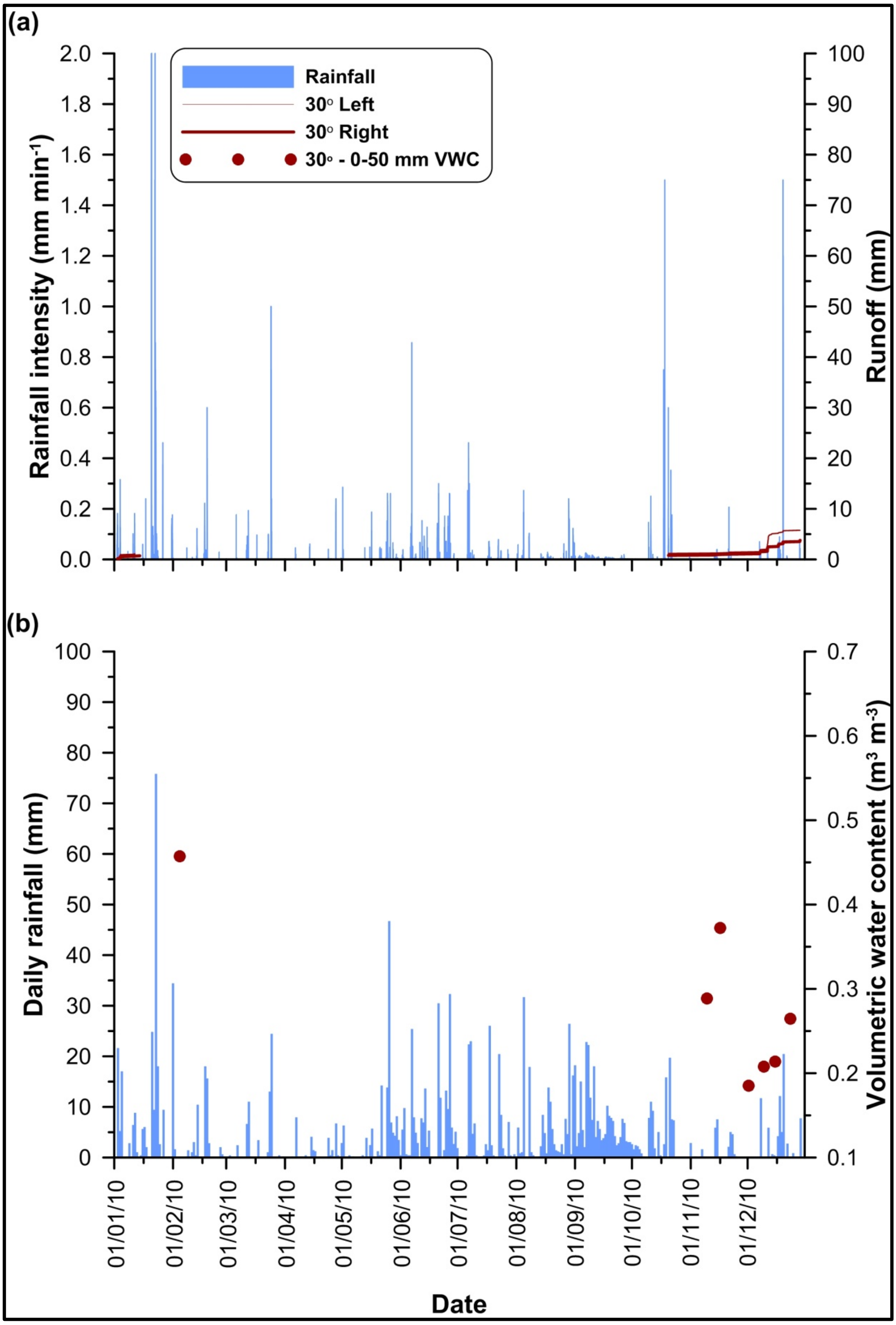

Figure 5.6 **Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1East site during 2010.**

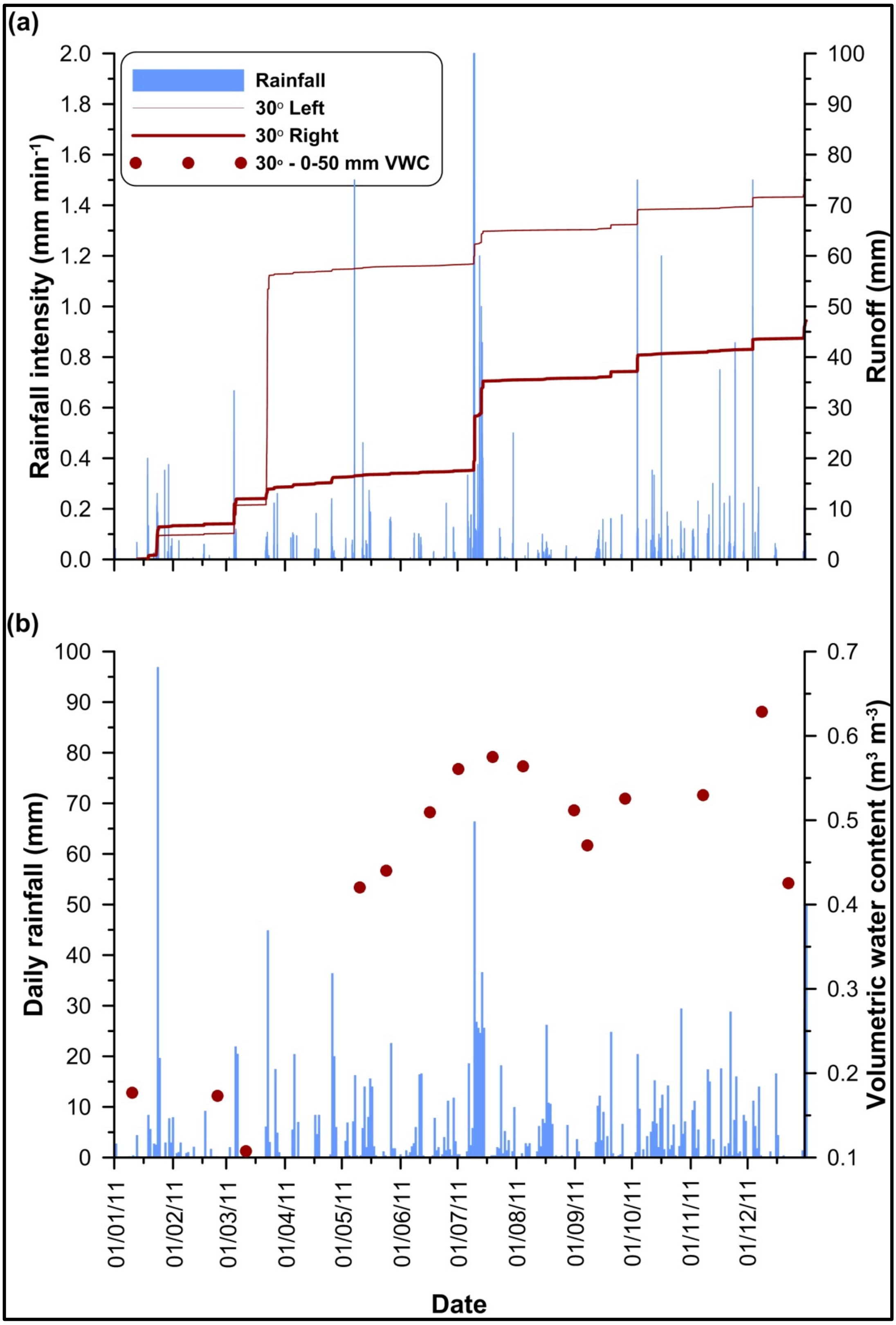

Figure 5.7 Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C1East site during 2011.

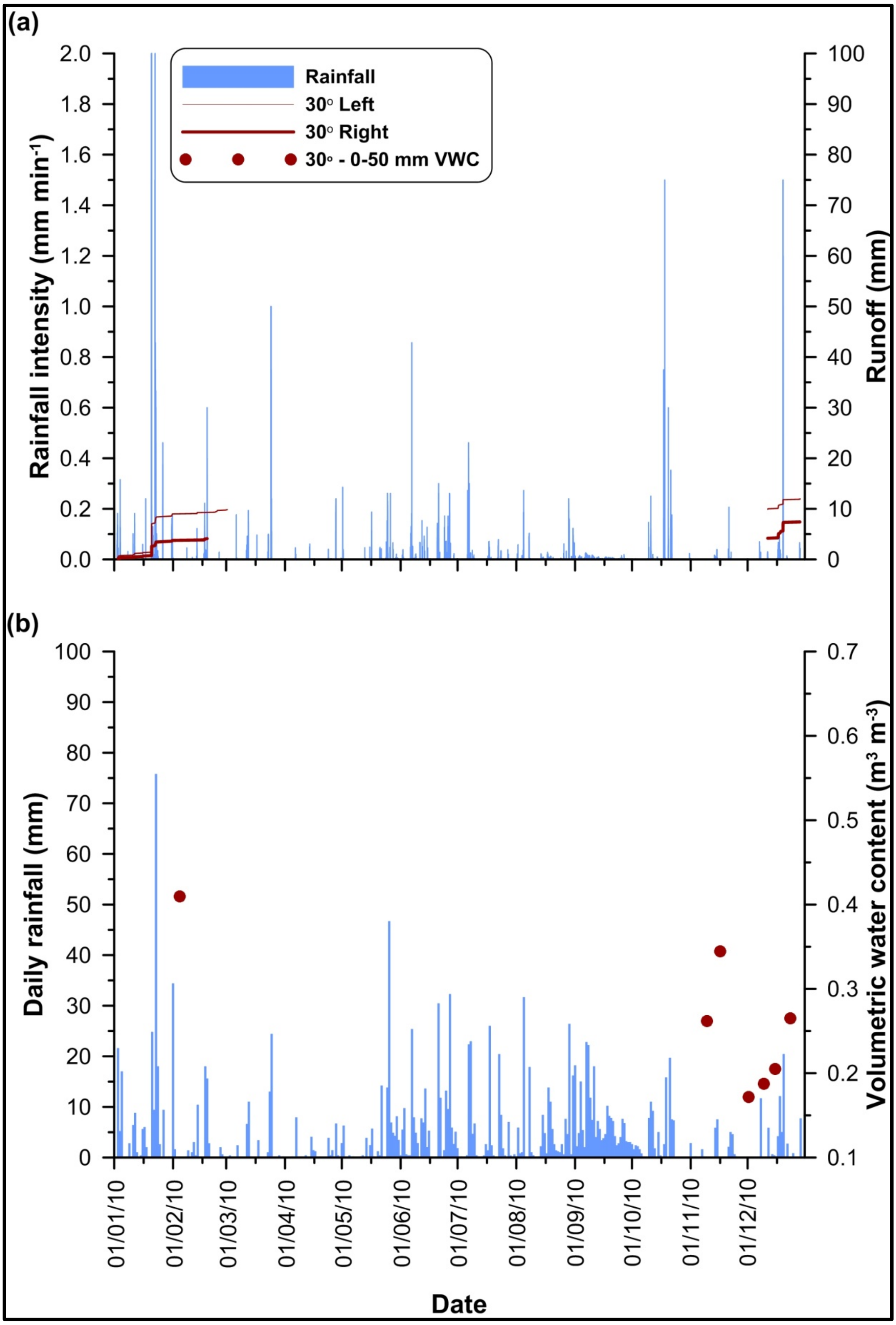

Figure 5.8 Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C2East site during 2010.

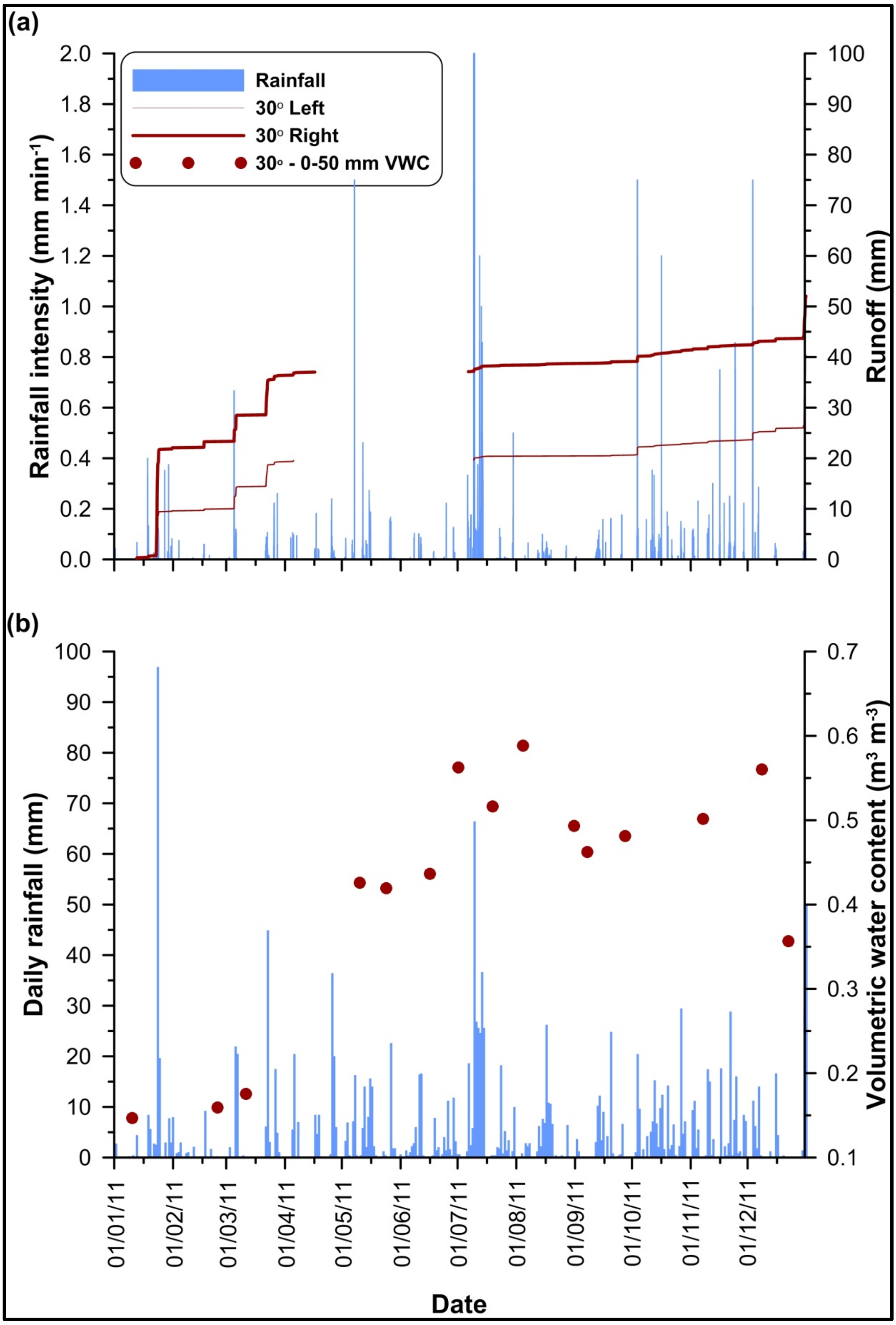

Figure 5.9 **Cumulative runoff and rainfall intensity (a) and daily rainfall and volumetric water contents (b) for the C2East site during 2011.**

A summary of the rainfall and runoff data in Figures 5.2 through to 5.9 is given in Table 5.1.

Table 5.1 Summary rainfall and runoff statistics for all logger sites for the years 2010 and 2011.

Year	2010				2011			
Aspect	C1 North	C1 South	C1 East	C2 East	C1 North	C1 South	C1 East	C2 East
Rainfall (mm)	1470				1564			
Runoff ShL (mm)[1] [% of rainfall]	82 [6]	87 [6]	n/a	n/a	88 [6]	86 [6]	n/a	n/a
Runoff ShR (mm)[1] [% of rainfall]	83 [6]	60 [4]	n/a	n/a	80 [5]	75 [5]	n/a	n/a
Runoff StL (mm)[1] [% of rainfall]	52 [4]	#	6 [*]	12 [*]	55 [4]	#	76 [5]	40 [3]
Runoff StR (mm)[1] [% of rainfall]	41 [3]	97 [7]	4 [*]	7 [*]	72 [5]	108 [7]	47 [3]	52 [3]

[1] – Calculated on a horizontal projection basis.
* - insufficient runoff coverage over the year to calculate a meaningful value.
[#] - unreliable data from the C1South steep left plot

Missing values for Table 5.1 are denoted by '#', and refer to the 30^{o} left plot for the C1South site. Despite the remedial measures that were successful with the other plots (Chapter 3), the data from this plot exhibited significant evidence of false tips and thus was discarded.

Significant gaps in runoff data are evident in Figures 5.2 through to 5.9. The effects of these gaps on the values in Table 5.1 are discussed below.

5.3 Discussion

Figures 5.2 to 5.9 show that most of the runoff occurred on just a few days during both years and that relatively small quantities of rainfall were lost as surface runoff.

5.3.1 2010

The runoff data for the C1North site (Figure 5.2a) is almost complete for this year – apart from a gap from mid September to mid October. There were a number of distinct runoff events from both shallow and steep slopes (in late January, late March, late April, late May, early to mid September, and mid December). The single exception to dual runoff responses from both steep and shallow slopes occurred during early to mid September when the soils were at their wettest (Figure 5.2b), with the VWC of the 0-300 mm depth being about 0.45 and 0.50 m^3 m^{-3} for the steep and shallow slopes respectively. Rainfall, although of very low intensity, occurred almost every day. The resulting response from the shallow plots was a series of successive runoff events totalling approximately 50 mm during this period, indicating that the presence of a water table near the surface of the shallow plots was contributing to runoff. There was however, very little corresponding runoff from the steep plots.

As there was 78 mm of rainfall from mid September to mid October (the period when surface runoff was not monitored) it is likely that runoff from the steep North slopes would have been negligible and runoff from the shallow North slopes would have been minor. Accordingly, the runoff values given in Table 5.1 for C1North in 2010 are quite likely to be a reasonable reflection of runoff from steep slopes during that year and may slightly under-estimate runoff values for the shallow slopes.

For those events prior to May, the soil water status was unknown but assumed to be comparatively dry since there were longer periods without rain and the summer-autumn period would have experienced higher evaporation rates. Typically, runoff events during this time (as well as the ones in late May and mid December) occurred when the soils were dry and rainfall intensities were high (>0.25 mm min^{-1}). The VWC of the 0-300 mm depth from May onwards indicate that in nearly all cases, the C1North steep slopes were drier (by about 0.025 m^3 m^{-3}) than their shallow counterparts. This difference appears to have been reasonably constant during the measurement period but widened somewhat when the soils rapidly became wetter from mid May through to the beginning of June. The VWC of the 0-50 mm depth in the late spring and early summer months tended to be much drier (by about 0.05 m^3 m^{-3}) than their 0-300 mm counterparts, indicating that moisture conditions at the surface of the soil profile were often quite different to that of the bulk profile.

Despite the large number of gaps in the runoff data for the C1South site (Figure 5.4a), three features emerge from the observed data. The first is a runoff event for the shallow left plot (the only one functional at the time) in late January, the second is a smaller runoff event which occurred in late March, and the third is a series of closely spaced runoff events which occurred during September - all three runoff events being coincident with ones taking place at the C1North shallow site. The last event occurred when the soil at this site was very wet (Figure 5.4b, 0.50-0.525 m^3 m^{-3}) and therefore at, or above, field capacity, so the runoff mechanism was likely to have been due to saturation surface runoff resulting from a high water table. Rainfall at this time was of very low intensity (0.01 mm min^{-1}) but occurred almost every day with daily rainfall totals of 2-5 mm. Unlike the C1North steep plots, the C1South plots exhibited appreciable runoff during this early spring event.

The VWC of the 0-300 mm depth shows that the C1South steep and shallow slopes were similar (during winter and spring at least), in contrast to the separation between slopes observed for the C1North site. Additionally, the runoff responses to rainfall events were more muted on the C1South site than the C1North site. Spot VWC values at 0-50 mm depth suggest that during spring when the soil was beginning to dry out, the surface of the profile was much drier (by 0.025-0.075 m^3 m^{-3}) than the 0-300 mm values, similar to the differences observed at the C1North site.

C1East runoff data (Figure 5.6a) and VWC data (Figure 5.6b) for 2010 is, unfortunately, minimal and little can be gleaned from either of these figures.

C2East runoff data (Figure 5.8a) and VWC data (Figure 5.8b) for 2010, although also minimal, does capture two runoff events (late January, mid December) which correspond to those observed at C1North. These events occurred when the soil was identified as being dry

(0.2 m^3 m^{-3} for 0-50 mm depth in mid December), and assumed to be dry in late January (given the rainfall distribution and summer evaporation rates). As with C1North, these events occurred when rainfall intensity was high.

5.3.2 2011

The runoff data for C1North for 2011 (Figure 5.3a) is mostly complete, with just a few missing days. There are several runoff events, occurring in late January, early March, mid March, early July, mid September, early October, and early December. With one exception, all events showed runoff from both the shallow and steep slopes. This exception was in early July when there was a high runoff response from the shallow slopes and a very small response from the steep slopes. This behaviour was similar to that in the early spring of 2010 (early to mid September) and can be attributed to the presence of a water table in the shallow slopes. Unlike 2010 however, this runoff event was preceded by a series of high intensity rainfall events (1.5-2.0 mm min^{-1}). Despite the magnitude of this rainfall intensity, almost all of the incident rainfall infiltrated the soil surface. The VWC of the 0-300 mm depth (Figure 5.3b) immediately prior to the event was about 0.41 m^3 m^{-3} and the VWC of the 0-50 mm depth 8 days prior to the event was 0.48 m^3 m^{-3}. Thus the soils on the C1North steep slopes would appear to have a very high intrinsic infiltrability (at least 2.0 mm min^{-1}).

For the late January, early March, and mid March events, soil conditions were quite dry (0.20 m^3 m^{-3} VWC at 0-300 mm depth for the steep slopes) and were coupled with rainfall intensities ranging from 0.1-0.7 mm min^{-1}. The mid September event occurred when the soil (0-300 mm depth) was moist and rainfall intensity was lower (0.16 mm min^{-1}). The early October and early December events occurred under conditions of moist soil (a VWC of 0.45 m^3 m^{-3} for the 0-300 mm depth) and intense rainfall (1.5 mm min^{-1}). An examination of the rainfall patterns and intensities during those periods where runoff data was missing would suggest that Table 5.1 annual runoff values for the North steep slopes are likely to be accurate for 2011 and that runoff for the shallow slopes will be slightly under-estimated, with the possibility of additional runoff (resulting from the presence of a water table) from those slopes in late July and mid August.

The 0-300 mm depth VWC values for the steep slopes were consistently drier than the shallow slopes (as in 2010). The magnitude of this difference (up to 0.12 $m^3 m^{-3}$) tended to be greatest during the months of January through to the beginning of May, after which time the differences were considerably reduced to an average of about 0.025 $m^3 m^{-3}$ i.e. during the winter, spring, and early summer months. Runoff responses to rainfall events also tended to be greatest for the months of January through to the end of April when soils were drier and rainfall events more discrete. The 0-50 mm depth VWCs were drier (by about 0.1 $m^3 m^{-3}$) than their 0-300 mm depth counterparts from January through to April, while tending to be slightly wetter during the winter months, again indicating that surface soil water contents (particularly during summer and autumn) were different to those in the bulk profile.

The runoff data for C1South (Figure 5.5a) is reasonably complete from April onwards. A number of runoff events were observed; the largest occurring in early July when there was consistent daily rainfall coupled with a series of high intensity rainfall events (1.5-2.0 mm min^{-1}). This rainfall input had little effect on VWC at 0-300 mm depth (Figure 5.5b, 0.50 $m^3 m^{-3}$ for the steep slopes) and indicates that all runoff was attributable to saturation of the soil resulting from a rising water table enhanced by interflow from above the plots. This affected both the steep and shallow slopes. Subsequent events occurred in mid August, late September, early October, and early December. In these instances the soil was wet (0.47-0.50 $m^3 m^{-3}$ for the steep slopes at 0-300 mm depth) and rainfall intensity varied. It is very likely however, that a rising water table still prevailed and that all runoff was due to saturation runoff. Prior to July, VWC data at 0-50 mm depth during January to March suggests that the soil at this time was drier and that runoff may have occurred from both slope categories when rainfall intensity was high enough. In this case however, it is unlikely that the runoff mechanism would have been related to a rising water table.

Over the period of 0-300 mm depth VWC coverage, there was little difference in volumetric water content between steep and shallow slopes, although the shallow left plot tended to be slightly wetter than the rest. Generally, the VWC values fluctuated around the 0.50 $m^3 m^{-3}$ level from May to the end of the year and only at the end of the year did the soil show signs of drying. Responses to rainfall events were more muted than the C1North site over this period; in both cases however, the onset of the summer soil drying phase was delayed markedly (approximately two months) compared to that of 2010. The VWC data at 0-50 mm depth for May through to December were all wetter than their 0-300 mm depth counterparts with the shallow slopes wetter (by about 0.05-0.075 m^3 m^{-3}) than the steep slopes in most cases. Some of the values for the shallow slopes approach a VWC of 0.70 m^3 m^{-3}, indicating a very wet surface, and thus making it very likely that rainfall would have been diverted as saturation runoff.

