AQUALINC RESEARCH LIMITED

A Review of Literature Relevant to Hill Country Irrigation in New Zealand

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SUMMARY

The Hill Country Irrigation Project (HCIP) is a three-year, MAF Sustainable Farming Fund project focused on providing hill country irrigators with the knowledge and resources required to achieve environmental and production performance objectives for irrigation on challenging hill country terrain.

This report summarises the key findings of an international literature review, conducted for the purpose of identifying the state of existing knowledge relevant to hill country irrigation practices. The review was carried out by J. Powers, with technical support from I. McIndoe.

The area of irrigated hill country farming is expanding in New Zealand. However, the review identified that detailed information on how to design and manage irrigation systems to achieve efficient water use, to minimise runoff and drainage to lower areas on hill country, is limited. Most information is focussed on irrigation in general without being specific about slope and aspect, and more suited to plains and downland areas.

One of the key challenges for hill country irrigation designers and managers is coping with variability arising from interactions between soils, landforms, plants, and climate. Soil properties (texture, depth, bulk density, macropore volume, organic matter content, and infiltration rate) have been shown to be highly variable in both space and time. The causes of these variations are numerous, and their interrelationships are extremely complex. There are few consistent trends in this variability across sites, suggesting the need for site-specific information.

Several irrigation design guidelines have been produced that include some advice for hill country situations, but are not specifically written for that environment. Some region-specific guidelines have been produced for New Zealand hill country farm management, such as for the North Otago region. There is still a need for a comprehensive resource that incorporates irrigation design and management guidelines within the recommendations for how to manage a hill country farm as a whole.

Inappropriately designed and managed irrigation systems expose farmers and their production systems to undesirable outcomes such as unsustainable production and adverse effects on the environment. Key issues include soil erosion, sub-surface and surface soil compaction (already evident on some fragile Otago soils), loss of organic matter, reduced soil fertility and induced hydrophobicity. These factors potentially reduce soil water holding capacity and soil infiltration rates, making irrigation management more challenging.

General mitigation methods to address these issues have been documented. They include a combination of actions that address the physical effect of irrigation and farm machinery on soil, controlling stock movement and grazing intensity, modifying soil properties and appropriately considered crop species selection. Some of these measures have been demonstrated to be partially successful (e.g. grazing at optimal soil moisture and managing grazing frequency).

To make irrigation management even more challenging, plant water use and soil moisture is also affected by several factors commonly occurring on hill country properties. These include slope aspect and angle, localised climate, elevation, soil micro-storage and vegetation cover.

Key parameters arising from these factors that need to be accounted for in design are irrigation application intensity (the rate that water is applied to the soil) relative to soil infiltration rate (the rate that soil can absorb water), soil water holding capacity, the frequency of irrigation events and the depth of water applied.

Design and installation codes developed by Irrigation NZ and other organisations contain some information for designing and installing irrigation systems for hill country farms. However, these generally describe ways to modify "flat-land" techniques for hill slopes, and there are no guidelines specifically for hill country irrigation design that incorporate the variation in soils, climatic and topographical factors. The advice provided in the existing guidelines relates to decreasing the application intensity for sloping land.

Some additional guidance is provided for hydraulic design for sites with excessive elevation differences, and for operating travelling irrigators on rolling topography. None of the existing irrigation design guidelines appear to discuss the spatial variability of soil properties or how to manage them.

One limitation to the efficient design and management of irrigated hill country systems in New Zealand is the lack of local soil information. For example, in North Otago, the main soil types have been classified in great detail. However, the spatial distribution of the different soil types is only known at a very broad scale. Detailed, farm-specific soil maps (and probably on-going surveys of soil quality) are required if irrigation design and management are to effectively consider soil variability.

Some guidelines exist for choosing irrigation system type. Existing literature suggests that most surface irrigation methods are not well-suited to the hill country, unless the slopes are moderate and the soils have a very high infiltration rate and an erosion-resistant structure.

Issues with application intensity are best addressed at the design stage as application intensity cannot be readily adjusted by management. The best irrigation methods for controlling application intensity in hill-country situations include drip/micro and solid-set irrigation systems, but tend to be the most expensive.

Application depth and return interval are the most commonly adjusted elements of an irrigation system. However, the extent that these can be adjusted may be limited by the technical specifications of the irrigator or the labour requirements for moving the equipment, particularly where very shallow application depths and short return intervals are required. The best irrigation methods for maximising control over application depth and return interval include drip/micro, solid-set, and centre-pivot irrigation systems.

The technology and knowledge to be able to design, install, and manage highly efficient irrigation systems on hilly terrain, is improving. Current development includes advanced sprinkler design, field and catchment-scale soil moisture monitoring, variable depth application methods and GPS guidance systems. The concept of management units, that is designing for and managing irrigation applications on areas with different combinations of slope angle, slope aspect, soil depth, or soil infiltration rate separately, is worthy of investigation.

Some tools exist for measuring soil moisture and quantifying spatial soil moisture variability. Current research is focusing on making this type of information available to irrigation managers in "real-time". "Precision irrigation" technologies are also under development that will allow for the management of different irrigation zones in a flexible manner.

In summary, this literature review has shown that while some information is available for designing and managing irrigation on hill country properties, significant gaps in knowledge exist. Information needs include, but are not limited to:

- Quantification of relevant soil properties at a scale appropriate for irrigation design and management.
- The relationship between irrigation watering time and soil infiltration rates for hill country soils in NZ.
- The relationship between slope, soil infiltration rates and recommended application intensities.
- The impact of micro-storage on infiltration on sloping ground.
- The presence and location of compacted soils and soil pans and the effect on soil water storage and infiltration rates.
- The impact of specific farm management actions/ active management on relevant soil properties.
- Advice on ways to design hill country farms around the irrigation system, to better integrate farm systems and irrigation systems.
- The value and practicality of management units and methods to quantify management units for irrigation design and operation.
- Cost-benefit relationships between different irrigation system types and potential irrigation/ production performance on hill slopes.
- Practical ways to determine soil moisture on farms with widely varying slopes, aspect, crop growth patterns and soil properties.
- The range of appropriate inputs available to monitor soil moisture and irrigation performance on hill country farms, which ones to use and how to apply them.
- How to turn measurements and data on various irrigation parameters into management decisions.
- Irrigation design guidelines for hill country systems.
- Education of irrigation system designers and system operators.

INTRODUCTION

Project background

The Hill Country Irrigation Project (HCIP) is a three-year, MAF Sustainable Farming Fund project focused on providing hill country irrigators with the knowledge and resources required to achieve environmental and production performance objectives for irrigation on challenging hill country terrain.

The HCIP will collate existing 'Good Management Practice' information for hill country irrigation, identify knowledge gaps, and explore new solutions to provide a comprehensive design and management guide specifically for hill country irrigators.

A key part of the project will be field trials of new technology and management practices that have significant potential to improve hill country irrigation performance. Benchmarking tools will also be developed to help local irrigators assess their current performance and drive efficiency improvement. The project will be based on a collaborative, irrigator-led approach, and will work alongside irrigation schemes to achieve noticeable change where it counts – on the ground.

The HCIP project team comprises representatives from Irrigation New Zealand, the lower Waitaki River irrigation schemes, the Otago Regional Council, Crown Research Institutes, and other industry stakeholders.

Purpose of this document

The purpose of this document is to summarise the key findings of an international literature review, conducted for the purpose of identifying the state of existing knowledge relevant to hill country irrigation practices.

Scope of the literature review

This document is intended to provide a review of literature relevant to irrigation in a hill country environment. It covers publications produced in New Zealand and overseas.

The review provides a summary of the relevant information for each topic discussed, and a consensus or range of applicable values if there are multiple views. Gaps in knowledge are also highlighted.

The review is indented to include content within the following four key Themes:

- Irrigated hill country farming systems;
- Soil, water, and plant physical interactions;
- Irrigation system design; and
- Irrigation system management.

1 IRRIGATED HILL COUNTRY FARMING SYSTEMS

HCIP Preamble: *Irrigation management cannot be done in isolation of other aspects of managing a farm business. Being able to identify the information needed to incorporate and integrate irrigation best practice with other management best practices is crucial.*

1.1 The main challenges for hill country farming enterprises

The United Nations' Food and Agriculture Organisation (FAO) produced a document for land management extension officers working in hilly regions (Shaxon, 1999). In it, they refer to "steeplands" as any land with a slope greater than 12% (acknowledging that there are many other definitions for "steep"), and recognise that farm management on this terrain can be particularly challenging.

Shaxon (1999) identifies and summarises many of the management challenges particular to hill country, including issues of slope aspect, climate-elevation interactions, variable soil type, variable rooting depth, variable fertility, soil erosion, soil structure, and crop selection factors. Many of these topics are well-studied as individual components of hill country farming systems (e.g. Faber, 2004; Framiglietti *et al.*, 1998; Holden, 2009; Kincaid, 2002; Ribolzi *et al.*, 2011), and will be discussed in more detail later. However, there appears to be few comprehensive references that combine all of this information together, and even fewer that also include aspects of irrigation design and management.

The FAO promotes individual farm management plans because many of the factors affecting hill country management are site-specific (Shaxon, 1999). This approach has been adopted in many places around the world, including within New Zealand (Ritchie, 2000; ORC, undated). The effectiveness of existing plans at addressing the challenges of hill country farming has not been reviewed (or the reviews have not been made readily available).

There is an emphasis in the scientific literature and in regional or site-specific farm plans on *soil conservation* in hill country (e.g. Shaxon, 1999; Ritchie, 2000), which appears to stem from mainstream recognition of erosion as a widespread issue in the 1980's. Soil risks such as compaction and erosion are relevant for irrigation because they result in a changed ability of the soil to take in and store irrigation water.

It is widely understood that soil erosion is of primary concern on cultivated land, but that it can also be a significant issue for pasturelands on steep slopes (Pimentel *et al*., 1995). However, soil compaction is often of bigger concern than erosion for pasturelands (McDowell *et al.*, 2008; Houlbrooke, 2011). Erosion and compaction are not the only soil-related issues relevant to irrigated hill country farming in New Zealand, and this is discussed further in Section 2.

