MANAGEMENT PRACTICES AND TECHNOLOGIES FOR REDUCING NITROGEN AND PHOSPHORUS LOSSES FROM SOILS RECEIVING FARM DAIRY EFFLUENT

A thesis presented in partial fulfilment
of the requirements for the degree of

Doctor of Philosophy
in
Soil Science

MASSEY UNIVERSITY

Palmerston North, New Zealand

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2012

This thesis is dedicated to my wife Jolanda,

and my children Nicholas and Jasmine.

Thank you for your encouragement,

inspiration and love!

ABSTRACT

The loss of nutrients to the aquatic environment caused by the irrigation of farm dairy effluent (FDE) is a prominent and contentious feature of dairy farming in New Zealand. This thesis investigates management practices and technologies with potential to reduce nitrogen (N) and phosphorus (P) losses in drainage water from mole and pipe drained dairy pasture soils irrigated with FDE.

Farm dairy effluent management was both monitored, using remote sensing technologies, and modelled on a case study farm. During the winter and spring of 2008, an estimated 7,890 m^3 of FDE was applied in excess of the soil water deficit (SWD). System constraints were the cause of about two-thirds (5,070 m^3) of this over-applied FDE volume. It was estimated that as much as 502 kg TN and 83 kg TP could have been lost to surface waters due to inadequate infrastructure. The two main system constraints were the farm's insufficient FDE storage capacity (2,000 m^3) and the inability of the farm's irrigator to apply small application depths (<8 mm). Furthermore, this study highlighted the significant loss of nutrients that can occur under FDE irrigation and reinforced the need for tools to assist farmers with FDE management.

A number of tools were developed to help farmers manage FDE irrigation. The use of a soil water balance, incorporating actual farm daily rainfall, is an effective method for informing the scheduling of FDE irrigations. Also, the risk of over-application of FDE to soils caused by travelling irrigator breakdowns or stoppages was substantially reduced by the use of a breakdown alert and automatic shut-off system developed and evaluated in this study.

Given the elevated risk of P losses from soils treated with FDE, a method of capturing P from drainage waters was investigated. A field experiment was conducted to quantify the ability of Papakai tephra, installed into mole and pipe drainage systems, to remove P from drainage waters. This drainage system reduced TP losses in drainage by about 50% (c. 0.14 kg P/ha) over a drainage season, which equated to a 2.8 kg P reduction for a 20-hectare effluent block.

As farmers frequently crop effluent block soils, the effect of summer forage cropping on nutrient losses was quantified. The practice of spring cultivating long-term dairy pasture, summer forage cropping and autumn regrassing increased the quantity of TN measured in drainage water, over three drainage seasons (2006 to 2008), by 84% (21 kg N/ha), compared to long-term pasture. If this study had commenced in spring with a more typical pattern of rainfall and drainage, this increase is estimated to have only been about 23.7% (5.9 kg N/ha). Based on these results, summer forage cropping is estimated to increase whole-farm drainage water N losses by about 5%, when 10% of a farm's area is cultivated each year.

Of the management practices and technologies studied, the greatest opportunity to reduce the losses of N and P to surface water from the case study farm's effluent block, is through investment in FDE system infrastructure, particularly adequate storage capacity, and the use of decision support and fail-safe tools to assist the implementation of *deficit irrigation* of FDE.

ACKNOWLEDGEMENTS

There are many people I want to acknowledge and thank for their contribution to this research study. Firstly, I thank Professor Mike Hedley, my principle PhD supervisor, for providing me with the opportunity to undertake this PhD study. Mike’s excellent guidance, continual support and feedback at various stages during this research study and thesis writing have been extremely valuable. This thesis has also benefited considerably from the advice and support I received of Associate Professor Dave Horne, my second PhD supervisor. Dave’s openness to discuss ideas and provide useful feedback is greatly appreciated.

I also thank my colleagues in the Institute of Natural Resources, Massey University, for their support. I especially thank; Lance Currie for managing the financial and technical support requirements of my research projects; Bob Toes for always being available to help and provide useful technical advice with experimental work; Ross Wallace, Ian Furkert, Glenys Wallace, Mark Osborne, Manuel Bermudez, Leighton Parker and Linda Yates for their assistance with laboratory and field work; Anne West for her guidance with statisitcal analysis; Dave Scotter for providing soil water balance information; Mike Bretherton for providing software programming expertise; Christine Christensen for her editorial feedback; and Liza Haarhoff for helping prepare this thesis for printing.

I want to acknowledge the staff of Massey University’s Farm Services and No.4 Dairy Farm for their assistance with field trials, and Mark Carter (DataCarter Ltd) for helping with the development of the irrigator fail-safe system. The research presented in this thesis has also benefited from the financial support and/or services provided by the following organisations; Fertilizer & Lime Research Centre (Massey University), Dairy Insight, Sustainable Farming Fund (MAF), DairyNZ, Harmonic Ltd, Horizons Regional Council, and Baycity Technologies Ltd.

I greatly appreciate the support and encouragement I have received from family and friends. Most importantly I thank Jolanda, my wife, for her love and understanding; and Nicholas and Jasmine, my children, for their patience and inspiration. I am also grateful to my parents, Brian and Anita, and my parents-in-law, Martin and Pita, for their support and care; and John Koolaard for providing helpful statistical advice and

encouragement. I also want to acknowledge Kelvin Squire, my intermediate level schoolteacher, who’s enthusiastic and inspirational teaching, and encouragement has had a significant influence on my educational aspirations ever since.

Ultimately, I thank our Creator for bringing into existence the astonishingly wondrous and beautiful world and universe we live in. In every aspect, I observe remarkable complexity, design and order, which not only make scientific inquiry possible but also fascinating and purposeful. I also thank Him for providing, through His Son, the values of integrity, grace and hope, which are the foundations of a meaningful life.

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CHAPTER 1: Introduction

1.1 Reasons for the study

At the time of writing this thesis, the New Zealand dairy industry produced exports worth approximately NZ$ 10 billion annually, making it the country's largest export earner and an important contributor to its economic prosperity. This achievement comes on the back of a period of rapid expansion and intensification in dairy farming. Between 1994 and 2009, the number of dairy cows increased by 50% nationally, to 4.25 million cows, and the area of grazed dairy pastures increased by 30%, to 1.52 million hectares (Livestock Improvement Corporation, 2009).

The rapid growth of dairying, however, has not been without environmental cost. In particular, increased nutrient losses from pastoral land to surface and ground water have been associated with a decline in the quality of the country's fresh water resource (Quinn *et al*., 1997; Wilcock *et al*., 1999; Ballantine *et al*., 2010). This has occurred despite the presence of legislation (Resource Management Act, 1991) requiring that the use of agriculture land should be managed to minimise negative impacts on the wider environment. Furthermore, continued high levels of non-compliance by farmers with local authority regulations, has been damaging to the industry's reputation and raised public awareness of the need to reduce the environmental cost. In particular, many farmers have had difficulty complying with regional council regulations for the management of farm dairy effluent (FDE). This is especially a problem on soils that allow a high degree of connectivity between drainage water and surface water bodies (i.e. 'high risk' soils), such as mole and pipe drained soils or soils prone to generating surface run-off due to factors such as low hydraulic conductivity or surface hydrophobicity (Houlbrooke *et al.,* 2004a). In New Zealand, mole and pipe drainage systems are widely used, including for intensive dairying in the Manawatu, Northland, Southland and Otago regions.

Over the past 15 years, land application has become the main method used for treating FDE in most regions of New Zealand. Compared with pond only treatment, land treatment substantially reduces the quantities of nitrogen (N) and phosphorus (P) from FDE that can contaminate surface waters (Houlbrooke *et al*., 2004b). However, surface runoff and/or drainage from poorly managed land application of FDE can still contribute to the eutrophication of fresh water rivers and lakes (Monaghan & Smith, 2004; Houlbrooke *et al.*, 2008). As a consequence, much effort has focused on research to improve FDE land treatment systems (Houlbrooke *et al.*, 2004a; Houlbrooke *et al.*, 2004b; Monaghan & Smith 2004). A key outcome of this work has been the development and evaluation of the deferred irrigation approach to FDE management. On mole and pipe drained soils the use of a more strict form of deferred irrigation, so called *deficit irrigation*, has been identified as best practice (Houlbrooke *et al.*, 2004b). *Deficit irrigation* involves deferring irrigation until the soil water deficit is larger than the minimum application depth of the irrigation system, as operated by the farmer. *Deficit irrigation* has been shown to minimise the losses of nutrients and pathogens from land applied FDE on mole and pipe drained soils (Houlbrooke *et al.*, 2004b; Collins *et al.*, 2007).

More recently, data on FDE land treatment system compliance with regional council rules has shown that nationally the level of full compliance has dropped from 64% in the 2007/08 season to 60% in the 2008/09 season (Ministry of Agriculture and Forestry, 2010). In part, this decrease in compliance reflects increased compliance monitoring and the inclusion of feed pads and other rainfall catchment areas in monitoring protocols, which were previously limited to farm dairies. However, the relatively high levels of continued non-compliance demonstrates that a significant proportion of dairy farmers continue to have problems with FDE management, particularly around storage and application techniques that avoid runoff of raw or partially treated FDE to surface waters.

Previous research studies have helped to establish how FDE land treatment should be managed to minimise direct losses of nutrients during FDE applications (Houlbrooke *et al.*, 2004b). However, there has been limited research conducted to determine what assistance farmers need to implement these practices effectively. In particular, there has been little attention given to the development and evaluation of tools that farmers require to enable them to consistently implement *deficit irrigation* at a farm scale. Greater technical assistance and research into the development of low maintenance, simple and fail-safe systems, have also been identified as important developments for reducing the risk of FDE runoff and, therefore, the risk of non-compliance (Davies *et* *al.,* 2007). In addition, the availability of farm-specific daily decision support information on soil and climate conditions is important for informing daily management. Accordingly, there is a need for further research to evaluate decision support and fail-safe tools to determine which ones will help farmers implement and manage *deficit irrigation* of FDE.

Once FDE applications are sufficiently well managed, to avoid losses of nutrients in surface runoff and/or drainage water occurring at the time of application (i.e. irrigation induced surface runoff and/or drainage), other nutrient management issues with FDE land treatment systems will also require mitigation. These issues include elevated P losses in rainfall-induced winter mole and pipe drainage water and the accelerated accumulation of potassium (K) in soils used for FDE land treatment. Phosphorus losses in rainfall-induced winter drainage, from mole and pipe drained soils, have been shown to be higher from land receiving FDE compared to non-effluent areas (Houlbrooke *et al*., 2003). In situations where drainage waters are excessively enriched in P, it has been proposed that the use of high P adsorbing materials, as fill in drainage ditches or in underground mole and pipe drainage networks, could be effective in trapping P before it can enter surface waters (Heal *et al.,* 2004; Monaghan *et al.,* 2005; Houlbrooke, 2005; McDowell, 2007).

New Zealand has an abundance of naturally occurring materials with high P adsorption capacities, such as soils and moderately weathered materials derived from volcanic tephra. Moderately weathered tephra, containing the mineral allophane, shows particular promise for removing P from wastewater (Ryden & Syers, 1975, Liesch, 2010) and could also be useful for removing P from mole and pipe drainage waters. Further research is required to evaluate the use of tephra filled drainage systems as a potential mitigation option for reducing P loss in mole and pipe drainage from FDE treated soils.

Another nutrient management problem on soils irrigated with FDE is the accelerated accumulation of soil K. Above-optimal soil K levels are undesirable on dairy farms as they increase the risk of metabolic disorders in dairy cows, such as hypocalcaemia (milk fever) and hypomagnesaemia (grass staggers). Summer forage cropping has been shown to be a useful strategy for reducing excessive levels of potassium (K) that can accumulate in soils receiving K-rich FDE (Longhurst *et al*., 2000; Houlbrooke *et al*., 2004b; Salazar *et al*., 2010). However, the cultivation of long-term pasture for growing summer forage crops, has the potential to also increase the loss of NO_3^- in drainage water (Shepherd *et al*., 2001; Monaghan *et al*., 2002; Smith *et al*., 2008). There are limited field-scale trials assessing the effect of spring cultivation of long-term pasture, summer forage cropping and autumn re-grassing on N and P losses in mole and pipe drainage. Therefore, further research is required to quantity these losses.

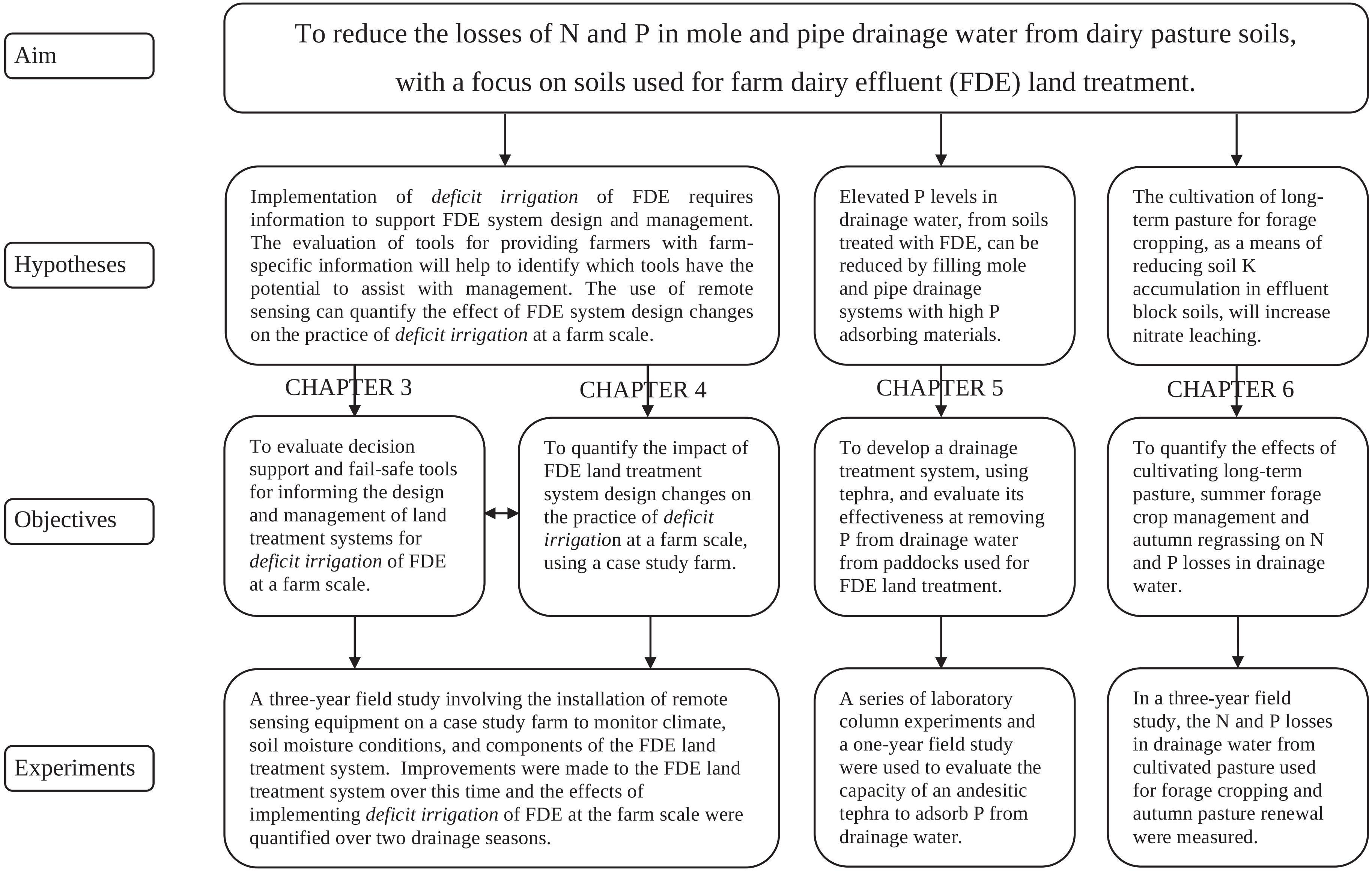
1.2 Research focus and objectives

The overarching aim of this thesis is to investigate management practices and technologies with potential to reduce the losses of N and P from mole and pipe drained dairy pasture soils, with a focus on soils used for FDE land treatment. The thesis has the following research objectives:

- To evaluate decision support and fail-safe tools for informing the design and management of land treatment systems for *deficit irrigation* of FDE to land at a farm scale.
- To quantify the impact of system design changes on the practice of *deficit irrigation* at a farm scale, using a case study farm.
- To develop a novel drainage treatment system, using andesitic tephra, and evaluate its effectiveness at removing P from drainage water from soils used for FDE land treatment.
- To quantify the effects of cultivating long-term pasture soils, summer forage crop management and autumn regrassing on N and P losses in drainage water from a mole and pipe drained dairy pasture soil.

1.3 Thesis structure

This thesis comprises seven chapters including this introduction chapter and a review of literature (Chapter 2). Chapters 3-6 report on the research experiments conducted in this study over a six-year period of part-time PhD research. Each of the four research chapters have their own introduction, materials and methods, results and discussion, and conclusions sections. A journal article arising from Chapter 5 was published in the *Australian Journal of Soils Research* (Hanly *et al.*, 2008). An overview of each of the four research chapters is provided in Figure 1.1. The main findings of Chapters 3-6 are discussed in a final summary (Chapter 7).



To reduce the losses of N and P in mole and pipe drainage water from dairy pasture soils, with a focus on soils used for farm dairy effluent (FDE) land treatment.

Implementation of *deficit irrigation* of FDE requires information to support FDE system design and management. The evaluation of tools for providing farmers with farm-specific information will help to identify which tools have the potential to assist with management. The use of remote sensing can quantify the effect of FDE system design changes on the practice of *deficit irrigation* at a farm scale.

Elevated P levels in drainage water, from soils treated with FDE, can be reduced by filling mole and pipe drainage systems with high P adsorbing materials.

The cultivation of long-term pasture for forage cropping, as a means of reducing soil K accumulation in effluent block soils, will increase nitrate leaching.

To evaluate decision support and fail-safe tools for informing the design and management of land treatment systems for *deficit irrigation* of FDE at a farm scale.

To quantify the impact of FDE land treatment system design changes on the practice of *deficit irrigation* at a farm scale, using a case study farm.

To develop a drainage treatment system, using tephra, and evaluate its effectiveness at removing P from drainage water from paddocks used for FDE land treatment.

To quantify the effects of cultivating long-term pasture, summer forage crop management and autumn regrassing on N and P losses in drainage water.

A three-year field study involving the installation of remote sensing equipment on a case study farm to monitor climate, soil moisture conditions, and components of the FDE land treatment system. Improvements were made to the FDE land treatment system over this time and the effects of implementing *deficit irrigation* of FDE at the farm scale were quantified over two drainage seasons.

A series of laboratory column experiments and a one-year field study were used to evaluate the capacity of an andesitic tephra to adsorb P from drainage water.

In a three-year field study, the N and P losses in drainage water from cultivated pasture used for forage cropping and autumn pasture renewal were measured.

Figure 1.1 An overview of the four main research chapters comprising this thesis.

1.4 References

Ballantine D, Booker D, Unwin M, and Snelder T (2010). *Analysis of national river water quality data for the period 1998-2007*. A report prepared for the Ministry for the Environment by National Institute of Water & Atmospheric Research Ltd (Updated December 2010, NIWA Project: MFE10502). 64p.

Collins R, McLeod M, Hedley M, Donnison A, Close M, Hanly J, Horne D, Ross C, Davies-Colley R, Bagshaw C, Matthews L (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research*, 50, 267-278.

Davies A, Kaine G and Lourey R (2007). Understanding Factors Leading to Non-compliance with Regulations by Dairy Farms. Environment Waikato Technical Report 2007/37 (www.ew.govt.nz). 58 pages.

Hanly JA, Hedley MJ, Horne DJ (2008). Evaluation of tephra for removing phosphorus from dairy farm drainage waters. *Australian Journal of Soil Research*, 46, 542-551.

Heal KV, Smith KA, Younger PL, McHaffie H, Batty LC (2004) Removing phosphorus from sewage effluent and agricultural runoff using recovered ochre. In *Phosphorus in Environmental Technology: Principles and Applications*, ed. V.-J. E., IWA Publishing. London, pp. 321-335.

Houlbrooke DJ (2005). A Study of the Quality of Artificial Drainage Under Intensive Dairy Farming and the Improved Management of Farm Diary Effluent Using 'Deferred Irrigation'. Chapter 11: Summary. PhD Thesis, Massey University, Palmerston North. 181-187.

Houlbrooke DJ (2008). Best practice management of Farm Dairy Effluent in the Manawatu-Wanganui region. Report prepared for Horizons Regional Council (February 2008). 44 pages.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA (2004a). The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research*, 47, 587-596.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR (2004b). Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deficit irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research,* 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2003) The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association* 65, 179-184.

Liesch AM (2010). Wastewater phosphorus removal by two different types of andesitic volcanic tephra. Journal of Natural Resources & Life Sciences Education, 39, 40-44.

Livestock Improvement Corporation (LIC) 2009. New Zealand Dairying Statistics 2008/09. Prepared by LIC and Dairy NZ. www.lic.co.nz. p7.

Longhurst RD, Roberts AHC, O'Connor MB (2000). Farm dairy effluent: a review of published data on chemical and physical characteristics in New Zealand. *New Zealand Journal of Agricultural Research,* 43:7-14

McDowell RW (2007). *Assessment of altered steel smelter slag and P-socks to remove phosphorus from streamflow and runoff from lanes*. Report prepared for Environment B.O.P. (June 2007). 19 pages.

Ministry of Agriculture and Forestry (2009). The Dairying and clean streams accord: snapshot of progress 2007/2008. Published in March 2009 by Ministry of Agriculture and Forestry (www.maf.govt.nz). 12 pages.

Monaghan RM, Paton RJ, Drewry JJ (2002). Nitrogen and phosphorus losses in mole and tile drainage from a cattle-grazed pasture in eastern Southland. *New Zealand Journal of Agricultural Research,* 45, 197–205.

Monaghan RM, Paton RJ, Smith LC, Drewry JJ, Littlejohn RP (2005) The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. *New Zealand Journal of Agricultural Research* 48, 227-240.

Monaghan RM, Smith LC (2004). Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research*, 47, 417–428.

Ryden JC, Syers JK (1975). Use of tephra for the removal of dissolved inorganic phosphate from sewage effluent. *New Zealand Journal of Science* 18, 3-16.

Salazar ME, Hedley MJ, Horne DJ (2010). Can turnips be used to reduce soil K loading on the effluent block? Proceeding from the NZ Grassland Association Conference, 72, 247-250.

Shepherd MA, Hatch DJ, Jarvis SC, Bhogal A (2001). Nitrate leaching from reseed pasture. *Soil Use and Management*, 17, 97-105.

Smith LC, de Klein CAM, Monaghan RM, Catto WD (2008). The effectiveness of dicyandiamide in reducing nitrous oxide emissions from a cattle-grazed, winter forage crop in Southland, New Zealand. *Australian Journal of Experimental Agriculture*, 48(1-2), 160-164.

Quinn JM, Cooper AB, Davies-Colley RJ, Rutherford JC, Williamson RB (1997). Land use effects on habitat, water quality, periphyton, and benthic invertebrates in Waikato, New Zealand, hill-country streams. *New Zealand Journal of Marine and Freshwater Research*, 31, 579-597.

Wilcock RJ, Nagels JW, Rodda HJE, O'Connor MB, Thorrold BS, Barnett JW (1999). Water quality of a lowland stream in a New Zealand dairy farming catchment. *New Zealand Journal of Marine and Freshwater Research*, 33, 683-696.

CHAPTER 2: Literature review

2.1 Introduction

Dairy farming in New Zealand has experienced rapid expansion and intensification over the past fifteen or more years. Between 1994 and 2009, the number of dairy cows increased by 50% nationally, to 4.25 million cows, and the area of grazed dairy pastures increased by 30%, to 1.52 million hectares (Livestock Improvement Corporation, 2009). This growth in dairying has increased the quantities of farm dairy effluent (FDE) being generated nationally. During this period the use of land application became widely adopted as the preferred method used for treating FDE in most regions. Accordingly, the management of FDE land treatment systems has become an important aspect of nutrient management on most dairy farms.

Farm dairy effluent consists of dairy cattle excreta, collected during the time cattle spend in the farm dairy and on yards, diluted with water used to wash the milking plant and farm dairy yards, and from rainfall collected on yards. The volumes and composition of cattle excreta collected and the volumes of wash water and rainfall collected vary between farms and over time on the same farm, therefore, the composition of FDE can also be highly variable. For example, Longhurst *et al.* (2000) reports that the solids content of FDE, sampled from more than 63 sites, varied from 0.04 to 5.2 % DM (average 0.9% DM).

Farm dairy effluent is typically rich in both organic and inorganic nutrients. Based on analyses conducted on up to 73 FDE samples (Longhurst *et al*., 2000) the average nutrient concentrations were 269 mg/L of total nitrogen (TN) (comprising 219 mg organic N/L; 48 mg ammonium N/L; 2 mg nitrate N/L), 69 mg/L of total phosphorus (TP) and 370 mg/L potassium (K). Wang *et al*. (2004) reported an average dissolved reactive P (DRP) concentration in FDE of 26 mg P/L based on 11 FDE samples. When applied in 10 mm FDE applications, these average TN, TP and K concentrations equate to 26.9 N/ha, 6.9 kg P/ha and 37.0 kg K/ha, respectively.

Prior to the widespread adoption of land application, a common method used for treating FDE in New Zealand was two-pond treatment systems. The standard design of two-pond systems comprises an anaerobic pond followed by a facultative (or aerobic) pond and the treated effluent is discharged to a receiving drain, stream or river (Sukias *et al.,* 1996). These systems were primarily designed to reduce microbial enteric pathogen populations, biochemical oxygen demand (BOD) and suspended solids (SS) in wastewaters, and, therefore, they are less effective at removing other potential contaminants, such as nitrogen (N), phosphorus (P), which also contribute to the continuing degradation of water quality (Sukias *et al*., 1996; Toor *et al.*, 2004; Wang *et al*., 2004; Muirhead *et al.*, 2008; Ballantine *et al*., 2010).

Since 1991, the Resource Management Act (RMA) has been the statutory framework for managing water quality and for restricting discharges to water (Forsyth, 1996). Implementation of the RMA has placed greater responsibility on regional councils to address surface water contamination, and has created a demand for increased enforcement of standards (Sukias *et al*., 1996). The need for improved treatment of FDE has led to the widespread adoption of land treatment in most regions of New Zealand.

Land treatment involves the application of FDE to land in order to use the soil/plant system to prevent potential contaminants (i.e. nutrients and faecal microbes) from being transferred to the aquatic environment in surface runoff and/or drainage water (Monaghan *et al*., 2007). Achieving effective treatment of microbial enteric pathogens, organics with BOD, and key growth limiting nutrients (i.e. nitrogen and phosphorus) involves retaining FDE in the soil's active root zone long enough to allow the soil to physically adsorb, biologically immobilise and transform these components, including using plant growth to attenuate soil nutrient loads (Houlbrooke *et al*., 2010). When land treatment systems are well managed they have the potential to minimise the losses of all potential contaminants to surface and ground waters (Houlbrooke *et. al*., 2004b; Monaghan and Smith 2004; Wang *et al*., 2004). In addition, the application of FDE to land has the additional benefit of improving pasture and crop production by providing a source of irrigation water and by improving soil fertility (Roberts *et al.*, 1992; Di *et al.*, 1998; Degens *et al.*, 2000; Bolan *et al.*, 2004). Re-application of FDE to land can represent a potential saving of 10-15% in a farm's annual fertiliser requirements (Monaghan *et al*., 2007).

Although land treatment is designed to reduce the quantity of nutrients transferred to waterways, compared to two-pond treatment and direct discharge to stream, problems can still result if not well managed (Houlbrooke *et al*., 2004c). Excessive FDE application rates or inappropriate timing of applications and excessive drainage can lead to a range of adverse effects, including; nitrate (NO_3^-) leaching, overland flow and surface water contamination by nutrients and faecal microbes, waterlogging of soils, and soil nutrient imbalances that can result in animal health problems (Cameron & Di, 2004; Houlbrooke *et al*., 2004b; Monaghan & Smith, 2004; Wang *et al.*, 2004; Hawke & Summers, 2006).

Farm dairy effluent contains N in mainly organic and ammonium forms, and typically contains very little NO_3^-. Therefore, the risk of NO_3^- leaching from land applied FDE will be related to nitrification activity of FDE treated soils and whether this results in an increased accumulation of soil NO_3^- immediately prior to a period of drainage (Di & Cameron, 2002). Studies involving the application of farm effluents and fertilisers to soil lysimeters have shown that NO_3^- leaching from FDE is generally lower than from urea and ammonium fertilisers applied at the equivalent rate of N (Di *et al*., 1998; Silva *et al*., 1999). The lower NO_3^- leaching from FDE has been attributed to it containing a proportion of organic N, which needs to go through both mineralisation and nitrification before being converted to NO_3^-. Farm dairy effluent applied at annual loads of up 200 kg N/ha/year has been shown to cause minimal increases in NO_3^- leaching in seasonal (i.e. winter/spring) rainfall-induced drainage, particularly when applied in split applications or during summer (Silva *et al*., 1999; Cameron & Di, 2004). Because most regional councils currently have a maximum limit either 150, or, 200 kg N/ha/year permitted to be applied to land as FDE, it is unlikely that substantial elevated NO_3^- leaching will occur when these limits are adhered to.