The only complete coverage for runoff events in any one year occurred with C1East in 2011 (Figure 5.7a) so that the runoff values given in Table 5.1 are an accurate reflection of runoff from these plots during that year. There appears to be an anomalous runoff response for the C1EStL plot on the 22 March when there was a 45 mm surface runoff event compared with a 2 mm response for the adjacent right plot. The total incident rainfall for this event was 45 mm and delivered a maximum intensity of 2.00 mm min^{-1}. The disparate runoff responses of these paired plots suggests that the left plot probably experienced a significant number of false tips, due perhaps to rain water short-circuiting the data cable. Apart from this single event (where the VWC values at 0-50 mm depth were around 0.56 m^3 m^{-3}, Figure 5.7b), the runoff responses for the left and right steep plots tracked together reasonably well.

Intrinsic infiltrability for the soil at this site was found to be at least 1.5 mm min^{-1} as evidenced by a lack of runoff response to a 1.5 mm min^{-1} rainfall event on 07 May. It may be surmised that runoff occurring in early July was probably due to the presence of a rising water table. All other runoff events for this year (late January, early March, mid March, late April, early October, and early December) experienced rainfall intensities less than 1.5 mm min^{-1} and runoff would also have been the result of a mechanism other than saturation runoff.

Runoff data and rainfall intensities for C2East during 2011 are shown in Figure 5.9a, with daily rainfall totals and 0-50 mm depth VWC values displayed in Figure 5.9b. There is a large gap (mid April to the beginning of July) where runoff data is absent. Fortunately, the high intensity (2.0 mm min^{-1}) rainfall event in early July was captured and clearly showed that there was minimal response from the steep plots. This event occurred at a time when the soils were quite wet (around 0.56 m^3 m^{-3}) and provides good evidence that the steep soils at this site (as with C1North) have a very high intrinsic infiltrability (of at least 2.0 mm min^{-1}). The remaining observed runoff events occurred in late January, mid February, early March, mid March, early October, early December, and mid December. Prior to mid April (when the soils were drier), runoff responses were larger in magnitude, although the associated rainfall intensities were lower. After the end of June (when the soils were wetter), runoff responses were much smaller in magnitude, despite having associated rainfall intensities that were much higher. The rainfall pattern and intensity occurring during the runoff data gap (mid April to the beginning of July) suggest that there may have been a runoff event in early May. However, reference to the C1East data at the same time in 2011 showed that there was no runoff response to this rainfall event and it would seem likely that the C2East steep slopes would follow a similar pattern of behaviour.

5.3.3 General Discussion

The preceding sections have made a number of common observations based on the rainfall, soil moisture, and runoff data gathered for the years 2010 and 2011. These are:

Some very large infiltration rates were observed on the steep slopes in C1North, C1East, and C2East (1.5-2.0 mm min^{-1}). It is very probable that the C1South steep soils have similar intrinsic infiltrability values; however no opportunity was available to observe this, primarily because of the lack of runoff data (due to equipment malfunction) and secondly, because of the susceptibility of the site to interflow and/or the presence of a rising water table in winter. However, since soils at all the sites had similar textures and that organic matter contents were highest at the C1South sites (hence, likely, higher infiltrability), then there is sufficient support for the claim that intrinsic infiltrability of the C1South soils is at least equal to that of the C1North soils.

There is also some evidence that the soil at the shallow plots at C1North has a high intrinsic infiltrability i.e. there was an intense rainfall event (1.5 mm min^{-1} peak intensity and 12.1 mm of rainfall on 7 May 2011) for which there was a muted runoff response (0.7-0.9 mm). The soils at both the C1North and C1South shallow sites are at times susceptible to runoff induced by a rising water table. While there was runoff at the C1East steep slopes during the mid July 2011 event, it is believed that, despite the high intrinsic infiltrability of the soil, the physical location of this site, which was at the toe of a slope (as was C1South), caused another runoff producing mechanism to come into play. During high duration/intensity rainfall events, the bottom of the slope would be likely to receive inputs from subsurface flow and this would promote the development of a rising water table, which would then contribute to saturated runoff.

It is highly likely therefore, that all steep slopes (and probably all the shallow slopes) at the sites have soils with an intrinsic infiltrability of at least 2.0 mm min^{-1}.

Two types of runoff have been observed. The first was saturated flow which was commonly observed during winter when soils were wet at the C1South site for both the shallow and steep plots. Saturated flow was also observed at the shallow plots at the C1North site during periods of prolonged and/or intense rainfall in the winter and spring months. The second type of runoff usually occurred both when the soils were drier and when rainfall intensities were greater than 0.1 mm min^{-1}, despite the high intrinsic infiltrability inferred above. Thus there was a throttling process occurring as the soils became drier. This process reduced the infiltrability of the soil so that rainfall intensity above some threshold was able to generate Hortonian runoff. The obvious and most likely explanation for this behaviour is that the soil became water repellent.

Combining the above observations, it is proposed that nearly all of the runoff from the steep slopes associated with C1North, C1East, and C2East was repellency-induced (although there may have been a chance of saturated flow on the C1East steep slopes when the soils were very wet), and that repellency-induced runoff occurred when rainfall intensities were greater than 0.1 mm min^{-1}. In contrast, runoff from C1South steep slopes was dominated by saturated flow during the winter and spring months when the soils were wet. For all shallow plots, runoff was induced by repellency whenever the soils were sufficiently dry.

Both the design of the runoff plots and the installed data measurement systems were unable to account for the contribution of subsurface flows and/or rising water tables to saturation-induced runoff events. Accordingly, the remainder of this discussion will focus on those events for which it can be deduced were caused by Hortonian surface runoff arising from the establishment of soil water repellency. These events will then be analysed further in order to help quantify the effect that soil water repellency has on soil infiltration rates, and to try and identify the conditions necessary for repellency-induced runoff to occur. Table 5.2 summarises these water repellency-induced runoff events.

Table 5.2 **Rainfall and runoff data for the major repellency-induced runoff events.**

Year	Date	Event	Rainfall (mm)	Maximum Rainfall Intensity (mm min^{-1})	Aspect	Runoff Shallow (mm)[1] [% of rain]		Runoff Steep (mm)[1] [% of rain]	
						Left	Right	Left	Right
2010	20 Jan	1	24.8	2.00	C1North	12.1 [49]	12.9 [52]	9.7 [39]	14.5 [59]
					C1South	5.9 [24]	*	*	*
					C1East	n/a		*	*
					C2East	n/a		5.6 [23]	1.9 [8]
	24 Mar	2	24.4	1.00	C1North	4.8 [20]	2.8 [12]	6.1 [25]	3.9 [16]
					C1South	3.1 [13]	1.9 [8]	1.8 [7]	3.7 [15]
					C1East	n/a		*	*
					C2East	n/a		*	*
	24 May	3	60.5	0.26	C1North	5.1 [8]	2.5 [4]	10.7 [18]	5.4 [9]
					C1South	*	*	*	*
					C1East	n/a		*	*
					C2East	n/a		*	*
2011	23 Jan	4	99.4	0.26	C1North	9.7 [10]	2.1 [2]	4.1 [4]	12.7 [13]
					C1South	*	*	*	*
					C1East	n/a		3.7 [4]	5.0 [5]
					C2East	n/a		7.8 [7]	18.3 [18]
	5 Mar	5	42.4	0.67	C1North	3.6 [9]	1.6 [4]	6.5 [15]	9.9 [23]
					C1South	*	*	*	*

					C1East	n/a		3.6 [9]	4.0 [9]
					C2East	n/a		2.6 [6]	2.2 [5]
	22 Mar	6	44.9	0.11	C1North	1.9 [4]	1.0 [2]	2.2 [5]	5.6 [13]
					C1South	*	*	*	*
					C1East	n/a		42.7[2] [95]	1.9 [4]
					C2East	n/a		4.2 [9]	7.4 [17]
	19 Sep	7	25.6	0.16	C1North	3.5 [14]	5.4 [21]	2.6 [10]	1.9 [7]
					C1South	5.5 [22]	4.3 [17]	36.2[2] [141]	6.5 [25]
					C1East	n/a		0.7 [3]	1.1 [4]
					C2East	n/a		0.2 [1]	0.2 [1]
	3 Oct	8	30.0	1.50	C1North	7.0 [23]	9.4 [31]	12.7 [42]	8.3 [28]
					C1South	0.7 [2]	1.1 [4]	13.5[2] [45]	3.2 [11]
					C1East	n/a		3.0 [10]	3.2 [11]
					C2East	n/a		1.5 [5]	1.1 [4]
	3 Dec	9	11.2	1.50	C1North	3.9 [35]	4.3 [38]	6.0 [54]	5.9 [53]
					C1South	1.2 [11]	1.2 [11]	1.9 [17]	2.5 [22]
					C1East	n/a		1.9 [17]	2.1 [19]
					C2East	n/a		1.5 [13]	0.5 [5]

1 – Calculated on a horizontal projection basis.
2 – Runoff responses for these plots are suspect
* – data unavailable

Table 5.3 Rainfall and initial 0-300 mm depth VWC values for the major repellency-induced runoff events at the C1North site.

Year	Event	Date	Rainfall (mm)	Maximum rainfall intensity (mm min^{-1})	VWC (m^3 m^{-3}) Shallow	VWC (m^3 m^{-3}) Steep
2010	1	20 Jan	24.8	2.00	*	*
	2	24 Mar	24.4	1.00	*	*
	3	24 May	60.5	0.26	0.25-0.27	0.23-0.26
2011	4	23 Jan	99.4	0.26	0.21-0.21	0.19-0.19
	5	5 Mar	42.4	0.67	0.21-0.22	0.18-0.19
	6	22 Mar	44.9	0.11	0.22-0.22	0.18-0.18
	7	19 Sep	25.6	0.16	0.41-0.43	0.37-0.39
	8	3 Oct	30.0	1.50	0.35-0.39	0.34-0.35
	9	3 Dec	11.2	1.50	0.40-0.42	0.37-0.39

* – data unavailable.

Tables 5.2 and 5.3 list a number of critical parameters associated with repellency-induced runoff. The 0-300 mm depth VWC values will be referenced in the discussion below in terms of gauging the dryness (and hence the likelihood of repellency) of the soil. It should be noted however, that repellency is likely to be a surface effect and 0-50 mm depth VWC values would give a better description of the repellency status of a soil immediately prior to a runoff event. Unfortunately, these values were collected manually and the dates of collection do not coincide with the dates of the runoff events. Figures 5.2-5.9 give a sense of the relative differences between the 0-50 and 0-300 mm VWC values. As a general observation, the 0-50 mm VWC values tend to be drier in summer and autumn and wetter during winter and spring.

The first repellency-induced runoff event occurred on 20 January 2010 and was associated with a large and sustained peak intensity (1.5-2.0 mm min^{-1}) delivering 24.8 mm of rainfall.

Runoff fractions were high from both shallow and steep slopes at C1North (39 to 59 %) with 24 % from the C1South shallow slopes and 8-23 % from the C2East steep slopes. Unfortunately no VWC data was available for perusal but it is suspected that the magnitude of the runoff fractions was likely to be the result (in part at least) of differing soil water contents (and so degrees of water repellency), existing at the sites when the event happened. The C1North site, due to its aspect, would have been more likely to experience drier soil conditions and hence a greater degree of water repellency.

The second event occurred on 24 March 2010 and involved a similar quantity of rainfall (24.4 mm) although it was delivered at about half the peak intensity (1.0 mm min^{-1}). Again, the C1North shallow and steep slopes diverted similar fractions of the rainfall to runoff (12 to 25 %). No VWC values are available so it is difficult to ascertain whether the reduced runoff fractions were the result of the lower intensity rainfall and/or more moist (less repellent) soils. Similarly, runoff fractions from both the steep and shallow slopes at the C1South sites were roughly equal, covering a range of 7-15 %. As with the C1North site, VWC data was lacking, making it difficult to assess the soil water status at the site, but it is assumed that soils were more moist there, thus resulting in lower runoff fractions than the C1North site.

The third event occurred on 24 May 2010. Data for this day was missing from the C1South, C1East, and C2East sites. A total of 60.5 mm of rainfall was delivered with a peak intensity of 0.26 mm min^{-1}. Runoff fractions were much smaller with this event and there was a difference in runoff fractions between the C1North shallow (4 to 8 %) and steep (9 to 18 %) slopes. VWC values (0-300 mm depth) were available for this event and indicate that the shallow slopes had similar values to the steep slopes.

The fourth event occurred on 23 January 2011 and runoff was observed at the C1North, C1East, and C2East sites (logger failure prevented data capture at the C1South site). A large amount (99.4 mm) of rainfall was delivered with a peak intensity of 0.26 mm min^{-1}. Unlike the third event which had a similar peak intensity, there was little difference in runoff fractions (2 to 13 %) between the steep and shallow slopes at C1North. Runoff fractions for the C1East and C2East slopes were similar. C1North soil (0-300 mm) conditions were quite dry (0.19-0.21 m^3 m^{-3}) with the shallow slopes marginally wetter than the steep slopes.

The fifth event occurred on 5 March 2011. A total of 42.4 mm of rain was delivered with a peak intensity of 0.67 mm min^{-1}. C1North shallow slopes diverted less rainfall to runoff (4 to 9 %) than their steep counterparts (15 to 23 %) with the C1East and C2East steep slopes presenting somewhat lower fractions than C1North – perhaps due to slightly moister soil conditions at these sites. Soil conditions at the C1North site were dry – 0.18-0.22 m^3 m^{-3} with the shallow slopes again being marginally drier than the steep slopes.

The sixth event occurred on 22 March 2011. On that day, 44.9 mm of rain was delivered with a relatively low peak intensity of 0.11 mm min^{-1}. Again, C1North shallow slopes diverted less rainfall (2 to 4 %) than their steep counterparts (5 to 13 %) and were also wetter (0.22 m^3 m^{-3}) than the steep slopes (0.18 m^3 m^{-3}). The C1East and C2East steep slopes presented a range of runoff fractions (4 %, 9 to 17 % respectively), the latter being consistent with the C1North values. The C1East steep left plot data is strongly suspect, giving a value of 95 % diversion of rainfall to runoff.

The seventh event occurred on 19 September 2011 and was observed at all sites with varying degrees of responsiveness. Rainfall was 25.6 mm with a peak intensity of 0.16 mm min^{-1}. C1North soil moisture conditions were now wetter (0.41-0.43 m^3 m^{-3} for the shallow slopes, 0.37-0.39 m^3 m^{-3} for the steep slopes) and these conditions resulted in a rainfall diversion of 14 to 21 % for the shallow slopes and 7 to 10 % for the steep slopes. C1East steep slopes shed 3 to 4 % of rainfall, while C2East steep slopes diverted 1 % of the rainfall. Runoff data was able to be collected at the C1South site for this event and gave higher runoff fractions (17-22 % for shallow slopes, 25 % for steep slopes) than the C1North site. Data from the C1South steep left plot is highly suspect (141 %). For the C1North site, runoff behaviour for this event was quite different from its predecessors. The relatively high shallow slope runoff fractions, and the reversal in behaviour with the shallow slopes producing more runoff than the steep slopes, suggest that saturation runoff was significant on these slopes, while the steep slopes experienced some degree of water repellency despite the relatively moist soil conditions. In comparison, the runoff behaviour associated with both slopes at the C1South site was very likely due to saturation runoff, given the wet soil conditions existing at the time (0.50-0.55 m^3 m^{-3} for 0-300 mm depth, up to 0.60 m^3 m^{-3} for 0-50 mm depth).

The eighth event occurred on 3 October 2011 when 30.0 mm of rain fell at a peak intensity of 1.50 mm min^{-1}. Soil moistures for the C1North shallow slopes (0.35-0.39 m^3 m^{-3}) were slightly wetter than for the steep slopes (0.34-0.35 m^3 m^{-3}), resulting in runoff fractions of 23 to 31 % and 28 to 42 %, respectively. The corresponding runoff values for the C1East and C2East steep slopes were much less, 10 to 11 % and 4 to 5 % and again may reflect different topsoil water contents and so the degrees of repellency between the sites. For C1South, prevailing wet soil conditions (0.47-0.51 m^3 m^{-3}) would have been very likely to promote saturation runoff observed at this site (2-4 % for the shallow slopes, 11 % for the steep slopes). Once again, the data provided by the C1South steep left plot appears to be problematic (45 % of rainfall). The C1North shallow slopes may again have experienced saturated runoff during this event (as soil water contents were still relatively high). It appears that the steep slopes, despite having soil profiles that were relatively moist, still exhibited some throttling of their infiltrability and the intensity of rainfall in this instance was sufficient to produce repellency-induced runoff. If several rain-free sunny days occur after a wet period, it is possible for the top 300 mm of the soil profile to remain quite wet while the top few mm becomes dry enough to induce repellency.

The ninth (and last) event occurred on 3 December 2011. The rainfall associated with this event delivered 11.2 mm with a peak intensity of 1.50 mm min^{-1}. Soil moistures were wetter than the previous event, 0.40-0.42 m^3 m^{-3} for the C1North shallow slopes and 0.37-0.39 m^3 m^{-3} for the steep slopes, resulting in runoff fractions of 35 and 38 % and 53 and 54 % respectively. Corresponding steep slope values for C1East and C2East were 17 and 19 % and 5 and 13 %. C1South runoff fractions for both shallow slopes (11 %) and steep slopes (17-22 %) were much less than C1North. Soil moistures were much wetter than C1North with 0-300 mm depth VWC values in the region of 0.45-0.51 m^3 m^{-3}. For this event, it appears that the 0-50 mm VWC values would have been much higher (Figure 5.5). As hypothesised for the previous event, the C1North shallow slopes may have experienced saturated runoff due to the relatively high soil moisture values. Despite the high water contents of the steep soils, some water repellency appeared to have been present there and the intensity of the rainfall event was sufficient to produce runoff, even though the amount was relatively small.

The re-appearance of repellency-induced runoff events on the same plots during the course of a year suggest that there is a cyclic process in place whereby SWR develops as the soil dries out and is then removed once a rainfall event of a particular intensity and duration occurs. If the rainfall intensity is sufficiently high and the soil is sufficiently dry, then repellency-induced runoff will occur. For all nine SWR-related events described in the above discussion, the timing of peak rainfall intensities almost exactly matched the timing of the runoff event, indicating a water repellent surface. This and the observed 0-300 mm depth VWC status of the soil immediately prior to these events suggest that two conditions are required for repellency-induced runoff to occur:

1) The rainfall intensity needs to exceed some threshold value, and

2) The topsoil needs to be drier than some threshold value.

These threshold values are examined in more detail in the section below.

5.3.4 Infiltration Rates

It has been established that the intrinsic infiltrability of the steep soils at C1North, C1East and C2East was at least equal to 2.0 mm min^{-1}. It is likely that this also holds true for the C1North shallow soils as well as the C1South shallow and steep soils, although this has been difficult to demonstrate because of the masking effect afforded by rising water tables and/or subsurface flow at these locations. It has also been established that these high intrinsic infiltrabilities were compromised at certain times, most noticeably when soil conditions were drier. In an attempt to assess the characteristics of soil infiltration responses to rainfall events during dry conditions, the repellency-induced runoff events listed in Table 5.2 were examined in detail. In particular, inspection of one of the repellency-induced runoff events (Event 1, 2010 and Figures 5.10, 5.11, 5.12) indicated that the rainfall event generating the runoff response had a number of unique characteristics.

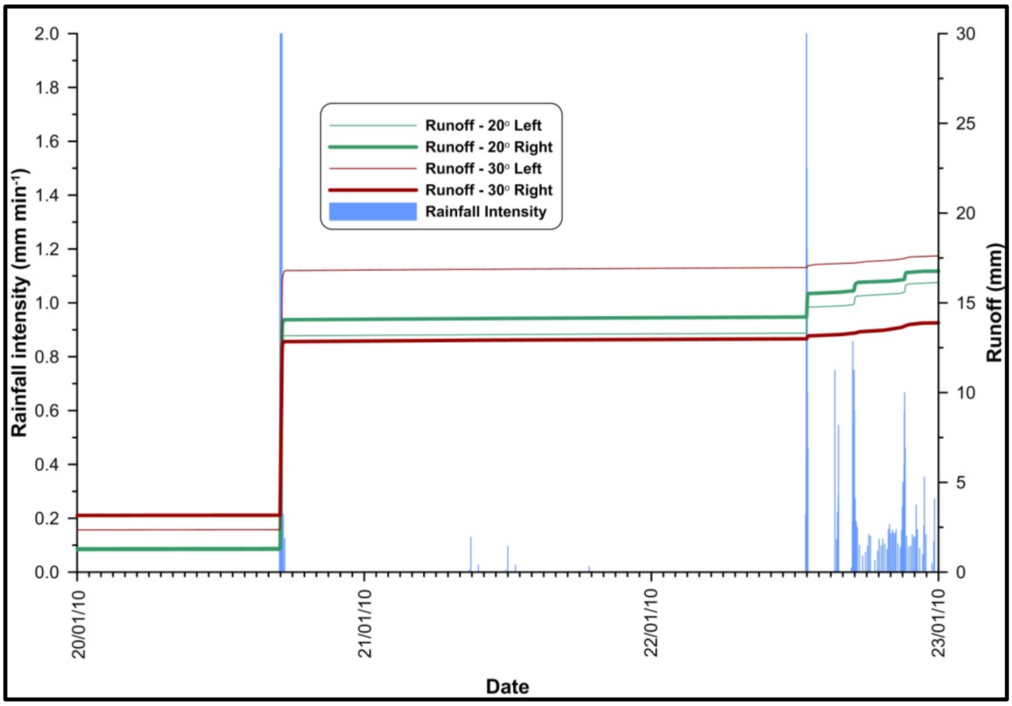

Figure 5.10 Cumulative runoff and rainfall intensity associated with runoff event 1 in 2010 for the C1North site.

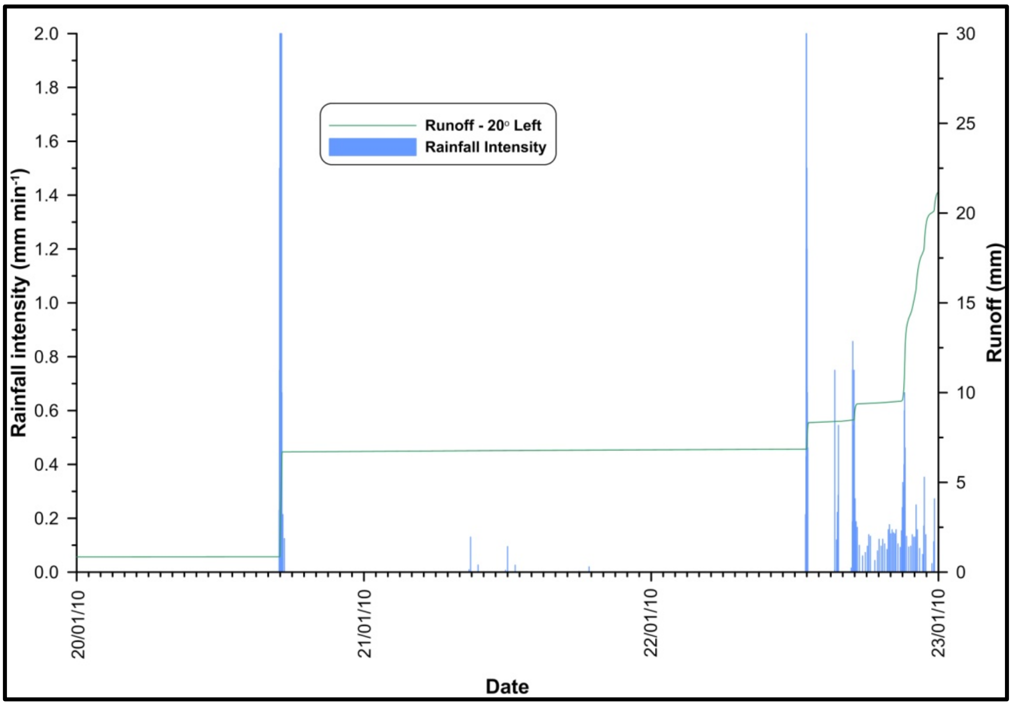

Figure 5.11 Cumulative runoff and rainfall intensity associated with runoff event 1 in 2010 for the C1South site.

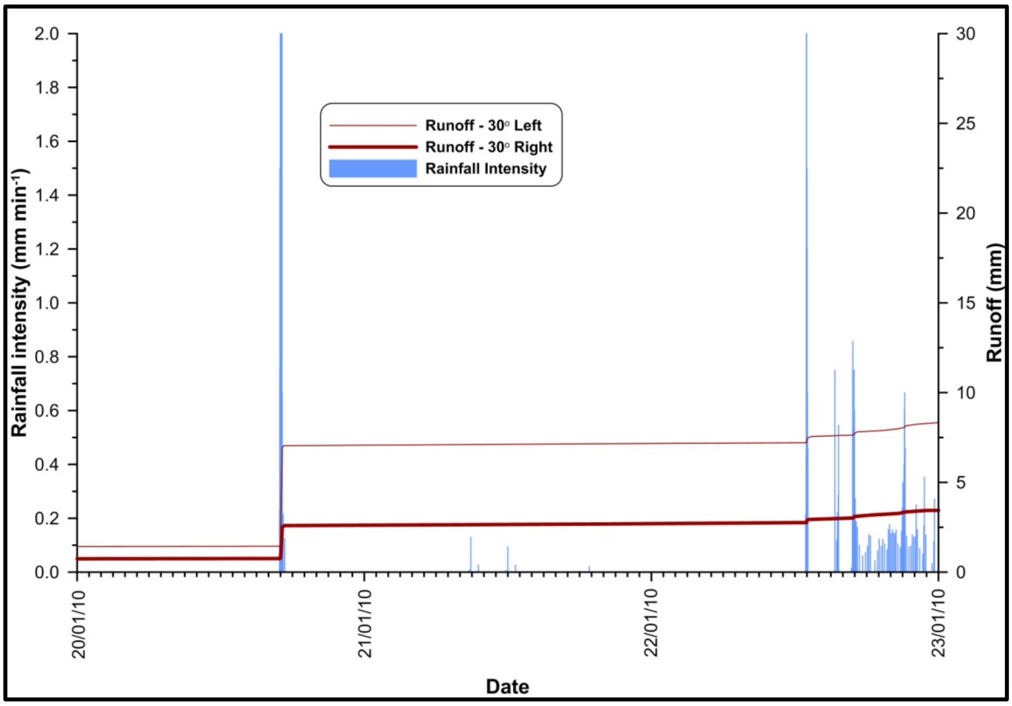

Figure 5.12 Cumulative runoff and rainfall intensity associated with runoff event 1 in 2010 for the C2East site.