Discussions of *variability* within hill country environments are also common in the literature. Soil and climate factors that affect plant growth are known to be highly variable along and across hill slopes, and within and between growing seasons (López *et al.*, 2003; Bodner *et al.* 2008; Paton & Houlbrooke, 2010). This variability underpins many of the problems encountered when managing inputs to hill country farms, such as fertiliser and irrigation water. The published literature seems to focus on quantifying the scale and extent of variability within the hill country landscape, and on working out methods for managing this variability (e.g. Bitelli, 2011; McCarthy, 2010; Smith, 2010). Current methods for measuring and managing variability are discussed as one component of hill country irrigation management in Section 4.

In order for irrigation in the hill country to be successful, the design of irrigation systems must take into consideration the capabilities of the land, and must result in a system that allows managers to meet their targets. The FAO has produced guidelines for assessing the suitability of land for irrigation (FAO, 1985). While the FAO methodology is not designed specifically for hilly environments, it includes slope angle and other topographic features as evaluation criteria. Similar land evaluation tools, such as the New Zealand Land Use Classification System (Lynn *et al.* 2009) and those described by Rossiter (1996) have been developed for region- or country-specific land capability assessment.

Regardless of how land is chosen for irrigation development, the unique limitations of each piece of land must be considered when designing an irrigation system. Some guidelines exist for helping irrigation designers with this task (e.g. USDA, 1997; INZ, 2007). Existing irrigation design guidelines are discussed further in Section 3, along with some of the more recent technological advances relevant to hill country irrigation systems.

1.2 Hill country farming systems in New Zealand

New Zealand has experienced a period of land use intensification over the past 15-20 years (Houlbrooke *et al.*, 2011). Much of this intensification has occurred in areas that were less economic to farm in the past, such as on hillslopes or on dry, shallow soils requiring significant fertiliser or irrigation inputs (McDowell *et al.* 2008).

A prime example of one such area is the Waitaki district in North Otago. This is one of New Zealand’s most drought-prone districts because of its generally shallow soils and warm, dry climate (mean 500-550 mm rainfall, Jan-Feb median evapotranspiration of 4.4 mm/day) (McDowell *et al.* 2008). This area has undergone significant intensification of pastureland, following the implementation of a large community irrigation scheme in the area (Houlbrooke *et al.*, 2011). Land use in the Waitaki district is characterised predominantly by hilly tussock-land (57%) and grasslands (32%) used for lamb or beef cattle finishing, dairy support grazing, or dairy farming (Houlbrooke *et al.*, 2011).

The Otago region contains approximately 15% of New Zealand's irrigated land (Statistics New Zealand, 2007). The Waitaki district contributes over two-thirds of this area (Statistics New Zealand, 2007), making it one of the most extensively irrigated hill country districts in the country. Two-thirds of the irrigation in Waitaki is spray irrigation, one-quarter is flood irrigation, and 3% is drip or micro-irrigation (Statistics New Zealand, 2007).

1.3 Summary and discussion

Irrigated hill country farming is becoming more common in New Zealand. The Waitaki district in North Otago is a prime example of this, being one of the most extensively irrigated hill country districts in the country. Land use in Waitaki is characterised primarily by hilly tussock-land and grasslands used for lamb or beef cattle finishing, dairy support grazing, or dairy farming. Throughout the remainder of this review, this region will be used to demonstrate examples or relevant issues.

There is an emphasis in the scientific literature on *soil conservation* for the hill country. This is important for maintaining good conditions for the infiltration and storage of irrigation water, and for maximising the productivity of hill country systems. Important soil properties and protection methods are discussed in detail in Section 2.

Several irrigation design guidelines have been produced that include some guidance for hill country situations, but are not specifically written for these landscapes. Existing irrigation design guidelines are discussed further in Section 3, along with some of the more recent technological advances relevant to hill country irrigation systems.

One of the most difficult challenges for hill country farm management is coping with variability arising from complex interactions between soils, landforms, plants, and climate. Current research focuses on quantifying the scale and extent of variability within these landscapes, as a step towards better management. Current methods for measuring and managing variability are discussed as one component of hill country irrigation management in Section 4.

Some region-specific guidelines have been produced for New Zealand hill country farm management, including some for the North Otago region. There is still a need for a comprehensive resource that incorporates irrigation design and management guidelines within the recommendations for how to manage a hill country farm as a whole.

2 SOIL-WATER-PLANT PHYSICAL INTERACTIONS

HCIP Preamble: *The biggest challenge that the project area faces is runoff of excess irrigation water. Detailed knowledge of the region's soil types, their properties and how those properties relate to the management of irrigation will be a key focus for the project.*

2.1 Soil-water-plant interactions on hillslopes

The literature contains a huge amount of information regarding soil-water-plant interactions. There exists entire research organisations, scientific journals, and text books dedicated to the topic. It is widely understood that the fundamental principles of soil-water-plant interactions will apply regardless of topography. It is not within the scope of this review to discuss these fundamental principles in detail. However, there are a number of topics that emerge as particularly relevant when considering soil-water-plant interactions in the specific context of irrigated hill country.

The textbooks of Hillel (1998), Langer (1990), and Kirkham (2005) provide a good basis in the widely accepted principles regarding soil-water-plant physical interactions from the soil physics perspective, plant science perspective, and a holistic soil-water-plant systems perspective (respectively). These sources agree that all three components of the soil-water-plant system play important roles in the behaviour of the system as a whole, but some components are more easily manipulated than others. Agricultural plant species may be selected or changed to match the soil and climate combination at a given location, and the water balance may be altered through irrigation or drainage practices. But, the soil component is less easily altered, and can be viewed as the primary controlling factor in the soil-water-plant relationship.

Scientific studies of soil physical properties and their effects on the soil water balance and on plant production have been undertaken for over 100 years (e.g. Cameron & Gallagher, 1908). More recent studies have built on earlier work, and are able to describe in detail the more desirable properties of soils for use in agriculture (e.g. Drewry *et al.*, 2008; Hamza & Anderson, 2005; López *et al.*, 2003; Ribolzi *et al.*, 2011). In general, it may be said that a more desirable soil is a soil that:

- is well-drained,
- has a structure that allows for good root growth and water infiltration,
- has a water holding capacity that allows for adequate storage of water through dry periods, and
- has a level of fertility adequate for the crop being grown.

Soil properties have been shown to be highly variable in both space and time within hill country environments. The causes of these variations are numerous, and their interrelationships are extremely complex (Ridolfi *et al*., 2003; Framiglietti *et al*., 1998).

How do soil structure and drainage vary within a hilly landscape, and what are the effects of this variability?

Soil structure affects the infiltration and storage of water in the soil, and the availability of water to plants for growth (Drewry *et al.*, 2008). If irrigation water is being applied, soil structure can affect potential irrigation efficiency (efficiency = the percent of applied water that is used by plants). Soil structure can also affect the ability of plant roots to establish themselves (McDowell *et al.*, 2008). Soil structure has been shown to be both spatially and temporally variable within hill country environments (Stavi *et al.*, 2010; Lobb, 2011), and this is considered to be one of the main complicating factors relevant to the management of hill country systems.

The literature describes various measureable properties of soil that relate to soil structure and its effect on the soil-water-plant system. These include soil texture (percent sand, silt, and clay), soil depth, bulk density, macropore volume, organic matter content, and water infiltration rate (Bresler *et al.*, 1984; Famiglietti *et al.*, 1998; McDowell *et al.*, 2008; Hillel, 1998).

Soil texture (percent sand, silt, and clay) plays an important role in determining the soil's water holding capacity. Fine-textured soils tend to have a higher total water holding capacity than coarse-textured soils. However, water is held more tightly in the smaller pores formed in fine-textured soils, and this pore water is therefore less available to plants. Fine-textured soils tend to have slower infiltration rates. Soil texture can also have profound effects on how the soil behaves in wet (e.g. high silt, low clay content = highly water-dispersive, compactable soil) or dry (e.g. some soils go extremely hard) conditions. (Hillel, 1998; McDowell *et al.*, 2008)

Soil texture is a site-specific attribute that is a function of the soil's parent material, soil age, and the historic weathering conditions at the site (Hillel, 1998). The soil texture at a given location cannot be readily altered by human activity. In hilly landscapes, a variety of different weathering patterns can have taken place, and soil texture variability can be relatively high, down to scales of tens of metres (Famiglietti *et al.*, 1998). In general, there tends to be a larger fraction of clay and silt particles at the bottom of slopes because they are most easily transported downhill by erosion processes (Bodener *et al.*, 2008; Gregorich *et al.*, 1998).

Soil depth refers to the size of the soil profile available for root growth and water extraction (usually measured in centimetres or millimetres). Soil depth has been shown to vary considerably within a hilly landscape, with deeper soil generally occurring at the bottoms of slopes (Lobb, 2011; Anderson & Fly, 1955) and within concave, rather than convex, land features (Heimsath *et al.*, 1997). However, the degree of soil depth variability within a landscape is also controlled by the site's history and the land management strategies being practised there (Lobb, 2011).

A shallow soil depth limits the amount of space available for plant root growth and soil water storage (Letey, 1985; Houlbrooke *et al.*, 2011). More careful irrigation management is therefore required on shallower soils. Generally, shallow soils require more frequent watering and smaller applied depths of water in order to maintain an adequate soil moisture content (USDA, 1997).

Soil depth also plays an important part in the downslope movement of water within hilly landscapes. Graham *et al.* (2010) showed that a shallow impeding layer resulted in more baseflow from an experimental hillslope at the Maimai Experimental Watershed near Reefton, New Zealand. This was attributed to lateral preferential flow channels that developed along the boundary with the impeding layer. This demonstrates that applied irrigation water may be lost from some hillslopes via the subsurface, without infiltrating into deeper soil layers, and without any visible surface runoff.