Nutrient budgeting, using a model like OVERSEER®, can be used to estimate the required size of a farm's effluent block to achieve the required annual N load (Wheeler *et al*., 2006; Monaghan *et al*., 2007). However, even when the annual N loading rate of

FDE is well managed to adhere to regional council limits, other nutrient management issues can still occur. Other key issues that have been identified are:

i. Direct losses of nutrients and faecal microbes from FDE-induced surface runoff and drainage at the time of application (Houlbrooke *et al.*, 2004b; Monaghan & Smith, 2004; Houlbrooke *et al.*, 2008),
ii. Higher indirect losses of P in seasonal drainage from effluent blocks (Nash and Murdoch, 1997; Monaghan *et al.,* 2002; Houlbrooke *et al.,* 2003), and
iii. Excessive accumulation of K in effluent block soils (Salazar et al., 2010).

This review of literature focuses on the aforementioned nutrient management issues, with the aim of identifying gaps in knowledge that could inform improved management of FDE land treatment systems. Section 2.2 focuses on reviewing literature relating to the causes of direct losses of nutrients and pathogenic microbes in FDE-induced surface runoff and drainage at the time of application. This section also discusses the use of *deficit irrigation* for minimising direct losses of nutrients to surface waters during FDE applications. Section 2.3 focuses on literature on the indirect losses of P in seasonal drainage from effluent blocks and explores the potential for using "end of pipe" treatment methods for removing P from drainage waters. Section 2.4 reviews the literature on the use of forage cropping to lower soil K levels in effluent blocks. The potential impact of forage cropping on increasing nutrient losses, particularly on NO_3^- leaching, is also discussed.

2.2 Implementing deficit irrigation to minimise the risk of FDE-induced surface runoff and drainage

2.2.1 FDE-induced surface runoff and/or drainage

One of the major pathways for nutrients, and other potential contaminants, to be lost during land application of FDE is the immediate generation of FDE-induced surface runoff and/or drainage. This occurs when individual FDE irrigation events exceed the soil's infiltration, or, water holding capacities, respectively (Houlbrooke *et al.*, 2004b; Monaghan *et al.*, 2007). These losses are important as they can represent a relatively large proportion of the quantities of contaminants, especially P, transferred from dairy farms to surface waters (Houlbrooke *et al.*, 2004b; Monaghan & Smith, 2004).

In a study conducted on a mole and pipe drained dairy farm soil in the Manawatu region, Houlbrooke *et al*. (2004b) quantified the consequence of applying a 25-mm

FDE irrigation on nutrient losses to surface water, when the soil water deficit (SWD) was 6 mm. This single irrigation event resulted in 8 mm of surface runoff and 10 mm of drainage, which combined contained the equivalent of 42% (or 12 kg N/ha) and 23% (or 1.9 kg P/ha) of the quantities of TN and TP, respectively, present in the applied FDE. These nutrient losses equate to almost half of the TN and about one and a half times the TP that is typically transferred to the aquatic environment from grazed dairy pastures annually on a per hectare basis (Houlbrooke *et al.*, 2004b; Houlbrooke, 2005). At the same research site, Hedley *et al*. (2005) studied the effect of an 8 mm FDE irrigation, when the SWD was < 2 mm, on the transfer of the enteric pathogen *campylobacter* in FDE-induced surface runoff and drainage. Thermophilic *campylobacter* in the originally applied FDE ranged from 460 to >1,100 MPN/100 ml. This irrigation event caused 2.8 mm of surface runoff and 2.3 mm of drainage on average, which also had *campylobacter* concentrations of >1,100 MPN/100 ml at peak flow rate.

On a mole and pipe drained dairy farm soil in the West Otago region, Monaghan & Smith (2004) also reported the occurrence of FDE-induced drainage caused by FDE irrigations made at application depths greater than the SWD. The concentrations of TN, TP and faecal microbes (*Escherichia coli*) measured in some of the drainage samples collected were also similar to that of the originally applied FDE. At the same site, Ross & Donnison (2003) observed that when FDE irrigations caused preferential flow, *campylobacter* concentrations in the drainage water were also similar to those in the applied effluent. These studies demonstrate that land treatment of FDE under certain conditions can result in significant losses of contaminants to surface waters. In order to minimise these losses it is important to understand the factors that influence them. The main causes of FDE-induced surface runoff and drainage have been identified as:

i. Soil and landscape risk factors (McLeod *et al*., 2008; Houlbrooke & Monaghan, 2010),
ii. Soil moisture conditions at the time of irrigation (Houlbrooke *et al*., 2004b; Monaghan & Smith, 2004) and
iii. FDE irrigator performance (i.e. application depth and rate; Houlbrooke *et al*., 2004a; Monaghan & Smith, 2004; Houlbrooke *et al*., 2006).

2.2.2 Soil and landscape risk factors

The critical soil and landscape risk factors that influence contaminant losses during FDE irrigations are those that lead to the generation of overland flow and/or drainage through macropores (preferential flow). Houlbrooke & Monaghan (2010) describe the three primary transport mechanisms as being matrix flow, preferential flow and overland flow. Of these, both preferential flow and overland flow have been identified as the main pathways by which potential FDE contaminants can be rapidly transferred in FDE-induced surface runoff and/or drainage to surface water. These losses occur when FDE applications are made in excess of the SWD and/or when the application rate of FDE is higher than for the soil's infiltration rate. Accordingly, Houlbrooke & Monaghan (2010) recommend that FDE management practices should be matched with soil and landscape features in order to prevent direct losses of FDE contaminants.

Soils with artificial drainage, very coarse soil structure, impeded drainage or low infiltration rates, or, on sloping land (>7^{o}) were identified as having high potential for generating either preferential flow or overland flow when FDE was applied to soils in excess of the SWD (i.e. 'high risk' soils). McLeod et al. (2008) also assessed the potential for different soils to allow the contaminants in land applied FDE to by-pass the soil matrix via preferential flow. McLeod et al. (2008) generated microbial breakthrough curves for twelve New Zealand soils, which commonly occur in dairying regions, to help classify them based on their potential for faecal microbe by-pass flow during FDE irrigations. Soils were grouped as having high, medium, or low potential, for microbial bypass flow. Soils with a coarse soil structure tended to have high potential for by-pass flow. In contrast, soils with a fine, porous nature were classified as having a low potential for by-pass flow.

2.2.3 Soil moisture conditions

Houlbrooke & Monaghan (2010) recommend that to minimise the risk of preferential flow or overland flow occurring during FDE irrigation on to 'high risk' soils, then management needs to take into account soil moisture conditions. The use of more strict deferred irrigation criteria, called *deficit irrigation*, has been advocated as it has been shown to minimise the losses of nutrients and faecal microbes applied in FDE to 'high risk' soils and landscapes such as mole and pipe drained soils (Houlbrooke *et al*., 2004b; Monaghan & Smith, 2004). *Deficit irrigation* involves the storage of FDE and then only applying FDE at application depths smaller than the SWD. Houlbrooke *et al.* (2004b) evaluated *deficit irrigation* of FDE over three years on a grazed dairy pasture soil with mole and pipe drainage. During the study the application of FDE using *deficit irrigation* resulted in minimal direct losses of nutrients to surface waters, with less than 1% of the total N and P applied as effluent nutrients being lost. Monaghan & Smith (2004) also observed that when the highest application depth of the irrigator's application profile was less than the SWD then no direct drainage of FDE occurred.

2.2.4 FDE irrigator performance

The third important factor influencing whether FDE-induced surface runoff, or drainage, occurs during irrigation is the performance of the irrigation system. Small rotating travelling irrigators, commonly used for FDE irrigations, have traditionally had relatively high instantaneous application rates, usually greater than 100 mm/hr, and poor application depth uniformity, with a two- to three-fold difference between the highest and lowest application depths (Houlbrooke *et al.*, 2004a; Monaghan & Smith, 2004). The risk of preferential flow and overland flow increases with application rates. McLeod *et al*. (1998) demonstrated that application rates ≤ 10 mm/hour minimised leachate movement into subsoils. Houlbrooke *et al.* (2006) also showed that the use of low rate applicators (e.g. temporary in-place sprinkler systems), delivering rates of ≤ 4 mm/hour, decreased the potential for preferential flow and increased the likelihood of retaining the applied nutrients and faecal microbes in the soil's root zone. Also, Houlbrooke *et al.* (2006) showed that low rate applicators reduced the risk of exceeding a soil's infiltration capacity, thus preventing ponding and overland flow of applied FDE. The use of irrigators capable of irrigating FDE at low application rates and depths also increases the scheduling opportunities during periods of very low SWDs (i.e. winter and early spring) and, therefore, reduces the FDE storage capacity required to practice *deficit irrigation* in some regions (Monaghan *et al.*, 2007).

Another important cause of excessive applications of FDE is when travelling irrigator breakdowns or stoppages occur. Travelling irrigator breakdowns are a common cause of non-compliance with regional council regulation (Davies *et al.*, 2007), because they result in very high FDE application depths, due to the irrigator stopping in a single place and applying FDE to a small area for extended periods. While some causes of irrigator breakdowns can be avoided, for example, through irrigator maintenance or checking the strength of irrigator anchor points, other causes can be difficult to foresee and prevent without constant monitoring of the irrigator. Therefore, in order to reduce this risk a fail-safe system may be required, which can automatically turn off the irrigator pump when an irrigator breakdown occurs.

2.2.5 Deficit irrigation of FDE

Although *deficit irrigation* has been researched at the paddock scale and has been shown to be best practice for 'high risk' soils and landscapes, its implementation at the farm scale has not been researched. As previously discussed, the principles of *deficit irrigation* are relatively simple, involving the storage of FDE and only irrigating to land when it can be applied at an application depth less than the SWD. However, the ability of a farmer to adopt and consistently manage *deficit irrigation* will depend on a number of critical factors, which include: climate, soil drainage characteristics and land slope, rate of FDE generation, FDE storage capacity, type of irrigation system, labour availability and skills, and access to decision support information. Therefore, information is required to identity the type of changes individual farms need to make and the tools they require in order to allow them to consistently practice *deficit irrigation*.

In New Zealand, during the lactation season, land treatment of FDE has commonly involved the daily collection of FDE in a small concrete sump as yards and the farm dairy are washed after each milking. A centrifugal effluent pump, which pumps effluent directly to a small rotating travelling irrigator, automatically empties the sump. These systems typically have only enough storage capacity to store the quantity of FDE generated over a period of < 3 days, consequently, there is minimal storage buffer to allow FDE irrigation to be deferred based on soil moisture conditions. Therefore, land treatment by *deficit irrigation* of FDE has additional design and management requirements, compared with daily irrigation systems, which are critical to the performance of the system (Houlbrooke *et al.*, 2004a). Three key requirements needed for the successful practice of *deficit irrigation*, are:

i. Adequate farm-specific FDE storage capacity (Houlbrooke *et al.*, 2004b),
ii. Scheduling irrigations guided by accurate daily SWD information (Houlbrooke *et al.*, 2004b),
iii. Reliable irrigator operation (Davies *et al.*, 2007).

Storage of FDE is a key component of many land application systems because it provides flexibility in scheduling FDE irrigations. In the past, FDE storage requirements were determined using average estimates for the number of days that storage was required and industry averages for FDE generation (Dexel, 2007). However, the required size of FDE storage capacity will vary between farms and also between years on the same farm. For example, there can be as much as a five-fold difference in storage requirements between farms solely due to soil type differences (i.e. different ‘soil risk’ categories). Accordingly, the use of industry averages is unlikely to be adequate for consistently determining FDE storage requirements for individual farms.

Given the crucial role of storage in determining whether or not *deficit irrigation* can be practised, it is recommended that farm-specific information is used when calculating the storage needs of individual farms. It is also important to account for the influence that that year-to-year climate variation has on storage requirements. Farm dairy effluent storage capacity can represent a significant capital investment. Therefore, it is important to determine the correct amount of storage capacity required for individual farms rather than using industry averages or a ‘one size fits all’ approach, which can result in some farms being over capitalised and others having inadequate storage facilities. Therefore, further information is required to develop a method for farmers to determine their farm-specific FDE storage requirements.

Farmers also require daily information on the size of the SWD to inform when it is safe to irrigate and how much to apply. Estimates of soil moisture need to have a high degree of accuracy and reliability because of the potential environmental consequences and financial penalties associated with applying FDE in excess of the SWD on ‘high risk’ soils and landscapes (Houlbrooke *et al.*, 2004b; Davies *et al.*, 2007). Much past research has focused on comparing different methods for measuring soil moisture for the purpose of informing the scheduling of water irrigation in summer. However, there is limited research information on the effectiveness of different methods for accurately measuring small SWDs (i.e. < 10mm) during winter and early spring when soils are at or near field capacity. This level of accuracy is necessary for scheduling FDE to comply with *deficit irrigation* criteria, particularly during winter and spring, when the risk of surface runoff and drainage are greater due to wet soil conditions. Therefore, an assessment of methods for accurately estimating small SWDs is required to determine their usefulness for informing the scheduling of FDE irrigations.

2.2.6 Research needs

To date, relatively little attention has been paid to the need to equip farmers with the knowledge and tools that they need to successfully design and manage FDE land treatment systems. Some of the major factors affecting farmers' decision making can include the ease and technical compatibility of the solution and testability or validity of the solution (Guerin & Guerin, 1994). Frost (2000) points out that the solutions to resource management and farming system problems require both technical information and investment in personal development. Ridley (2004) explains that the most obvious areas that science can assist farmer decision making, regarding environmental management, includes the development of solutions that are simple, practical and compatible with the farmer's existing knowledge.

Davies *et al.* (2007) reports the results of a survey of Waikato dairy farmers in relation to their views on the causes of FDE system non-compliance with regional council regulations. In the study it was concluded that the performance of FDE land treatment systems could be improved by the provision of technical assistance for system design and management, and that there was a need for research into the low maintenance, simple and fail-safe systems.