The intense rainfall event on 20-01-2010 began at 4:50 pm and ended at 5:21 pm. A rapid (repellency-induced) runoff response ensued from the monitored plots at various times between 4:57 and 4:59 pm. There was then negligible rainfall until 1 pm on 22-01-2010 (44 hours later) when there was another intense single rainfall event initially similar in intensity to the first. Unlike the first event, this elicited no runoff response from the steep slopes and only a small response from the shallow slopes. It would appear then, that for the steep soils on the C1North and C2East aspects, repellency was effectively eliminated by the earlier single intense rainfall event of 24.8 mm lasting about 30 minutes. This rainfall event was unusually long and consistent in intensity (1.5-2.0 mm min^{-1}) and provides an opportunity to calculate the changes in the repellency-throttled infiltration rate of the C1North, C1South, and C2East soils. Because of the consistency in rainfall rate (Figure 5.13), it is assumed that the change in ponded water depth on the steep plots during the event was negligible and, therefore, the infiltration rate during the event can be found as the difference between the rainfall intensity and the surface runoff rate.

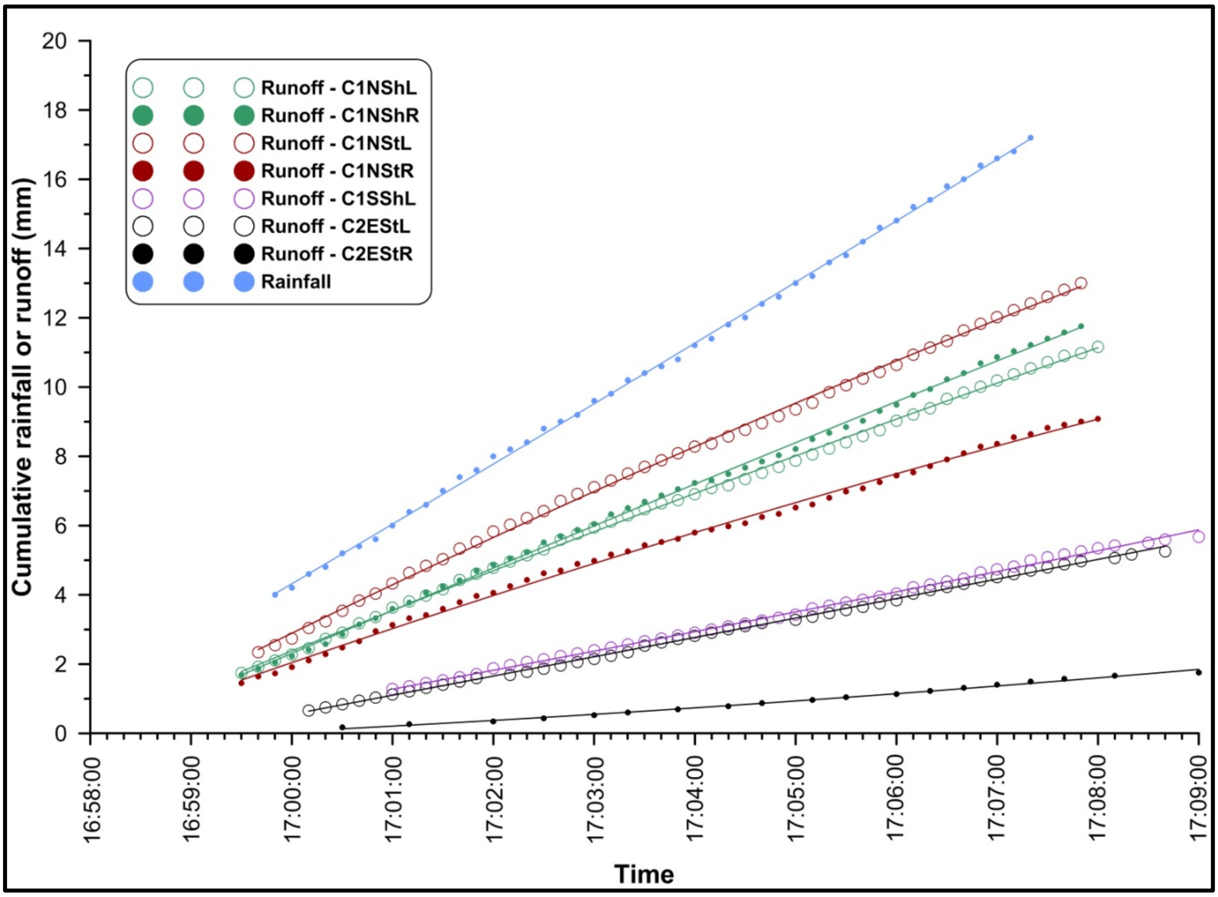

Figure 5.13 **Cumulative runoff and rainfall associated with runoff event 1 on 20-01-2010 for the C1North, C1South, and C2East sites. Solid lines are fitted quadratic functions.**

Using least squares regression, each rainfall and runoff data set in Figure 5.13 was fitted with a quadratic equation. Table 5.4 lists the fitted parameters for each of these curves.

Table 5.4 **Table giving fitted quadratic equation parameters for the cumulative rainfall and runoff curves in Figure 5.13**

Cumulative Plot	Quadratic polynomial ($Ax^2 + Bx + C$)			
	A	B	C	R^2
Rainfall	0.00457	1.69593	0.05261	0.9994
Runoff C1NorthShL	-0.01072	1.23375	-0.63707	0.9989
Runoff C1NorthShR	-0.00515	1.26835	-0.82735	0.9990
Runoff C1NorthStL	-0.01782	1.50690	-0.76254	0.9988
Runoff C1NorthStR	-0.01502	1.07403	-0.54699	0.9977
Runoff C1SouthShL	0.00448	0.51371	-0.21152	0.9980
Runoff C2EastStL	0.00106	0.54849	0.00176	0.9986
Runoff C2EastStR	0.00578	0.13534	-0.08331	0.9951

Since the fitted equations describe the accumulation of rainfall/runoff with respect to time, the derivatives of these equations should give instantaneous rainfall intensities and runoff rates over a 12 minute period of the event. Figure 5.14 shows the resulting calculated infiltration rates of the soils at the C1North, C1South, and C2East sites during this event. Each line has been plotted from the time runoff commenced.

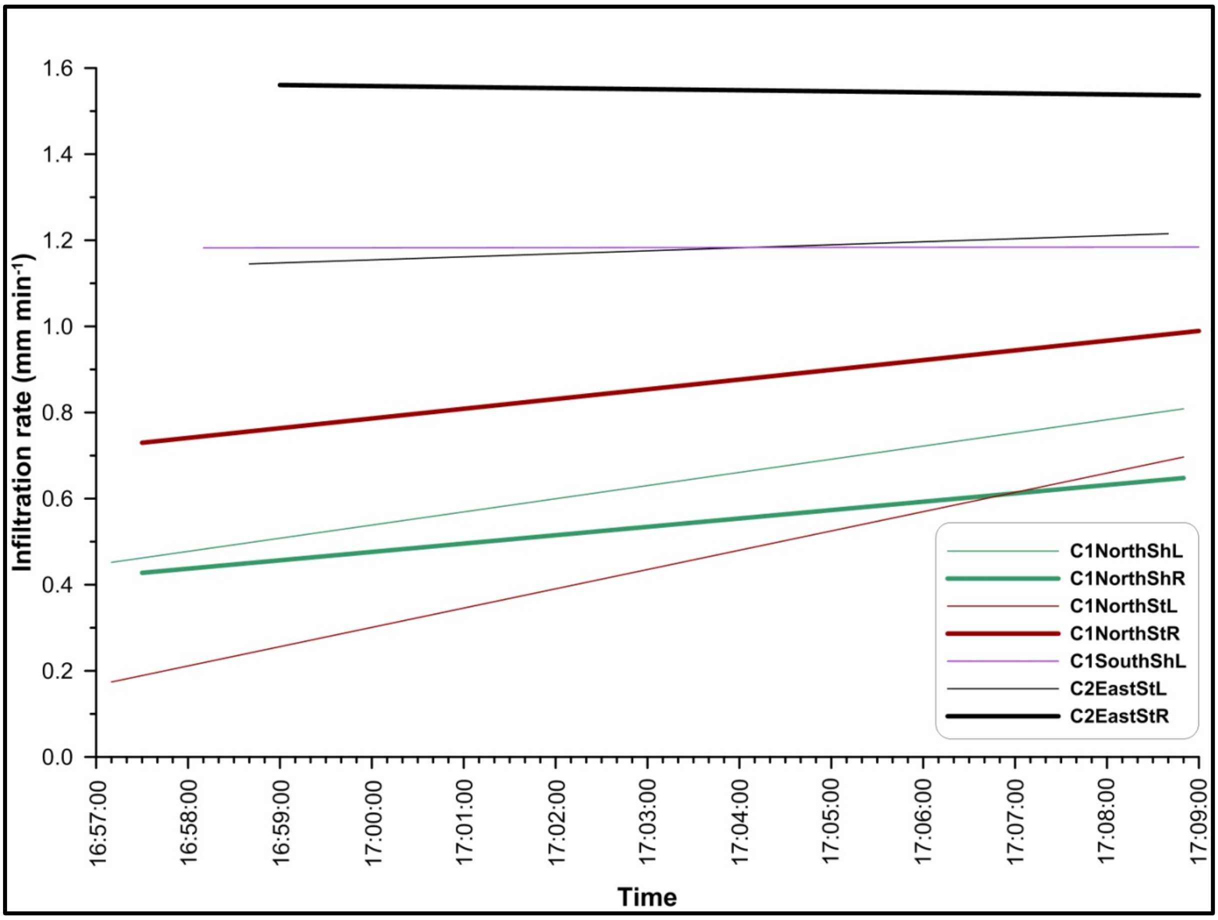

Figure 5.14 Infiltration rates associated with runoff event 1 on 20-01-2010.

Unfortunately no VWC data was available to examine the change in soil moisture status during this event. However, the rainfall pattern from 11 January 2010 (the last minor runoff event) to this event showed that 24 mm was delivered in a small number of spaced and moderately intense (0.05-0.25 mm min^{-1}) rainfall events. The spacing of these events coupled with high summer evaporation rates was apparently sufficient to produce at least moderately dry surface soils exhibiting soil water repellency, the extent of which is likely to depend on the slope and aspect in question. Certainly, the intrinsic infiltrability of soils at the C1North site (>= 2.0 mm min^{-1}) was considerably throttled to a range of 0.2-0.7 mm min^{-1} at the start of the event, and there appeared to be no obvious difference between steep and shallow slopes. The C1South and C2East sites were less repellent with initial infiltration rates ranging from 1.15-1.55 mm min^{-1} at the start of the event. The C1North soils which initially exhibited high SWR also experienced a strong improvement in infiltration rate, at least during the first 12 minutes of the event. In contrast, the C1South and C2East soils, which initially had higher infiltration rates, changed little during those first 12 minutes. This suggests that initial recovery from severe SWR on hill country slopes may be quite rapid. In the present study, the first stage of this recovery saw infiltration rates increase from 0.2-0.7 mm min^{-1} to 0.6-0.9 mm min^{-1} in a period of 12 minutes (Figure 5.14). Where SWR is less developed, initial infiltration rates are higher but appear to be relatively stable under short term ponding i.e. they do not increase to the same extent as those infiltration rates which were initially severely throttled (Figure 5.14).

5.4 Conclusions

The two types of runoff, Hortonian and saturation excess, each require a specific approach to their detailed examination. Saturation runoff, resulting from a rising water table or subsurface flow from further up the hillslope intercepting the surface, requires at least a whole sub-catchment approach. While the experimental setup employed in this study was capable of identifying local events that were saturation-induced and measuring the volumes produced, it was unable to measure the wider contribution of rising water tables and subsurface flow to these volumes. Hortonian runoff is a soil surface phenomenon and is thus a process which is more suitable for examination by the small plot experimental approach adopted for this study.

Of particular interest is the phenomenon of soil water repellency in New Zealand hill country pastoral systems and its role in throttling the infiltration rate of soils as the topsoil dries out, thereby increasing the potential for Hortonian runoff and decreasing the soil's ability to replenish plant available water during dry periods. Examination of the major runoff events in 2010 and 2011 (yielding more than 1 mm or so of runoff) showed that these runoff events were few in number (less than 10 per annum) and constituted less than 5 % of the annual rainfall. It would appear then, that for these two years at least, runoff induced by soil water repellency was not a major phenomenon in the hill country research site.

Comparison of both rainfall intensities and runoff responses when the soil surface was thoroughly moist and so not repellent, showed that the steep soils associated with the northern and eastern aspects had high intrinsic infiltrability (=> 2.0 mm min^{-1}), and it is argued that the soils on the other slope and aspect combinations had similarly high values. Despite these intrinsic infiltrability values being greater than the intensity of the heaviest rainfall, runoff events were observed in which the infiltration rate of the soil could not absorb the rain falling. These runoff events were associated with drier soil conditions coupled with higher rainfall intensity events. Under these conditions, runoff responses could be quite high with sometimes half of the rainfall running off the plots. When soils were moister, regardless of the rainfall intensity, there was a negligible runoff response, except where interflow and a rising water table produced saturation excess runoff. It is argued that the observed reduction in infiltration rate when the topsoil was drier was the result of the establishment of soil water repellency. It is suggested that in order for this to occur, the topsoil had to be drier than a critical value and that rainfall intensity had to exceed a threshold value of 0.1 mm min^{-1}.

Detailed examination of the unique 25 mm rainfall event in January 2010 and the associated repellency-induced runoff responses enabled the calculation of the infiltration rates of the soils with time over 10 minutes of steady heavy rain. The resulting data showed that on the plots with initially more repellent soils (with infiltration rates of 0.2-0.7 mm min^{-1}) the infiltration rates increased to approximately 1.0-1.1 mm min^{-1} over about 30 minutes, after which time the residual repellency disappeared completely over a period of 44 hours or less. In contrast, the infiltration rate of the plots with less repellent soils tended to remain static during the first 12 minutes of heavy rainfall, but with complete recovery after 44 hours. It would seem that soil water repellency can readily and quite rapidly disappear after the addition of relatively small quantities (25 mm or less) of heavy rainfall, however it will re-appear when the soil becomes sufficiently dry.

CHAPTER 6

A LABORATORY STUDY OF RUNOFF AND WATER REPELLENCY USING A HILL COUNTRY SOIL

6.1 Introduction

One of the major conclusions drawn in the preceding chapter is that the high intrinsic infiltrability of the soils at the Alfredton research area was compromised during drier soil conditions by the establishment of soil water repellency (SWR). The associated reduced soil infiltration led to some Hortonian overland flow. Furthermore, detailed examination of these specific runoff events showed that a single rainfall event of 25 mm was sufficient to mitigate the initially low infiltration rates of the more repellent soils over a 30 minute period.

The short-lived nature of SWR after rainfall was interesting enough to prompt further examination of this behaviour under controlled conditions. Standard techniques for the measurement of SWR involve water droplet penetration time (WDPT) and molarity of ethanol droplet (MED) tests. While well established, the major drawbacks of these tests are that they are potentially time-consuming and are highly susceptible to micro-scale variations in SWR on the soil surface. The recent development and construction of the ROMA (RunOff Measurement Apparatus) device at 'Plant and Food Research' in Palmerston North afforded an opportunity to use this instrument in a study of soil slab samples from the research area at Alfredton.

The main attraction in using the ROMA device was the ability to simultaneously measure both runoff and drainage from a dry and intact soil slab in a relatively short period of time. Additionally, the SWR variability associated with point WDPT and MED tests was largely eliminated. Although the ROMA apparatus attempts to simulate field conditions as closely as practicable, it is recognised that the technique it employs to apply water to the soil slab does not closely resemble rainfall impacting a soil surface under field conditions, and therefore the results presented in this chapter should be interpreted cautiously and be seen as indicative of general behaviour rather than as attempts to explain specific details of the field observations.

The major objective of this chapter therefore, is an attempt to confirm (under laboratory conditions) the short-lived nature of SWR observed in the field when subjected to intense rainfall in the January 2010 runoff event described in detail in Chapter 5.

6.2 Methodology

Soil samples were collected from the research area (described in Chapter 3) from both the steep and shallow slopes associated with the C1North and C1South sites on 12-01-2012. Three replicates were sampled from each slope and aspect category and were taken in close proximity to their related runoff plots. Plate 6.1 shows the sampling process. The sampling and transport procedures were carried out in a manner which preserved the soil structure as much as possible. Upon arrival at the laboratory, the soil slabs were cut down to the final dimensions (460 mm long x 170 mm wide x 50 mm deep) required for placement in the RunOff Measurement Apparatus (ROMA) located at Plant and Food Research in Palmerston North (Le Mire et al., 2011). The soil slabs were weighed, and the sculpted trimmings used to determine the gravimetric water content of the slabs at sampling.

Plate 6.1 Collection of a soil slab from a point close to one of the C1North shallow slope runoff plots.

The ROMA apparatus (Plate 6.2) was developed by Plant and Food Research in order to better quantify the effect of soil moisture content on soil water repellency (SWR), and in turn, on runoff. Its main advantage over the standard SWR measurement techniques of water droplet penetration time (WDPT) and molarity of ethanol droplet (MED) tests is its decreased sensitivity to micro-scale variability of surface SWR, making it more representative of repellent soil surface behaviour at the small plot scale.

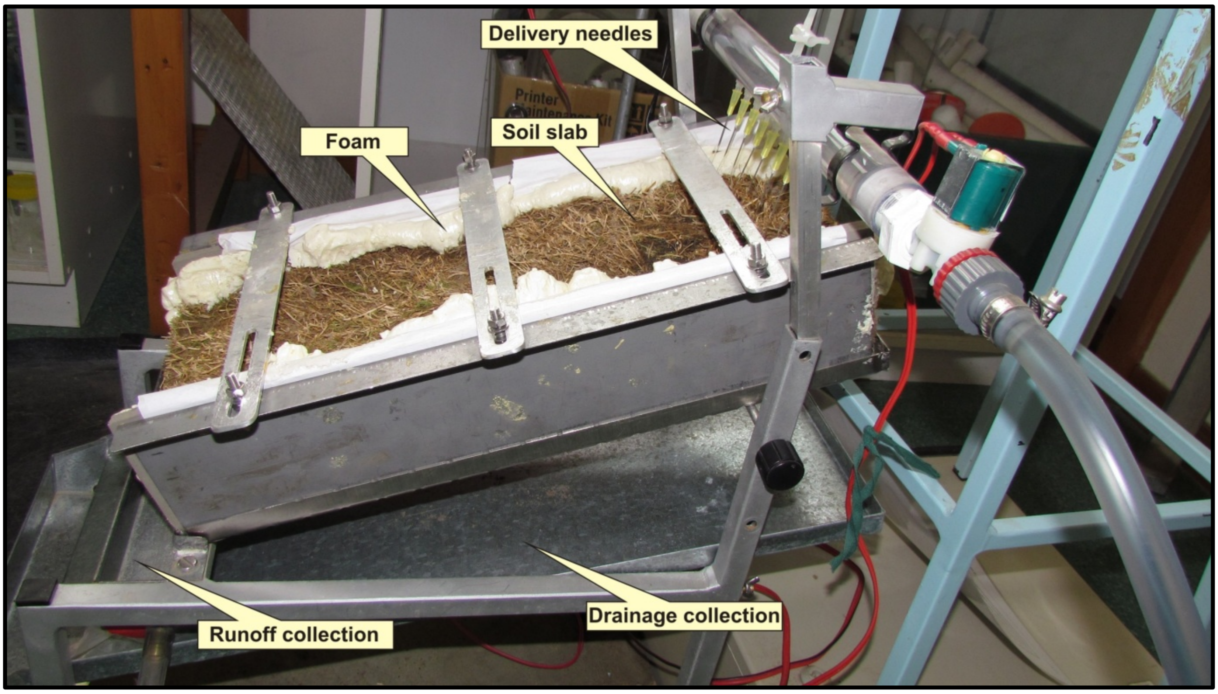

Plate 6.2 **Side view of the ROMA apparatus. Foam is applied to prevent edge flow at the sides of the slab, and water (or 30 % ethanol) is delivered at a constant rate via eight hypodermic needles set in a line across the width of the slab at the top of the slope. The angle of the slope was fixed at 22 degrees.**

In the laboratory, the soil slabs were air-dried to a constant mass prior to placement in the ROMA apparatus, by which stage all of the pasture had died off. The air-dried mass, and the initial moist mass, in conjunction with the initial gravimetric water content values, allowed the air dry gravimetric water contents to be calculated. The gravimetric water contents were then changed to volumetric water contents assuming a bulk density of 806.7 kg m^{-3} (from Table 3.6 in Chapter 3). The resulting values are given in Table 6.1. The long sides of the slab were then clamped and sealed with foam to prevent preferential infiltration at the edges. The system was then set at an angle of 22 degrees (similar to that of the slope angle of the shallow plots at the research area).

Reverse osmosis treated water was applied via a line of eight fixed-position hypodermic needles, 1 cm above the soil surface and 2 cm apart at the top of the slab. During the course of the experiment, the combined delivery rate of the water through these needles was fixed at 90 mL min^{-1} using a pressure head of 12 cm (27 cm for 30 % ethanol). This pressure head was maintained by the use of a floating switch. Runoff volumes were collected every 5 minutes in a collection tray at the bottom end of the slope. Drainage volumes were also collected every 5 minutes by means of a collection tray underneath the slab (the underside of the slab was supported by a perforated plate). Measurement of both runoff and drainage volumes continued until a steady drainage rate was achieved.

Once the water run was completed the wetted slabs were removed and then air-dried once again until calculated VWC readings were the same as those measured prior to the water run (Table 6.1). The ROMA experiment was then repeated using 30 % ethanol instead of water. No ethanol runoff was observed for any of the samples and drainage volumes were measured every 5 minutes. The 30 % ethanol run was used to demonstrate the response of the soil surface to infiltration and runoff without the influence of soil water repellency.

Table 6.1 Volumetric water contents (VWC) of 0-50 mm depth at field sampling and immediately prior to ROMA analysis.

Sample	VWC* in field (m^3 m^{-3})	VWC* prior to ROMA experiment (m^3 m^{-3})
C1North shallow R1	0.44	0.09
C1North shallow R2	0.49	0.11
C1North shallow R3	0.49	0.12
C1North steep R1	0.43	0.07
C1North steep R2	0.47	0.06
C1North steep R3	0.40	0.07
C1South shallow R1	0.54	0.16
C1South shallow R2	0.49	0.11
C1South shallow R3	0.54	0.06
C1South steep R1	0.59	0.07
C1South steep R2	0.50	0.04
C1South steep R3	0.44	0.07

* - converted from gravimetric values using 0-50 mm depth bulk density values listed in Chapter 3.

6.3 Results and discussion

6.3.1 General

Analysis was not performed on replicate 2 of the C1South steep sample because of the very uneven surface topography of this soil slab, which would have caused large surface ponding volumes and reduced SWR induced runoff. It is acknowledged that surface roughness on hill country slopes is likely to play a role in the amelioration of repellency upon rainfall, however, the objective of the ROMA experiment was to confirm the field observations regarding the transient nature of SWR on relatively even surfaces.

Summary data for the runoff curves displayed in Figures 6.1 and 6.2 are given in Table 6.2. Peak runoff has been defined as the maximum fraction of applied water diverted to runoff in any one 5 minute measurement interval. Steady-state runoff is defined as the fraction of applied water diverted to runoff after peak flow and which has also achieved some degree of stability over consecutive 5 minute intervals.

The runoff event in January 2010 (described in detail in Chapter 5) experienced rainfall intensities of 1.5 – 2.0 mm min^{-1}. While the water application rate of the ROMA apparatus (90 mL min^{-1}) cannot be directly converted to an equivalent rainfall intensity, a very rough calculation, that assumes a drip width of 10 mm down the slope of the soil slab (170 mm width), gives an approximate rainfall intensity of 50 mm min^{-1}. This is about 20-30 times greater than that of the rainfall event in January 2010, and is about 500 times greater than the threshold rainfall intensity value of 0.1 mm min^{-1} suggested for repellency-induced runoff in Chapter 7. The water application rate of the ROMA apparatus was therefore sufficient to produce runoff, provided that the soil slabs were dry enough.

Unfortunately, no topsoil field VWC data for the January 2010 runoff event was available for direct comparison with those of the air-dried soil slabs. However, the moisture values for all the slabs (Table 6.1) were much drier than the threshold topsoil moisture value of 0.28 m^3 m^{-3} suggested for repellency-induced runoff (Chapter 7), so that the slabs were very likely to be at least as repellent as the topsoil conditions existing immediately prior to the January 2010 event.