Bulk density is a measure of the compactness of the soil, and is inversely proportional to soil pore volume (Hillel, 1998). It is therefore an indicator of the total volume of water a soil can hold, and can also influence water infiltration (Hillel, 1998). The majority of studies investigating soil bulk density appear to be in “damaged” or intensively managed pasture soils, and few of them concentrate on the effects of slope steepness. In cropping soils, it can generally be said that bulk density is lowest after ploughing (Steinhardt & Trafford, 1974; Osunbitan *et al.*, 2005), and landscape position has little effect. In pasturelands, soil bulk density is often highest on flatter areas (i.e. the tops and bottoms of hillslopes), where animal traffic is highest (Oztas *et al.*, 2003; Sheath & Carlson, 1998). No change in bulk density was observed with the addition of irrigation water in a trial conducted in the North Otago (New Zealand) hill country (Houlbrooke *et al.*, 2010).

Soil macropores may be defined as large soil pores (usually > 100 µm or >-3.0 kPa capillary potential) that are hydraulically effective in terms of channelling flow through the soil (Beven & Germann, 1982; Ela *et al.*, 1992). A large volume of macropores in a soil can indicate a high water infiltration rate (Beven & Germann, 1982) and a low degree of soil compaction (Houlbrooke *et al.*, 2011). Soil macropores are thought to be a major pathway by which water enters soils, and are considered to be significant contributors to the down-slope movement of water within hillslopes, particularly under moist soil conditions (Holden, 2009; Steenhuis *et al.*, 1988; Tromp-van Meerveld & McDonnell, 2006; Tsuboyama *et al.*, 1994). The literature presents few results about the distribution of macropore density within hilly landscapes, although it suggests that land use and management strategies may be just as important as landscape factors such as slope or position.

Organic matter can increase soil strength and resilience (McDowell *et al.*, 2008; Hamza & Anderson, 2005) and has a positive influence on water infiltration (Franzluebbers, 2002). In erosive situations, less organic matter may be seen on the tops of slopes (Miller *et al.*, 1988; Elliott & Efetha 1999). The literature presents few results about the distribution of organic matter within hilly landscapes, although it suggests that land use and management strategies may be just as important as landscape factors such as slope or position (e.g. Elliott, 1999). At least one study suggested that the addition of irrigation water increased organic matter inputs through enhanced plant growth (Houlbrooke *et al.*, 2011), possibly balancing or overriding the rate of removal.

There is no consistency in the literature with regard to **water infiltration** characteristics relative to hillslope position – some studies show infiltration is higher on steeper slopes (Ribolzi et al., 2011; Holden, 2009), while others show that it is lower (Joshi & Tamb, 2010). However, good water infiltration has been linked to the previously discussed soil properties. There is a consistently reported positive correlation between infiltration and organic matter content (Franzluebbers, 2002), and between infiltration and macropore volume (Beven & Germann, 1982). There is a consistently reported negative correlation between infiltration and bulk density (Hillel, 1998). Bodner *et al.* (2008) showed that infiltration characteristics change throughout the season, and are highly dependent on climatic effects such as rainfall intensity, soil drying, and frost.

Scherrer et al. (2007) provides a particularly good discussion of the complex interplay between infiltration, surface runoff, and the subsurface downslope flow of water within a hillslope, including descriptive diagrams. This study showed that site-specific factors often control the movement of water within hillslope systems.

How does soil moisture vary in a hilly landscape?

In the hill country, the distribution of water within the landscape is dependent on a number of factors, including the soil structural properties just discussed. The literature describes a number of other contributing factors including slope aspect, elevation, micro-climates, vegetation cover, and the slope angle.

The effects of **slope aspect** on the soil water balance are well studied in the literature. In general, it may be said that sunny aspects are subjected to more solar radiation, and thus more soil water extraction occurs via evapotranspiration (Bretherton *et al.*, 2010; Faber, 2004; Reid, 1973). However, this effect may be somewhat masked in some situations, particularly if long dry periods are experienced. Reid (1973) showed that during a dry period, decreasing soil moisture levels resulted in slowed evapotranspiration on the sunny aspects, while shaded aspects were not affected to the same degree. Irrigation will create more frequent wet conditions, resulting in fewer dry spells, and likely resulting in more evapotranspiration from sunny aspects.

Jackson (1967) showed that other factors such as surface albedo and advection have the potential to further affect differences between aspects at some times of the year. Jackson (1967) also showed that annual evapotranspiration on sunny aspects can be higher on sloped land than on flat land, primarily due to increased specific land area.

Extremely **localised climates** have been observed in hilly landscapes, and can contribute to the variable nature of soil moisture in these regions. Hills affect the flow of winds, which can impact on evapotranspiration and can lead to localised differences in temperature, humidity, and rainfall patterns on the sub-kilometre scale (White, 1990). Temperature has also been shown to decrease with **elevation**, at the so-called “adiabatic rate” leading to reported decreases in evapotranspiration, resulting in reduced pasture production of up to 450 kg/100m altitude (White, 1990 – Otago, New Zealand).

The extent of **vegetation cover** is essentially a function of all of the other soil and climate factors previously discussed (Smetham, 1990). However, plants can also provide feedback to the soil water balance by:

- extracting water for transpiration (Hillel, 1998),
- growing roots that affect water infiltration (Archer *et al.*, 2002),
- buffering water droplet impact and mitigating soil erosion (Wischmeier & Smith, 1978), and
- contributing organic matter to build soil structure (Hamza & Anderson, 2005).

As a result, significantly less erosion, and better infiltration properties have been observed on hillslopes with a high percentage of vegetative cover (Basher, 1995; Carroll *et al.*, 2000; Meek *et al.*, 1992).

The overall effect of **slope angle** on soil water content is not clear. A traditional model of hillslope soil moisture variability predicts lower soil water content on hilltops and steep slopes, higher soil water content on shady aspects and slope bottoms, and more variability in wet conditions than in dry conditions (Framiglietti *et al.*, 1998). This model has been demonstrated to be true by a number of field trials (e.g. Hanna *et al.*, 1982; Ridolfi *et al.*, 2003) However, Framiglietti *et al.* (1998) highlight several additional field trials that contradict this traditional thinking, and argue that the integrated effects of terrain, soil, and crop on soil moisture are not yet fully understood. Zhu & Lin (2011) showed that the controls on soil moisture variability can vary by season, soil depth, and the degree of soil-topography variability at a given spatial scale, further supporting the need for more work in this area, including additional terrain-soil-crop combinations.

Issues related to soil fertility

Soil fertility has long been known to vary within hilly landscapes (López *et al.*, 2003; Langer, 1990). Fertility management is not discussed in detail in this review, but there are several known interactions between fertility and other soil and landscape properties that are worth discussing in the context of hill country irrigation.

In New Zealand, fertility is usually managed through the addition of fertilizers. Lambert *et al.*, (2000) conducted a study in the Hawke’s Bay hill country that indicated reduced fertility on steeper slopes, despite the addition of fertilisers. This was at least partially attributed to higher animal excreta inputs on the flatter areas, but could also be due to downslope movement of nutrients.

Variability in any of the previously discussed soil or landscape features may lead to different results being obtained at different sites.

Land use intensification (including irrigation and nutrient additions) is contributing to surface water quality issues in the New Zealand hill country (McDowell *et al.*, 2008). This problem is related to the generation of surface runoff by irrigation, which can carry nutrients into waterways. Management strategies aimed at minimising runoff from irrigation and at increasing the uptake of nutrients into the soil matrix are therefore considered beneficial for maximising soil fertility.

High soil fertility is thought to have positive effects on organic matter input into soils (Lambert *et al.*, 2000), and organic matter is thought to improve the availability of nutrients to plants (López *et al.*, 2003). Irrigation has been shown to increase organic matter inputs through increased plant growth (Houlbrooke *et al.*, 2011). Thus, proper irrigation techniques have the potential to indirectly enhance nutrient uptake in addition to providing water for plant growth.

2.2 Soil risk factors

The main soil risk factors relevant to hill country irrigation practices may be deduced from the information regarding soil-water-plant interactions presented in Section 2.1, and include the following:

- Erosion (structure/depth)
- Compaction (structure/infiltration/SWC)
- Loss of organic matter (structure/infiltration/SWC)
- Hydrophobicity (infiltration/drainage/SWC)

Erosion is the most common soil degradation problem discussed in the published literature, and is arguably the biggest risk to soil quality worldwide (Pimentel *et al.*, 1995; Kelley, 1990). The negative effects of erosion include loss of soil depth, degradation of soil structure, loss of fertility, and pollution of waterways with sediment and nutrients (Pimentel *et al.*, 1995).

Soil erosion is caused by the overland flow of water and wind. Erosion is of primary concern on cultivated land, where bare soils are often exposed to the elements, and where loosened soils are more easily carried away (Pimentel *et al.*, 1995). But erosion can also be a significant issue for pasturelands, particularly if they are overgrazed (Pimentel *et al.*, 1995) or on steep slopes (Shaxon, 1999). Splash erosion is most commonly observed on croplands, whereas gully erosion is more common on pasturelands (Shaxon, 1999). In hill country, erosion generally results in deeper soils on footslopes, and shallower soil on ridges (Miller *et al.*, 1988). Erosion can also result in further slowed infiltration due to surface sealing caused by "in-washing" of fine soil particles (Assouline, 2004). The addition of irrigation water increases the potential for erosion to occur.

There are a number of published guidelines for soil erosion mitigation (e.g. Shaxon, 1999; Cairns *et al.*, 2001) which are discussed further in Section 2.3.

Soil compaction can result in significant degradation of soil structure, and a subsequent reduction in water infiltration rate and water holding capacity (Hamza & Anderson, 2005; McDowell *et al.*, 2008). Compaction is often measured as bulk density or macroporosity. Many studies appear to consider a soil with a macroporosity of approximately < 10% as negatively influenced by compaction (Houlbrooke *et al.*, 2011).

Soil compaction is often of bigger concern than erosion in pasturelands (McDowell et al., 2008; Houlbrooke, 2011). In pasturelands, significant compaction can be caused by animal treading (Warren *et al.*, 1986; McDowell *et al.*, 2008). This is most severe in wet conditions, but can be significant even in relatively dry conditions (McDowell *et al.*, 2008). Houlbrooke *et al.*, (2011) found that the addition of irrigation water to a North Otago hill country pasture resulted in more soil compaction than an equivalent dryland system.