In order to assist farmers implement and manage *deficit irrigation* land treatment systems, this literature review has identified the following key questions that require further research:

i. What is an effective method for estimating farm-specific FDE storage requirements?
ii. Which method of determining soil moisture conditions will be sufficiently accurate and accessible to allow farmers to schedule FDE irrigations using *deficit irrigation* criteria?
iii. What type of fail-safe system for travelling irrigators will provide an effective method of preventing the over-application of FDE associated with irrigator breakdowns or stoppages?

iv. What are the quantifiable benefits of deploying the decision support and fail-safe tools for FDE management that are assessed in this study?

2.3 Losses of P in seasonal drainage waters from artificially drained effluent block soils and the potential for using “end of pipe” treatment methods for P removal

2.3.1 Prior research

Mole and pipe drainage systems are commonly employed by intensive agriculture in temperate regions of the world to overcome the imperfect drainage caused by fine textured sub-soils. In New Zealand, mole and pipe drainage systems are widely used, including land used for intensive dairying in the Manawatu, Northland, Southland and Otago regions. Accelerated P loss in surface runoff and in mole and pipe drainage water from dairy farms has been reported and quantified in a number of research studies (Sharpley and Syers, 1979; Nash and Murdoch, 1997; Monaghan *et al.*, 2002; Houlbrooke *et al.*, 2003). As discussed in the previous section, P losses can be accelerated when FDE applications to land cause immediate surface runoff or drainage (Houlbrooke *et al.*, 2004b). However, P losses in rainfall-induced winter and spring drainage have also been shown to be higher from dairy pasture soils receiving FDE compared to non-effluent areas.

Houlbrooke *et al*. (2003) quantified the dissolved reactive (DRP) losses in winter and spring drainage waters from eight mole and pipe drained grazed dairy pasture plots during 2002. Four plots received a total application of 63 mm of two-pond treated FDE, spread over seven applications (average of 9 mm per application), during summer months when the SWD was > 20 mm, while the other four plots did not receive FDE (i.e. non-effluent plots). Farm dairy effluent irrigations did not induce drainage at any of the seven applications, due to irrigation depths being smaller that the SWD at the time of application (i.e. *deficit irrigation*). However, the DRP losses in rainfall-induced drainage, during the subsequent winter and spring, were about four times higher from the four plots that had received the summer FDE applications compared to the non-effluent plots on average, being 0.51 and 0.13 kg P/ha, respectively. The average DRP concentration in drainage water from the effluent plots was 0.18 mg P/L, which is well above the 0.01 mg P/L concentration that is considered to be the trigger level for promoting aquatic weed and algae growths in lowland streams and rivers (ANZECC, 2000). Following another season of *deficit irrigation* at this site in 2003, Houlbrooke *et al*. (2008) reported DRP losses in winter/spring rainfall-induced drainage of 0.77 and 0.14 kg P/ha for the effluent and non-effluent plots, respectively.

Monaghan & Smith (2004) also observed a carry-over of increased P losses from applied FDE to subsequent drainage events. In contrast to Houlbrooke *et al.* (2003), the additional P losses measured by Monaghan & Smith (2004) were mostly attributed to increases of dissolved organic P (DOP) rather than DRP.

Elevated P losses in winter and spring drainage waters are difficult to prevent through management alone, as they were generally not associated with excessive or poorly timed applications of FDE. Accordingly, the use of ‘end of pipe’ treatment methods may be necessary to reduce these losses. In situations where drainage waters are excessively enriched in P, it has been suggested that the use of high P adsorbing materials, as fill in drainage ditches or in underground mole and pipe drainage networks, could be effective in trapping P before it can enter surface waters (Heal *et al.*, 2004; Monaghan *et al.*, 2005).

2.3.2 P removal systems

Much of the research conducted on the capacity of P adsorbing materials to remove P from water has focused on their use in constructed wetland systems (Mann, 1997; Sakadevan and Bavor, 1998; Tanner *et al.*, 1999; Brix *et al.*, 2001; Gruneberg and Kern, 2001; Pant *et al.*, 2001; Naylor *et al.*, 2003; Heal *et al.*, 2005; Drizo *et al.*, 2006). Constructed wetlands, with subsurface flow, are widely used throughout the world to treat a wide variety of wastewaters (Del Bubba *et al.*, 2003). However, constructed wetlands generally have a greater potential to remove N, by biological denitrification, than they do to remove P (Arias *et al.*, 2001). The main methods of P removal from wastewaters in constructed wetlands are sediment trapping, plant uptake, assimilation by micro-organisms and physico-chemical processes. Among the physico-chemical processes, P adsorption by soil/media and precipitation reactions play an important role (Del Bubba *et al.*, 2003). Phosphorus removal efficiency is often high initially and then decreases after some time as the P adsorption capacity of the media is exhausted. Accordingly, it is important to select a media with a high P adsorption capacity for sustained P removal over the long term (Arias *et al.*, 2001).

2.3.3 High capacity P sorbing/precipitating materials

The material properties important for influencing P adsorption include the presence of minerals with reactive iron (Fe) or aluminium (Al) hydroxide or oxide groups on their surfaces, and calcareous materials, which can promote calcium (Ca) phosphate precipitation (Zhu *et al.*, 1997; Drizo *et al.*, 1999). Also, adsorption is controlled by the material's pH dependent surface charge and adsorptive surface area. Materials with small particle size have large surface areas for a given volume and, therefore, the potential to enhance P adsorption capacity (Zhu *et al.*, 1997). However, materials with smaller particles size, when packed in beds, also have lower hydraulic conductivity, which can lead to the occurrence of the either restricted flow or by-pass flow. The latter can result in insufficient contact between the wastewater and the media within the constructed wetland (Drizo *et al.*, 1999). Anion competition, such as the competitive adsorption of phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}), is another factor that needs consideration when evaluating the effectiveness of media to adsorb P from drainage or wastewaters (Parfitt, 1982; Ryden *et al.*, 1987). Table 2.1 provides a list of materials used in studies to assess their potential to remove P from solution.

Table 2.1 List of materials used in studies to assess their potential to remove P from solution.

Materials	**Publications**
Naturally occurring materials:	
Gravel	Mann, 1997; Naylor *et al*., 2003
Sands	Arias *et al*., 2001; Brix *et al*., 2001; Pant *et al*., 2001; Del Bubba *et al*., 2003
Soils	Sakadevan & Bavor, 1998
Peat	Naylor *et al*., 2003
Tephra	Ryden & Syers, 1975; Liesch, 2010
Allophane, ferrihydrite, goethite	Parfitt, 1989
Sandstone	Mann, 1997
Limestone	Baker *et al*., 1998; Drizo *et al*., 1999; Arias *et al*., 2003; Naylor *et al*., 2003; Shilton et al., 2005
Serpentinite	Drizo *et al*., 2006
Dolomite	Pant *et al*., 2001
Zeolite	Sakadevan & Bavor, 1998; Drizo *et al*., 1999
Shale	Drizo *et al*., 1999; Pant *et al*., 2001
Bauxite	Drizo *et al*., 1999
Synthetic/ manufactured materials:	
Light expanded clay/ light-weight aggregates	Zhu *et al*., 1997; Drizo *et al*., 1999
Activated aluminium oxide	Baker *et al*., 1998; Genz *et al*., 2004
Iron/calcium oxide	Baker *et al*., 1998
Granulated ferric hydroxide	Genz *et al*., 2004
Waste materials:	
Coal combustion fly ash	Mann, 1997; Drizo *et al*., 1999; McDowell, 2005
Burt oil shale	Drizo *et al*., 1999
Ochre from mine drainage treatment	Heal *et al*., 2005
Steel industry slags	Mann, 1997; Sakadevan & Bavor, 1998; Gruneberg & Kern, 2001; Naylor *et al*., 2003; Shilton *et al*., 2005; Drizo *et al*., 2006; Shilton *et al*., 2006

A number of research studies have focused on using high P adsorbing materials as ‘active’ filters, which are separate filtration units attached to constructed wetlands or wastewater treatment systems (Arias *et al.*, 2003; Shilton *et al.*, 2005; Shilton *et al.*, 2006). Shilton *et al.* (2005) explains that the term ‘active’ refers to chemical properties of a media that support treatment mechanisms, in addition to the media’s physical filtering ability.

Sakadevan & Bavor (1998) assessed the P adsorption capacities of soils, two industrial by-products and a zeolite for their potential as substrates to remove P in constructed wetlands. Both Freundlich and Langmuir adsorption isotherms were used to describe the adsorption characteristics of these substrates. One of the industrial by-products, namely blast furnace slag, showed the highest P adsorption capacity of 44.2 g P/kg slag. The soil samples, which were collected from an operating constructed wetland system, had P adsorption capacities of 4.2 to 5.2 mg P/g soil. The zeolite had a P adsorption capacity of 2.15 mg P/g zeolite. While the adsorption capacity of the slag was very high, this was achieved using solution P concentrations of up to 8,000 mg P/L (Figure 2.1). Consequently, this level of P adsorption capacity may not be achievable in the field when used to treat wastewaters or drainage waters with much lower P concentrations. For example, typical values for sewage treatment plant wastewaters are < 10 mg P/L (McArthur & Clark, 2007), farm dairy effluents (FDE) < 50 mg P/L (Longhurst & Nicholson, 2011) and dairy farm drainage waters < 0.5 mg P/L (Houlbrooke *et al*., 2003).

The sorption isotherm produced by Sakadevan & Bavor, (1998) indicates the blast furnace slag is likely to adsorb < 2 g P/kg slag when used for sorbing P from effluents and drainage waters (Figure 2.1). The lower P removal rates would require that large volumes of sorption media are required, which may raise logistical constraints.

Shilton *et al.* (2005) investigated the use of limestone and iron slag as potential ‘active’ filter substrates. In a field experiment, final effluent from a sewage treatment plant’s two-stage facultative pond system was continually fed through columns of either limestone or iron slag, using a 12 hour hydraulic residence time, over a period of 4,400 hours. The limestone filter achieved only 18% P removal, while the slag achieved an average removal of 72%. Although the total P removed from the effluent during the study was not provided, it is estimated to have been about 0.9 mg P/g media for the slag filter.

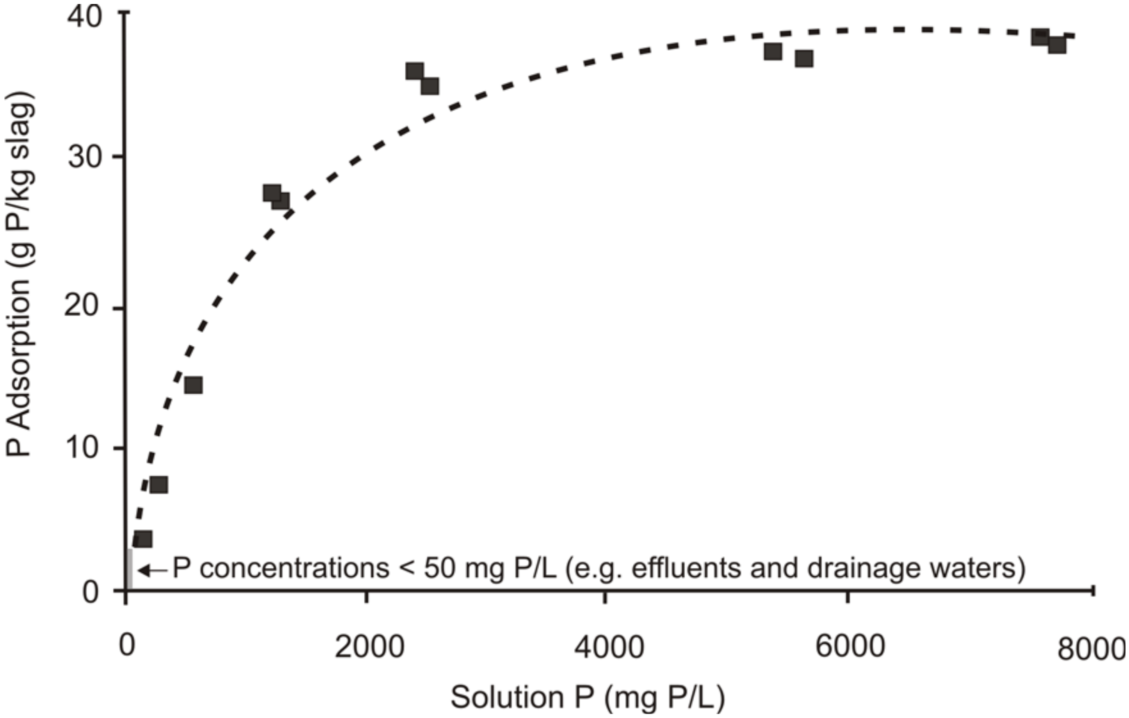


Figure 2.1 Relationship between equilibrium solution P (mg P/L) and adsorbed P (g/kg slag) for blast furnace slag (adapted from Sakadevan & Bavor, 1998).

Pratt and Shilton (2010) report on the performance of a full-scale active steel slag filter used for removing P from effluent. The filter achieved a P adsorption capacity of 1.23 mg P/g slag, reaching 75% P-removal during its first 5 years, after which its performance decreased sharply.

By-product materials, such as fly ash from coal-fired power plants and steel industry slags, have particular potential for widespread application as they are produced in large quantities and often present storage or disposal problems (Douglas *et al.*, 2004). While these materials have the advantage of being relatively inexpensive, a major drawback is their toxicity. For example, steel slags can contain concentrations of arsenic, cadmium and mercury above the levels permitted for disposal on land (McDowell, 2004). Also, McDowell (2004) demonstrated that fly ash, when applied to soil, has the potential to cause boron toxicity to plants.

In some instances, by-product materials have increased P losses from soil despite containing P adsorbing iron and aluminium compounds. For example, McDowell (2005) showed that fly ash, when added to some soils, increased soil P losses by raising soil pH from below 6 up to between 6 and 7 where P is most soluble. This increase in pH was attributed to inputs of calcium and magnesium carbonates and oxides contained in the fly ash.

New Zealand has abundant naturally occurring materials with high P adsorption capacities, such as soils and moderately weathered materials derived from volcanic tephra (ash and lapilli), which also have potential as substrates for use in ‘active’ filters. The presence of hydrous oxides of iron and aluminium, as a function of the degree of weathering, has been shown to influence the P adsorbing capacity of tephra (Parfitt, 1989). Ryden and Syers (1975) demonstrated that of the tephra materials they studied, moderately weathered andesitic tephra had the greatest potential for removing P from effluent. They observed that andesitic tephra from Taranaki, New Zealand, was capable of removing between 80% and 97% of P from a synthetic P solution containing 5 mg P/g tephra.