Table 6.2 **Peak water runoff and steady-state runoff values and timings for the ROMA samples.**

Sample	Peak runoff (% of applied water)	Time to achieve peak runoff (min)	Steady-state runoff (% of applied water)	Time to achieve steady-state runoff (min)	Total runoff (% of applied water)#
C1North shallow R1	16	10	0	20	8
C1North shallow R2	51	25	2	40	21
C1North shallow R3	48	5	4	100	22
C1North steep R1	67	10	2	30	27
C1North steep R2	26	5	4	185	8
C1North steep R3	38	5	0	30	29
C1South shallow R1	6	5	0	15	6
C1South shallow R2	52	5	0	30	26
C1South shallow R3	43	5	0	35	13
C1South steep R1	49	10	0	120	25
C1South steep R2	n.a.	n.a.	n.a.	n.a.	n.a.
C1South steep R3	58	10	0	20	10

n.a. – not analysed
- over the shorter duration of: 120 minutes or whenever runoff stopped

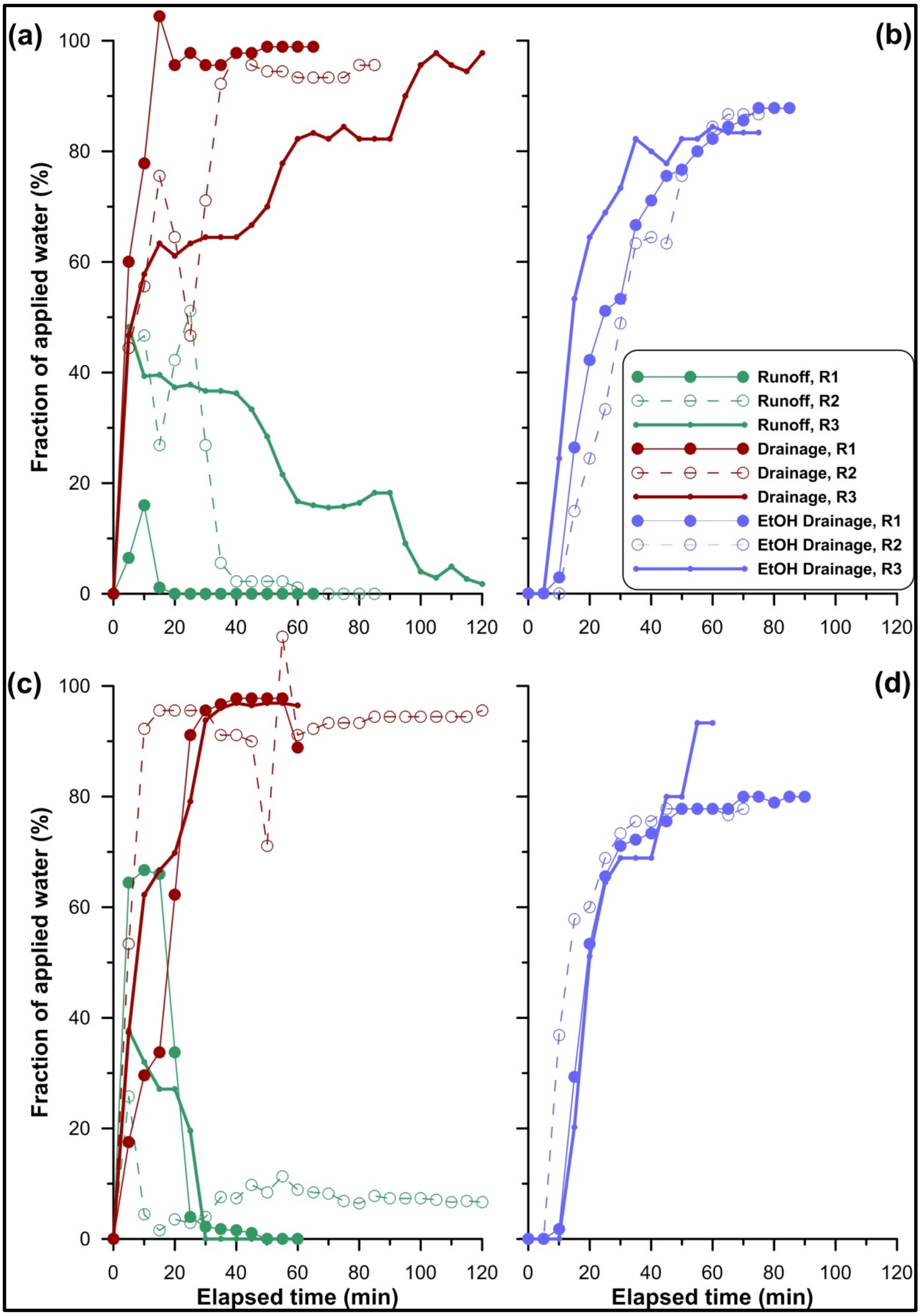

Figure 6.1 **Runoff and drainage fractions relative to input for (a) water applied to the C1North shallow site (b) ethanol applied to the C1North shallow site, (c) water applied to the C1North steep site (d) ethanol applied to the C1North steep site. R1, R2, and R3 are replicate analyses.**

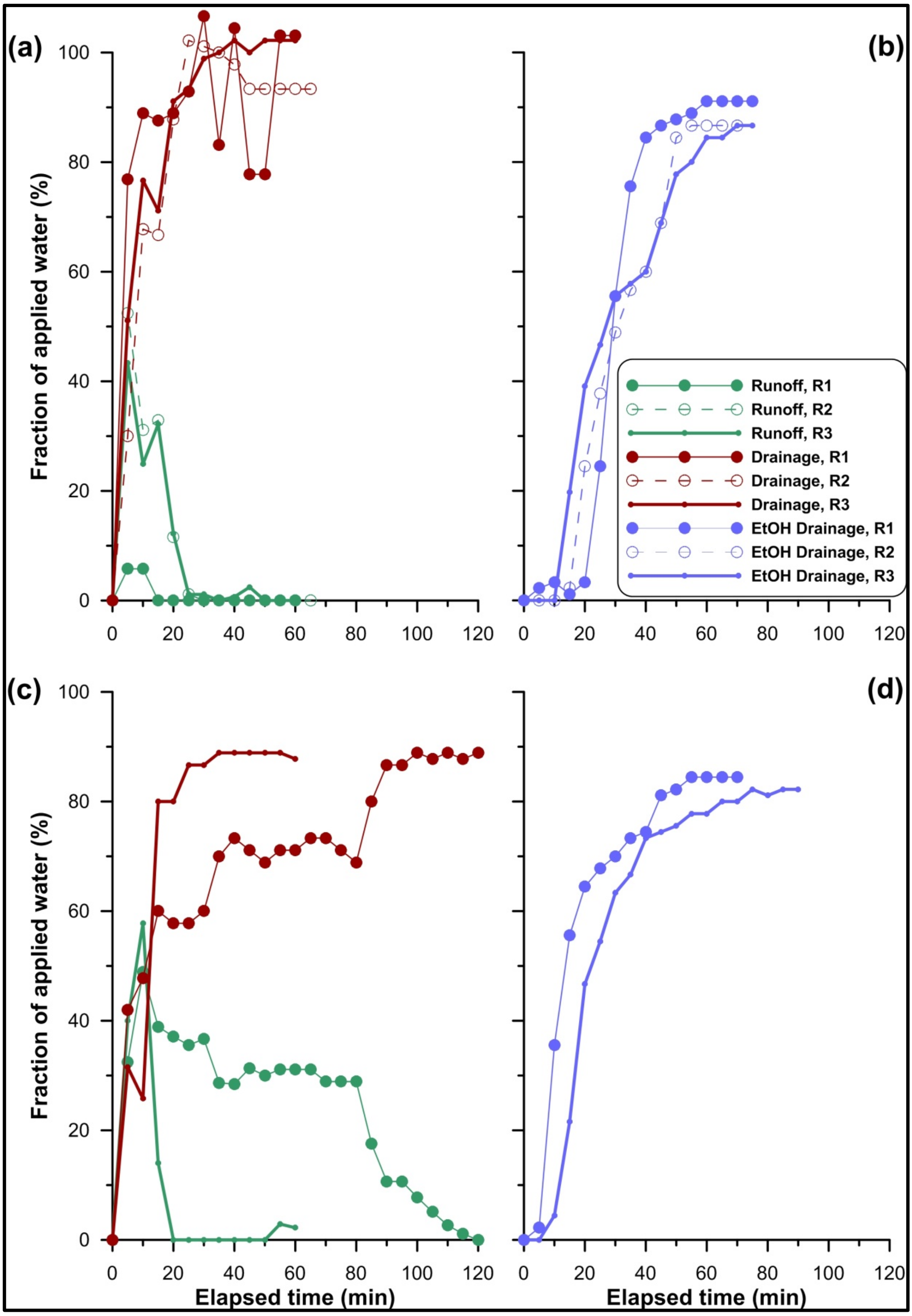

Figure 6.2 **Runoff and drainage fractions relative to input for (a) water applied to the C1South shallow site (b) ethanol applied to the C1South shallow site, (c) water applied to the C1South steep site (d) ethanol applied to the C1South steep site. R1, R2, and R3 are replicate analyses.**

6.3.2 Soil moistures

The mean VWC values for the replicate slabs taken at each of the sampling sites were 0.473, 0.433, 0.523, and 0.510 $m^3 m^{-3}$ for the C1NorthSh, C1NorthSt, C1SouthSh, and C1SouthSt sites, respectively. These field moisture contents were unusually large given the mid January (2012) sampling date. While there were only three replicate samples at each site, the soil slabs were of sufficient size to adequately represent the soil water status of their respective slope and aspect categories (i.e. a very large sample volume). The mean VWC values confirm the trends observed in the preceding chapter; namely that southern aspect soils are wetter than their northern counterparts and shallow slopes are wetter than steep slopes. However, in this case, due to the high variability in VWC of the slabs from the southern steep slope, there was little difference in VWC contents between the southern steep and shallow slopes.

6.3.3 Runoff and drainage

Peak runoff values are highly variable, ranging from 6 to 67 % of applied water, and there is no clear distinction between North and South aspect soils and steep and shallow slope soils (Figures 6.1 and 6.2 and Table 6.2). Substantial proportions of the applied water ran off most of the slabs even if this runoff only lasted relatively short periods of time. This suggests that the slabs were highly repellent. The time taken to reach peak runoff flows is very consistent, with values ranging from 5 to 10 minutes after the application of water. The marked decrease in runoff following peak runoff is interesting. Presumably, breakdown in SWR over macropore pathways may have occurred during this time, leading to enhanced drainage and reduced runoff. Preferential surface runoff pathways and ponding were observed for most samples during the initial stages of the experiment when runoff was dominant.

Total runoff values for the samples (as a fraction of applied water) appear to be segregated into two groups – those exhibiting fractions of 5-10 %, and those that lie in the range of 20-30 %. The former group generally consists of samples that showed low peak runoff and shorter steady state times which are indicative of high interception of runoff by macropores. The latter group generally exhibited high peak runoff and short steady state times, indicating relatively low interception of runoff by macropores and the mitigation of repellency over a period of time consistent with that observed in the field at Alfredton.

The C1North shallow R2 sample exhibited a double peak flow: the first occurring after 10 minutes with 47 % runoff, and the second after 25 minutes with 51 % runoff. The timing of the first peak is consistent with all of the other ROMA samples. The reason for this second peak is not clear. Perhaps the second (higher) peak could be due to macropore(s) clogging during that period.

Drainage patterns for water were complementary to those for runoff (as would be expected). Comparison with the 30 % ethanol drainage patterns showed faster responses to drainage fractions for the water. This would suggest that the initial preferential runoff paths for water over the surfaces of the ROMA samples often intercepted macropores, leading to an almost immediate drainage response. The ethanol eliminated the influence of SWR so that no Hortonian flow occurred, and was much more likely to infiltrate the ROMA sample as matrix flow. Thus resultant ethanol drainage appeared later than the water drainage which resulted from preferential infiltration. Given the initial dryness of the ROMA samples, appreciable time would also have been spent with the ethanol filling empty pore spaces.

While the times taken to reach peak runoff flows are very consistent, the times taken for drainage to achieve steady-state are variable, with values ranging from 15 to 185 minutes. Having said this, the majority of samples appeared to reach (more or less) steady-state drainage after approximately 30 minutes. Again, there appears to be very little distinction between North and South aspect soils and steep and shallow slope soils in terms of their steady-state drainage times.

Most samples exhibited runoff which peaked after 5 to 10 minutes and then rapidly decreased to negligible or no runoff after 40 minutes or less. There were two samples however where runoff decreased quite slowly over time – C1North shallow R3 and C1 South steep R1. The ethanol drainage curves for these two samples were similar to the other ROMA samples, indicating that soil textures were also similar. Both samples exhibited similar total runoff fractions (22 and 25 % respectively). The overall implication then is that for these two samples, preferential runoff flow intercepted fewer macropores so that rapid drainage was less prevalent, and that most infiltration underwent slower matrix flow, thus delaying the start of drainage. In terms of runoff, the presence of fewer macropores intercepting the preferential runoff pathways would have prolonged Hortonian flow until SWR had almost completely dissipated.

It must be emphasised that the application of water to the soil slabs in the ROMA experiment does not simulate the behaviour of rainfall which (under field conditions) would wet the entire surface of the slab during an event, resulting in shorter and less persistent preferential runoff pathways.

6.4 Conclusions

Runoff and drainage response studies using a suite of soil slabs taken from steep and shallow slopes on both the North and South aspects of the Alfredton research area were performed using the ROMA apparatus sited at the Climate Laboratory of Plant and Food Research in Palmerston North. The major objective of this exercise was an attempt to confirm the short-lived nature of SWR that was observed in the field at Alfredton and discussed at length in the previous chapter.

The laboratory results confirm the transient behaviour of SWR, namely that most of the air-dried soil samples exhibited repellency-induced runoff responses which largely dissipated within 30 minutes of the application of water to the surface of an extremely dry soil.

The large variability in peak runoff rates and the time taken to reach steady-state drainage are probably best explained by differences in soil surface topography at this scale. If any differences in runoff and infiltration responses exist between the soils from the different slope and aspect combinations, then they are masked by the highly variable nature of the surfaces in terms of their micro topography and the potential “patchiness” of SWR.

Due to the way in which water was applied to the soil surfaces, preferential runoff pathways tended to be long and appeared to intercept sufficient macropores so that drainage responses were more rapid than those of the 30 % ethanol runs. Most of the ethanol runs showed similar behaviour suggesting that there was little difference between the slabs (in terms of soil texture and structure). With the application of water, two samples displayed prolonged runoff and drainage behaviour, suggesting that (for these samples) fewer macropores were intercepted by runoff and that slower matrix flow played a larger role in the production of drainage.

CHAPTER 7

STREAM FLOW AND WATER REPELLENCY IN PAIRED HILL COUNTRY CATCHMENTS

7.1 Introduction

In a comprehensive review of soil water repellency, Doerr et al. (2000) stated:

"The main hydrological impacts of soil water repellency reported in the literature are (a) reduced infiltration capacity; (b) increased overland flow; (c) spatially localised infiltration and/or percolation, often with fingered flow development; (d) effects on the three-dimensional distribution and dynamics of soil moisture; (e) enhanced streamflow responses to rainstorms; and (f) enhanced total streamflow."

Chapter 5 of this thesis presented runoff data for small scale plots on hill country near Alfredton, thereby addressing impacts (a) and (b) in the above statement. The objective of this chapter is to investigate impacts (e) and (f) i.e. enhanced streamflow responses to rainstorms and enhanced total streamflow. As a first step, the model for repellency-induced runoff described in Chapter 4 was refined using the data in Chapter 5. This improved model was tested against volumetric soil water content and runoff data measured at the Alfredton site. To assess the effects of repellency-induced runoff on stream flow, the (larger) runoff events predicted by the refined model were then compared with the associated responses in stream flow.

As stream flow was not monitored in the Alfredton catchment, several years of detailed rainfall and stream flow data for paired hill country catchments near Waipawa (approximately 97 km NE from the Alfredton site) were used in this exercise. The Waipawa data was kindly provided by the National Institute of Water and Atmospheric Research (NIWA).

Since the Waipawa catchments have about half the average annual rainfall of the Alfredton research area, the application of the refined model to this data set will also allow an estimation of the relative importance of repellency-induced runoff at sites with less rainfall than the Alfredton research area.

7.2 The Waipawa site

A description of the Waipawa site is given by Gillingham et al. (1998). It is situated about 4 km west of Waipawa township and comprises north and south facing slopes containing both easy (15 to 20^{o}) and steep (25 to 30^{o}) slopes. The soil is Waipawa stony loam which is approximately 600 mm deep. The grazed pasture was predominantly browntop with negligible legume content. Information about the twin catchments is given by Gillingham and Gray (2006). Each catchment was equipped with a double v-notch weir and with equipment which recorded stream flow at 5 minute intervals. The north catchment was 12.6 ha in area: the south catchment was 12.8 ha in area. Both catchments consisted of three or more smaller sub-catchments. Rain gauges in each catchment recorded rainfall at 15 minute intervals.

7.3 The refined model

The model of repellency-induced runoff described in Chapter 4 (also Bretherton et al. (2010)) used only daily rainfall as an input. One of the concluding remarks in that chapter suggested that a more detailed experimental study of surface runoff would help improve the model. The detailed rainfall and runoff data collected at the Alfredton research area (and described in Chapter 5) now make this possible, and the resulting improvements are described below.

Many of the features in the model described in Chapter 4 have been carried over into the refined model and are repeated here for convenience. Repellency-induced runoff is only simulated to occur if two conditions are satisfied:

1) The topsoil is drier than a certain trigger water content value, and

2) The rainfall intensity is greater than a certain threshold value.

To simulate the topsoil volumetric water content, two daily water balances are calculated in parallel, one for the whole root zone and the other for just the topsoil (taken here as 0-50 mm depth). The version of the Penman-Monteith equation suggested by Allen et al. (1998) is used to estimate the reference crop evaporation (E_0), along with Revfeim's (1982) equations to estimate how slope and aspect affect the incoming solar radiation. The discussion in Chapter 4 outlined some of the limitations of this approach but found it accurate enough to be useful.

Both daily water balances use the equation:

$$W_{n+1} = W_n + I - D - E \qquad (1)$$

where the equivalent depth of available water present at the start of the next day (W_{n+1}) is found as that at the start of the day (n) under consideration (W_n) plus any infiltration (I) less any excess water lost as drainage (D), and less the evaporation and plant water uptake (E) from the depth being considered during day n. When just the topsoil is considered, the subscript "s" will be added to these variables.

Total available water holding capacity values are assumed for both the whole root zone (W_{max}) and the 0-50 mm topsoil ($W_{\text{s,max}}$). The readily available water holding capacity is assumed to be half of the total available water holding capacity. E equals the reference crop evaporation rate (E_0) if:

$$W_n + I > W_{\text{max}} / 2$$

Once this readily available water is exhausted, E / E_0 is assumed to decrease linearly as further water is extracted, and will reach zero when all the available water has gone. So, if;

$$W_n + I < W_{\text{max}} / 2, \textit{ then } E = E_0 W_n / (W_{\text{max}} / 2)$$

This will hold unless the calculated E is less than the estimated topsoil evaporation and water extraction (E_{s}) – in this case E becomes E_{s}. Similarly for the topsoil, if;

$$W_{s,n} + I > W_{s,max} / 2, \text{ then } E_s \text{ is assumed to be equal to } E_0,$$

$$\text{otherwise } E_s = E_0 W_{s,n} / (W_{s,max} / 2)$$

Excess water (D) is assumed to be lost as deep percolation, or interflow down the slope to ensure that W never exceeds W_{max} at the end of the day. If;

$$W_n + I - E > W_{max}, \text{ then } D = W_n + I - E - W_{max}$$

$$\text{and if } W_{s,n} + I - E_s > W_{s,max}, \text{ then } D_s = W_{s,n} + I - E_s - W_{s,max}$$

A deficiency of this approach is that any water added to the root zone due to interflow from higher up the slope is ignored – any attempt to include this process would have considerably complicated the model.

The manner in which the amount of infiltrating water (I) is calculated is the main difference between the refined model described here and that of the earlier model described in Chapter 4. Instead of just considering daily rainfall, the refined model uses the detailed rainfall data to consider what happens during each day. A small amount of intense rain will not cause repellency-induced runoff as it can pond in surface indentations and/or enter macropores; accordingly, the rainfall intensity (Y) is calculated for each 1 mm of rainfall.

As in the earlier model, repellency is only assumed to throttle infiltration when the available water in the topsoil (or the corresponding topsoil water content) is less than some critical value ($W_{s,c}$). The model checks this once per day. At all other topsoil water contents, the soil is assumed to be permeable to rainfall of any intensity, that is, when:

$$W_{s,n} > W_{s,c}, \text{ then } I = P$$

where P is the size of the rainfall increment under consideration (1 mm). On the other hand, if;

$$W_{s,n} < W_{s,c} \text{ and } Y > Y_t$$

where (Y) is the rainfall intensity and Y_t is the throttled infiltration rate, then I equals the throttled infiltration rate (Y_t) multiplied by the time period over which that millimetre of rain fell. The repellency-induced runoff (R_r) for the period is then found as $P - I$, that is, the difference between the 1 mm of rainfall and the calculated infiltration.

The model does not attempt to simulate the spatially variable topsoil wetting often described in repellency-prone soils (impact (c) in the quote from Doerr et al. (2000) above). To do so would have meant a considerably more complicated model. Also, since no attempts were made to measure the spatial variability of the topsoil water content, no data would have been available to develop and test predictions that would have arisen from the inclusion of this feature.

7.4 Evaluating the model's parameters

Examination of runoff and rainfall intensity data given in Chapter 5 showed that a rainfall intensity greater than about 0.1 mm min^{-1} (6 mm hr^{-1} or 1 mm falling in 10 min) was needed to induce runoff – regardless of how dry the topsoil was. Accordingly, Y_t was set to this value so that when the soil was dry enough for repellency to induce runoff, the infiltration rate was throttled to 0.1 mm min^{-1} and rainfall in excess of this intensity was assumed to be repellency-induced runoff.

A value of 90 mm was assumed for the total available water holding capacity of the root zone (W_{max}), similar to the value of 87 mm used in the earlier model in Chapter 4. The comment was made there that this value of 87 mm was almost certainly an under-estimate, but in terms of modelling repellency-induced runoff, this parameter is not critical. The topsoil water content and its total available water holding capacity ($W_{s,max}$) however, are more important, since the process of repellency-induced runoff is dependent upon these values. Figure 7.1 shows the measured 0-50 mm depth volumetric water contents (see Chapter 5). For the two north aspect sites where repellency-induced runoff was most likely to occur (Chapter 5), nearly all the values fall between 0.1 m^3 m^{-3} and 0.5 m^3 m^{-3}, suggesting that $W_{s,max}$ = (0.5 – 0.1) x 50 = 20 mm and that the unavailable water content is 0.10 m^3 m^{-3} .

For $W_{s,c}$, the model was run over the two years, with trial and error suggesting a value of 9 mm. This value provided simulated runoff events which matched as closely as possible the repellency-induced runoff days observed on the North steep plots, and as few as possible when no such event was observed. Nine millimetres corresponds to a critical water content of 0.28 m^3 m^{-3}, and is the assumed topsoil water content which will trigger repellency-induced runoff when rainfall intensity exceeds 0.1 mm min^{-1}.

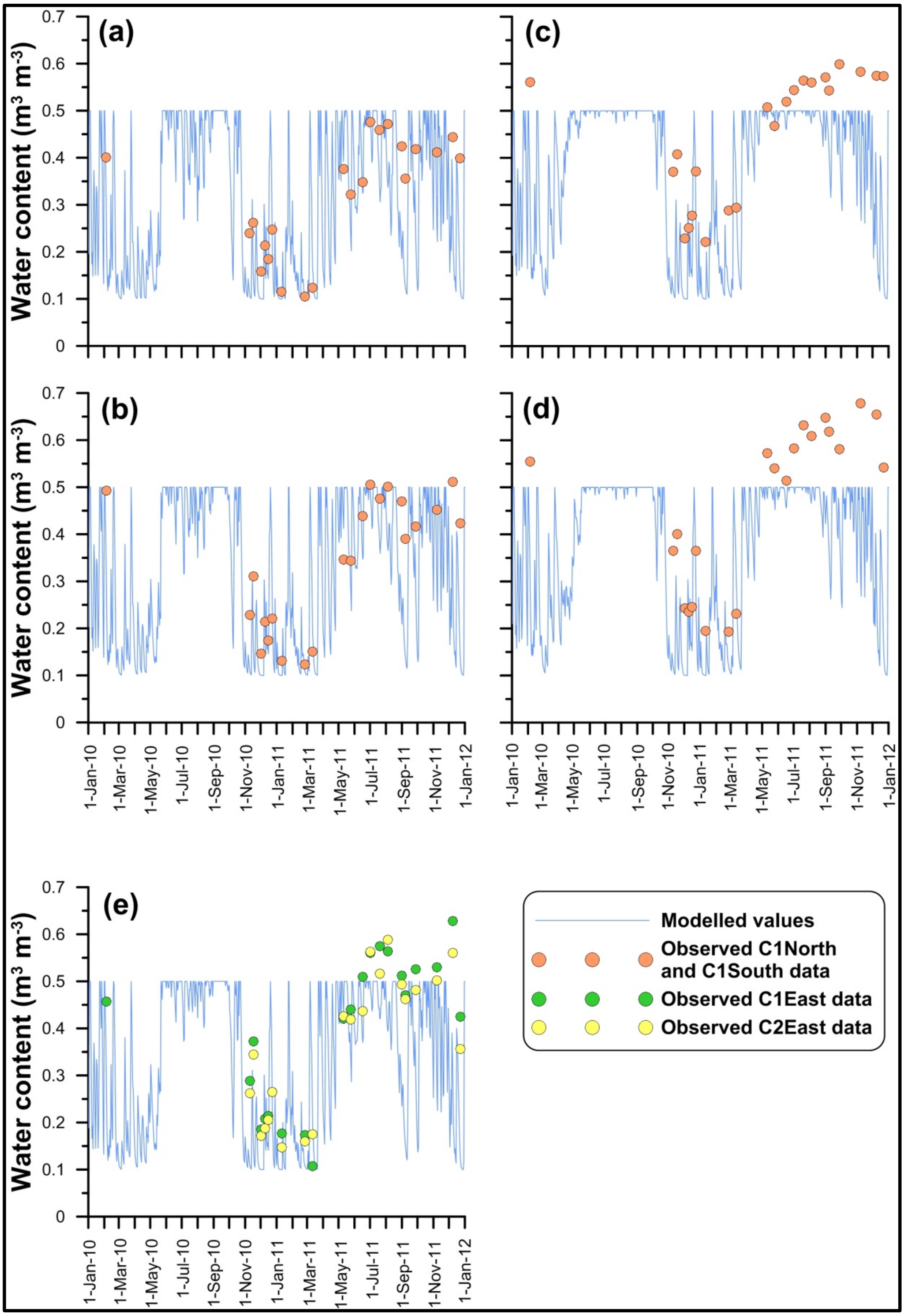

Figure 7.1 **Modelled and measured volumetric water contents in the top 50 mm of soil at locations (a) 30°N (30° slope N aspect site), (b) 20°N (c) 30°S, (d) 20°S and (e) 30°E on various sampling dates (Chapter 5).**

7.5 Comparison of model outputs with Alfredton data

Before using the model to simulate runoff in the Waipawa catchments, its accuracy in terms of simulating soil water content and repellency-induced runoff at the Alfredton research area for the years 2010 and 2011 needs to be assessed.