In hill country pastures, compaction often occurs in areas of heavy animal traffic (i.e. on hill tops, valleys, or along stock tracks) (Sheath & Carlson, 1998). Significant compaction can also occur in cropland, and is often evident as a sub-surface compact layer (i.e. the “tillage pan”) caused by the use of heavy machinery (Hamza & Anderson, 2005).

Compaction may occur at the soil surface (primarily in pasturelands) or at depth (in both cropped and pasturelands) (McDowell *et al.*, 2008). Both types of compaction can limit water infiltration rate (McDowell *et al.*, 2008). Subsurface-compacted soil can also limit rooting depth and water storage (Letey, 1985; Houlbrooke *et al.*, 2011). Graham *et al.* (2010) observed more baseflow from a hillslope with a dense sub-surface layer, resulting from lateral preferential flow channels that developed along the boundary with the impeding layer.

Loss of **organic matter** can lead to the degradation of other desirable soil qualities such as infiltration rate and soil water holding capacity (Franzluebbers, 2002). Soil organic matter content may be naturally low in some soils, but can also be reduced through management practices (Elliot & Efetha, 1999). Miller *et al.* (1988) observed higher organic matter concentrations at the bottoms of slopes, indicating that erosion can redistribute organic matter within a landscape. The addition of irrigation water could accelerate this process, although irrigation has also been shown to increase organic matter inputs by enhancing plant growth (Houlbrooke *et al.*, 2011). The negative effects of reduced organic matter content may be more noticeable on irrigated hillslopes, where the consequences of reduced infiltration rate and water holding capacity (i.e. surface runoff) will be more noticeable.

Hydrophobicity can decrease soil infiltration rate, increase surface runoff, and increase the preferential flow of water through soil macropores (Tillman *et* *al.*, 1989; Wang *et al.*, 2000). This can result in reduced soil water content, the potential for increased erosion, and the drainage of water beyond the reach of plant roots (Doerr *et al.* 2000). Because of this, irrigation is likely to be less efficient on hydrophobic soils. Hydrophobicity is most common in sandy soils and in areas experiencing a seasonally dry climate, but can occur in many other circumstances (Dekker et al. 2005; Doerr *et al.* 2000). Hilly landscapes are likely to exaggerate the effects of hydrophobic soils because water tends to moves along the soil surface more quickly when there is an elevation difference.

Hydrophobicity is widely considered to be caused primarily by coatings of long-chain organic compounds derived from plants. (Doerr *et al.*, 2000; Dekker *et al.*, 2005). The effects of hydrophobicity are similar to those of surface sealing caused by erosion/deposition processes or compaction, and the two may be confused at times. The main difference is that the effects of hydrophobicity tend to be worst early in an infiltration event and when the soil is dry (Tillman *et al.*, 1989; Wang *et al.*, 2000), whereas the effects of surface sealing do not tend to break down over time.

2.3 Protection of desirable soil properties for irrigation

As previously discussed, protection of desirable soil properties is important for good infiltration and storage of irrigation water in the soil, particularly on hillslopes. Some common soil protection methods are reviewed here.

The FAO has published several guideline documents that include detailed information about soil protection. Shaxon (1999) describes soil protection measures for slopes that challenge the use of "traditional" soil conservation structures. Shaxon (1999) argues that soil protection should target the source of degradation issues by trying to recreate "ideal forest floor" conditions as closely as possible. Implementing methods to maintain soil cover (e.g. mulch, crop residue, or good plant canopy density), increase recuperative or "rest" periods, and reduce disturbance (e.g. tilling or other traffic) create an environment that better mimics the conditions under which the soil was formed.

Another FAO document (Shaxon & Barber, 2003) also recommends maintaining good soil cover and organic matter content as the best ways to enhance water infiltration and to slow surface runoff and erosion processes. Windbreaks are promoted as a way of reducing the flow of air across plant leaves, thus slowing the removal of water from the soil via the plant. Ploughing methods or fallow periods with vigorous deep-rooting cover plants are promoted as a way to improve the structure of compacted soils or hard pans. This document also describes physical structures and earth modification (e.g. field contours, ridges) that, although less desirable than the other methods, can help to slow the downslope movement of water and improve infiltration.

Many of the soil protection methods suggested by FAO may be classified as "conservation agriculture" techniques (Shaxon & Barber, 2003). The underlying principles of these methods are also supported by similar guidelines produced elsewhere, including in New Zealand (WASCO, undated; ORC, undated).

Many soil protection strategies are also discussed in the scientific literature. Hamza & Anderson (2005) reviewed methods for ameliorating the effects of compaction, and described the following as potentially useful:

- Reducing pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil.
- Working soil and allowing grazing at optimal soil moisture.
- Reducing the number of passes by farm machinery and the intensity and frequency of grazing.
- Confining traffic to certain areas of the field (controlled traffic).
- Increasing soil organic matter through retention of crop and pasture residues.
- Removing soil compaction by deep ripping in the presence of an aggregating agent.
- Crop rotations that include plants with deep, strong taproots.
- Maintenance of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil/crop system to resist harmful external stresses.

Paton & Houlbrooke (2010) conducted a study in North Otago that showed a **fallow period** allowed for good natural recovery of soil structure (measured by macroporosity) between intensive grazings of winter cover crops. However, the recovery was not a full recovery, and the authors further recommended that winter forage blocks should be returned to perennial pasture after 1 or 2 years. They also note that direct-drilling of winter forage crops in North Otago reduced water and wind erosion susceptibility as compared to traditional cultivation.

Nie et al (1997) also demonstrate that a “fallow period” (no grazing) can improve air permeability, saturated and unsaturated hydraulic conductivity, soil moisture, and can decrease soil bulk density. This also reduced the root biomass in the shallower soil layers and increased root biomass at deeper layers, resulting in improved conditions for oversowing of new pasture.

Harrison *et al.* (1994) showed that significant improvements in soil porosity and hydraulic conductivity can be achieved after **subsoil loosening** of a compacted pasture soil. They noted an increased pasture root growth and overall production as a result. McDowell et al. (2008) describe a number of other studies that have shown the same result, but draw into question the long-term effectiveness of this treatment if subsequent changes are not made to the land use practices contributing to compaction. ORC (undated) state that great care is needed when conducting subsoil operations on some fragile soil types, e.g. some of North Otago’s yellow-gray earths.

Davies *et al.* (1989) showed that an **aeration** or "spiking" treatment (which is gentler than subsoil loosening) resulted in a doubling of pasture production on a compacted soil in Wales. Increase in the net uptake of nitrogen, phosphorus, and potassium were also recorded.

The FAO discusses the construction of **terraces** to slow the downslope flow of water, and to reduce erosion and increase infiltration (Shaxon & Barber, 2003). However, this can be expensive if large volumes of soil need to be moved, and is only feasible if the soil is deep enough to withstand the modifications (Burt *et al.*, 2000).

Ellis et al. (2006) used **tree belts** to capture approximately one-quarter to one-third of the runoff from a hillslope during three artificial rainfall events. The soil beneath the trees exhibited an infiltration rate that was 46% higher than the surrounding pasture soils. This was attributed to better soil structure due to the absence of stock and to a 50 mm cover of leaf litter over the soil surface. The leaf litter slowed the downslope flow of water, allowing more time for infiltration.

Cresswell & Kirkegaard (1995) reviewed earlier studies showing the ability of **plant roots** to loosen the structure of compacted soils. They further suggest that some perennial species (e.g. lucerne) may be better at loosening hardened subsoils than many tap-rooted annual crops (e.g. canola), which are traditionally thought to be better at performing this task.

Surface **soil amendments** have also been shown to increase infiltration and reduce erosion. Miller *at al*. (1998) demonstrated that surface additions of anionic polyacrylamide (PAM) increased aggregate stability in dispersible soils, and others (e.g. Wang *et al.*, 2011) have shown that this can increase infiltration and reduce erosion and nutrient loss.

Baumhardt et al. (1992) reviewed earlier studies showing that surface-applied gypsum can increase the permeability of soil that are susceptible to chemical dispersion and sealing. They further demonstrated a 38% increase in infiltration resulting from gypsum on a tilled soil. Although some studies had shown gypsum to be effective on undisturbed soils, this trial did not.

Others have studied the effects of PAM, gypsum, and other treatments in combination (e.g. Yu, 2003; Lee *et al.*, 2011). Hamza & Anderson (2005) recommend that aggregate-forming surface treatments be used whenever physical loosening practices such as deep ripping are practiced.

Different soil protection solutions are likely to work at different sites depending on soil texture, slope angle, farming enterprise, etc.

2.4 New Zealand hill soils: State of knowledge

As already shown, knowledge of soil properties is vital for managing soil-water-plant systems, particularly in the context of hill country irrigation. Generally speaking, there is a good amount of local knowledge regarding soil properties in various regions of New Zealand. However, this information may not necessarily be widely available, or may not be effectively used to manage irrigated hill country.

Online GIS-based soil information resources such as Grow Otago (http://growotago.orc.govt.nz/) and S-Map (http://smap.landcareresearch.co.nz/) are available for public use in New Zealand. These can be used to establish which soil types are present, basic landscape features, and their spatial distribution within a given area. However, it is questionable whether or not the spatial scale of the information in these databases is appropriate for farm-specific irrigation planning, and these resources do not provide much specific guidance for land managers. Also, as of the writing of this review, S-Map was not available for all regions of New Zealand, including Otago.

More comprehensive local information does exist. For example, the *North Otago Sustanable Land Management Guidelines* (ORC, undated) provides an excellent discussion of the main soil types in the North Otago region, and their physical and chemical properties relevant to management. The properties of the main soil types are summarised below:

- Yellow-Grey Earths of the Rolling Downlands

  These are silty-textured soils, derived from loess, and include the Timaru, Ngapara, Kauru, Claremont, Opuha, and Wakanui soils. These soils are low in clay and organic matter content, are highly dispersive in water, and include a naturally compacted subsurface layer at approximately 20-60 cm depth that restricts water infiltration, rooting depth, and available water holding capacity significantly. The most pronounced compact subsurface layers are found in the Timaru, Kauru, Opuha, and Claremont soils.