More recently, Liesch (2010) used a column study to assess the P adsorbing capacities of two tephra originating from andesitic volcanoes in the North Island of New Zealand. The study involved a synthetic inorganic P solution with an average concentration of 20.5 mg P/L and a solution residence time within each column of 3 hours. Of the two tephra assessed, the Okato tephra (<2 mm particle size fraction), collected from the North West of the Taranaki Region, had the highest P adsorbing capacity. By the end of the study the Okato tephra had removed nearly 8 g P/kg tephra with an average removal efficiency of 97%. The marginal P removal efficiency was about 75% at the time the study was stopped.

Although some andesitic tephra have high P adsorption capacities, one of the main challenges with using this material in filter systems is maintaining adequate hydraulic infiltration rates. Finer clay-sized tephra has potential to have higher P adsorption capacities because of its larger surface area for a given volume of material, compared to larger lapilli-size tephra, but will have slower hydraulic conductivity. Slower hydraulic conductivity can generate restricted flow or bypass flow around the outside of material, resulting in insufficient contact between the media and drainage water.

Liesch (2010) assessed the hydraulic infiltration rate into a 170 mm long vertical column containing fine tephra (<2mm), using a 200 mm standing head of tap water, over a 17-day period. At various time intervals the water flow was stopped and the infiltration rate was measured using a falling head of water. At the end of the assessment period, the infiltration rate had stabilised at 375 mm/hr. However, further assessments are necessary to determine if these infiltration rates are sufficient to maintain adequate hydraulic conductivity in artificial drainage systems. If not, then coarser lapilli-sized tephra may be required. For artificial drainage systems to be effective it is important that drainage flow rates are not restricted to a point that surface runoff is increased. Therefore, there will be a trade-off between P removal efficiency and hydraulic conductivity of the substrate used to fill the drainage system.

Further research is required to determine whether weathered soils, formed from andesitic tephra, have potential as effective substrates for removing P from dairy farm artificial drainage systems. Key questions that require further research:

i. Can tephra achieve adequate P removal efficiencies at the relatively short hydraulic residence time in drainage systems?
ii. What particle size fraction of tephra will maintain adequate drainage flow rates?

2.4 Management of unwanted nutrient accumulation on soils used for land treatment of FDE

In New Zealand, the recommended method for planning the area of land required for FDE treatment is via nutrient budgeting using the OVERSEER® Nutrient Budgets software model. The OVERSEER® model estimates the flow of nutrients that become FDE, which can then be used to determine the required effluent block size to achieve a particular annual N or K loading rate in applied FDE.

When FDE is applied at annual rates of either 150 or 200 kg N/ha (i.e. regional council limits) then the equivalent rates of K applied in FDE can be as much as 206 or 275 kg K/ha/year (assuming N and K concentrations in FDE of 269 mg N/L and 370 mg K/L; Longhurst *et al.*, 2000). These rates of K are sufficient to raise soil K Quick Test values each year by approximately 1.5-2 units on Pallic soils or 3-4 units on Allophanic soils (Roberts & Morton, 1999).

2.4.1 Using forage cropping to accumulate supplementary feed and lower potassium levels in effluent block soils

In the Manawatu region, it is typical for dairy farms to cultivate an area of long-term pastoral land each year for growing summer forage crops (e.g. turnips or green feed maize) and for pasture renewal. Summer forage crops are a valuable component of seasonal feed supply, as they accumulate larger quantities (e.g. >two-fold) of forage dry matter (DM) compared with pasture, which can be grazed in summer when plant growth is often limited by inadequate soil moisture.

Summer forage cropping can also be a useful strategy for reducing the excessive levels of K in soils, which is an issue that can commonly arise in effluent block soils. Above optimal soil K levels are undesirable as they increase the risk of metabolic disorders in dairy cows, such as hypocalcaemia (milk fever) and hypomagnesaemia (grass staggers). Summer forage cropping can reduce the accumulation of soil K by increasing the net transfer of K out of the effluent block when the crop is grazed for short durations each day (Salazar *et al*., 2010). It has been estimated that if a turnip crop was grazed for 3 hours each day, in combination with grazing pasture on other areas of farm, net removals of K from the effluent block of 283 kg K/ha could be achieved (Salazar, 2006).

2.4.2 Risk of accelerated N loss as a consequence of forage crop cultivation

While there is a range of benefits of growing summer forage crops on dairy farms, the cultivation of long-term pasture also poses risks of increased nutrient losses, particularly N, to surface and ground water (Shepherd *et al*., 2001; Monaghan *et al*., 2002; Smith *et al*., 2008). Under long-term pastures considerable quantities of soil organic N can accumulate (Haynes, 2000). The cultivation of pastoral soils causes net N mineralisation from pasture residues and soil organic matter (Davies *et al*., 2001; Eriksen & Jensen 2001, Eriksen *et al*., 2008). The higher levels of soil mineral N that result, primarily NO_3^-, are beneficial for supplying N to subsequent crops (Eriksen *et al*., 2008). However, excess soil NO_3^- accumulating immediately prior to a period of drainage contributes to NO_3^- leaching (Shepherd *et al*., 2001; Di & Cameron 2002).

In a field study conducted in Western England, Shepherd *et al*. (2001) measured the effect of both autumn and spring reseeded pasture (ploughing and resowing grass) on soil mineral N status and NO_3^- leaching from field sites that had previously been sheep grazed pastures of various sward ages (2, 5 and >50 years) and soil organic matter contents. At the location where the sward age comparisons were made on the same soil type (silty clay loam), autumn cultivation increased NO_3^- leaching for the 5 and >50 year old swards by 23 kg N/ha (62%) and 51 kg N/ha (42%), respectively, compared to the undisturbed swards of the same ages. Reseeding in spring showed minimal influence on soil mineral N status and NO_3^- leaching in the following autumn, compared with undisturbed pasture. Similarly, leaching losses from autumn reseeds in the second winter after cultivation were the same as undisturbed pasture. Therefore, the effect of ploughing pasture, for reseeding, on NO_3^- leaching was relatively short-term, being mostly in the first winter.

The timing of autumn pasture cultivation can also influence the accumulation of soil mineral N and the quantity that is prone to leaching. In field experiments conducted in the Canterbury Plains of New Zealand, Francis *et al*. (1995) quantified the effect of timing of cultivation of temporary leguminous pastures in autumn on winter NO_3^- leaching loses. Pastures ploughed in early autumn and left fallow accumulated 107-142 kg N/ha of soil mineral N by winter commencement, with subsequent N leaching losses in winter being 72-106 N kg/ha. When pasture cultivation was delayed until late autumn there was a reduction in the accumulation of soil mineral N, to 42-120 kg N/ha, and in leaching losses, to 8-52 kg ha.

The quantity of NO_3^- leached from autumn cultivation can also be influenced by the type of cover crop grown over winter and the timing of crop development in relation to the start of the winter drainage season. Francis *et al*. (1998) observed in a field experiment that when cover crops are established in early autumn (March), following ploughing in of temporary pastures, then the crop yield and N content were substantial by the start of winter (above ground herbage N content 50-71 kg N/ha), reducing the accumulation of soil mineral N that would be prone to leaching. However, in the following year when cover crops were established a month later (April) there was minimal DM accumulation and N uptake prior to the start of winter.

McLenaghen *et al*. (1996) studied the effect of five catch crops (ryecorn, ryegrass, mustard, lupin, bean) on NO_3^- leaching, following the autumn ploughing of a grass ley, compared with a bare fallow soil. All cover crops, except beans, decreased the amount of NO_3^- being leached, with ryegrass, ryecorn and mustard achieving the lowest leaching values of approximately 2.5, 4 and 7 kg N/ha, respectively, compared to 33 kg N/ha for the bare follow treatment. Ryegrass, although not as vigorous in shoot growth as ryecorn and mustard, had the greatest root yields recorded at final harvest, which was likely to have contributed to its ability to reduce NO_3^- leaching. In general, winter cover crops are most effective when they are sown early in autumn and take up a large proportion of soil NO_3^- before drainage occurs. Ideally, cultivation should be timed to coincide with subsequent crop demand in order to minimise leaching losses.

Autumn cultivation has been shown to result in higher leaching losses compared to spring cultivation, as there is a shorter duration after autumn cultivation for the crop to take up soil NO_3^- before the drainage season begins (Francis, 1995; Djurhuus & Olsen, 1997). Summer forage cropping in New Zealand dairy farms involves both a spring and an autumn cultivation. Sowing of the forage crop follows cultivation of long-term pasture in spring and then sowing of new pasture follows autumn cultivation of the forage crop residues, post-grazing. There are a number of factors that will influence the potential for NO_3^- leaching as a result of these practices, which include.

i. Proportion of soil mineral N take up by the forage crop (McLenaghen *et al*.,1996; Francis *et al*., 1998).
ii. Quantity of dairy cow excretal N returned during grazing (Silva et al., 1999; Ledgard, 2001, Lindsay *et al.,* 2009, Christensen *et al*., 2011).
iii. Timing of autumn cultivation and resowing of the new pasture (McLenaghen *et al*., 1996).
iv. The proportion of soil mineral N taken up by the new pasture prior to the start of winter drainage (Francis, 1995).

Because NO_3^- leaching is influenced by the various interactions between management, soil properties and climate, it is important to assess the combined impact of the aforementioned factors. Also, pasture renewal results in changes to soil properties and pasture botanical composition that may influence NO_3^- leaching in subsequent seasons.

However, there is limited information from field-scale studies assessing the influence of these practices over a number of years.

If summer forage crops are to be recommended as a strategy to reduce K accumulation on land previously used for FDE applications then information is required on the potential for cultivation to increase N and P losses via drainage. In particular, information is required to determine the contribution forage cropping makes to overall farm NO_3^- leaching on mole and pipe drained soils in New Zealand pastoral based dairy systems. This literature review identified the following key questions that require further research:

i. Does cultivating long-term pasture for summer forage cropping and pasture renewal increase N and P losses in drainage water from a mole and pipe drained dairy pasture soil.

ii. If so, how long do the above practices continue to influence N and P losses in drainage?

2.5 Summary

Based on this review of literature there are three key areas, relating to the environmental impacts of FDE land treatment systems that require further research. Firstly, to minimise the direct losses of nutrients and faecal microbes, during FDE irrigation to ‘high risk’ soils and landscapes, there is a need for famers to have the necessary tools and information to enable the implementation and consistent management *deficit irrigation* systems. The benefit of these management tools need to be quantified. Secondly, elevated losses of P in rainfall-induced winter and spring drainage waters from effluent block soils are difficult to directly control through management and, therefore, the use of ‘end of pipe’ P removal has been proposed as an option that requires further research to assess the feasibility of such treatment methods. Finally, the use of summer forage cropping to reduce the accumulation of K on effluent block soils has potential to increase NO_3^- leaching, however, there is limited research quantifying such losses on mole and pipe drained soils in New Zealand.

The three main research areas relating to FDE land treatment systems that are the focus this thesis are:

i. To develop and evaluate tools that farmers can use to assist the implementation and management of *deficit irrigation* systems.
ii. To evaluate the use of weathered andesitic tephra for use in dairy farm artificial drainage systems as an ‘end of pipe’ treatment method for reducing P losses in winter and spring drainage waters from effluent block soils.
iii. To quantify the impact of forage cropping of long-term pasture, a strategy advocated for reducing K accumulation in effluent block soils, on NO_3^- leaching.

2.6 References

ANZECC (2000) Australian and New Zealand guidelines for fresh and marine water quality. Volumes 1 and 2. Australian and New Zealand Environment and Conservation Council, Canberra, ACT, Australia.

Arias CA, Brix H, Johansen NH (2003) Phosphorus removal from municipal wastewater in an experimental two-stage vertical flow constructed wetland system equipped with a calcite filter. *Water Science and Technology,* 48, 51-58.

Arias CA, Del Bubba M, Brix H (2001) Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. *Water Research,* 35, 1159-1168.

Baker MJ, Blowes DW, Ptacek CJ (1998). Laboratory Development of Permeable Reactive Mixtures for the Removal of Phosphorus from Onsite Wastewater Disposal System. *Environmental Science & Technology*, 32 (15), 2308–231

Ballantine D, Booker D, Unwin M, and Snelder T (2010). *Analysis of national river water quality data for the period 1998-2007.* A report prepared for the Ministry for the Environment by National Institute of Water & Atmospheric Research Ltd (Updated December 2010, NIWA Project: MFE10502).

Bolan NS, Horne DJ, Currie LD (2004). Growth and chemical composition of legume-based pasture irrigated with dairy farm effluent. *New Zealand Journal of Agricultural Research,* 47, 85-93.

Brix H, Arias CA, Del Bubba M (2001) Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. *Water Science and Technology,* 44, 47-54.

Cameron KC, Di HJ (2004). Nitrogen leaching from different forms and rates of farm effluent applied to a Templeton soil in Canterbury, New Zealand. *New Zealand Journal of Agricultural Research*, 47, 429-437.

Christensen, CL, Hedley, MJ. Hanly, JA & Horne, DJ, 2011. Nitrate leaching and pasture accumulation during two years of duration-controlled grazing in the Manawatu. In: Adding to the knowledge base for the nutrient manager. (Eds L.D. Currie and C L Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Davies A, Kaine G and Lourey R (2007). *Understanding Factors Leading to Non-compliance with Regulations by Dairy Farms*. Environment Waikato Technical Report 2007/37 (www.ew.govt.nz).

Davies MG, Smith KA, Vinten AJA (2001). The mineralisation and fate of nitrate following ploughing of grass and grass-clover swards. *Biology and Fertility of Soils*, 33, 423-434.

Del Bubba M, Arias CA, Brix H (2003) Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. *Water Research*, 37, 3390-3400.

Degens BP, Schipper LA, Claydon JJ, Russell JM, Yeates GW (2000). Irrigation of an allophanic soil with dairy factory effluent for 22 years: responses of nutrient storage and soil biota. *Australian Journal of Soil Research*, 38, 25-35.

Dexel (2007). *A guide to managing farm dairy effluent (Manawatu/Wanganui).* http://www.dairynz.co.nz/. 40 pages.

Di, HJ & Cameron KC 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, 46, 237-256, 2002.

Di HJ, Cameron KC, Moore S, Smith, NP (1998). Nitrate leaching and pasture yields following the application of dairy shed effluent or ammonium fertiliser under spray or flood irrigation: results of a lysimeter study. *Soil Use and Management*, 14, 209-214.

Djurhuus J, Olsen P (1997). Nitrate leaching after cut grass/clover leys as affected by time of ploughing. Soil Use and Management, 13, 61-67.

Douglas GB, Robb MS, Coad DN, Ford PW (2004) A review of solid phase adsorbents for the removal of phosphorus from natural and waste waters. In *Phosphorus in Environmental Technology: Principles and Applications*, ed. V.-J. E., IWA Publishing. London, pp. 291-320.