Figure 7.1 shows the simulated and measured VWCs in the top 50 mm of soil. It has already been mentioned that this layer is important since the model is obviously very sensitive to the trigger value (0.28 m^3 m^{-3}) at which repellency-induced runoff commences. For the North steep and shallow sites, both the simulated and measured values are in close agreement suggesting that ignoring spatially localised infiltration (effect (c), Doerr et al. (2000) above) has not seriously impaired the model's ability to simulate the topsoil water content at the small plot scale. The agreement is not as good for the other sites, with some of the observed values being higher than the simulated ones, particularly in winter for the South and East aspects. As discussed in Chapter 4, at times, these other sites exhibited runoff patterns suggesting contributions from interflow from further up the slope, and this is likely to be the major reason for the discrepancy between the observed water contents and the simulated values.

Figure 7.2 shows the equivalent depths of available water in the root zone of the steep and shallow North plots as simulated and measured via TDR – these were the only plots for which TDR measurements were available. When converting the TDR measured water contents in the top 300 mm depth into available water values, an unavailable water content of 0.15 m^3 m^{-3} was assumed since this was the driest value measured. Agreement is generally close, suggesting that the model with its assumed parameter values is simulating the soil water balance reasonably accurately. When the soil profiles became dry, the measured values are larger than the simulated ones. It is likely that this is caused by the rooting zone being deeper than the 300 mm being measured by the TDR probes. Soil profile observations (Chapter 3) confirm the presence of roots down to 500 mm at the North aspect and down to 650 mm at the South aspect, indicating that 0-300 mm TDR data does not fully represent the plant water extraction zone. In addition, when the soil was at its wettest, the measured values were sometimes higher than the simulated values. There are probably two reasons for this. The first reason is contribution of interflow from areas above the plots – the model ignores this, as has been mentioned previously. The second reason, which interacts with the first, is that the model assumes that the soil profile cannot be wetter than field capacity at the end of each day. In reality, it often takes a few days for the excess water to drain out of the root zone (Jury et al., 1991).

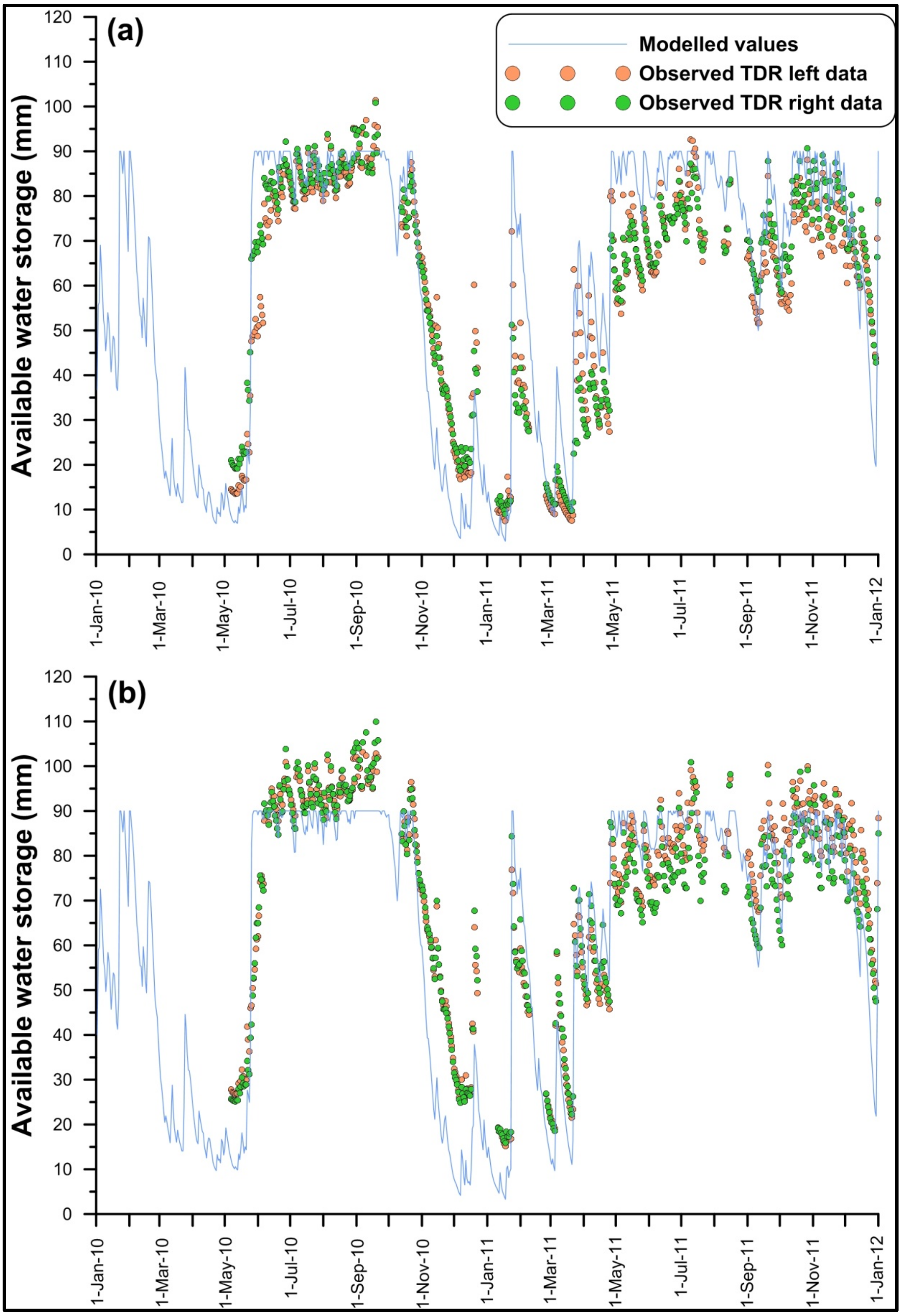

Figure 7.2 **Modelled available water contents in the root zone at locations (a) 30°N (30° slope N aspect site) and (b) 20°N. Measured values were calculated using data from 300 mm deep TDR probes.**

The cumulative measured and simulated runoff from the North steep plots for 2010 and 2011 is shown in Figure 7.3. Data for only these plots are shown, as it was suspected that interflow and/or a rising water table caused additional runoff from the other plots. Examination of the steep plot data suggests that the agreement between measured and simulated runoff is at best only fair – this is not surprising since a very simple model is being used to simulate a complex phenomenon.

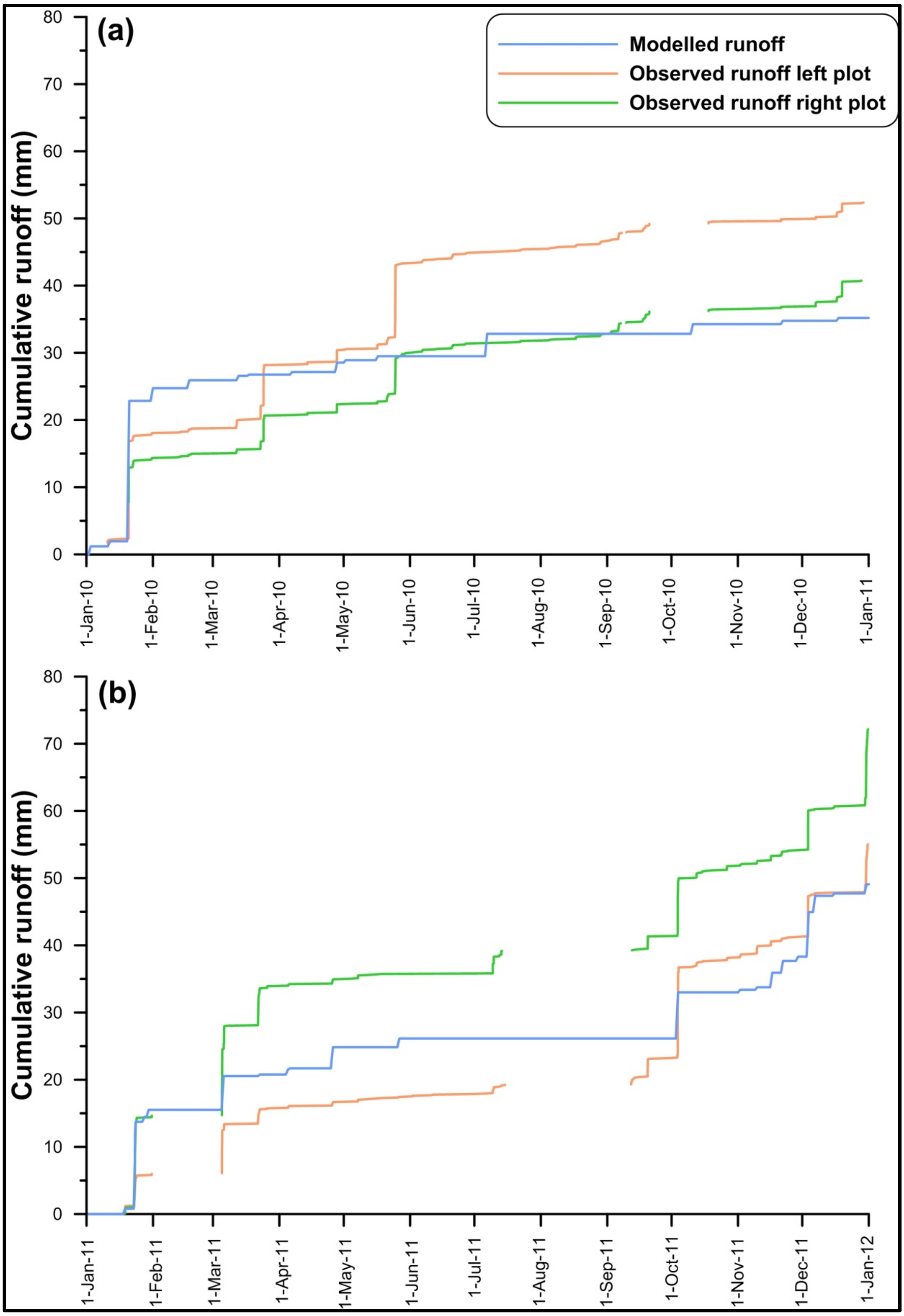

Figure 7.3 **Cumulative runoff for left and right plots and modelled cumulative runoff for the North steep site in (a) 2010 and (b) 2011.**

The runoff values measured on the nine days when there was more than 2 mm of repellency-induced runoff are given in Table 7.1. The rationale behind the selection of these runoff events and the mechanism producing them are described in Chapter 5. The simulated runoff values are also given. On these nine occasions, when repellency-induced runoff occurred from the North steep plots, runoff also occurred (and was predicted by the model) from the other plots i.e. the predicted runoff was the same for all three aspects and both slopes (as the topsoil water content at all sites was less than the trigger value). The measured runoff from all of the plots on the nine days is treated as a single data set with the means and standard deviations being given in Table 7.1. On the day with most runoff (20-01-2010), the model overestimates the runoff by nearly three standard deviations. On four runoff days, the model simulates zero or negligible runoff. On the other four runoff days, the simulated values are within one standard deviation of the mean of the measured values. It can be concluded therefore, that while the model has some obvious limitations, it appears to be accurate enough to indicate the magnitude of plot-scale surface runoff and when it occurs.

Table 7.1. Measured (mean and standard deviation) and modelled Alfredton runoff (mm) from all plots on key days (see Chapter 5).

Date	Measured		Model
	Mean	SD	Mean
20 Jan 2010	8.9	4.6	20.9
24 Mar 2010	4.4	1.4	0.0
24 May 2010	5.9	3.4	0.0
23 Jan 2011	7.9	5.5	12.9
5 Mar 2011	4.3	2.7	5.0
22 Mar 2011	3.5	2.4	0.3
19 Sep 2011	2.5	1.7	0.0
3 Oct 2011	5.8	4.2	5.8
3 Dec 2011	3.3	2.1	6.6
Sum	**46.5**		**52.6**

7.6 Application of the model to the Waipawa site

The model for repellency-induced runoff described above required modification before it could be applied to the Waipawa catchments. As described above, the Alfredton rainfall data was segmented into 1 mm increments: if the trigger rainfall intensity for repellency-induced runoff was 0.1 mm min^{-1}, then 1 mm of rainfall had to fall in less than 10 minutes to generate runoff. At Waipawa, rather than measuring the time at which a certain increment of rain fell, the amount of rain falling during each 15 minute period was recorded. Tomlinson (1980) describes how these differences can be taken into account - these calculations suggest that the trigger intensity for the Waipawa data is 0.08 mm min^{-1}.

The daily maximum and minimum temperature, solar radiation, wind speed, and vapour pressure values needed to calculate the reference crop evaporation were obtained from the nearest site on the NIWA virtual climate database. An average slope of 20^{o} was assumed for both North and South catchments. The average rainfall values from the two catchments were used for each 15 minute period, except when data was missing; in which case either the North or South values were used. It was assumed that the soil in the Waipawa catchments was similar enough to that at the Alfredton site for the same assumptions to be made about the available water storage capacity, and about the maximum topsoil water content at which repellency-induced runoff would occur.

The model was used to estimate the amount of repellency-induced runoff from the Waipawa catchments for the years 1999 - 2001 and 2004 – 2008, a total of eight years. Rainfall data from the site was not available for a period of several months in late 2002 and early 2003, so these years were not included, although a daily soil water balance was run for the last six months of 1998 and for 2002 and 2003, to provide soil water storage values to start the model on 01-01-1999 and 01-01-2004. For the eight years, an average of 52 mm yr^{-1} of repellency-induced runoff was simulated for the North site and 45 mm for the South site, being 7 % and 6 % of the average rainfall of 793 mm yr^{-1}. Given the dissimilar rainfalls and the assumptions regarding soil properties, these values are remarkably similar to the 3 % value simulated at Alfredton for the years 2010 and 2011 when the average rainfall was 1517 mm yr^{-1}. Due to the lower annual rainfall experienced by the Waipawa site, the model indicates that these catchment areas experienced more numerous occurrences of water repellency than that at Alfredton. Over the 8 years of data at Waipawa, the topsoil moisture content was at or below the trigger value for an average of 248 days of the year for the North catchment and 198 days of the year for the South catchment. This compares with 152 and 110 days per year over 2 years of study for the shallow slopes at Alfredton. For both sites, it would appear that there was ample opportunity for repellency-induced runoff to occur (much more so for the Waipawa site), and suggests that repellency-induced runoff is very dependent on the frequency of high intensity rainfall events.

In the introduction to this chapter, the quote from Doerr et al. (2000) noted enhanced total stream flow and enhanced stream flow responses to rainstorms onto water repellent soils. Having shown that it is likely that about 45 - 52 mm yr^{-1} of runoff occurred due to SWR, consideration is now given to the effects of this runoff on the total amount of stream flow, and its arrival in the stream causing sudden peaks in stream flow (i.e. on the days when repellency-induced runoff was simulated to have occurred).

As a first step, the effect of repellency on the total amount of stream flow is considered. All models have limitations, but one of their attractive features is that they allow the user to switch processes on and off in a manner that is not possible under field conditions. If the simplistic assumption is made that stream flow is the sum of the runoff and the excess water draining out of the bottom of the soil profile, then stream flow with and without repellency-induced runoff can be estimated using the model developed here. The simulated 8-year average stream flow values for the North facing catchment are 232 mm yr^{-1} with runoff and 198 mm yr^{-1} assuming no runoff – a difference of 34 mm yr^{-1}. The corresponding values for the South facing catchment are 350 mm yr^{-1} with runoff and 322 mm yr^{-1} assuming no runoff, a difference of just 28 mm yr^{-1}. These relatively small differences between runoff and the no-runoff scenarios are almost certainly overestimates, as it has been assumed that all of the repellency-induced runoff appears on the same day as stream flow. No account has been taken of runoff infiltration on lower and perhaps flatter areas in the catchment where the topsoil has stayed moist and non-repellent due to interflow and capillary rise. This would mean more stored water and evaporation from these areas, and so less excess water and stream flow than modelled. The discrepancy in the simulated runoff from the North and South catchments is due to the different estimates of the reference crop evaporation, reflecting the differences in solar radiation. The average E_0 value for the North facing catchment is 1039 mm yr^{-1}, while it is only 799 mm yr^{-1} for the South facing catchment.

The average measured stream flow over the eight years was 186 mm yr^{-1} (ranging from 111 to 321 mm yr^{-1} for the individual years) for the North catchment and 220 mm yr^{-1} (ranging from 145 to 378 mm yr^{-1}) for the South catchment. The simulated average North catchment stream flow (assuming no repellency-induced runoff) given above is very close to the observed value. For the South catchment however, the simulated value is 46 % higher than the measured value. One possible reason for this discrepancy is that not all the South catchment faced exactly South as assumed in the model, so that actual evaporation was probably higher than that simulated. Despite this, the measured stream flow from both catchments is less than that expected when runoff is ignored.

In summary, comparison of the measured stream flow with that simulated by the model under 'runoff' and 'no runoff' scenarios suggests that repellency-induced runoff has little effect on the total volume of water flowing out of the catchments.

Returning again to the quote from Doerr et al. (2000) in the introduction to this chapter, the remaining question to address is to what extent, if any, repellency-induced runoff events cause sudden peaks in stream flow. This can be investigated by looking at the detailed rainfall and stream flow data on the days that the model predicts the greatest repellency-induced runoff to occur. In the eight years for which data was available, there were 13 days at the North catchment and 12 days at the South catchment on which the model simulated more than 10 mm of repellency-induced runoff. Figures 7.4, 7.5, and 7.6 show the rainfall intensity and North catchment stream flow for each of the 13 days for the North catchment. Data for the North catchment was chosen as the topsoil there would usually be drier than that in the South catchment, and so repellency is more likely to develop.

An obvious feature of the data in Figures 7.4, 7.5 and 7.6 is that the peaks in rainfall intensity and stream flow occurred at about the same time on most days. This observation is consistent with repellency-induced runoff moving rapidly to the stream. There are other mechanisms however, which could also be responsible for such behaviour. One is rainfall landing on the stream itself – a 1 m wide stream running through a square 12.6 ha catchment has a length of 355 m, so that 0.28 % of the rain on the catchment falls directly on it. It is also possible that rainfall saturated the land adjacent to the stream, so that further rain did not infiltrate, but instead moved rapidly across the surface to the stream. It is likely that this saturation-excess mechanism was responsible for the stream flow peak on 19-12-2007 when there was 59.5 mm of rainfall. Rain started at 3:00 am and continued until midnight, with peaks in rainfall intensity and stream flow both occurring at about 11:30 am. From the evidence given in Chapter 5 regarding repellency and re-wetting, the topsoil would have been unlikely to have been repellent at this stage. Even by 5:00 am on that day, repellency seemed to have dissipated since there was no rapid stream flow response to intense rainfall at this time. The behaviour on that day is in contrast to that observed on 01-12-2008 when the most intense rain was in the first hour of the rainfall event and the stream flow peak occurred just after the peak rainfall intensity, suggesting a probable contribution by repellency-induced runoff.

The data associated with the day with the greatest modelled runoff (01-01-2000) may not be reliable, as in the notes attached to the stream flow data is the comment "Flow data affected by a very intense hail storm on 1-Jan-2000". Because of the unreliability of the data gathered on 01-01-2000, the stream flow values for the first day (01-01-2000) cannot be taken as repellency-induced flow.

For the remaining key events (Figures 7.4, 7.5, and 7.6), there are two distinctive patterns. The first pattern shows a sudden onset of high intensity rainfall followed by a very rapid response in stream flow (09-12-2000, 07-10-2001, 20-10-2001, 30-01-2006, 01-12-2008). It is this behaviour that is probably indicative of repellency-induced runoff. The second pattern is shown by those days exhibiting rainfall for some significant time before peak stream flow is observed (17-01-1999, 28-11-1999, 09-12-2001, 18-10-2004, 08-02-2006, 21-03-2006, 19-12-2007). In this case the discussion given in Chapter 5 suggests that repellency would have diminished significantly by the time of peak stream flow. In addition, saturation excess runoff from areas close to the stream would be more likely to have been influencing stream flow.

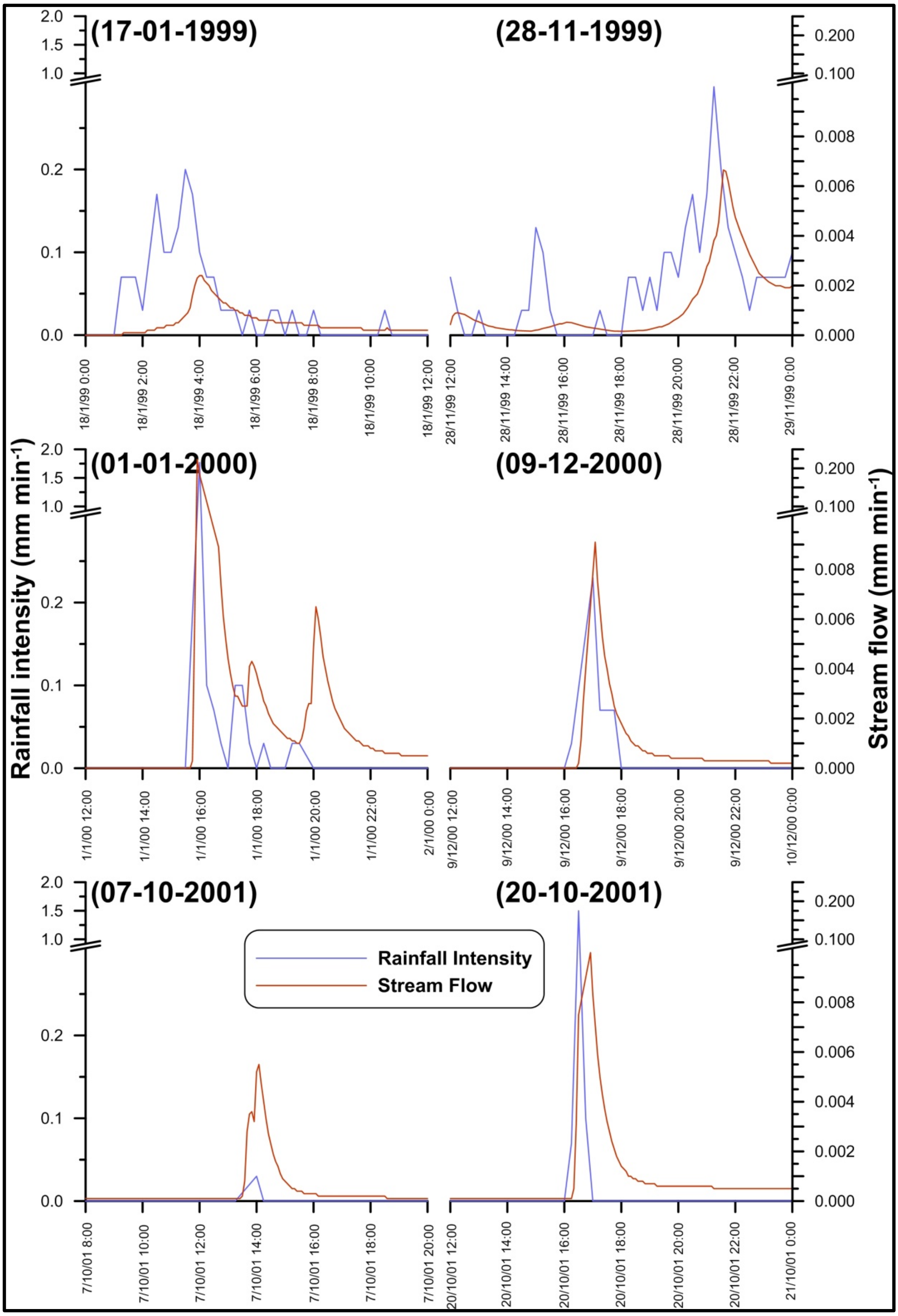

Figure 7.4 **Rainfall intensity (15 minute periods) and stream flow data (5 minute periods) for the North Waipawa catchment for key dates in 1999, 2000, and 2001 when the model simulated more than 10 mm day^{-1} of repellency-induced runoff.**