- Brown Granular Clay (“tarry” soil)

  These are deep soils derived from basaltic ash, having very high clay content and a strongly developed structure that withstands cultivation without much risk of degradation or erosion. Deep rooting depths may be achieved in this soil. Although, there is a narrow range of soil water contents where this soil is easily workable – it is hard when dry and highly plastic when wet. The main brown granular clay is the Waiareka soil.

- Rendzina

  These are shallow soils overlaying limestone. They are well drained, have good structural stability, and are resistant to physical degradation. These soils are susceptible to drought because of the shallow rooting depth. The main Rendzina soil is the Oamaru soil.

ORC (undated) provide good guidance to land managers operating on these soil types. It discusses aspects such as managing soil structure (particularly around compaction), maintaining organic matter, maintaining soil biological activity, maintaining fertility, and some notes on the limitations for irrigation. Some of the mitigation practices discussed in Section 2.3 may work on some of these soils, but their effectiveness may be limited on some of the more fragile yellow-grey earths.

A series of academic studies have also been conducted recently in the North Otago region, which tend to generally agree with ORC (undated). Houlbrooke *et al.* (2011) described the soils of this region as poorly structured, with a pronounced compact layer at approximately 50 cm depth. They conducted a field trial that showed both irrigation and intensive cattle grazing worsened the degree of soil compaction compared to dryland sheep grazing. Paton & Houlbrooke (2010) found that a North Otago soil exposed to a single winter forage crop grazing event did not recover to the level of a low intensity farming system, even after 11 months of cattle exclusion. These studies indicate a fragile soil that is slow to recover from damage. Houlbrooke *et al.* (2011) recommend long-term monitoring of management on these soils, and suggest that reduced stocking rates and other "high compaction risk strategies" may need to be considered.

A large number of additional publications and reports exist that describe soil properties in the New Zealand hill country (e.g. Watt, 1972; Arand *et al.*, 1991; Bruce, 1984; Webb, 1992; McIntosh, 1992; Morton *et al.,* 1996; Rutherford, 1996; Rickard & Cossens, 1968; Rickard *et al.*, 1971; WASCO, 1985). However, many of these are detailed reports that could not be adequately reviewed within the scope of this project. Suffice to say that a considerable amount of work has been done to study and classify New Zealand soils, including those in the North Otago hill country. However, the high degree of variability seen in the hill country is still likely to necessitate some form of site-specific soil classification when determining properties relevant to irrigation.

2.5 Summary and discussion

Soil properties have been shown to be highly variable in both space and time within hill country environments. The causes of these variations are numerous, and their interrelationships are extremely complex. There are few consistent trends in this variability across sites, suggesting the need for site-specific information.

Soil structural elements important for irrigation that may be measured include:

- texture
- depth
- bulk density
- macropore volume

- organic matter content, and
- infiltration rate

In addition, soil moisture is affected by a number of other factors, including:

- slope aspect
- localised climates
- elevation
- vegetation cover, and
- slope angle.

These soil structural elements and "other factors" are all variable within hill country environments. One of the key challenges for hill country irrigation designers and managers is quantifying and managing for this variability.

Some of the most important risks to soil properties relevant for irrigation are summarised in Table 1.

Table 1: Key hill country soil risks.

Risk category	**What's at risk?**
Erosion	structure / depth
Compaction	structure / infiltration / SWC
Loss of organic matter	structure / infiltration / SWC
Hydrophobicity	infiltration / drainage / SWC
Loss of fertility	organic matter / plant growth

Erosion is the primary concern on cultivated land, where bare soils are often exposed to the elements, and where loosened soils are more easily carried away

Soil compaction is often the biggest soil degradation concern for pasturelands. Both surface and sub-surface compaction may result from animal treading, particularly when stocking rates are high or when the soil is wet. Compaction can contribute to a reduced infiltration rate and reduced soil water holding capacity, which in turn can make irrigation management more difficult.

Methods exist to mitigate or avoid the types of soil damage listed in Table 1. Hamza & Anderson (2005) summarise these as follows:

- Reducing pressure on soil either by decreasing axle load and/or increasing the contact area of wheels with the soil.
- Working soil and allowing grazing at optimal soil moisture.
- Reducing the number of passes by farm machinery and the intensity and frequency of grazing.

- Confining traffic to certain areas of the field (controlled traffic).
- Increasing soil organic matter through retention of crop and pasture residues.
- Removing soil compaction by deep ripping in the presence of an aggregating agent.
- Crop rotations that include plants with deep, strong taproots.
- Maintenance of an appropriate base saturation ratio and complete nutrition to meet crop requirements to help the soil/crop system to resist harmful external stresses.

Strong evidence of widespread surface and sub-surface compaction damage exists in New Zealand hill country pastoral systems. This has been particularly well documented in North Otago in the last five years. This compaction damage is partially due to the fragile soil types in the region, but is also affected by management.

Some of the North Otago soils (e.g. the yellow-gray earths) require very careful management, particularly if they are to sustain high production irrigated agriculture. Some of the mitigation methods discussed above have been demonstrated as at least partially successful in this region (e.g. grazing at optimal soil moisture and managing grazing frequency). Work is ongoing in this area.

One limitation to the efficient management of irrigated hill country systems in New Zealand is the lack of local soil information. For example, in North Otago, the main soil types have been classified in great detail; however, the spatial distribution of the different soil types is only known at a very broad scale. Detailed, farm-specific soil maps (and probably on-going surveys of soil quality) are required if irrigation design and management are to effectively consider soil variability.

3 IRRIGATION SYSTEM DESIGN

HCIP Preamble: *Too often there is a disconnect between the design specification of the irrigation systems that are installed and the performance expectations of irrigators and regulatory bodies. Specific hill country irrigation design parameters are required. The focus on financial considerations must also include maintenance, operating costs (including labour) and longevity of systems on what can be challenging terrain. Financial considerations should not be the default overriding factor in the decision of which system to install.*

3.1 Existing guidelines for hill country irrigation design

There are several existing irrigation design guidelines that include information about irrigation in hilly landscapes. However, none of these are aimed solely at hill country design – many of them include short sections about how to modify standard designs for hillslopes. The vast majority of design guidelines relevant to hilly landscapes relate to spray or drip/micro irrigation, and do not generally cover surface irrigation methods.

The FAO has produced an irrigation manual (Savva & Frenken, 2001). This manual provides design guidance including some factors relevant to hilly landscapes. It describes how spray irrigation intensity should be modified for sloping land (see Table 2).

Table 2: Application intensity adjustment for slope (Savva & Frenken, 2001).

Soil group	**Slope**		
	6-8%	**9-12%**	**13-20%**
Clay	6	4	3
Clay Loam	12	9	6
Silt Loam	20	15	10
Sandy Loam	32	24	16
Sand	> 32	> 24	> 16

Based on the guidance provided by Savva & Frenken (2001), the North Otago yellow-gray earths are likely to require application intensities of < 10 mm/hr.

Savva & Frenken (2001) also gives fairly detailed recommendations of how to adjust irrigation designs for windy conditions. For example, sprinkler or run spacing or spray angles may be adjusted.

The United States Department of Agriculture has also produced a 754-page irrigation engineering handbook (USDA, 1997). This includes detailed information about soil properties relevant to irrigation (similar to what is presented in Section 2), and provides guidance for modifying standard irrigation design for hillslopes.

USDA (1997) provides guidance regarding site assessment and design basics, including how to calculate crop water requirements, rooting depth, and application intensity. Table 2-1 in USDA (1997) lists soil conditions that have the potential to restrict irrigability. These include:

- slope > 3%
- permeability < 0.5 mm/hr
- depth to bedrock or pan < 100cm, and
- depth to water table < 900cm.

USDA (1997) recommends that spray irrigation designs should not exceed the soil infiltration rate, taking into consideration the amount of surface micro-storage available and the length of time over which the water is applied. It provides detailed instructions about the extent to which application intensity should be reduced for sloping land. However, it only considers slopes of up to 8%. Table 3 shows an example of the recommendations presented in USDA (1997) for a 25 mm application depth. More detailed information is found within Chapter 2 of the document.

Table 3: Application intensity adjustment for slope in mm/h (USDA, 2007).

Intake Family (sprinkler)	**Slope**		
	0%	**3%**	**8%**
A	18	7.5	6
B	43	20	18
C	70	35	30
D	137	73	61

Note: This is for a 25mm application depth; recommended application intensities will be lower for larger application depths.

USDA (1997) recommends further reductions in the application intensity based on the condition of the soil. For example, the following factors may influence the infiltration rate of the soil (degree of potential influence shown in brackets):

- Organic content (±10%)
- Compaction (up to -50%)
- Hardpan (up to -50%)
- Vegetative cover (±20%)
- Erosion (up to -20%)

USDA (1997) provides further guidance for determining the degree of erodibility of different soils on different slopes (see Table 2-14 in USDA, 1997).

Based on the guidance provided by USDA (1997), the North Otago yellow-gray earths are likely to require application intensities of < 10 mm/hr.

Irrigation New Zealand has developed an irrigation design standard (INZ, 2007) that also includes some guidance for designing irrigation for hilly landscapes. It states that a site's topography, soil water holding capacity, and infiltration rate should be assessed prior to starting a design, but any specific guidance is limited to a discussion about the adjustment of application intensity on slopes. Table 4 shows the application intensities recommended by INZ (2007) for long applications (longer than 90-120 minutes) onto a range of slope angles.

Table 4: Application intensity adjustment for slope (INZ, 2007).

Soil group	**Slope**		
	0-14%	**14-22%**	**> 22%**
Sands and shallow sandy loams	32	25	20
Sandy loams over heavy subsoil	20	17	13
Medium loams over heavier subsoil	17	13	10
Clay loams over clay subsoil	13	10	8
Silt loams and silt clays	10	8	5
Clays	6	5	4
Peat	17	-	-

Note: This is for 90-120 minute application duration (i.e. the expected K_{sat}). Recommended application intensities may be higher for shorter application durations.