Drizo A, Forget C, Chapuis RP, Comeau Y (2006) Phosphorus removal by electric arc furnace steel slag and serpentinite. *Water Research*, 40, 1547-1554.

Drizo A, Frost CA, Grace J, Smith KA (1999) Physico-chemical screening of phosphate-removing substrates for use in constructed wetland systems. *Water Research*, 33, 3595-3602.

Eriksen J, Askegaard M, Søegaard K (2008). Residual effect and nitrate leaching in grass-arable rotations: effect of grassland proportion, sward and fertiliser history. *Soil Use and Management*, 24, 373–382.

Eriksen J, Jensen LS (2001). Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands. *Biology & Fertility of Soils* 33, 139-145.

Forsyth KA (1996). Regional Plans and Water Quality. *Tertiary Treatment Options for Dairyshed and Piggery Wastewaters* (Ed. IG Mason). Proceedings of a seminar held at Massey University (20 June 1996), 9-17.

Francis GS (1995). Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. *Journal of Contaminant Hydrology*, 20, 313-327.

Francis GS, Bartley KM, Tabley FJ (1998). The effect of winter cover crop management on nitrate leaching losses and crop growth. *The Journal of Agricultural Science*, 131, 299-308.

Francis GS, Haynes RJ, Williams PH (1995). Effects of timing of ploughing in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching an spring wheat growth. *The Journal of Agricultural Science*, 124(1), 1-9.

Frost FM (2000). Value orientations: impact and implications in the extension of complex farming systems. *Australian Journal of Experimental Agriculture*, 40(4), 511 - 517

Genz A, Kornmüller A, Jekel M (2004). Advanced phosphorus removal from membrane filtrates by adsorption on activated aluminium oxide and granulated ferric hydroxide. *Water Research* 16, 3523-30.

Gruneberg B, Kern J (2001) Phosphorus retention capacity of iron-ore and blast furnace slag in subsurface flow constructed wetlands. *Water Science and Technology*, 44, 69-75.

Guerin LJ & Guerin TF (1994). Constraints to the adaption of innovations in agricultural research and environmental management: a review. *Australian Journal of Experimental Agriculture*, 34, 549-571.

Hawke RM, Summers SA (2006). Effects of land application of farm dairy effluent on soil properties: a literature review. *New Zealand Journal of Agricultural Research*, 49, 307-320.

Haynes RJ (2000). Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biology & Biochemistry* 32, 211-219.,

Heal KV, Dobbie KE, Bozika E, McHaffie H, Simpson AE, Smith KA (2005) Enhancing phosphorus removal in constructed wetlands with ochre from mine drainage treatment. *Water Science and Technology*, 51, 275-282.

Heal KV, Smith KA, Younger PL, McHaffie H, Batty LC (2004). Removing phosphorus from sewage effluent and agricultural runoff using recovered ochre. In *Phosphorus in Environmental Technology: Principles and Applications*, ed. V.-J. E., IWA Publishing. London, 321-335.

Hedley MJ, Ionas G, Horne DJ, Hanly JA, Collins R, Donnison A (2005). *Pathogen Transmission Routes: Farm Animals to Water Bodies (2004 - 2005).* Report prepared for MAF NZ (April 2005).

Houlbrooke DJ (2005). *A Study of the Quality of Artificial Drainage Under Intensive Dairy Farming and the Improved Management of Farm Diary Effluent Using 'Deferred Irrigation'*. PhD Thesis, Massey University, Palmerston North. p 211.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA (2004a). The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research*, 47, 587-596.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO (2004b) Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research*, 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2004c) A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality. *New Zealand Journal of Agricultural Research,* 47, 499-511.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2003) The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association,* 65, 179-184.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA (2008) Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research,* 46, 45–52.

Houlbrooke DJ and Monaghan R (2010). Land application of farm dairy effluent: development of a decision framework for matching management practice to soil and landscape risk. In: *Farming's future: minimising footprints and maximising margins* (Eds L.D. Currie and C.L. Lindsay). Occasional Report No. 23. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 35-45.

Houlbrooke DJ, Monaghan RM, Muirhead RW (2010). Matching farm dairy effluent management practices to soil and landscape features. New Zealand Land Treatment Collective: Proceedings for the 2010 Annual Conference, Dunedin, 11-19.

Houlbrooke DJ, Monaghan RM, Smith LC and Nicolson C (2006). Reducing contaminant losses from land applied farm dairy effluent using K-line irrigation systems. In: Implementing sustainable nutrient management strategies in agriculture (Eds L.D. Currie and J.A. Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 290-300.

Ledgard S (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, 228(1), 43-59

Liesch AM (2010). Wastewater phosphorus removal by two different types of andesitic volcanic tephra. Journal of Natural Resources & Life Sciences Education, 39, 40-44.

Lindsay CL, Hanly JA, Hedley MJ, Horne DJ (2009). Controlling nitrogen and phosphorus loss from dairy farms using restricted grazing practices. In *Nutrient Management in a Rapidly Changing World* (Eds. L D Currie and C L Lindsay), Occasional Report No. 22, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 295–302

Longhurst, B., Nicholson, B. 2011: Rapid on-farm method of estimating NPK content of dairy effluents for land application. In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 8 pages.

Longhurst RD, Roberts AHC, O'Connor MB (2000). Farm dairy effluent: a review of published data on chemical and physical characteristics in New Zealand. *New Zealand Journal of Agricultural Research,* 43, 7-14.

McArthur K, Clark M (2007). Nitrogen and Phosphorus Loads to Rivers in the Manawatu-Wanganui Region: *An Analysis of Low Flow State: Technical Report to Support Policy Development*. New Horizons Regional Council. Report No: 2007/EXT/793.

McDowell RW (2005) The effectiveness of coal fly-ash to decrease phosphorus loss from grassland soils. *Australian Journal of Soil Research,* 43, 853-860.

McDowell RW (2004) The effectiveness of industrial by-products to stop phosphorus loss from a Pallic soil. *Australian Journal of Soil Research,* 42, 755-761.

McLenaghen RD, Cameron KC, Lamkin NH, Daly ML, Deo B (1996). Nitrate leaching from ploughed pasture and effectiveness of winter catch crops in reducing leaching losses. New Zealand Journal of Agricultural Research, 39, 413-420.

McLeod M, Aislabie J, Ryburn J, McGill A (2008). Regionalising potential for Microbial bypass flow through New Zealand soils. *Journal of Environmental Quality,* 37, 1959-1967.

McLeod M, Schipper LA, Taylor MD (1998). Preferential flow in a well drained and a poorly drained soil under different overhead irrigation regimes. *Soil Use and Management,* 14, 96–100.

Mann RA (1997). Phosphorus adsorption and desorption characteristics of constructed wetland gravels and steelworks by-products. *Australian Journal of Soil Research,* 35, 375–84.

Monaghan RM, Hedley MJ, Di HJ, McDowell RW, Cameron KC, Ledgard SF (2007). Nutrient management in New Zealand pastures: Recent developments and future issues. *New Zealand Journal of Agricultural Research,* 50, 57–67.

Monaghan RM, Paton RJ, Drewry JJ (2002) Nitrogen and phosphorus losses in mole and tile drainage from a cattle-grazed pasture in eastern Southland. *New Zealand Journal of Agricultural Research,* 45, 197-205.

Monaghan RM, Paton RJ, Smith LC, Drewry JJ, Littlejohn RP (2005) The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. *New Zealand Journal of Agricultural Research*, 48, 227-240.

Monaghan RM, Smith LC (2004). Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research,* 47, 417–428.

Muirhead RW, Monaghan RM, Donnison AM, Ross C (2008). Effectiveness of current best management practices to achieve faecal microbial water quality standards. In *Carbon and nutrient management in agriculture* (Eds. L.D. Currie and L.J. Yates) Occasional Report 21. Fertilizer and Lime Research Centre, Massey University, Palmerston North, 382-397.

Nash D, Murdoch C (1997) Phosphorus in runoff from a fertile dairy pasture. *Australian Journal of Soil Research,* 35, 419-429.

Naylor S, Brisson J, Labelle MA, Drizo A, Comeau Y (2003) Treatment of freshwater fish farm effluent using constructed wetlands: the role of plants and substrate. *Water Science and Technology*, 48, 215-222.

Pant HK, Reddy KR, Lemon E (2001). Phosphorus retention capacity of root bed media of sub-surface flow constructed wetlands. *Ecological Engineering,* 17, 345–355.

Parfitt RL (1982) Competitive adsorption of phosphate and sulphate on goethite (-FeOOH): a note. *New Zealand Journal of Science,* 25, 147–148.

Parfitt RL (1989). Phosphate reactions with natural allophane ferrihydrite and goethite. *Journal of Soil Science,* 19, 359-369.

Pratt C & Shilton A, 2010. Active slag filters—simple and sustainable phosphorus removal from wastewater using steel industry byproduct. *Water Science and Technology,* 62 (8), 1713-1718.

Ridley AM (2004). The role of applied science in helping farmers make decisions about environmental sustainability. *Australian Journal of Experimental Agriculture*, 44, 959-968.

Roberts AHC, Morton JD (1999). *Fertiliser Use on New Zealand Dairy Farms – The principles and practice of soil fertility and fertiliser use on New Zealand dairy farms.* New Zealand Fertiliser Manufacturers' Association, Auckland, NZ, 18.

Roberts AHC, O'Connor MB, Longhurst RD (1992). Wastes as plant nutrient sources: issues and options. In *The use of wastes and byproducts as fertilisers and soil amendments for pastures and crops.* (Eds. P.E.H. Gregg and L.D Currie). Occasional Report 6, Fertilizer and Lime Research Centre. Massey University, Palmerston North, New Zealand, 44-55.

Ross C, Donnison A (2003). Campylobacter and farm dairy effluent irrigation. *New Zealand Journal of Agricultural Research*, 46, 255-262.

Ryden, JC, Syers, JK (1975) Use of tephra for the removal of dissolved inorganic phosphate from sewage effluent. *New Zealand Journal of Science*, 18, 3-16.

Ryden JC, Syers JK, Tillman RW (1987) Inorganic anion sorption and interactions with phosphate sorption by hydrous ferric oxide gel. *Journal of Soil Science*, 38, 211–217.

Sakadevan K, Bavor HJ (1998). Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. *Water Research*, 32, 393-399.

Salazar ME (2006). Use of turnips to reduce potassium accumulation on areas receiving farm dairy farm effluent. M.Appl.Sc. thesis. Massey University.

Salazar, ME, Hedley, MJ & Horne, DJ (2010). Can turnips be used to reduce soil K loading on the effluent block? Proceeding from the NZ Grassland Association Conference, 72, 247-250.

Sharpley AN, Syers JK (1979) Loss of nitrogen and phosphorus in tile drainage as influenced by urea application and grazing animals. *New Zealand Journal of Agricultural Research*, 18, 183-187.

Shepherd MA, Hatch DJ, Jarvis SC, Bhogal (2001). Nitrate leaching from reseed pasture. *Soil Use and Management*, 17, 97-105.

Shilton A, Pratt S, Drizo A, Mahmood B, Banker S, Billings L, Glenny S, Luo D (2005) 'Active' filters for upgrading phosphorus removal from pond systems. *Water Science and Technology*, 51, 111-116.

Shilton AN, Elmetri I, Drizo A, Pratt S, Haverkamp RG, Bilby SC (2006) Phosphorus removal by an 'active' slag filter-a decade of full scale experience. *Water Research,* 40, 113-118.

Silva RG, Cameron KC, Di HJ, Hendry, T (1999). A lysimeter study of the impact of cow urine, dairy shed effluent, and nitrogen fertiliser on nitrate leaching. *Australian Journal of Soil Research,* 37, 357-369.

Smith LC, de Klein CAM, Monaghan RM, Catto WD (2008). The effectiveness of dicyandiamide in reducing nitrous oxide emissions from a cattle-grazed, winter forage crop in Southland, New Zealand. *Australian Journal of Experimental Agriculture,* 48(1-2), 160-164

Sukias JPS, Davies-Colley RJ and Tanner CC (1996). Pond Upgrading Options. *Tertiary Treatment Options for Dairyshed and Piggery Wastewaters* (Ed. IG Mason). Proceedings of a seminar held at Massey University (20 June 1996), 19-30.

Tanner CC, Sukias JPS, Upsdell MP (1999) Substratum phosphorus accumulation during maturation of gravel-bed constructed wetlands. *Water Science and Technology,* 40, 147-154.

Toor G, Condron L, Di H, Cameron K, Sims J (2004). Impact of farm-dairy effluent application on the amounts and forms of phosphorus by leaching from irrigated agriculture. *New Zealand Journal of Agricultural Research,* 47, 479-490.

Wang H, Magesan G, Bolan N (2004). Overview of the environmental effects of land application of farm effluents. *New Zealand Journal of Agricultural Research,* 47, 389-403.

Wheeler D, Ledgard SF, Monaghan RM, McDowell R, and DeKlien C (2006). OVERSEER® Nutrients Budgets Model – What is it, what it does? In *Implementing sustainable nutrient management strategies in agriculture.* (Eds. L.D. Currie and J.A. Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 231-236.

Zhu T, Jenssen PD, Maehlum T, Krogstad T (1997) Phosphorus sorption and chemical characteristics of lightweight aggregates (LWA) - Potential filter media in treatment wetlands. *Water Science and Technology,* 35, 103-108.

CHAPTER 3:
Tools for informing the design and management of deficit irrigation FDE land treatment systems

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Chapter's context: Reducing diffuse and point source nutrient losses from dairy farms requires identifying effective mitigations or management practices and determining how these can best be implemented on farm. The literature review (Chapter 2) highlighted that FDE management can have a significant influence on the losses of nutrients in surface runoff and drainage waters from dairy farms, particularly on 'high risk' soils. A major constraint to farmer adoption of improved management practices, such as *deficit irrigation* of FDE, is the availability of decision support and fail-safe tools needed to assist implementation. The objective of this Chapter is to develop and evaluate of such tools to help identify those that can provide the information and automation farmers require to assist the implementation of *deficit irrigation* FDE land treatment systems.

3.1 Introduction

Land application is the main method currently used for treating farm dairy effluent (FDE) in most regions of New Zealand. Compared with pond only treatment, land treatment substantially reduces the quantity of nutrients from FDE that can contaminate surface water, rivers and lakes (Houlbrooke *et al*., 2004b). However, surface runoff and/or drainage from poorly managed land application of FDE can still contribute to the eutrophication of fresh water rivers and lakes (Monaghan & Smith, 2004; Houlbrooke *et al.*, 2008).