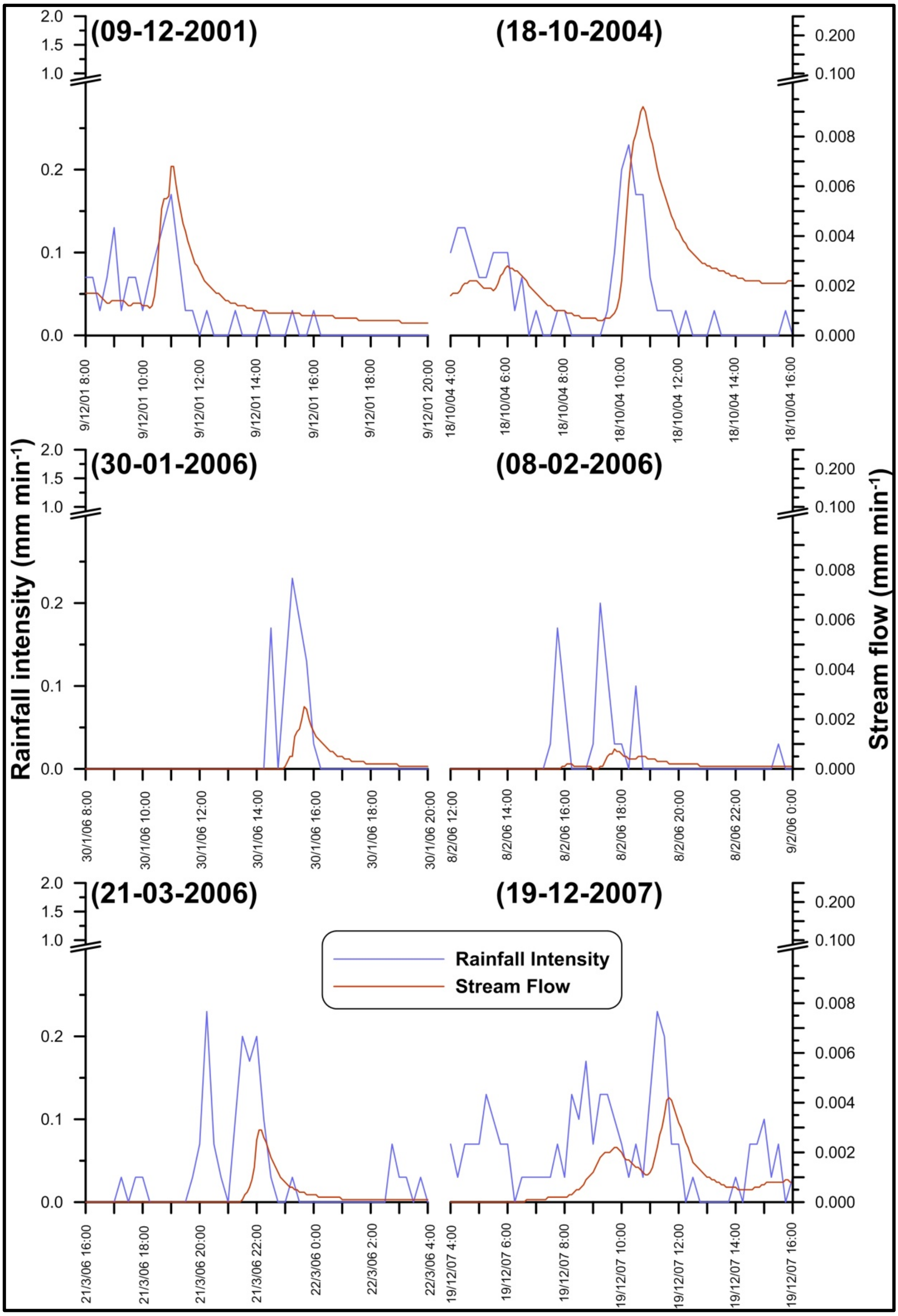

Figure 7.5 Rainfall intensity (15 minute periods) and stream flow data (5 minute periods) for the North Waipawa catchment for key dates in 2001, 2004, 2006, and 2007 when the model simulated more than 10 mm day^{-1} of repellency-induced runoff.

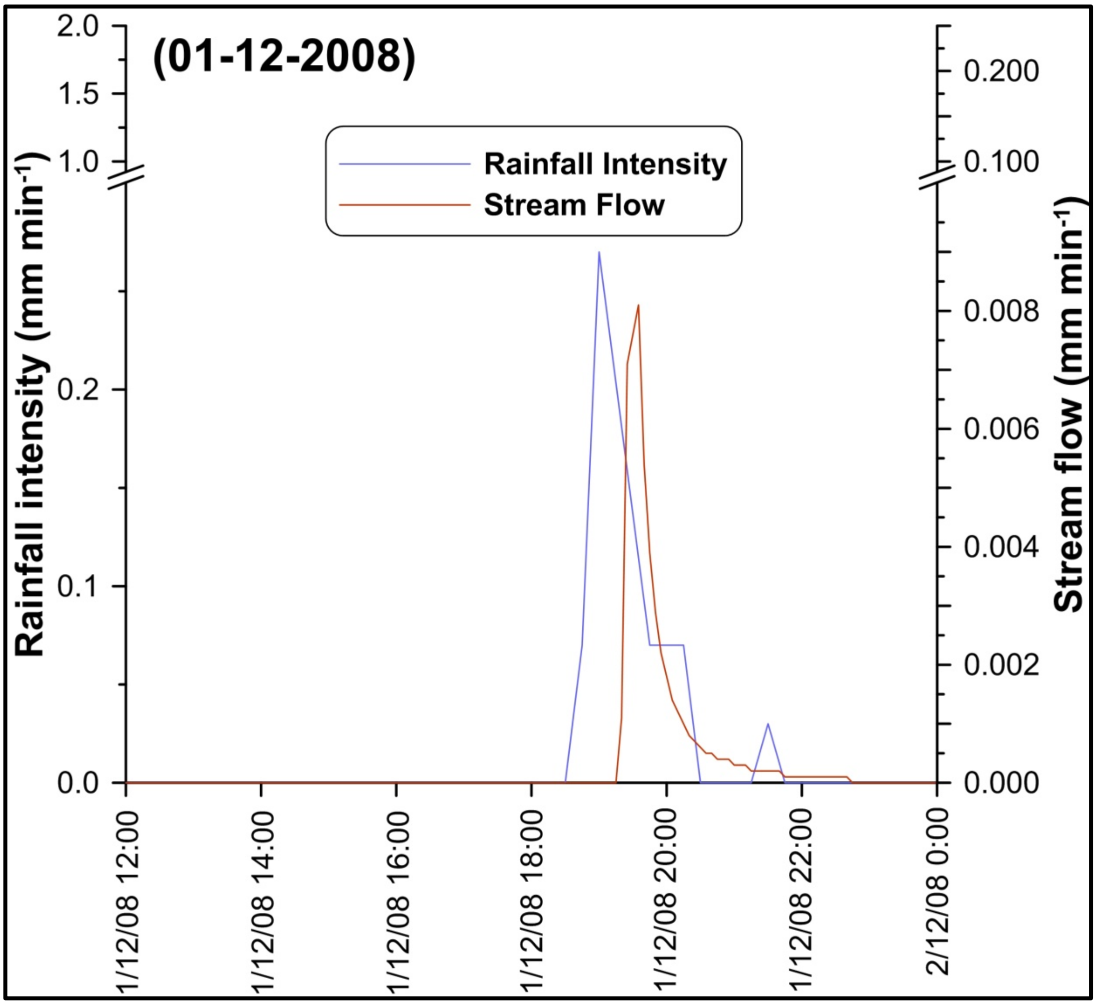

Figure 7.6 **Rainfall intensity (15 minute periods) and stream flow data (5 minute periods) for the North Waipawa catchment for the key date in 2008 when the model simulated more than 10 mm day^{-1} of repellency-induced runoff.**

Table 7.2 lists the key days in descending order in terms of the amount of modelled repellency-induced runoff. Rainfall, stream flow from the North and South catchments, the ratios of these two values expressed as a percentage, and the fraction (%) of rainfall the model simulates as being repellency-induced runoff are also given for these key days.

Table 7.2 **Modelled repellency-induced runoff, rainfall, and North and South catchment stream flow for the 13 key days where simulated daily repellency-induced runoff exceeded 10 mm. Flow values are spread over the whole catchment.**

Date	Modelled Runoff (mm)	Rain (mm)	North Flow (mm)	South Flow (mm)	Flow as % of Rain		Flow as % of modelled runoff	
					North	South	North	South
01-01-2000[1]	36.6	47.5	4.2	5.4	8.8	11.4	11.5	14.8
20-10-2001[2]	21.5	27.0	0.9	1.1	3.3	4.1	4.2	5.1
09-12-2001[3]	17.6	54.5	1.4	1.4	2.2	2.2	8.0	8.0
17-01-1999[3]	16.6	51.5	0.1	0.0	0.2	0.0	0.6	0.0
21-03-2006[3]	16.6	32.0	0.2	0.1	0.6	0.3	1.2	0.6
09-12-2000[2]	15.3	22.5	0.6	0.5	2.7	2.2	3.9	3.3
28-11-1999[3]	13.7	53.5	0.9	0.6	1.7	1.1	6.6	4.4
30-01-2006[2]	12.8	19.5	0.2	0.1	1.0	0.5	1.6	0.8
01-12-2008[2]	11.8	20.0	0.3	0.2	1.5	1.0	2.5	1.7
08-02-2006[3]	11.3	20.0	0.1	0.1	0.5	0.5	0.9	0.9
18-10-2004[3]	11.1	52.0	3.2	2.1	6.2	4.0	28.8	18.9
07-10-2001[2]	10.5	16.0	0.4	0.6	2.5	3.8	3.8	5.7
19-12-2007[3]	10.4	59.5	1.0	1.2	1.7	2.0	9.6	11.5
Mean of repellency days	*14.4*	*21.0*	*0.5*	*0.5*	*2.2*	*2.3*	*3.2*	*3.3*

[1] – Stream flow data suspect
[2] – Stream flow probably due to repellency-induced runoff
[3] – Stream flow due to saturation-induced runoff and/or repellency-induced runoff

For those days probably exhibiting repellency-induced runoff, the maximum daily stream flow was 1.1 mm, averaging just 5.1 % of the simulated repellency-induced runoff. Once again, this suggests that interflow and capillary rise tend to keep the topsoil lower down in the catchments moist and less repellent (but not saturated) on those days when repellency-induced runoff occurs higher up in the catchments. Given such a scenario, most of the repellency-induced runoff would have been able to infiltrate before it reached the stream.

The North catchment maximum rainfall intensity and peak stream flow for each of the 13 key days, and the ratios of these two numbers expressed as a percentage are shown in Table 7.3. If just the repellency-induced runoff key days are examined (for the reasons given in the preceding paragraph), then the peak (5 minute) stream flow was 0.0121 mm min^{-1} and all the peak flows were less than 3 % of the peak (15 minute) rainfall intensity. It can thus be concluded that enhanced streamflow responses to rainstorms (impact ‘e’ of Doerr et al. (2000)) were minor.

Table 7.3 Maximum 15 minute rainfall intensity and maximum 5 minute North catchment stream flow for the 13 key days where simulated daily repellency-induced runoff exceeded 10 mm. Maximum stream flow values are spread over the whole catchment.

Date	Maximum Rainfall Intensity (mm min^{-1})	Maximum Stream Flow (mm min^{-1})	Flow/Rainfall Intensity (%)
01-01-2000[1]	1.77	0.2237	12.6
20-10-2001[2]	1.50	0.0114	0.8
09-12-2001[3]	0.40	0.0068	1.7
17-01-1999[3]	0.27	0.0011	0.4
21-03-2006[3]	0.63	0.0029	0.5
09-12-2000[2]	0.57	0.0114	2.0
28-11-1999[3]	0.30	0.0067	2.2
30-01-2006[2]	0.40	0.0025	0.6
01-12-2008[2]	0.43	0.0121	2.8
08-02-2006[3]	0.37	0.0008	0.2
18-10-2004[3]	0.23	0.0092	4.0
07-10-2001[2]	0.53	0.0055	1.0
19-12-2007[3]	0.23	0.0042	1.8
Mean of repellency days	*0.69*	*0.0086*	*1.4*

[1] – Stream flow data suspect
[2] – Stream flow probably due to repellency-induced runoff
[3] – Stream flow due to saturation-induced runoff and/or repellency-induced runoff

If the whole eight years are considered (rather than just the days when repellency-induced runoff was expected) then the maximum daily stream flow was 26.6 mm (on 16-02-2004) and there were 19 days with more than 10 mm of measured stream flow from the North catchment. Given that the maximum flow on the key repellency days was 1.1 mm, it can again be concluded that repellency-induced runoff made an insignificant contribution to stream flow. Further, in terms of peak stream flow, the maximum value of 0.0121 mm min^{-1} associated with repellency-induced runoff is only a fifth of the maximum flow of 0.0643 mm min^{-1} observed on 18-07-2007 when repellency would not have been a factor. The rainfall intensity and stream flow for the period when that peak flow occurred (from 11 pm on 17-07-2007 to 1:30 am on 18-07-2007) are shown in Figure 7.7. Seventy-six mm of rain fell on 17-07-2007 and a further 32 mm fell on 18-07-2007. The high rainfall on 17-07-2007, coupled with the sharp peak in stream flow at the time of the most intense rainfall, indicate that saturation excess (and perhaps infiltration excess) runoff was involved, and that these mechanisms can produce peak flows much higher than those shown in Figures 7.4, 7.5, and 7.6 where repellency is likely to have been involved.

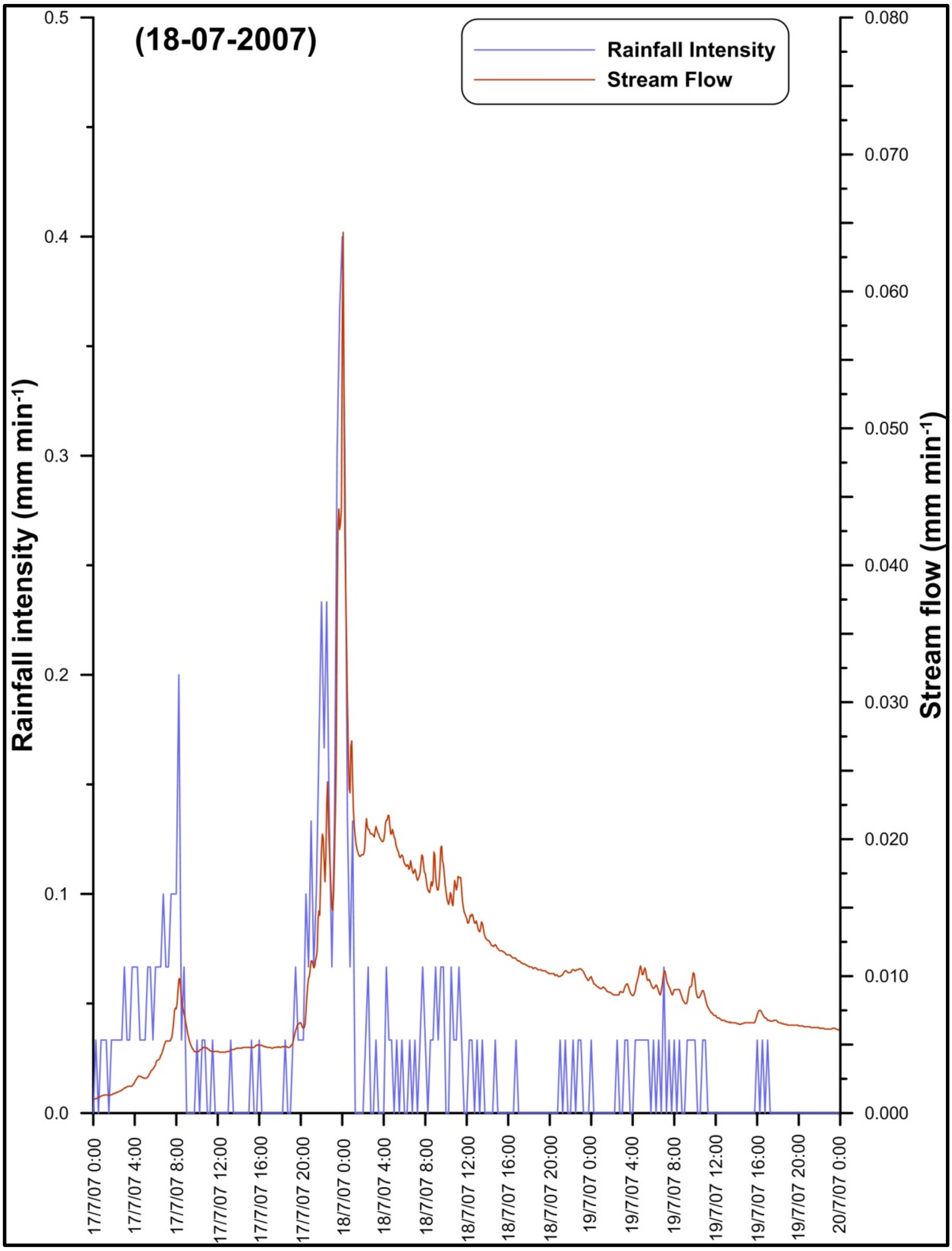

Figure 7.7 **Rainfall intensity (15 minute periods) and stream flow data (5 minute periods) for the North Waipawa catchment when the 8 year maximum daily stream flow was observed.**

7.6 Conclusions

By assuming that repellency-induced runoff only occurs when both the 0-50 mm depth water content is less than 0.28 $m^3\ m^{-3}$ and the rainfall intensity (for 1 mm increments) is greater than 0.1 mm min^{-1}, the refined model very approximately simulated the timing and amount of (plot-scale) repellency-induced runoff at Alfredton.

The refined model was used to simulate repellency-induced runoff in dry hill country (paired Waipawa catchments over eight years). On average, only 52 mm yr^{-1} of repellency-induced runoff was simulated to have been generated in the North catchment, and 45 mm yr^{-1} in the South catchment. This equated to 7 and 6 % of the rainfall, similar to the percentages measured at Alfredton with its much higher rainfall (Table 5.1).

Examination of the stream flow hydrographs on the days when the model simulated more than 10 mm of repellency-induced runoff showed a maximum of 1.1 mm of stream flow – this flow equated to approximately 5 % of the modelled runoff. In addition, for each of those days, the peak stream flow was less than 3 % of the peak rainfall intensity. These results imply that at least 95 % of the repellency-induced runoff infiltrates before it reaches the stream, presumably soaking into unsaturated soil nearer to the stream which remains moist enough to suppress water repellency. Overall, the highest daily stream flows (over 25 mm day^{-1}) and peak stream flow rates (about 0.06 mm min^{-1}) were recorded on the second of two consecutive very wet days; conditions under which water repellent runoff was highly improbable.

Thus the overall conclusion is that repellency-induced runoff plays a very minor (perhaps negligible) role in the Waipawa catchments in terms of influencing both the stream flow peaks and the total amount of stream flow generated.

CHAPTER 8

THE EFFECT OF REPELLENCY-INDUCED RUNOFF ON PASTURE PRODUCTION IN HILL COUNTRY

8.1 Introduction

Firstly, a point of clarification. Where appropriate, all the data presented here is based on horizontal surface area. Unfortunately, many other authors do not specify whether or not their surface area units are actual or projected horizontally. In such cases, the quoted values are assumed not to be projected. If the slope angle is given, the projected value is calculated and stated here as an italicised number (enclosed in square brackets).

Hill country pastures in New Zealand are highly variable, both in species composition and growth pattern. A primary reason for this variation is the influence of slope and aspect, both of which affect microclimate, stock grazing behaviour, soil pattern, soil water dynamics, and soil fertility (Gillingham, 1974; Lambert and Roberts, 1976; Rumball and Esler, 1968). Papers by Gillingham and Bell (1977), Ledgard et al. (1982a), Radcliffe and Lefever (1981), and Radcliffe et al. (1977), have documented the generally warmer and drier nature of northern aspects, and the greater pasture production on shallower rather than steeper slopes. Specifically, Gillingham (1974) reported that annual pasture production decreased by 109 kg DM ha^{-1} for each degree increase in slope in steep (around 30^{o} slopes) Raglan hill country (Gillingham (1974) do not provide data to allow the calculation of horizontally corrected values). Lambert et al. (1983) report a decrease of 225 [*198*] and 277 [*241*] kg DM ha^{-1} per degree increase in slope for low and high fertility sites, respectively, in hill country (Ballantrae research farm), 20 km north of Palmerston North. This effect was attributed to a range of factors including; lower soil organic matter contents resulting from topsoil erosion on steeper slopes, and lower soil moisture availability in soils on sloping land relative to soils on flat land.

Generally, while the influence of slope on soil moisture, solar radiation, pasture production and animal behaviour is well known (Gillingham et al., 1998; White, 1990), both Ledgard et al. (1982b) and Gillingham (1974) report little difference between aspects in terms of annual production rates. Gillingham et al. (1998) measured pasture production and species composition from 80 plots and measured 0-75 mm depth gravimetric soil moistures over 3 years on North and South facing steep and easy slopes near Waipawa. Half the plots received a high P application rate (to maintain an Olsen P of 28), while the other half received a low P application rate (to maintain an Olsen P of 9). Half of each of the P regimes received 30 kg N ha^{-1} as urea. They found that while soil moisture levels varied considerably during the year, they were always higher on southern slopes compared to northern slopes and that northern easy slopes were always wetter than northern steep slopes. Within each aspect, pasture production was higher at all times on easy slopes compared to steep slopes. In addition, pasture production on the North facing steep slope was greater than any of the South slopes during winter and the highest production levels were observed on North easy slopes. P responses occurred between spring and autumn on South slopes and North easy slopes, while N responses were highest in autumn and winter, particularly on the North steep slopes. On the basis of these observations, the authors surmised that the differences in production between slopes were related to the higher moisture levels on easy slopes. The exception occurred in winter when the drier steep northerly slopes out-performed southern aspect slopes, with the authors suggesting that warmer winter temperatures on the steep northern aspect were responsible for its higher winter production rate.

The effect of aspect on soil moisture content and, in turn, its effect on pasture composition has been observed by Gillingham et al. (2003). They argue that higher evapotranspiration rates and lower soil moisture levels on northern slopes are more likely to discourage legume persistence, and hence the availability of N for productivity. The potential for lower productivity pasture on steeper northern slopes, and the problem posed by soil water deficits on steeper slopes, is further exacerbated by grazing animals transferring nutrients away from steeper terrain to easier slopes (Gillingham et al., 1980), so that depletion of nitrogen, and to a lesser extent phosphorus and sulphur, is likely to occur on the northern steeper slopes (as opposed to northern shallow slopes) resulting in lower pasture production.

Pasture production on steep slopes comprised of Waingaro steepland yellow-brown earth soils and Dunmore yellow-brown loam soils has been claimed by Bircham and Gillingham

(1986) to be highly dependent on the re-wetting frequency of the soils, and they note that that this will vary markedly from season to season and year to year. Their argument was strongly dependent upon the results from their soil water balance model which assumed a pasture rooting depth of only 150 mm. Included in their model was a soil rewetting function for the top layer in their 4-layer (each 37.5 mm depth) model, which ensured that duration (3.3 days) rather than the intensity of rainfall controlled the rate of soil rewetting. Although the term “water repellency” was not specifically mentioned, the inclusion of the rewetting function was a response to the authors’ observation that “... on a dry, steepland soil, often only the surface few millimetres of the profile will be re-wetted during a rainfall event, almost regardless of the intensity of rainfall”.

In contrast, Bretherton et al. (2010) showed that for Atua silt loam soil at the Alfredton site, the effective rooting depth was at least 350 mm. They went on to produce a refinement of the Bircham and Gillingham (1986) model, simplifying it to two layers, with the infiltration rate through the top layer (50 mm depth) being restricted to 5 mm day^{-1} when soil moisture in that layer was below a threshold value of 0.25 m^3 m^{-3}. The effect of water repellency on infiltration rate was thus accounted for in this manner, with the model indicating that re-wetting frequency was not as critical for pasture production as suggested by Bircham and Gillingham (1986). The Bretherton et al. (2010) paper can be found in Chapter 4.

Very few studies have directly examined the effect of soil water repellency on pasture production in New Zealand hill country. Of note is a study by Müller et al. (2010) who examined 3 control sites and 3 hydrophobic sites at Maraetotara in the Hawke’s Bay. The hydrophobic sites had been previously associated with ‘dry patch syndrome’ (Deurer et al., 2007), and the work by Müller et al. (2010) suggested an estimated loss of pasture production of 30-40 % as a result of soil water repellency. Other influencing factors such as pasture species, fertiliser history, and sward density do not appear to have been considered, and a lack of supporting statistical analysis suggests that these figures should be treated with some circumspection.

Another hill country pasture study where soil water repellency may have influenced observed production data is that of Moir et al. (2000a). Based on data from trial sites at Whareama, Gladstone, and Mauriceville in the Wairarapa hill country, the authors showed that there was a correlation between pasture growth per mm of actual evapotranspiration and the available P status of the soil. Their proposed model calculated the reference crop evapotranspiration using the Priestly and Taylor method (Priestly and Taylor, 1972) and then used a simple soil water balance to estimate the actual evapotranspiration. They assumed that pasture production was proportional to the estimated actual evapotranspiration and that the proportionality constant was related to soil fertility (as reflected by the Olsen P value). Although this model was generally able to simulate pasture yield, the notable exception was the over-prediction of pasture production immediately after rainfall to soils that had been dry for prolonged periods. The authors speculated that the soil surface may have become water repellent during these periods and sporadic heavy rainfall then might have been mostly lost as runoff. Other factors such as a lag time between rainfall and the recovery of pasture were also discussed.