For applications of 20 minutes or less, INZ (2007) suggests that the application intensities presented in Table 4 may be safely multiplied by a factor of two. This means that for shorter application durations, the North Otago yellow-gray earths are likely to require application intensities of < 10-20 mm/hr. For longer-duration application events, an intensity of < 10 mm/hr would be required.

INZ (2007) does not recommend any adjustment to the application intensity unless the slope angle is > 14%. This is a different approach to both Savva & Frenken (2001) and USDA (1997).

INZ (2007) provides a general discussion about soil depth, suggesting that soils with a limited depth cannot hold as much water at once, and will require smaller applications of water.

INZ (2007) also discusses some of the hydraulic design issues encountered in hilly landscapes. It describes how elevation differences require careful consideration when selecting pumps, pipes, sprinklers, pressure regulators, and other system components so that an even application can be achieved at all points in the system.

In addition to the design guidelines, there are text books describing the design and operation of agricultural irrigation systems (e.g. Benami & Ofen, 1983; Hoffman *et al.*, 2007; Irrigation Association, 2011). These could not be reviewed in detail within the scope of this project, but an initial review of Benami & Ofen (1983) and Hoffman *et al.* (2007) shows that they provide a large amount of information on basic fundamentals, but do not include much specific guidance for irrigation on slopes. The Irrigation Association in the USA have recently published a new textbook (Irrigation Association, 2011) that promises to be the definitive guide on irrigation design, but this was not available in New Zealand at the time of this review.

3.2 Irrigation methods for hillslopes

Humans have been irrigating hillslopes for centuries (Crook *et al.*, 2008), although Aldridge *et al.* (1980) described a lack of experience with design, construction, and application of irrigation in the hill country in modern society. The limited nature of specific design guidance for hill country irrigation systems discussed in Section 3.1 seems to provide further indication of a deficiency in this area.

Aldridge *et al.* (1980) provided a good summary of some of the more traditional surface irrigation methods used on slopes (hillside terraces, contour race irrigation, border strips), as well as some more modern spray and drip methods (hand shift, solid set, roll line and tow line, travelling booms, travelling guns, centre-pivots, drip). This includes a discussion of the pros and cons of each of the irrigation methods, and is in general agreement with more recent assessments of irrigation suitability (e.g. USDA, 1997; Burt *et al.*, 2000; Newell *et al.*, 2002; McIndoe, 2004). This discussion is summarised in the following sections:

Surface methods

Surface irrigation methods require a water source at sufficient elevation to supply the water to the irrigation site by gravity. Erosion is the main risk with surface irrigation methods because they necessitate water flowing over the land surface. Some surface irrigation methods were in use on New Zealand hill country at the time of the review by Aldridge *et al.* (1980), but it is uncertain how common they are at present time.

- Hillside Terraces

  This is one of the oldest techniques for irrigating hillslopes, and involves levelling the land into steps or terraces to create flat surfaces for better water containment and infiltration. Aldridge *et al.* (1980) proposes that terracing could be useful in modern agriculture, although probably in a modified form. Terraces and levees are commonly used as an erosion control measure to slow the down-slope flow of water (Shaxon & Barber, 2003). They are also used in dryland situations to improve the natural infiltration of rainwater. Burt et al. (2000) pointed out that terracing is only feasible where soil depth is adequate to withstand the land modification procedure.

- Contour Race Irrigation

  This irrigation method requires that races are constructed across-slope, following contours approximately 40m apart. By this method, water is directed down a main race, then into the across-slope races. When the across-slope races are full, they overflow, watering the downhill surface. Any excess is caught by the next race. This method has been used in Central Otago on slopes of up to 20% (Aldridge *et al.*, 1980). Because of the high velocity overland flow generated, this method is likely to require a high infiltration rate and an erosion-resistant soil in order to be successful.

- Border Strip

  This method requires the levelling of land into narrow terraces that follow the natural contours. This results in curved border-strips of varying widths, each of which is likely to require a different volume of water to irrigate. This method has been used on slopes up to 3% in Marlborough and the Canterbury high country (Aldridge *et al.*, 1980) and is probably not suited to steeper slopes. If this method is implemented properly, it is likely to generate very little high-velocity surface flow. Thus, this is likely to result in the least soil erosion of the surface methods.

Spray methods

Burt *et al.* (2000) suggests that sprinkler irrigation is more suited to rolling topography than surface irrigation, particularly if the soil is too shallow to allow the re-shaping of the topography or too variable to allow efficient use of surface methods. A number of common sprinkler irrigation methods are reviewed for their suitability in the hill country:

- Hand Shift and Towable Sprinkler Systems

  This requires manual moving of individual sprinklers or lines of sprinklers. These systems are generally inexpensive to set up and apply water with a low application intensity (McIndoe, 2004). Burt *et al.* (2000) describe this as one of the best methods for hills. It allows for precise placement, allowing for the management of variable soil properties (USDA, 1997) and can be used on any slope that is able to walked on (Aldridge *et al.*, 1980) provided that adequate pressure and pressure regulation are provided (McIndoe, 2004). Labour requirements are likely to limit its use, particularly in situations where more than one shift is required per day. High-value crops are the most likely application.

- Solid Set

  Solid set systems consist of sprinklers that are permanently mounted on risers, usually in some sort of grid pattern. This is a low labour, high capital cost system that can be used on any slope (USDA, 2007) and can easily be automated (McIndoe, 2004). Water availability, pumping pressure, and soil infiltration characteristics are the limiting factors for how much area can be covered (Aldridge *et al.*, 1980). These systems offer a high degree of flexibility in management, and Burt *et al.* (2000) say this is one of the best technical solutions for hilly landscapes.

- Roll Line

  Aldridge *et al.* (1980) claims that these can easily be used on slopes of 10%, and have the potential to be used on slopes of up to 20% if locking devices are installed. However, USDA (1997) does not consider this a good technology for use on sloping land. This is old technology that has been largely replaced by more labour efficiency methods in the New Zealand market (McIndoe, 2004).

- Travelling Booms

  Fixed- and rotating-boom irrigators are limited by carriage stability, ground clearance, and drive power on hilly terrain (Aldridge *et al.*, 1980), and are best suited to rectangular-shapes paddocks (McIndoe, 2004). Work done by Newell *et al.* (2002) suggests that travelling irrigators may not be able to keep a constant speed on hills (and thus can't apply a constant depth), as they already struggle to do so on flat land. For rotating-boom machines, the travel speed and boom rotation speed are linked – windy conditions or hills will affect the rotation speed and travel speed of the machine, which in turn affects the water application pattern (McIndoe, 2004). Fixed-boom machines have independent drive mechanisms, but often have high application intensities unless high-pressure sprinklers are used (McIndoe, 2004). Aldridge *et al.* (1980) generally recommends higher pressure and faster travel speeds to minimise droplet impact and erosion.

- Travelling Guns

  Travelling guns have been used in New Zealand on slopes of up to 50% (Aldridge *et al.*, 1980). These are generally easy to shift, and require a relatively small capital investment (McIndoe, 2004). However, these machines require a very high operating pressure to achieve good coverage, generally resulting in high operating costs (McIndoe, 2004). Fast travel speeds (lower applied depth), high pressure operation (greater throw distance), and short return periods are recommended to achieve best performance on hills (Aldridge *et al.*, 1980). Management strategies include operating along ridges to spread water farther downslope on either side, along valley bottoms to throw water up the sides of hills, or adjusting the throw angle depending on the location within the property. Newell et al. (2002) describes the pond-and-drain application characteristics of gun system, which may cause runoff and erosion issues on hill slopes. USDA (1997) does not recommend the use of guns on hillslopes for this reason.

- Centre-Pivots

  Centre-pivots are being used on slopes of up to 20% (Aldridge *et al.*, 1980), but this may require alterations to tower drive systems, span lengths (shorter is more stable), span pipe thickness (thicker is stronger), and tower joints that will add to the already considerable capital investment. Centre-pivots allow for very low application depths, but have the potential for very high application intensity if the machines are too long (McIndoe, 2004). Overall, centre-pivots are a very low labour input, high capital cost option, that have the potential for a great deal of flexibility and control (e.g. “variable rate” technology, discussed further in Section 4.3).

Drip- and micro-irrigation methods

Drip- and micro-irrigation methods may be used on any slope, and in most soil types (USDA, 1997). These are very expensive to install, and are thus typically used only for high-value crops (e.g. grapes or trees) (McIndoe, 2004). They require careful design and pressure regulation, but are easily automated and are often highly efficient (McIndoe, 2004), with very little opportunity for the generation of surface runoff or erosion. Labour input is primarily restricted to regular maintenance activities.

3.3 Emerging technologies

There are several emerging technologies designed to extend the functionality of standard irrigation systems to cope with the special challenges of hill country irrigation.

Some **modern sprinkler designs** attempt to minimise application intensity and droplet impact energy to improve water infiltration and minimise soil damage. This appears to be particularly true of centre-pivot sprinkler manufacturers (e.g. Senninger, 2012; Nelson, 2012) who appear to be competing to design sprinklers with a maximum throw radius and selectable droplet sizes. Selecting sprinklers with smaller droplets and larger throw radius will reduce application intensity, but may be more affected by wind.

Soil moisture monitoring technology appears to be another big area of growth in the irrigation industry. There are many different ways to measure soil moisture (see Section 4.3), but measuring and managing spatial and temporal variability is a bigger (and arguably more important) challenge in hill country systems. Several high-tech, ground- and satellite-based methods for monitoring soil moisture are currently under development (e.g. Huisman *et al.*, 2003, Bittelli, 2011; Hedley & Yule, 2009; Basso, 2000), and these are discussed further in Section 4.3. Some recent studies also investigate methods for aerial mapping of other soil properties that are spatially variable, like soil texture (Heil & Schmidhalter, 2012).