The risk of FDE reaching surface water is higher on soils with a high degree of connectivity to fresh surface water systems. Therefore, the soils and landscapes that pose the greatest risk (i.e. 'high risk' soils) are: mole and pipe drained soils (Houlbrooke *et al.*, 2004b), soils with impeded drainage, soils with a rising (or ground) water table, very shallow stony soils, and sloping soils (Houlbrooke & Monaghan, 2010).

The deferred irrigation approach to FDE management has been shown to minimise the losses of nutrients and pathogens from land applied FDE on mole and pipe drained soils (Houlbrooke *et al.,* 2004b; Collins *et al.,* 2007). Deferred irrigation involves the storage of FDE and the strategic scheduling of irrigations when sufficient soil water deficit (SWD) exists to avoid the risk of generating surface runoff, or direct drainage, of FDE. On 'high risk' soils, the use of a more strict version of deferred irrigation, which adheres to *deficit irrigation* criteria, has been identified as best practise (Houlbrooke *et al.,* 2004b). *Deficit irrigation* involves deferring irrigation until the SWD is larger than the minimum application depth of the irrigation system, as operated by the farmer. For example, the minimum application depth of many small rotating travelling irrigators is about 8 mm, whereas sprinkler irrigation systems can achieve smaller application depths.

Although *deficit irrigation* has been researched at the plot scale (i.e. proof of concept; Houlbrooke *et al.,* 2004b), it has not been researched at the farm scale. The likely adoption and success of *deficit irrigation* at the farm scale can be constrained by a number of critical factors. These include 'natural' constraints, such as climate, soil drainage characteristics and land slope, and 'farm infrastructure/management' constraints, such rate of FDE generation, FDE storage capacity, type of irrigation system, labour availability and skills, and access to decision support information (Hanly *et al.,* 2008).

Non-compliance with regional council FDE regulations continues to be a major issue in many regions of New Zealand (Ministry of Agriculture and Forestry, 2009), highlighting the need for further improvements in the management of land applied FDE. Effective daily management is also critical to the performance of FDE land treatment systems (Houlbrooke *et al.,* 2004a; Hanly *et al.*, 2010). Common causes of non-compliance, with regional council guidelines, include:

- FDE storage pond overflow,
- FDE irrigations scheduled at applied depths that exceed the SWD, or
- travelling irrigator breakdowns (Davies *et al.,* 2007).

Greater technical assistance in system design and management, and research into the development of low maintenance, simple and fail-safe systems, have been identified as important developments for reducing the risk of non-compliance (Davies *et al.,* 2007). In addition, non-compliance can be reduced through the use of incentives to encourage buffering within the system, such as increased FDE storage capacity and the provision of emergency exchange services to cover periods of equipment failure (e.g. pumps and travelling irrigators).

Storage of FDE is a key component of many land application systems because it provides flexibility in scheduling FDE irrigations. When FDE storage capacity is inadequate, FDE contamination of surface water can occur due to pond overflow or surface runoff and/or drainage following FDE irrigation to soils at, or near, field capacity (Houlbrooke *et al.,* 2008). In the past, FDE storage requirements were determined using average estimates for the number of days that storage was required and industry averages for FDE generation (Dexel, 2007; Houlbrooke, 2008). However, the required size of FDE storage capacity will vary between farms and also between years on the same farm. For example, there can be as much as a five-fold difference in storage requirements between farms solely due to soil type differences (i.e. different 'soil risk' categories). Accordingly, the use of industry averages is unlikely to be adequate for consistently determining FDE storage requirements for individual farms.

Given the crucial role of storage in determining whether or not *deficit irrigation* can be practised, it is recommended that farm specific information is used to calculate the storage needs of individual farms (e.g. *FDE Storage Calculator,* Appendix). The volume of storage capacity that is defined as 'adequate' to allow the practice of *deficit irrigation* is determined assuming that FDE will be land applied on every day there is sufficient soil water deficit (SWD). The volume of 'adequate' storage can be determined by quantifying the rate that FDE is generated and the rate that it can be irrigated to land, using *deficit irrigation* criteria.

Storage ponds can still be at risk of overflow on farms that have 'adequate' storage capacity if FDE irrigation scheduling is not managed in the way that was envisaged when the storage was designed. Scheduling of FDE irrigations at application depths smaller than the SWD requires daily information on the size of the SWD to inform when it is safe to irrigate and how much to apply. Estimates of soil moisture need to have a high degree of accuracy and reliability because of the potential environmental consequences and financial penalties associated with applying FDE in excess of the SWD on ‘high risk’ soils and landscapes.

Breakdowns or stoppages of small rotating travelling irrigators are another common cause of non-compliance on dairy farms. These irrigator stoppages can result in very high FDE application depths because the irrigator stops travelling but continues to apply FDE to only a small area. While some causes of irrigator stoppages can be avoided, for example, through irrigator maintenance or checking the strength of irrigator anchor points, other causes can be difficult to prevent without constant monitoring of the irrigator. Therefore, to reduce the risk of irrigator stoppages, an automated fail-safe system is likely to be required to shut off the pump when a stoppage occurs.

To date, relatively little attention has been paid to the need to equip farmers with the knowledge and tools that they need to successfully design and manage the application of FDE to land. Because the research information evaluating such tools is limited, a study was conducted at Massey University’s No.4 Dairy Farm to assess the benefits of decision support and fail-safe tools for informing the management of land treatment systems practicing *deficit irrigation* of FDE. The specific objectives of the study were to:

i. Identify and quantify the key parameters influencing farm FDE storage requirements and demonstrate a modelling approach (e.g. *FDE Storage Calculator*) for determining farm-specific FDE storage requirements.
ii. Compare methods for providing farms with accurate daily SWD information.
iii. Develop and test a travelling irrigator pump automatic shut-off and alert system for preventing irrigator stoppages.

3.2 Materials and methods

3.2.1 Case study farm

This study involved monitoring aspects of the FDE land treatment system at Massey University’s No.4 Dairy Farm located near Palmerston North, Manawatu, New Zealand. This case study farm is a seasonal supply dairy farm with; an effective area of 194 hectares, 470 milking cows (Jersey/Friesian cross) at peak lactation and an average lactation length of approximately 280 days. The majority of the cows’ diet consists of mixed perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) pasture, which is grazed in situ.

During the milking season, cows are milked twice-a-day in a 50 bale rotary farm dairy. The farm dairy holding yard is cleaned automatically after each milking with a manure scraper and water sprinkler system attached to the yard backing-gate. Farm dairy effluent is stored in a two-pond treatment system and irrigated to the farm’s effluent block for land treatment. At the start of this study in 2006, the storage capacity of the farm’s main FDE storage pond was 2,000 m^3 and FDE was applied to a 20 hectare effluent block using a small rotating arm travelling irrigator (Briggs Model 15). The effluent block paddocks are located on mole and pipe drained Tokomaru silt loam, a Fragic Perch-gley Pallic Soil (Hewitt, 1998), which ranges from flat to easy rolling topography. Mean annual rainfall for Palmerston North is 970 mm.

3.2.2 Monitoring and measurement

Monitoring equipment was installed on the case study farm between 2006 and 2009 to provide continuous measurement of various aspects of the FDE land treatment system, which are discussed in the following sections.

Rainfall, soil moisture and drainage monitoring

Rainfall was monitored using a tipping bucket rain collector (Davis Rain Collector II) and soil moisture was estimated using a soil water balance model (Scotter *et al.*, 1979) and an Aquaflex soil moisture sensor (#S1.99). The occurrence and magnitude of subsurface drainage events were monitored over a two-year period (2006 and 2007) on four pasture plots (40 × 40 m), each with an isolated mole and pipe drain system. In the corner of each drainage plot, a pit was excavated and a tipping-bucket flow meter was installed at the end of the drainage pipe to monitor drainage flow rates. Each tipping bucket was calibrated dynamically to account for larger tip volumes at higher flow rates. When a tipping bucket starts tipping there is a brief time when additional water can still enter the full side of the bucket. This additional water volume increases with flow rate, which can result in an underestimation of tip volume, known as ‘undercatchment’, at higher flow rates (Humphrey *et al*., 1997). All tipping buckets were instrumented with data loggers to provide continuous measurements of drainage flow rate (Plate 3.1).

Plate 3.1 An example of a tipping bucket flow meter and data logger used for measuring and recording drainage water flow rates.

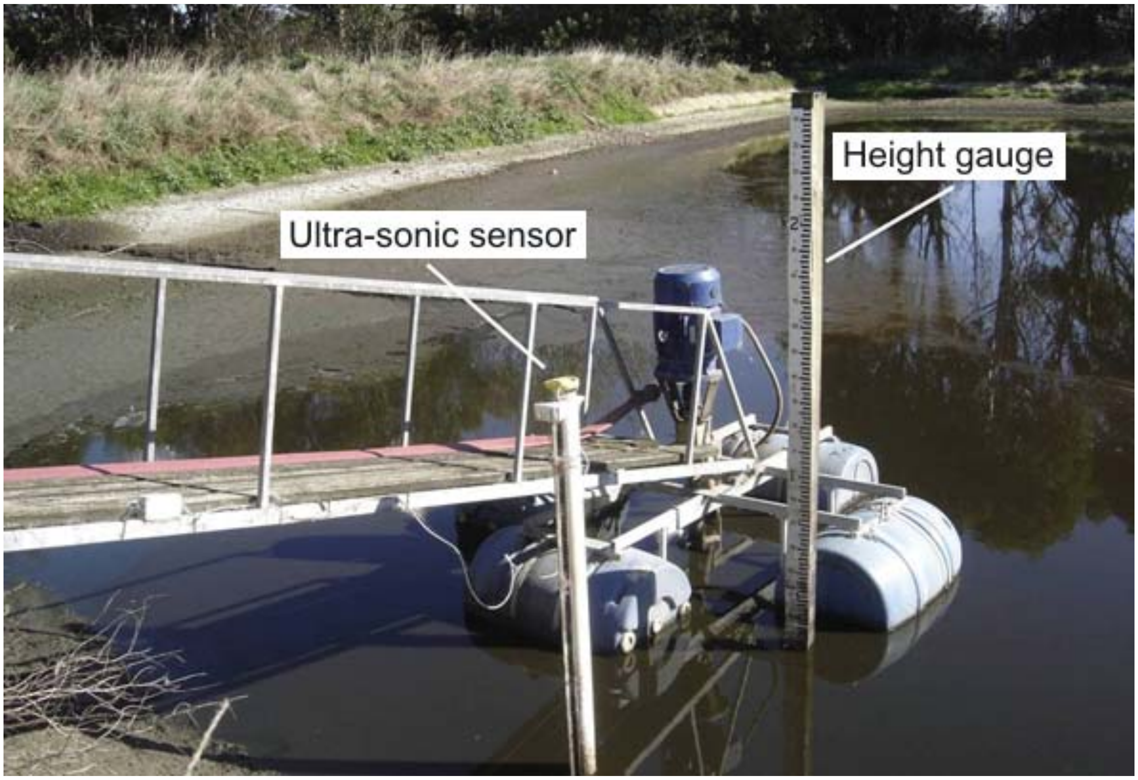

Plate 3.2 An ultra-sonic pond level sensor and height gauge installed in the storage pond at Massey University’s No.4 Dairy Farm.

FDE storage pond monitoring

Farm dairy effluent storage pond level was monitored using an ultra-sonic pond level sensor (EchoSonic LU05), installed in 2007, and a manual height gauge (Plate 3.2). The ultra-sonic sensor was attached to a steel “Y” post, which was driven into the bottom of the pond. Data from the ultra-sonic pond level sensor was sent wirelessly, via the cellular network, to a remote host server were the data was accessible via the Internet. The height gauge provided another measure of pond level to compare with the sensor readings.

Travelling irrigator monitoring and automatic pump shutoff system

When this study commenced, travelling irrigator remote monitoring and automatic pump shut-off systems where not commercially available. Therefore, initial monitoring of the travelling irrigator in this study was achieved with a Global Position System (GPS) data logger attached to the irrigator. A custom-built irrigator remote monitoring and automatic shut-off system device was invented and built as part of this study in collaboration with DataCarter Ltd, who provided the electronics expertise (Plate 3.3).

Plate 3.3 The small travelling irrigator (rotating boom) with the alert and remote sensing equipment installed at Massey University’s No.4 Dairy Farm (insert shows the combined cellular phone and GPS device).

The device, which incorporates both a Global Position System (GPS) sensor and wheel movement (magnetic reed) sensor, was installed on the farm's travelling irrigator in 2007. When the irrigator operates, the monitoring system logs GPS location and wheel movement and sends this data via a cellular network to a remote host server where it is accessible via the Internet. Wireless data transfer is necessary for irrigator telemetry because the movement of irrigators to different locations makes wired connections impractical. The two main methods used for wireless telemetry are radio communication and cellular networks. Wireless communications for travelling irrigators are likely to have more problems with reliability, compared to stationary monitoring systems (e.g. weather stations), because there are potentially more opportunities for communication interference from features in the landscape (e.g. trees and hills). Reliable communication is important for irrigator alert systems because extended breaks in communication may cause false alerts, which will lead to the system being overridden by farm staff in order to get the irrigator to operate.

For farms with good cellular phone reception, the use of a cellular network will be a relatively reliable method for wireless communication. For farms currently with inadequate cellular phone reception, then the use of radio communication is the only other main option available. However, intensive testing of the radio communication system should be carried out across the effluent block areas to ensure that communication is reliable enough to prevent false alerts.

3.2.3 Survey farms

Five farms from within the Manawatu-Wanganui Region were surveyed to collect the necessary farm information to model farm-specific FDE storage requirements. Each farm was visited and data was collected by either taking measurements during the visit or from information provided by the farm manager. For example, rainfall catchment areas (e.g. yards and feed pads) and FDE pond areas were either measured with a tape measure during the visit or remotely using Google Earth. Whereas information on cow numbers, effluent block area, pond depth, irrigator type and use, and farm dairy water use was obtained from the farm manager. For most of the farms, the farm dairy water use was determined by assessing the volume of tank water used during each milking. A summary of this information for each farm is presented in Table 3.3.

3.2.4 Modelling

The *FDE Storage Calculator*, developed at Massey University, was used to model farm-specific storage requirements for all the farms used in this study. While the development of the *Calculator* was not an integral part of this study, aspects of this study have been used to inform its development. Further details of how the *Calculator* works are provided in the Appendix. For the Massey University No.4 Dairy Farm case study the following irrigation scheduling criteria were used in the model:

i. *Deficit irrigation* criteria – FDE was only irrigated on days where the SWD was >10 mm for the travelling irrigator, or > 5 mm for the sprinkler irrigation system.
ii. On every 'irrigation day', an FDE volume of 120 m^3 was irrigated either at a depth of 8 mm when the travelling irrigator is used or 4.5 mm when a sprinkler irrigator is used.