There have been relatively few attempts to model pasture production in New Zealand hill country. Those models that have been developed might be categorised as; empirical models based on statistical analyses of regression functions fitted to research data (Lambert et al., 1983; Scott, 2002); decision-tree models based on the collation of numerous pasture production data sets (Murray et al., 2007; Zhang et al., 2006); and more mechanistic models based on soil fertility and meteorology as they affect soil moisture and evapotranspiration (Moir et al., 2000a; Moir et al., 2000b).

The objective of this chapter is to assess the impacts of repellency-induced runoff on pasture production at the Alfredton site. Pasture production data measured at the Alfredton site is presented. Differences in production existing between steep and shallow slopes and between North and South aspects are examined. Lastly the daily pasture production model proposed by Moir et al. (2000a) is used to approximately estimate the effect of repellency-induced runoff on pasture production on northern slopes.

8.2 Methodology

Given the nature of the repellency phenomena, the terrain and isolation of the research site made it impractical to measure the effect of repellency-induced runoff on pasture production in a conventional manner i.e. monitoring pasture growth on treatments with repellency-induced runoff and without repellency-induced runoff. In order to identify the impact of repellency on pasture growth rates, production was monitored at the Alfredton site as described below. The effect of repellency-induced rainfall on pasture growth would manifest itself as discrepancies between rainfall, soil moisture content and growth rates.

Stock exclusion cages were used to measure pasture growth at all the runoff sites at Alfredton – C1 North Shallow (C1NSh), C1 North Steep (C1NSt), C1 South Shallow (C1SSh), C1 South Steep (C1SSt), C1 East Steep (C1ESt), and C2 East Steep (C2ESt). These cages were placed at the site on 15 May 2006. The dimensions of the cages were 0.5 m by 1.0 m, giving them the same aspect ratio as the runoff plots (1.0 m by 2.0 m). The cages were orientated so that the longer length was aligned along the slope. There were duplicate cages at each site, giving a total of 12 cages. For those cages located on a 30^{o} slope, the horizontal surface area for a 1.0 m by 0.5 m cage is 0.435 m^2; and for a 20^{o} slope it is 0.470 m^2 - scaling of measurements was applied accordingly.

The mesh size of the wire on the cages was approximately 3-4 cm, thus allowing for the easy passage of top-dressed fertiliser and rainfall while at the same time excluding grazing stock. The experimental area was grazed mostly by sheep, with occasional grazing by cattle.

Initial statistical analysis of dry matter production from the 12 cages failed to distinguish any significant differences in pasture production between slope and aspect at the 95 % confidence level. In an attempt to improve the quality of the data, eight new sites were established on 4 December 2009. These sites were given the label of C2 North Shallow (C2NSh), C2 North Steep (C2NSt), C3 North Shallow (C3NSh), C3 North Steep (C3NSt), C4 South Shallow (C4SSh), C4 South Steep (C4SSt), C5 South Shallow (C5SSh), and C5 South Steep (C5SSt). All sites were located within the same main catchment area (see Plate 8.1) and again, each of the sites had duplicate cages, thus giving a total of 28 exclusion cages. The replication pattern after 4 December 2009 is summarised in Table 8.1 below.

Table 8.1 Summary of replication pattern for stock exclusion cages at the research site.

Aspect/Slope	Number of sites	Number of cages
North/Shallow	3	6
North/Steep	3	6
South/Shallow	3	6
South/Steep	3	6
East/Steep	2	4

Harvesting of the cages was carried out whenever appreciable growth had occurred, generally when pasture height reached 15 cm. Initially, hand shears were used to clip the grass down to 1 cm in height, but later, electric shears were used to reduce the time taken to harvest the pasture in the cages. Once harvested, the cages were re-positioned randomly, and the pasture was clipped down to 1 cm. Harvested pasture was transported back to Massey University in paper bags and then immediately placed in a drying oven at 60 ^{o}C for a week before being weighed.

The main catchment was aerially top-dressed on four occasions (Table 8.2).

Table 8.2 Summary of aerial topdressing events at the research site.

Date	Event
8 February 2007	Lime applied at 1000 kg ha^{-1}
24 January 2008	Sulphur super applied at 250 kg ha^{-1}
23 May 2011	Sulphur super applied at 200 kg ha^{-1}
31 January 2012	Di-calcic phosphate applied at 250 kg ha^{-1}

Statistical analysis of the data was performed using the SAS statistical software package employing a general linear model procedure, and was applied to the data when replication of aspects and slopes was increased on 04-02-2010. Prior to this date, there was only a single data set each for North and South aspect cumulative production, insufficient for valid statistical processing. Values provided are the probability that the null hypothesis is correct i.e. small values indicate that the two populations being tested (North versus South, steep versus shallow) are unlikely to be the same. For values less than 0.05, we can be 95 % confident that the two categories being measured are not the same. This statistical analysis was applied to each individual harvest and to the cumulative totals after each harvest. In each case, all steep and shallow samples were grouped together and tested, and then all North and South samples were grouped together and tested.

A pasture species composition study at a number of the research sites was carried out by Sanches (2009), a summary of which is given in Chapter 3. The range of pasture plants was diverse with grass species being dominated by browntop (*Agrostis capillaris*).

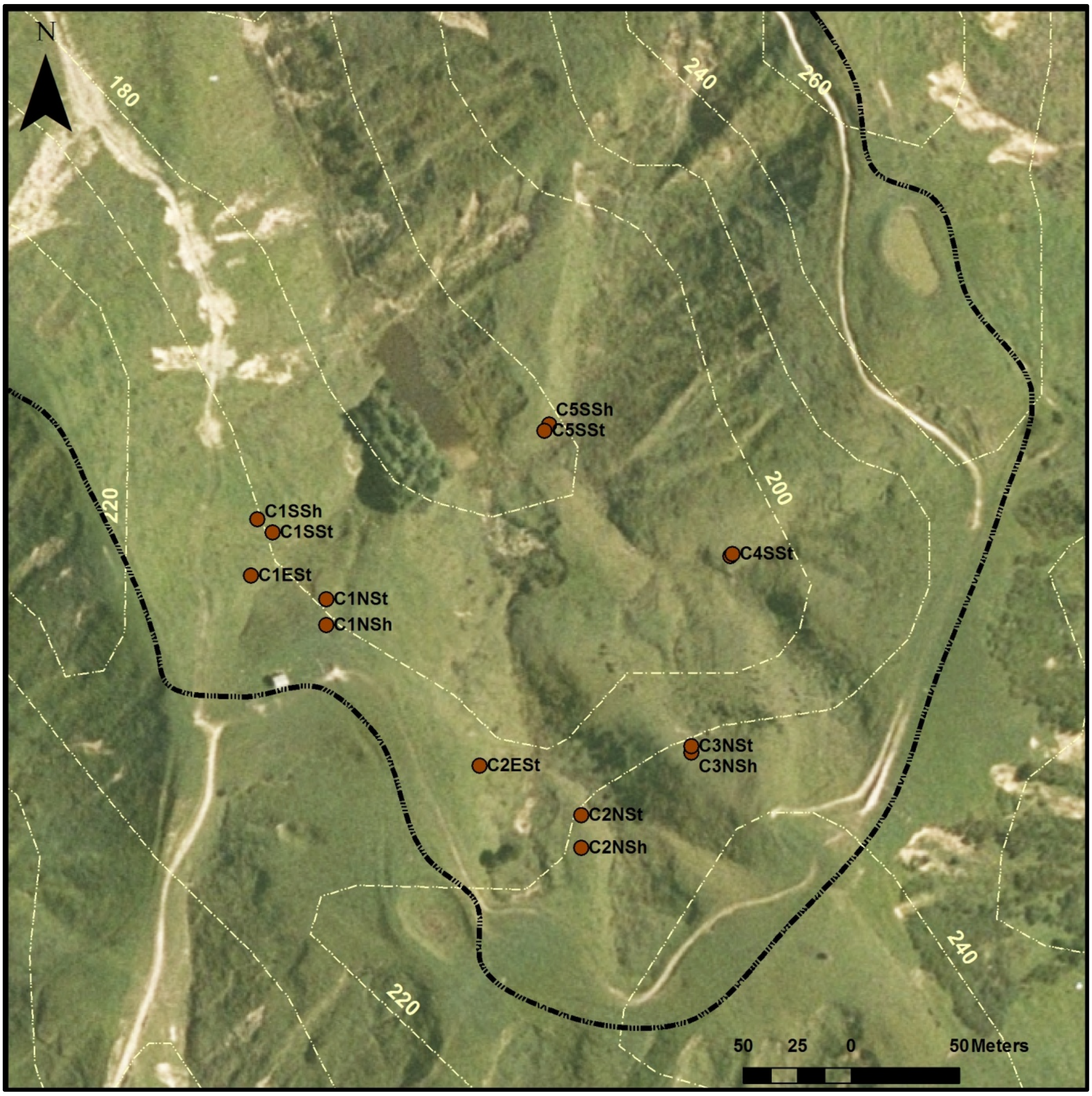

Plate 8.1 Location of the stock exclusion cages at the research area.

The Moir et al. (2000a) model (utilised later in this chapter) approaches pasture production from a semi-mechanistic viewpoint and is driven by a calculation of the daily soil water balance. Daily pasture production is predicted from the calculation of actual daily evapotranspiration and involves a growth factor *k* - a proportionality constant relating pasture production to actual evapotranspiration. Moir et al. (2000a) found a logarithmic relationship between *k* and soil Olsen P. The version of the Moir et al. (2000a) model used here varies slightly from the original in that the reference crop evaporation estimates were obtained using the Penman-Monteith equation rather than the Priestley-Taylor equation.

Different assumptions were also made about the soil's available water storage capacity. Details of the water balance calculations are given in Chapter 7.

8.3 Results and discussion

8.3.1 Pasture production - data

Initial harvesting of pasture samples was limited to a small number of cages (one site each for the North and South aspects and two for the East aspects). Exploratory statistical analysis indicated that aspect replication needed to be increased in order to improve the likelihood of being able to separate slope and aspect influences at the 95 % confidence level (taken here as a minimum level for discrimination between slopes and aspects). Accordingly, aspect replication was increased to 3 North and 3 South aspects on 04-12-2009.

The harvest values shown in Table 8.3 (with the cumulative values plotted in Figure 8.1) are provided as a reference, with Table 8.4 listing the probabilities that the null hypothesis stands for each individual harvest and for the cumulative harvests. In this discussion the null hypothesis is the assumption that there are no production differences between the data sets being examined.

Table 8.3 Individual dry matter yields for all harvests after 04-12-2009 at each of the sites. Values given are the means of the paired cages at each site.

Harvest Date	Site	Yield (kg ha^{-1})	Site	Yield (kg ha^{-1})	Site	Yield (kg ha^{-1})
04-02-2010	**C1SSh**	5591	**C2ESt**	4112	**C4SSh**	3644
	C1SSt	3073	**C2NSh**	4200	**C4SSt**	3172
	C1ESt	3058	**C2NSt**	1833	**C5SSh**	2845
	C1NSh	4694	**C3NSh**	5522	**C5SSt**	2714

	C1NSt	3467	**C3NSt**	5592		
12-08-2010	**C1SSh**	3030	**C2ESt**	2976	**C4SSh**	3871
	C1SSt	2219	**C2NSh**	1553	**C4SSt**	2510
	C1ESt	2571	**C2NSt**	1500	**C5SSh**	3320
	C1NSh	2383	**C3NSh**	4802	**C5SSt**	2720
	C1NSt	2450	**C3NSt**	2469		
16-11-2010	**C1SSh**	2662	**C2ESt**	2520	**C4SSh**	2836
	C1SSt	2181	**C2NSh**	4262	**C4SSt**	1760
	C1ESt	1597	**C2NSt**	3033	**C5SSh**	2198
	C1NSh	2893	**C3NSh**	4707	**C5SSt**	2057
	C1NSt	3158	**C3NSt**	4656		
15-12-2010	**C1SSh**	1427	**C2ESt**	1442	**C4SSh**	1876
	C1SSt	983	**C2NSh**	1114	**C4SSt**	1341
	C1ESt	733	**C2NSt**	980	**C5SSh**	1350
	C1NSh	1313	**C3NSh**	2262	**C5SSt**	974
	C1NSt	877	**C3NSt**	1460		
19-05-2011	**C1SSh**	4386	**C2ESt**	2452	**C4SSh**	4534
	C1SSt	3239	**C2NSh**	1934	**C4SSt**	3474
	C1ESt	3203	**C2NSt**	2047	**C5SSh**	2359
	C1NSh	3314	**C3NSh**	3252	**C5SSt**	3222
	C1NSt	2455	**C3NSt**	2409		

27-09-2011	**C1SSh**	2471	**C2ESt**	1495	**C4SSh**	2211
	C1SSt	601	**C2NSh**	2089	**C4SSt**	1409
	C1ESt	1609	**C2NSt**	1642	**C5SSh**	2734
	C1NSh	3827	**C3NSh**	2774	**C5SSt**	1208
	C1NSt	1477	**C3NSt**	1367		
08-12-2011	**C1SSh**	4713	**C2ESt**	2912	**C4SSh**	3484
	C1SSt	3209	**C2NSh**	4364	**C4SSt**	3006
	C1ESt	3597	**C2NSt**	2667	**C5SSh**	3911
	C1NSh	4182	**C3NSh**	4918	**C5SSt**	2379
	C1NSt	3727	**C3NSt**	3994		
12-01-2012	**C1SSh**	4560	**C2ESt**	2689	**C4SSh**	2730
	C1SSt	3663	**C2NSh**	3022	**C4SSt**	2742
	C1ESt	4081	**C2NSt**	3432	**C5SSh**	3343
	C1NSh	4226	**C3NSh**	4624	**C5SSt**	2075
	C1NSt	4753	**C3NSt**	3630		

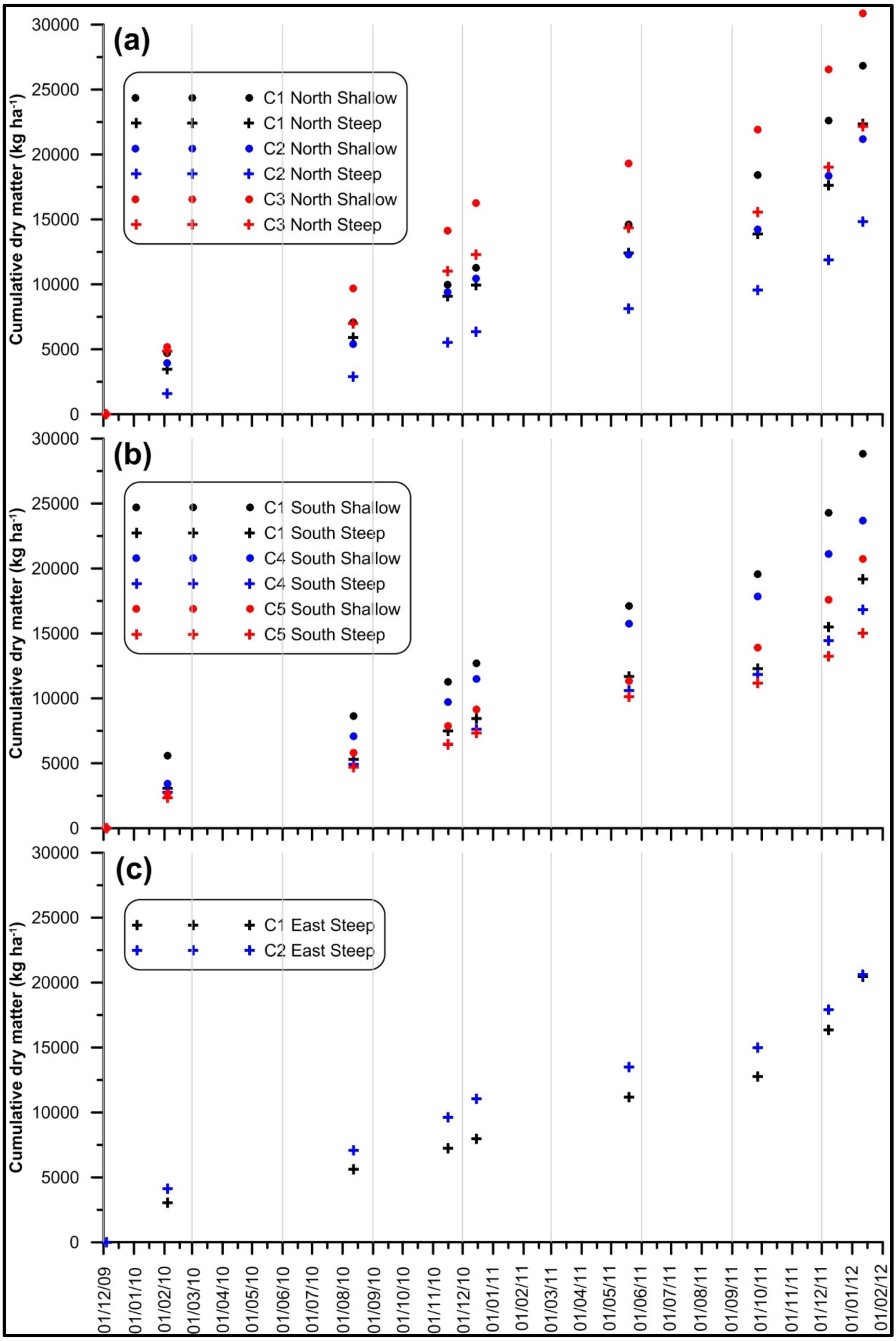

Figure 8.1 **Cumulative pasture production for North sites (a), South sites (b), and East sites (c). Vertical lines represent seasonal boundaries.**

8.3.2 Cumulative pasture production – effect of slope

Over the period 04-02-2010 to 27-09-2011 on the replicated aspects, the cumulative harvests for the two slopes over all aspects had diverged sufficiently to become significantly different (Table 8.4) with shallow slopes outperforming steep slopes. Over the duration of the trial (25 months) the annual average dry matter production on all North and South steep slopes was 9.8 t ha^{-1} compared with 12.5 t ha^{-1} over all North and South shallow slopes, a difference of 2.7 t ha^{-1}. Since the change in angle between the steep and shallow slopes at Alfredton is 10^{o}, the difference of 270 kg ha^{-1} per degree in production correlates reasonably well with that observed by Lambert et al. (1983) who found a pasture growth reduction of 277 [*241*] kg ha^{-1} per degree of increasing slope for high fertility sites at Ballantrae. While not included in the statistical analysis, the cumulative data for the C1East and C2East sites (steep slopes only) are shown for comparison, and indicate that annual pasture production on these slopes was quite similar to that of their northern and southern counterparts.

Table 8.4 **Summary of statistical processing of pasture data between steep and shallow slopes and for North and South aspects only. Values listed are the probability that there is no difference within the slope and aspect categories.**

Harvest Date	Individual		Cumulative	
	Slopes (trend)	**Aspects (trend)**	**Slopes (trend)**	**Aspects (trend)**
04-02-2010	0.164	0.375	0.164	0.375
12-08-2010	0.147	0.364	0.095	0.876
16-11-2010	0.327	0.004* (N > S)	0.112	0.234
15-12-2010	0.070	0.940	0.096	0.294
19-05-2011	0.344	0.029* (S > N)	0.101	0.755
27-09-2011	0.001* (Sh > St)	0.091	0.028* (Sh > St)	0.530
08-12-2011	0.013* (Sh > St)	0.213	0.019* (Sh > St)	0.441
12-01-2012	0.598	0.215	0.028* (Sh > St)	0.345

* >= 95 % confident that yield for aspect categories or slope categories are not the same.

8.3.3 Cumulative pasture production – effect of aspect

No significant differences in cumulative annual production were found between North and South aspects over all slopes, supporting the findings of previous studies by Gillingham (1974) and Ledgard et al. (1982b).

8.3.4 Cumulative pasture production – general

The above observations regarding cumulative pasture production confirm the reported findings of other researchers (Gillingham, 1974; Ledgard et al., 1982b; Zhang et al., 2006) where shallower slopes were associated with higher annual pasture production, apparently largely due to the greater availability of moisture on shallower slopes (see the 0-300 mm depth volumetric water content data in Figures 5.2 and 5.3 for the North aspect sites, Chapter 5), and the greater return of animal excreta (and so higher soil fertility indices (Gillingham and During, 1973; Radcliffe, 1968)). Generally speaking, differences in annual pasture production between North and South aspects are found to be insignificant, and only Zhang et al. (2006) included aspect differences (influenced by winter solar radiation) when predicting winter production. In their decision tree approach, northern slopes were predicted to almost double southern slope production whenever winter mean daily global solar radiation exceeded 3.5 MJ m^{-2} day^{-1}. The predictive ability of the Zhang et al. (2006) winter decision tree model, however, was only 57 %.

8.3.5 Individual harvests – effect of slope

Subsequent to 04-12-2009, statistical comparison between individual harvests (Table 8.4) showed significant differences in pasture production between steep and shallow slopes for two harvests, and significant, but contrasting, differences between North and South aspects for a further two harvests. Significant differences between production on North and South slopes covered the periods 19-05-2011 to 27-09-2011 and 27-09-2011 to 08-12-2011 with both periods showing enhanced production on the shallow slopes. Both these time periods coincide with the growth flush commonly experienced by pastures during spring and early summer, with the more fertile and more moist shallow slopes (Figures 5.3 and 5.5, Chapter

5) responding more than the steeper slopes to increasing temperatures and solar radiation input at this time.

8.3.6 Individual harvests – effect of aspect

There are two individual harvests showing significant aspect differences. The first occurred during the period 12-08-2010 to 16-11-2010 when North production was greater than South production. This period covered early to mid spring with North production being greatest in the C3 sub-catchment. Both the volumetric water content data provided in Chapter 5 and the soil water balance model described in Chapter 7 indicate that plant-available water was not limiting during this period, so the greater pasture production on northern slopes can most likely be attributed to the higher solar radiation inputs (and therefore higher temperatures) to those aspects at this time. The second individual harvest which showed a significant difference in DM production between aspects occurred during the period 15-12-2010 to 19-05-2011 when South production was greater than North production. This harvest period covered early summer through to late autumn and reference to 0-50 mm depth volumetric water content data given in Chapter 5 suggests that the C1South aspect was wetter than the C1North. Furthermore, 0-300 mm depth modelled data (See Chapter 7) indicates that plant-available water on the northern slopes was often limiting over this period. The difference in DM production between the two aspects therefore was most likely due to the higher availability of soil water on the southern aspects and therefore higher actual evapotranspiration rates.

8.3.7 Daily pasture growth rates

Figure 8.2 shows the daily dry matter (DM) production for each harvest period for all the sites over the entire trial period. Weighed samples for each harvest were expressed on a kg per projected flat hectare basis and then divided by the number of days since the last harvest. The break in the plots is due to the loss of harvest data on 04-12-2009.

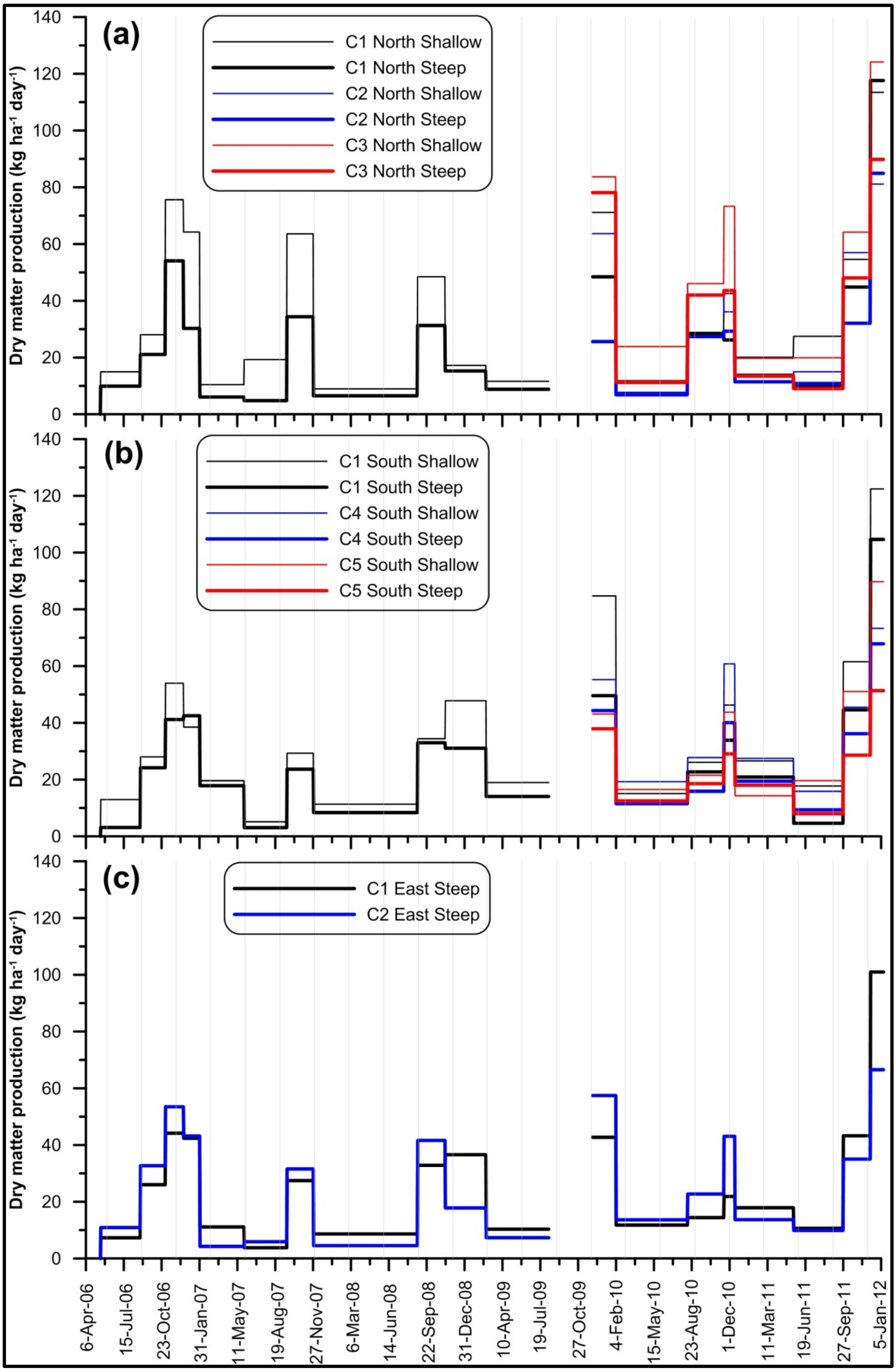

Figure 8.2 **Daily pasture production for North sites (a), South sites (b), and East sites (c). Vertical lines represent seasonal boundaries.**

Generally for all aspects and slopes, peaks in pasture production rates (Figure 8.2) were associated with the spring to mid-summer seasons when increasing soil temperatures and readily available soil moisture promoted the rapid growth of pasture. Conversely, troughs in pasture production rates were associated with the early autumn to winter seasons when solar radiation and soil temperatures were low or when large soil moisture deficits were prevalent. The exception to this general pattern of behaviour occurred for all aspects and slopes in December 2011 when very high growth rates were observed (up to 120 kg DM ha^{-1} day^{-1}). Unusually high rainfall during this month (137 mm) resulted in higher than normal soil moisture contents (between 0.4 and 0.5 m^3 m^{-3} down to 300 mm depth). The summer temperature and solar radiation regimes normally associated with the December month coupled with the high availability of plant available water and good soil fertility (Olsen P values averaging 26.5 µg P g^{-1} for shallow slopes and 24.5 µg P g^{-1} for steep slopes) resulted in very high pasture production rates.