Technologies to manage variability are being developed concurrently with the new monitoring techniques. Sadler *et al.* (2005) and Smith (2010) reviewed "**precision irrigation**" technologies, which are able to control the spatial distribution of applied water depth. These technologies can range from a simple on-off controller for individual sprinklers (Leib *et al.*, 2003) to computer control of multiple sprinklers on a moving boom over very precise and short time intervals (Sadler *et al.*, 2005; Smith, 2010). Many of the newer precision methods rely on a daily soil moisture model derived from satellite data (McCarthy *et al.*, 2010; Hedley & Yule, 2009; Basso, 2000). The focus of precision irrigation development has been primarily on centre-pivots, but the principles could be applied to any irrigation system. Both Sadler *et al.* (2005) and Smith (2010) identify the development of adequate information and decision support systems as the limiting factor for the adoption of precision irrigation technology.

GPS systems for placement of movable sprinklers are already commercially viable (e.g. Tracmap, 2010) and are being used for towable pod irrigation in New Zealand. These systems allow for the precise placement of sprinklers, which is particularly important within a variable landscape. As with precision irrigation technology, GPS placement technologies have the potential to be combined with remote sensing and soil moisture modelling methods.

3.4 Summary and discussion

Design codes exist that contain some information for designing irrigation systems for the hill country. But, these generally describe ways to modify "flat-land" techniques for hillslopes, and there are no guidelines specifically for hill country irrigation design. Most of the advice provided in the existing guidelines relates to decreasing the application intensity for sloping land. Some additional guidance is provided for hydraulic design for sites with excessive elevation differences, and for operating travelling irrigators on rolling topography.

None of the existing irrigation design guidelines appear to discuss the spatial variability of soil properties or how to manage them. This topic requires further work.

Some guidelines exist for choosing an irrigation system type, but these tend to be quite general, and are not widely circulated. Irrigation designers and operators require a better guideline for deciding how to irrigate in the hill country. In general, existing literature suggest that most surface irrigation methods are not well suited to the hill country, unless the slopes are moderate and the soils have a very high infiltration rate and an erosion-resistant structure. The best irrigation methods for reducing application intensity include drip/micro, solid-set, and hand shift or tow-line irrigation systems. The best irrigation methods for maximising control over the application depth include drip/micro, solid-set, and centre-pivot irrigation systems.

While the technology exists to be able to design, install, and manage highly efficient irrigation systems on hilly terrain, the best systems tend to be the most expensive. Work continues in this area. Some of the areas of current development include advanced sprinkler design, field- and catchment-scale soil moisture monitoring, variable application methods, and GPS guidance systems.

4 IRRIGATION SYSTEM MANAGEMENT

HCIP Preamble: *Knowing soil moisture levels and then managing irrigation accordingly is critical to the optimal application of water. Being able to determine the moisture level accurately and easily has been identified as something to improve on in the area.*

4.1 Management of the irrigation system

Many management practices that are applicable to irrigation of flat land also apply in the hill country, but may require special attention. INZ (2007), USDA (1997), and ORC (undated) provide good advice regarding management strategies that apply to all irrigation systems. Emphasis is placed on determining soil properties and matching irrigation applications to these.

As discussed in Section 2, soil properties of particular importance in hill country include soil infiltration rate (related to soil texture, macroporosity, organic matter content, hydrophobicity, etc.), soil depth (related to soil structure and layering), and soil water holding capacity (related to soil texture, soil depth, and organic matter content).

INZ (2007), USDA (1997), and ORC (undated) emphasise the importance of matching the application **intensity** to the soil water infiltration rate. The application intensity is primarily fixed at the design stage, and there is little a manager can do alter this. However, irrigation managers are likely to benefit from knowing the irrigation system's application intensity and how it relates to their soil infiltration rate, so they can make better decisions about when, where and how to irrigate. For example, soil infiltration rates are typically highest when the soil is dry (Hillel, 1998). So, irrigation systems with high application intensity could be set to operate at lower soil moisture "trigger levels" to maximise infiltration. A manager may also opt to irrigate for a shorter length of time and apply a smaller depth of water to avoid the lower infiltration rates experienced as the soil wets.

INZ (2007), USDA (1997), and ORC (undated) also emphasise the importance of matching irrigation **application depth** to the effective soil depth or rooting depth. An ideal application depth will not result in a soil moisture level greater than field capacity, but will supply enough water to the soil to keep it above the stress point until the next round of irrigation occurs. Large application depths can result in deep percolation (in well-drained soils) or saturation excess flow (if there is an impeding layer). Small depths may result in plant stress and reduced production if the return interval is not regular enough (Hsiao, 1973; Bray, 1997).

Application depth can be controlled by the irrigation manager in most cases by adjusting the length of time an irrigator operates, or by adjusting its travel speed (McIndoe, 2004). For stationary sprinklers, adjusting application depth involves a simple adjustment of on/off times. But, for many travelling irrigators, there is a limit to how much the travel speed (and thus, the application depth) may be practically adjusted.

The frequency of watering, or "**return interval**" should be matched to the application depth and soil water holding capacity, as discussed previously (INZ, 2007). Generally, systems with greater application depths can have longer return intervals (provided the soil can hold the water), and systems with shallower application depths require quicker return intervals. For stationary sprinklers and centre-pivots, adjustment of the return interval is easy – the frequency of operation may be set at any desired value. For movable sprinklers or travelling irrigators, the return interval will often be limited by the labour requirements to move the sprinklers. Generally, a return interval that requires sprinklers to be moved more frequently than every 12-24 hours, is not considered practical (McIndoe, 2004).

The spatial **variability** of both soil infiltration rate and soil depth complicates irrigation management in the hill country, as discussed in Section 2.1. Thus, quantifying this variability is important for good irrigation management. Areas with differing soil properties may need to be managed differently. For example, the operation of high intensity irrigation methods could be limited to areas with the highest soil infiltration rates. Or, the entire irrigation system could be managed based on "worst case" conditions to avoid the negative effects of runoff and erosion. Managing for "worst case" conditions would mean setting the application intensity and depth of the irrigation system to match the shallowest soil with the slowest infiltration rate.

There are also likely to be **soil-specific issues** that would benefit from particular irrigation management strategies. For example, the yellow-grey earths in North Otago would likely benefit from more regular wetting, to avoid hardening of the soil that can further reduce infiltration rate (ORC, undated). There is a need for more work investigating relevant soil-specific irrigation management practices for New Zealand hill country soils.

4.2 Non-irrigation management strategies that affect irrigation

In the hill country, there is a need to focus on irrigation management decisions that will maximise infiltration, and minimise surface runoff. But, it is also important to think about "non-irrigation" management decisions that affect irrigation. This is recognised by some of the research-oriented organisations in New Zealand, but has seen limited uptake with farmers (Bennett *et al.*, 1999). Several recent studies demonstrating the effectiveness of non-irrigation management strategies at increasing irrigation efficiency are discussed here.

The use of **management units** has been recommended as being particularly useful in hill country situations (e.g. Smetham, 1990; McDowell & Houlbrooke, 2009). Farms may be divided into management units based on differentiating factors such as slope angle, slope aspect, soil depth, or soil infiltration rate. These may be fenced off and/or managed separately. For example, different irrigation practices, pasture species, and/or stocking rates may be appropriate for different areas of a given farm.

Pasture species selection for the hill country also deserves renewed attention. Askin (1990) provides a good discussion of the history of pasture species used in New Zealand, and of the different factors affecting their use. While the discussion of particular cultivars is somewhat outdated (being over 20 years old), Askin (1990) makes the point that all relevant factors are not always considered when selecting pasture species for a particular area. It may be useful to include drought resistant species in a pasture mix, even under irrigated conditions (Skinner *et al.*, 2004), particularly when used on variable soils, where water infiltration is not well spatially distributed. It may also be useful to consider cold-tolerant species for use in the southern regions of New Zealand, and/or on shaded hill aspects. More work is required in this area.

Land use intensification has been shown to result in increased soil damage, including reduced water infiltration (McDowell *et al.*, 2008). White & Knight (2007) conducted a study in North Otago that showed that mowed land produced more pasture than cattle grazed lands, probably due to decreased impact on the soil. Reducing land use intensity (e.g. **stocking rates**) on sensitive soils may therefore help maintain soil quality. This could be combined with the management unit concept discussed previously.

Houlbrooke *et al.* (2011) showed that soil water content at the time of grazing had a bigger effect on soil compaction than stocking rate. **Grazing at lower soil moisture contents** resulted in less soil damage. Grazing at soil moisture contents close to, but slightly drier than, field capacity resulted in greatest compaction. Careful management of the timing of grazing events is likely to be more important in irrigated situations, because irrigation regularly returns the soil to wet (compactable) conditions and reduces natural recovery periods. Rest periods of several months may be necessary to recover soil properties damaged by grazing when the soil is too wet (McDowell, *et al.*, 2008).

Active soil management can also help to maintain or improve soil properties (e.g. macroporosity and organic matter content) that will in turn make irrigation more efficient (Hamza & Anderson, 2005). Soil management strategies are discussed in detail in Section 2.3, and are likely to make up an important part of a hill country farm's irrigation strategy.

4.3 Tools for irrigation management in the hill country

There are a number of existing and emerging technologies that have potential to aid hill country irrigation managers. The primary focus of this technology appears to be around measuring and managing variability within the landscape. Some of these technologies have already been discussed as emerging design tools in Section 3.3 (e.g. low intensity sprinklers, GPS guidance systems, and "precision irrigation").

4.3.1 Soil moisture monitoring

The scientific literature provides an in-depth discussion of soil moisture measurement, as this is the key soil factor that is being managed by irrigation. There exist several detailed reviews of soil moisture monitoring methods (e.g. Bittelli, 2011; Evett, 2007; Topp, 2003; Huisman *et al.*, 2003; Ahmad *et al.*, 2011), which are summarised in the following sections:

Direct soil water measurement

This method uses a physical sample of a soil to determine the weight of water as a fraction of the total soil weight (Bittelli, 2011). This is the most accurate method for measuring total soil water content, and is commonly used as the reference by which other methods are calibrated (Evett, 2007). This method is often too time-consuming to use as a management tool, so indirect methods were developed. All other methods discussed here are considered to be indirect methods.