For the North aspects, annual maximum pasture growth rates for the shallow slopes were higher than the steep slopes, peaking at 50 to 80 kg DM ha^{-1} day^{-1} during the months of September through to November. Steep slope growth rates over the same months were lower, ranging from 30 to 50 kg DM ha^{-1} day^{-1}. Steep and shallow slopes were more closely matched during autumn and winter with growth rates ranging between 10 and 20 kg DM ha^{-1} day^{-1}.

For the South aspects, spring and summer growth rates for the shallow slopes (30 to 80 kg DM ha^{-1} day^{-1}) were slightly higher than those for the steep slopes (20 to 50 kg DM ha^{-1} day^{-1}); the differences between the slope categories being somewhat similar to the differences between northern slopes. Steep and shallow autumn and winter growth rates were very similar to each other and to those for the northern aspects.

As a comparison, Ledgard et al. (1982b) measured production rates of 30 [*31.4*] kg DM ha^{-1} day^{-1} on easy (10-24^o) and 15 [*17.3*] kg DM ha^{-1} day^{-1} on steep (30^o) north-facing slopes (Dunmore silt loam soils near Whatawhata) during spring with Olsen P values of 6.4-10.7 µg P g^{-1}. Gillingham (1974) measured up to 40 [*46.2*] kg DM ha^{-1} day^{-1} during spring and 10 [*11.6*] kg DM ha^{-1} day^{-1} during the winter seasons on northern Waingaro steepland soil of 30^o slopes (described as having moderate soil phosphate levels). Both authors report that there was little difference between aspects in terms of production rates. The higher daily spring production rates in the present study may be due to the much high fertility of the soils at the Alfredton research site. Olsen P measurements (see Chapter 3) for the 0 - 75 mm depth soil samples taken in November 2006 and June 2012 gave mean values of 29 and 30 µg P g^{-1} for the North shallow and steep slopes, and 26 and 21 µg P g^{-1} for the South shallow and steep slopes, respectively.

In an attempt to isolate the principal controlling factors on hill country pasture production, Ledgard et al. (1982b) found that of factors such as; aspect, ryegrass and browntop composition, soil N & C levels, and soil moisture status; slope was most closely correlated with pasture growth rate. Partial correlation analysis in their study indicated that for a 20^o slope, the growth rate for winter and spring was 5 [*5.3*] and 30 [*31.9*] kg DM ha^{-1} day^{-1} respectively, while for a 30^o slope these decreased to 2 [*2.3*] and 15 [*17.3*] kg DM ha^{-1} day^{-1}. The higher growth rates observed on the different slope categories in this study compared to those quoted in the studies referred to above are again likely largely due to the much higher fertility status of the soils at this site.

8.3.8 Soil water repellency and pasture production

The above discussion provides context to consider the effects of repellency-induced runoff on pasture growth and demonstrates that the pasture growth data was about as reliable as might be expected given the challenges of measuring this within the complexity of a hill country environment. Inspection of this data in tandem with rainfall, repellency-induced runoff and soil moisture contents revealed that, although the soil was very dry on occasions and while this low soil moisture content limited pasture growth, there was no evidence that pasture growth was further throttled after rain due to the loss of water by repellency-induced runoff. Indeed, given the relatively small quantities of repellency-induced runoff reported in Chapter 5, it is not surprising that repellency did not have a marked effect on pasture growth at the site.

The effect of repellency-induced runoff on pasture growth can be further explored using the model described in Chapter 7 and the model of Moir et al. (2000a). The reason that repellency-induced runoff had a small effect on pasture growth is that repellency-induced runoff had a negligible effect on actual evapotranspiration. The water balance model described in Chapter 7 predicts that repellency decreased actual evapotranspiration by just 25 mm for North steep slopes and 22 mm for North shallow slopes. Since these values represent less than 2% of cumulative actual evapotranspiration over the approximately 2 year period, it is likely that the resultant decreases in pasture production as a result of repellency-induced runoff will be correspondingly small.

To further demonstrate that repellency-induced losses in pasture production at the Alfredton site were probably small, detailed meteorological data from the research site was used to calculate the daily soil water balance needed to drive the pasture production model developed by Moir et al. (2000a). The C1North site was selected because of the well-described repellency-induced runoff events observed there. Figure 8.3 shows simulated pasture production at that site for the years 2010 and 2011. The effect of repellency-induced runoff on pasture production was simulated by 'switching' repellency on or off in the model by setting the threshold 0-50 mm volumetric soil water content (Chapter 7) to either 0.28 or 0 m^3 m^{-3}, respectively.

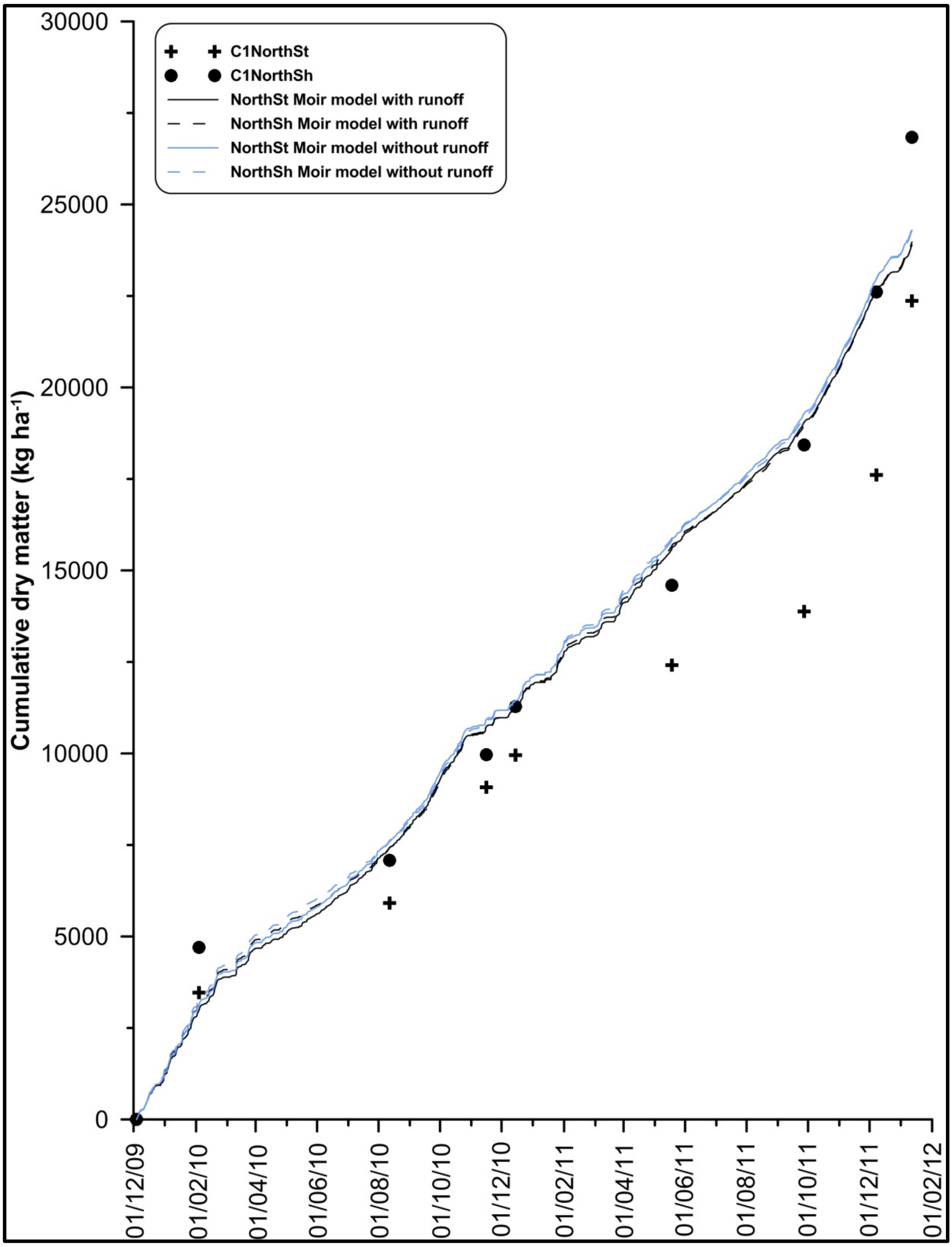

Figure 8.3 Modelled versus actual pasture production for the years 2010 and 2011 for the C1North aspect. Details are given in the text.

The Moir et al. (2000a) model suggests that there is very little difference in cumulative pasture production over the two years between ‘runoff’ and ‘no runoff’ scenarios for both steep and shallow slopes. The model simulates approximately a 1.5 % loss in production on both slopes due to repellency-induced runoff, equivalent to an annual production loss of less than 1 %. Table 8.5 summarises the output shown in Figure 8.3. In the model, the loss in production is solely a result of reduced soil water availability for evapotranspiration due to losses via repellency-induced runoff. This modelled loss in production contrasts with the work of Müller et al. (2010) who suggested that repellency-induced runoff may result in a 30-40 % loss in production but, as pointed out in the Introduction to this chapter, the relevance of these values to the present study is not clear.

Table 8.5 Actual and modelled pasture production data for the C1North site at Alfredton over the period 04-12-2009 to 12-01-2012.

Site/slope	Repellency-induced runoff?	Measured production (kg ha^{-1})	Modelled production (kg ha^{-1})	Modelled evapotranspiration (mm)
C1North 20^{o}	Yes	26832	23971	1447
	No	-	24343	1469
C1North 30^{o}	Yes	22364	23899	1525
	No	-	24296	1550

The Moir et al. (2000a) model does not predict large differences in pasture growth between slopes. This failure reveals some of the short-comings of the Moir et al. (2000a) model. The lines shown in Figure 8.3 were generated using k values (the proportionality constant relating pasture production to actual evapotranspiration) calculated using the relationship given by Moir et al. (2000a). The k values used were 15.7 and 16.6 kg ha^{-1} mm^{-1} for the North steep and shallow plots respectively. This relationship is very simple in that k is a function of only the Olsen P status. In other words, the relationship of k to Olsen P is specific to their data set and neglects many of the other factors that play a role in determining the relationship between pasture production and evapotranspiration which, in turn, may be unique to any site.

Although this chapter primarily focuses on the annual effect of soil water repellency on pasture production at Alfredton, it is recognised that uneven distribution of rainfall during the year in many North Island East Coast areas generally produces surplus pasture in late winter and spring, and a shortfall during the summer and autumn seasons when rainfall is low. The 'patchiness' of pasture growth due to localised infiltration and SWR is often evident during these periods (Deurer et al., 2011); quantifying this 'patchiness' however, would have required a stratified sampling approach.

8.4 Conclusions

No major effects of repellency-induced runoff were observed in the measurements of pasture growth at the Alfredton site. The output of the semi-mechanistic model of Moir et al. (2000a) was compared with field data observed at the C1North site in order to further investigate the likely effect of repellency-induced runoff on pasture production. Output values suggest that the effect of such runoff is to reduce pasture production by less than 1 % per annum.

Any likely influence of repellency-induced runoff on pasture growth is insignificant in comparison to other factors that influence variability of pasture growth in complex hill country landscapes. For example, statistical analysis of cumulative pasture production for the years 2010 and 2011 clearly showed the influence of slope on pasture production, with shallow slopes significantly out-performing steep slopes by 2.7 t ha^{-1} yr^{-1}. Total production for North and South aspects were similar, as were the differences between their steep and shallow slope production totals. Significant differences between North and South aspects in terms of production occurred for two harvests during the course of the trial. These differences suggested that production on southern slopes may be greater during the summer and autumn months in drier years when lower soil water contents constrained growth more on the northern slopes, and that northern slopes may out-perform southern slopes during the winter and spring when soil water is non-limiting and when solar radiation input is greater on the northern slopes.

CHAPTER 9

CONCLUSIONS

9.1 Summary

The primary focus of this thesis has been to examine repellency-induced runoff and to study its consequences in New Zealand hill country pasture systems, with particular attention on the East Coast of the North Island as represented by the research area at Alfredton and a catchment near Waipawa.

The potential consequences of soil water repellency were enumerated by Doerr et al. (2000) who cited reduced infiltration capacity, increased overland flow, spatially localised infiltration, changes in the distribution and dynamics of soil moisture, enhanced stream flow responses to rainstorms, and enhanced total stream flow. This thesis has investigated four key items on this list, namely those that relate to; the development and persistence of repellency and its effect on infiltration, overland flow, surface runoff, and stream flow. Furthermore, the effect of repellency-induced runoff on pasture production was considered.

Studies of repellency in New Zealand were initially confined to the repellent sands found in the Manawatu region and 'dry patches' in drought-prone East Coast hill country. However, more recent research (Deurer et al., 2011) has indicated that soil water repellency is widespread throughout New Zealand and that it is expressed most readily in sandy soils, in soils under permanent pasture, and under climatic conditions where extended dry periods are commonly observed (Doerr et al., 2006). The latter two conditions are frequently encountered in New Zealand's hill country pastoral farms yet there has been no major investigation of the consequences of repellency-induced runoff in hill country. Hence the significance of the research reported here.

In the first phase of the study (Chapter 4), manual sampling of surface runoff volumes and gravimetric soil water contents allowed an important conclusion to be made regarding the rooting depth, and hence the water extraction depth, of pasture in hill country. The data suggested that significant water extraction occurred down to a depth of at least 350 mm, conflicting with the value suggested earlier by Bircham and Gillingham (1986) of 150 mm. On the assumption of very shallow rooting pasture, Bircham and Gillingham (1986) calculated that only 38-57 % of the annual rainfall at their site was evaporated by pasture.

A soil water balance for the hill country site was developed. To achieve this, the model proposed by Bircham and Gillingham (1986) was simplified and then adjusted to include the increased water extraction from depth. This improved model provided more realistic pasture evaporation values of 65-80 % of annual rainfall at the site. The importance of the observation regarding rooting depth lies in its inferences for one of the major conclusions drawn by Bircham and Gillingham (1986) which was that the availability of moisture in hill country soils was highly dependent on rewetting frequency rather than the total rainfall. This statement is now questionable. Although the adjustment of rooting depth has little direct effect on the mechanism of repellency-induced runoff in the model, it does give a more realistic representation of the water available to pasture on a daily basis.

The refinement of the water balance model described by Bircham and Gillingham (1986), including the revised rooting depth, were important steps in the development of the soil water balance model used later to simulate repellency-induced runoff and to help assess the effects of soil water repellency on stream flow. Of particular note here, was the model's ability to predict surface soil moisture content.

The second phase of the study (Chapter 5) was undertaken after the installation of automated logging equipment. This equipment allowed real-time measurements of climatic data and surface runoff as well as volumetric soil moisture contents down to 300 mm depth. Analysis of the data showed that repellency-induced runoff events occurred less than 10 times per annum and that these events totalled less than 5 % of annual rainfall, strongly suggesting that this phenomenon was not a significant hydrological process at the research site. Detailed examination of the runoff response to specific (winter) rainfall events indicated that the soils at the research site had large intrinsic infiltrability values ($\geq$ 2 mm min^{-1}). Inspection of some key runoff events indicated that this infiltrability was occasionally compromised, particularly under dry soil conditions.

Upon rainfall, repellency at the research site was relatively short-lived, but reappeared once soil conditions had become sufficiently dry. Examination of a unique rainfall-runoff event in January 2010 indicated that the infiltration rate of initially repellent soil (with an infiltrability of 0.2-0.7 mm min^{-1}) increased over 30 minutes to about 1.0 mm min^{-1}, and that repellency had completely disappeared 44 hours later. This behaviour suggests that while soil water repellency sometimes has a marked effect on the infiltrability of the soil (reducing it by a factor of up to 10), it disappears quite quickly and only reappears again when the soil has become sufficiently dry.

The rapid disappearance of soil water repellency in the field was of sufficient interest to investigate the phenomenon further under laboratory conditions (Chapter 6). Intact 50 mm depth soil slabs (170 x 460 mm) were removed from the research site, air-dried, and analysed for drainage/runoff volumes over time under constant applications of water and then ethanol using the ROMA apparatus. Nearly all samples exhibited peak runoff flows after 5-10 minutes, with runoff volumes becoming negligible for most slabs after 30 minutes. The disappearance of runoff after 30 minutes closely matched the field measurements and confirmed the weak persistence of soil water repellency at the research site.

One of the consequences of soil water repellency proposed by Doerr et al. (2000) was its potential effect on stream flow during rainstorms and on total stream flow. Repellency was expected to enhance stream flow. Chapter 7 investigated the repellency/stream-flow relationship by examining rainfall and stream flow data from paired hill country catchments near Waipawa on the East Coast of the North Island. An additional benefit of using this data was that it allowed an assessment of the likely hydrological significance of repellency-induced runoff at a drier location.

In order to quantify the likely impact of repellency-induced runoff on stream flow characteristics, a number of components investigated in the earlier chapters were linked together so that a soil water balance model could be used to simulate repellency-induced surface runoff at a small plot scale. To this end, the refined Bircham and Gillingham (1986) model in Chapter 4 was further developed using the results from Chapter 5. Repellency-induced runoff was predicted to occur only when both rainfall intensity exceeded 0.1 mm

min^{-1} and the 0-50 mm depth soil water content dropped below 0.28 m^3 m^{-3}. A comparison of the predictions made by the adjusted model with observed surface runoff data at Alfredton indicated that, while there were some obvious limitations, the model appeared accurate enough to be used to give an indication of the timing and magnitude of plot scale repellency-induced runoff.

The model was then used to simulate runoff at the Waipawa site and this runoff was then matched against the stream flow data. Using 8 years of Waipawa rainfall data, the model predicted that, on average, there was 52 mm yr^{-1} of repellency-induced runoff from the North catchment and 45 mm yr^{-1} from the South catchment. These values represented 7 and 6 % of the average annual rainfall (793 mm), and are very similar to the repellency-induced runoff fractions observed at Alfredton, which has approximately twice the average annual rainfall.

Examination of Waipawa stream flow data on those days when the model predicted more than 10 mm of repellency-induced runoff showed a maximum stream flow of 1.1 mm, with an average flow that was just 3.3 % of the modelled runoff. Also for each of these days, peak stream flow was less than 3 % of the peak rainfall intensity. The implication here is that at least 95 % of repellency-induced runoff infiltrated before reaching the stream and that repellency-induced runoff played a very minor role in both peak stream flows and average stream flows at Waipawa.

The penultimate chapter in the thesis (Chapter 8) examined the effect of repellency–induced runoff on pasture production at Alfredton. There was little evidence that repellency-induced runoff adversely affected pasture production. Any likely effect of repellency-induced runoff will be relatively small when compared with other factors impacting on the variable nature of pasture growth in the hill country landscape. For example, pasture measurements over 2010 and 2011 clearly showed the influence of slope on pasture production with shallow slopes outperforming steep slopes by 2.7 t DM ha^{-1} yr^{-1}. The use of the soil water balance model developed in Chapter 7, in combination with the relationship between actual evapotranspiration and dry matter production described by Moir et al. (2000a), was used to roughly estimate the effect of soil water repellency on pasture production at Alfredton. Output values from the models suggested that repellency would reduce production by less than 1 % per annum.

To summarise; while there have been frequent comments in the literature regarding the potential effect of repellency-induced runoff in terms of reduced infiltration, enhanced overland flow, stream flow and reduced pasture production, there is very little information available quantifying its impact on hill country pasture systems in New Zealand. This thesis has confirmed that plot-scale infiltration is throttled by soil water repellency and that the magnitude of reduction (a factor of 10) is similar to that found by other researchers. However, the frequency of repellency events was less than ten per annum and accounted for less than 5 % of the annual rainfall (1500 mm), indicating that repellency was not a significant hydrological process at the Alfredton site. Soil water repellency at Alfredton was also shown to be transient with intrinsic infiltrability being fully restored less than 44 hours after substantial rainfall. At a dry Waipawa catchment, repellency-induced runoff amounted to only 6 % of annual rainfall and at least 95 % of the runoff infiltrated the soil before reaching the stream. At these sites at least, it is concluded that repellency-induced runoff had little effect on both stream peak flows and annual flow values.

9.2 Suggestions for further work

While this study has established that repellency-induced runoff was not a significant hydrological process at either of the sites investigated, it is acknowledged that hill country is, hydrologically, both complex and variable. Accordingly, there is scope for further research on the topic of soil water repellency in hill country. It is likely that repellency-induced runoff is widespread in hill country under permanent pasture. Its appearance and disappearance have been somewhat quantified at Alfredton and Waipawa, but remains largely unknown in other hill country areas. Furthermore, this research project did not examine the spatial variability of soil wetting and repellency-induced runoff, and there is certainly considerable latitude to examine this at the micro (≤ cm) scale. Also, instances of persistent repellency (observed as 'dry patch syndrome' in the Hawke's Bay) have the potential to directly affect pasture production and, to date, there has been very limited work done in this area.

Finally, the analytical techniques commonly associated with measuring the degree and persistence of repellency (MED and WDPT) had limited applicability to the plot-scale dimensions used in this study because of their very fine spatial resolution. The development of a field technique for the assessment of repellency of *in situ* samples up to a metre scale would be an extremely useful tool in aiding hillslope and catchment scale hydrologists in their studies of repellency-induced runoff. Initial investigations (Pullanagari, R. R.; pers. comm.) have examined the potential of visible/near-infrared reflectance spectroscopy (Vis-NIRS) to predict soil water repellency in the top 40 mm of soils under pastoral land use in the North Island of New Zealand. Soil water repellency was measured (each scanned area was approximately 4 cm^2) using the conventional techniques of WDPT and MED. Partial least squares regression of the reflectance data showed moderately accurate predictions for MED (R^2 = 0.67), but unsatisfactory predictions for WDPT (R^2 = 0.52). Useful wavelengths for predicting SWR appeared to be in the regions of 762–937 and 2102–2447 nm. Although these analyses were carried out on dried disturbed soil samples, the advantage of very rapid scanning using this technique indicates that further work in this area may be productive.

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APPENDICES

Statements of contribution

DRC 16

MASSEY UNIVERSITY
GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION TO DOCTORAL THESIS CONTAINING PUBLICATIONS

(To appear at the end of each thesis chapter/section/appendix submitted as an article/paper or collected as an appendix at the end of the thesis)

We, the candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of Candidate: Michael Bretherton

Name/Title of Principal Supervisor: Associate Professor David Horne

Name of Published Research Output and full reference:

Bretherton, M.R., D.R. Scotter, D.J. Horne, and M.J. Hedley. 2010. Towards an improved understanding of the soil water balance of sloping land under pasture. New Zealand Journal of Agricultural Research 53:175-185.

In which Chapter is the Published Work: Chapter 4

Please indicate either:

- The percentage of the Published Work that was contributed by the candidate: 80 %

  and / or

- Describe the contribution that the candidate has made to the Published Work:

Mike Bretherton
Digitally signed by Mike Bretherton
DN: cn=Mike Bretherton, o=Massey University, ou=Institute of Natural Resources, email=M.R.Bretherton@massey.ac.nz, c=NZ
Date: 2012.12.17 00:18:11 +13'00'

Candidate's Signature

11-12-2012

Date

David Horne
Digitally signed by David Horne
DN: cn=David Horne, o=Massey University, ou=Institute of Natural Resources, email=D.J.Horne@massey.ac.nz, c=NZ
Date: 2012.12.14 17:04:58 +13'00'

Principal Supervisor's signature

16-12-2012

Date