Water balance methods

A water balance is an estimation technique that uses rainfall measurements and climate data to calculate water inputs and evapotranspiration, and estimates the quantity of water lost from the soil each day. There can be a high degree of uncertainty associated with this method, which is caused by a number of factors including spatial variability of rainfall and other climate variables, variability of soil depth and water holding capacity, surface runoff, and lateral fluxes of water within a soil profile. (Evett, 2007)

Soil water potential

This is a direct measurement of the suction required to extract water from the soil matrix (usually expressed in pressure units, e.g. kPa or Bar). Common devices include tensiometers, soil psychrometers, gypsum blocks, and granular matrix sensors (Evett, 2007). These will often require continuous recalibration if an accurate soil moisture value is required, as this relationship between soil moisture and soil water potential can change with time. However, the soil water potential is often useful as a management tool, as plants respond directly to this, not water content (Evett, 2007). In general, the available sensor types include:

- Tensiometers

  These are the oldest of the common soil water potential sensors (Or, 2001; Evett, 2007). They often consist of a porous tip connected to a pressure measuring device via a water-filled tube. The porous tip allows the exchange of water between the soil and the body of the tensiometer. If the suction in the soil is greater than / less than the suction in the tensiometer, water is drawn out of / into the tensiometer via the ceramic tip, and the pressure is measured by the pressure measuring device. Tensiometers may be easily data-logged (Stannard, 1990; Or, 2001), but are limited to suctions of less than 100 kPa – the approximate "stress point" of many irrigated pasture species.

- Gypsum Blocks

  A block of calcium sulfate with two wires connected to metal mesh electrodes. The block responds to changes in soil water content by absorbing and releasing water. The electrical resistance of the block is related to the soil water potential through a calibration curve. The sensors can be datalogged, and the useful range of soil suction readings is 150 to 600 kPa. (Evett, 2007)

- Granular Matrix Sensors

  These work by the same principles as gypsum blocks, but include coarser pores, allowing suction readings in the range of 10 to 200 kPa. (Evett, 2007).

- Soil Psychrometer

  The soil psychrometer senses the relative humidity (vapor pressure) of the soil pore space. The vapor pressure is related to both the soil matric potential and the osmotic potential, and so is useful in saline soils. They have a large measurement range of soil suction of approximately zero to 8,000 kPa. But, their fragility, sensitivity to temperature gradients and contamination, and requirement for expensive measurement circuitry mean that they are not commonly used for irrigation management. (Evett, 2007).

Local scale soil water measurement

There a number of sensors available to estimate soil water content at individual points. These do not actually measure soil moisture directly, but determine some other property of the soil that is assumed to be correlated to soil water content. One of the main advantages to field sensors is that they can provide continuous real-time information via dataloggers and/or telemetry systems. They can also provide details at different depths within the soil profile. Disadvantages include the need for sensor calibration for use in different soil types, non-standardised methodologies, and measurement of very small soil areas (~0.01 m^2) within a large, highly variable landscape. (Bittelli, 2011)

The website www.sowacs.com (Sowacs, 2012) provides a fairly comprehensive list of commercially available sensors. In general, the available sensor types include:

- Neutron Thermalisation (neutron probe)

  This method requires a high-energy neutron source and a low-energy neutron sensor. High energy neutrons are emitted into the soil, usually through an access tube, and low energy neutrons (slowed and reflected by collisions with water molecules) are measured. This method can be highly accurate, but requires empirical calibration to individual soils, and cannot be automated. As the equipment is a source of radiation, special safety precautions and licencing may be required. (Evett, 2007).

- Thermal Properties

  Thermal methods measure the heat dissipation from a heat source in contact with the soil (Bitelli. 2011). The wetter the block the faster is the dissipation of heat away from the heating element (Evett, 2007). There are few commercial examples of these types of sensors (Evett, 2007).

- Electromagnetic (EM) Methods

  EM methods work by measuring a some change in an electromagnetic pulse (change in frequency, count of reflected pulses, phase angle, power loss, etc.) as it travels through the soil (Evett, 2007), and includes methods such as time domain reflectrometry (TDR) and its variant time domain transmission (TDT), capacitance, ground-penetrating radar (GPR), passive microwave, and remote active microwave or radar (Topp, 2003). These methods are easy to automate and data-log, and are becoming less expensive as more commercial variations become available.

  TDR and TDT appear to be the most popular of the EM methods for local scale soil moisture monitoring. TDR and TDT probes measure the velocity of a voltage increase along a probe in the soil, with wet soils slowing the pulse more than dry soils. TDR can be accurate in most soils, excluding those very high in organic matter or containing large amounts of high surface area clays. An accuracy of ± 0.02 m^3/m^3 may be expected without calibration (Evett, 2007). Probes may be any length (reported range is 0.05 to 1.5 m), with reduced accuracy and precision for very short probes.

Field and catchment scale soil water measurement

Individual, static sensors are not adequate for monitoring soil water content on a field or catchment scale. Some of the methods used for larger-scale soil moisture monitoring include:

- Ground Penetrating Radar (GPR)

  GPR techniques measure the propagation of electromagnetic waves through the ground. Huisman *et al.* (2003) describes in detail the four main variants of GPR that are used. In the case of the most commonly used systems, one antenna radiates short pulses of high-frequency (MHz to GHz) electromagnetic waves, and another antenna measures the signal as a function of time. These signals are calibrated to gravimetric soil water content measurements, eventually allowing estimation of the spatial distribution of soil moisture at the field-scale. To date, this technique has primarily been used for field-scale research projects, and not for irrigation management (Huisman *et al.*, 2003). It is uncertain from this review how this method would cope with hilly landscapes.

- Electrical Resistivity

  This method provides field-scale information by mounting electrical resistivity measuring equipment to a small vehicle, and recording it over time as the vehicle traverses a field. This method requires repeat measurement, and cannot be automated, but provides reasonably accurate and high-resolution information. (Bittelli, 2011)

- Remote Sensing

  Remote methods can include the use of visible, infrared, thermal, and microwave data to obtain soil moisture estimations over large areas through various calibration methods (Ahmad *et al.*, 2011). There is no need for manually repeated surveys with these methods as they are already automated. However, remote sensing methods provide lower resolution information than the previously mentioned "geophysical" methods (Bittelli, 2011).

4.3.2 Other tools for irrigation management

Some recent studies have investigated methods for aerial mapping of soil properties other than soil moisture, e.g. soil texture (Heil & Schmidhalter, 2012). Continued development of techniques to estimate the key soil properties discussed in Section 2.1 is important, as these affect the selection, design, and management of irrigation systems. Until more automated methods are developed, manual site surveys are required to establish soil properties.

Drewry et al. (2008) discusses some practical tools that have been developed in New Zealand for making location-specific grazing decisions based on soil quality, including a simple penetrometer, a look-up chart for grazing decisions, and some long-term soil quality management tools. Unfortunately these tools were not available for this review. Please refer to the original paper (p253, paragraphs 2 and 3) for further information.

The precision irrigation technologies discussed in Section 3.3 (see Sadler *et al.*, 2005 and Smith, 2010) warrant another mention here because they are not relevant only at the design stage. Technologies that allow irrigation operators to quantify variability and manage variable soils are likely to be extremely useful in hilly landscapes. Further development in this area should be encouraged.

4.4 Summary and discussion

Many management practices that are applicable to irrigation of flat land also apply in the hill country. But, management decisions including application intensity, application depth, and return interval may require special attention in hilly landscapes. As previously discussed, soil properties of particular importance in the hill country include infiltration rate, soil depth, and water holding capacity.

Application depth and return interval are the most commonly adjusted elements of an irrigation system. But, the extent that these may be adjusted may be limited by the technical specifications of the irrigator or the labour requirements for moving the equipment, particularly where very shallow application depths and short return intervals are required. This is less of an issue with drip/micro, solid-set, and centre-pivot systems.

Application intensity cannot be readily adjusted by management – this is generally fixed when the irrigation system is designed. However, irrigation managers are likely to benefit from knowing the irrigation system's application intensity and how it relates to their soil infiltration rate, so they can make better decisions about when and where to irrigate.

Of course, the spatial variability of soil and climate complicates irrigation management in the hill country. Quantifying this variability is important for good irrigation management, so that areas of land with differing soil properties may be managed differently. More work is needed here, particularly with regard to obtaining local information, e.g. for North Otago.

Some tools exist for measuring variability in soil properties. These are primarily aimed at quantifying spatial soil moisture variability. Current research is focusing on making this type of information available to irrigation managers in "real-time", although it appears as if this is not yet readily available on a commercial scale in New Zealand. "Precision irrigation" technologies are also under development that will allow for the management of different irrigation zones in a flexible manner.

In order to best manage soil-water-plant system, there is also need to consider management of the soil and plant components in addition to the irrigation component.

Pasture species selection for the hill country deserves renewed attention. While a lot of work has been done on this in New Zealand, all of the relevant factors may not always be considered by land managers when selecting pasture species for a particular area. It may be useful to reconsider the inclusion of drought resistant or cold-tolerant species in pasture mixtures, particularly in colder climates and on different hill aspects.

Active soil management can also help to maintain or improve soil properties that will in turn make irrigation more efficient. The timing of grazing events with optimal soil moisture contents is likely to be one of the most effective management strategies available for reducing soil compaction. Additional soil management strategies such as aeration, introduction of fallow periods, or application of soil amendments may also make up an important part of a hill country farm's irrigation strategy, depending on the soil types and risks present at the site.

The use of management units may also be particularly useful in hill country situations. For example, areas with different combinations of slope angle, slope aspect, soil depth, or soil infiltration rate may be managed separately.

This strategy is linked to the quantification of soil variability, and requires more work prior to implementation in New Zealand. For example, the scale and extent of variability in North Otago must be quantified before it can be determined whether or not it is possible to divide hills into effective Management Units in that region.

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