3.3 Results and discussion

3.3.1 Conceptual decision support management system for FDE land treatment

This section provides a conceptual overview of how the range of decision support and fail-safe tools mentioned in this Chapter can be combined into a management system for FDE land application (Figure 3.1). This integrated package of monitoring and communication technologies has the potential to provide farmers with real-time information for managing key components of the FDE system. On the basis of real-time, comprehensive data, it is assumed that farmers will be able to make informed decisions regarding planning and implementing FDE irrigation practices. The components of the FDE system that are important for management are; FDE storage capacity, irrigation scheduling, and irrigator performance and reliability. These aspects of FDE system design and management the FDE system are discussed in more detail in the following sections.

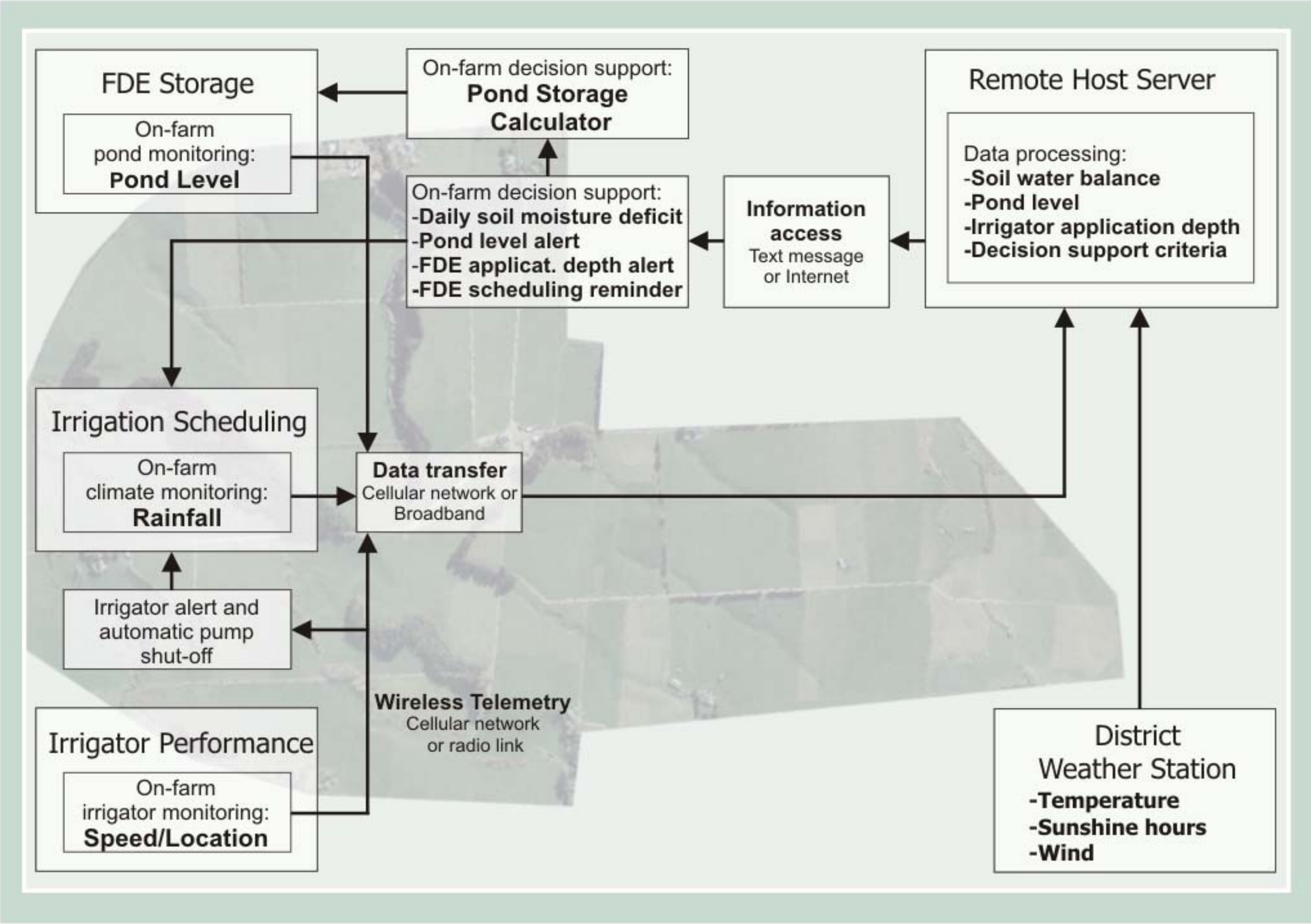

Figure 3.1 Components of a conceptual FDE land application decision support management system.

3.3.2 Determining farm-specific FDE storage requirements

As previously discussed (Section 3.1), storage of FDE is a key component of many land application systems because it provides flexibility in scheduling FDE irrigations. The use of farm-specific information is required to calculate the storage needs of individual farms. This section models the key parameters influencing farm FDE storage requirements on a case study farm and demonstrates the use of the *FDE Storage Calculator* for determining farm-specific FDE storage requirements on five survey farms.

Factors influencing FDE storage requirements on a case study farm

The volume of ‘adequate’ FDE storage capacity for a farm can be determined by modelling the rate that FDE is generated and the rate that it can be irrigated to land, using *deficit irrigation* criteria.

The total net FDE (FDE_{net}) is the volume of FDE that requires irrigation, and is calculated as;

$FDE_{net} = FDE_{milking} + FDE_{stormwater} - FDE_{evaporation}$

Where:

$FDE_{milking}$ is the daily volume of cow excreta (dung and urine) deposited in the farm dairy, on holding yards and on feed pads, combined with the volume of water used in the farm dairy for cleaning the milking plant and washing the holding yards; $FDE_{stormwater}$ is the daily stormwater volume entering FDE storage ponds from rainfall catchments areas, such as shed rooves, yards, feed pads, and from rain falling directly onto the storage ponds themselves; and $FDE_{evaporation}$ is the daily evaporation from the FDE storage ponds.

The rate of daily FDE irrigation is determined by:

- The occurrence of irrigation days (e.g. days when the SWD>irrigator minimum application depth),
- The application depth, and
- The area of land irrigated on each irrigation day.

FDE generation rate

Influence of farm daily water use

On dairy farms most of the FDE volume that is generated in the farm dairy is from water used to clean the milking plant and wash the holding yards after each milking, with a small proportion (5-10%) of the volume estimated to be coming from excreta (dung and urine) deposited by the milking cows (~5-7 L/cow/day; Haynes and Williams, 1993). The volume of water use can be estimated by either monitoring it in the farm dairy (e.g. from the change in the water level in holding tanks or by measuring the volume with a water meter) or by monitoring the change in the FDE storage pond level over a period when there is neither rainfall nor FDE irrigations, and accounting for evaporation from the storage pond.

On the case study farm, data collected from the ultra-sonic pond level sensor was used to estimate the volume of FDE generated during milking ($FDE_{milking}$). Between 29 December 2007 and 4 January 2008 (Figure 3.2), which was a period when there was neither rainfall nor irrigations made, the increase in pond level was equivalent to an average increase in FDE volume of 50 m^3/day, after evaporation from the ponds had been accounted for. This average daily rate of FDE generation equates to an annual volume of 14,000 m^3 for a 280 day lactation season. About 3 m^3/day of the $FDE_{milking}$ volume is estimated to be from excreta deposited by the milking herd and, therefore, the contribution of water use is estimated to be 47 m^3/day. For the farm’s herd of 470 milking cows this volume of water use is equivalent to 100 L/cow/day.

The farm dairy on the case study farm is a relatively new 50 bale rotary milking system with an automatic yard washing system incorporated into the backing gate. The farm has a relatively small milking herd (470 cows), compared to the capacity of its farm dairy and the size of the holding yards (1,000 m^2). This resulted in high per cow water use (100 L/cow/day) compared to other reported figures of 50 L/cow/day (Vanderholm, 1984). This facility was built with capacity for an increase in cow numbers (up to c. 800 cows), which would reduce the water use on a per cow basis, as some components of water use do not necessarily increase proportionally with cow numbers (e.g. yard washing).

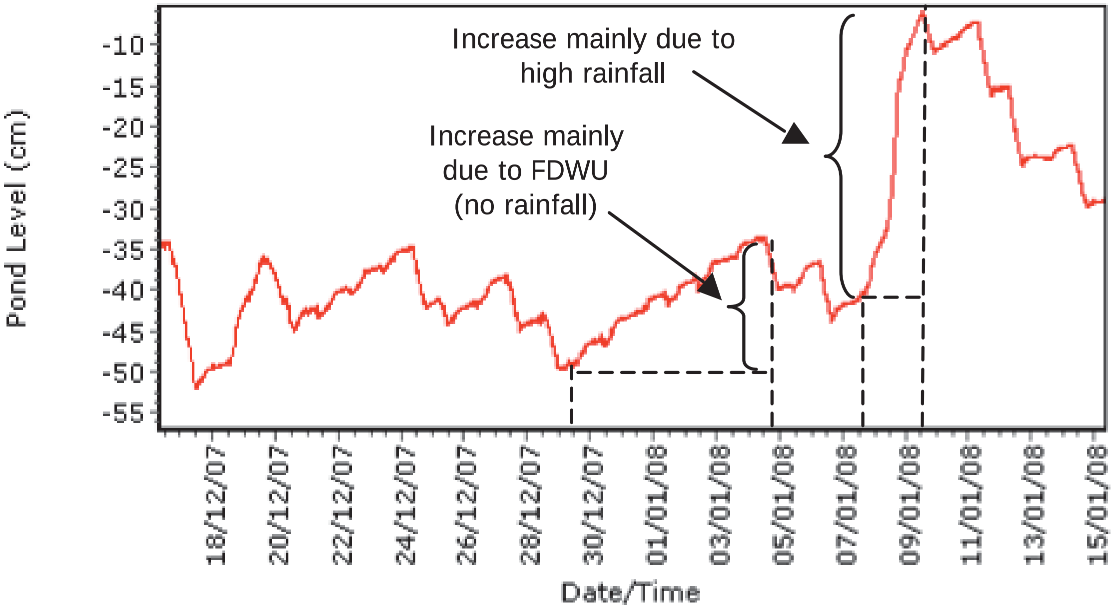

Figure 3.2 FDE level in the second treatment pond at the case study farm (pond level is the distance that the FDE level is below the overflow point; FDWU means farm dairy water use).

Influence of climate and rainfall on catchment area

Climate, particularly the quantity and seasonality of rainfall, influences the volume of FDE generated on a dairy farm from stormwater ($\text{FDE}_{\text{stormwater}}$) entering FDE ponds from rainfall catchment areas. Therefore, the actual volumes of $\text{FDE}_{\text{stormwater}}$ in any one year can vary considerably from estimates based on long-term average monthly rainfall data.

During the 2007/2008 season, the total rainfall catchment area on the case study farm, including the FDE ponds, was 7,300 m^2 (Plate 3.4, Table 3.1). The contribution that this catchment area makes to the volume of $\text{FDE}_{\text{stormwater}}$ generated is an estimated 7,081 m^3 in a year with average rainfall (970 mm rainfall), or as much as 9,855 m^3 in a year with high rainfall (1,350 mm rainfall). The large contribution of stormwater to FDE generation on the case study farm is due to its atypically large catchment area. On farms with smaller catchment areas, and with the same rainfall, the contribution of storm water to FDE generation will obviously be smaller. Conversely, in regions with higher rainfall (e.g. Waikato) stormwater could also make up a large component of FDE volume, even when rainfall catchment areas are only of moderate size.

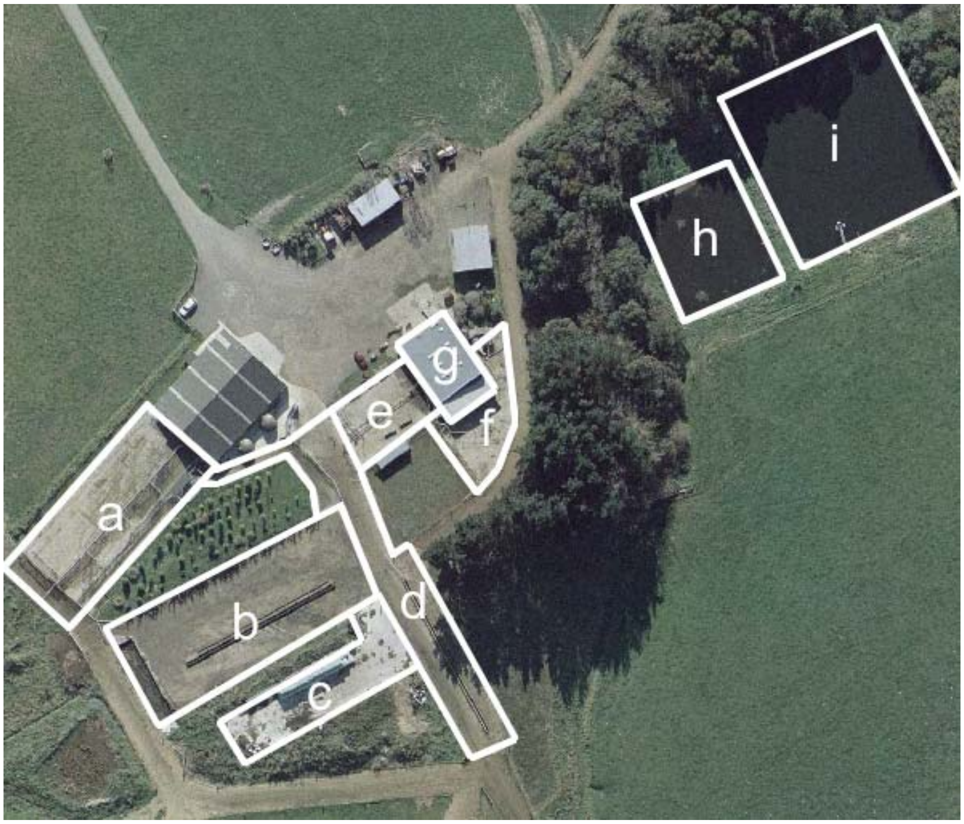

Plate 3.4 The layout of all the rainfall catchment areas directing storm water into the FDE storage ponds on the case study farm in 2008 (refer to Table 3.1 for area descriptions).

Table 3.1 The sizes of rainfall catchment areas, on the case study farm, before and after storm water diversion.

Rainfall catchment	**Area (m^2)**	**Is storm water diversion practical?**
a. Farm dairy holding yard	1000	*Potentially**
b. Feed pad	1500	*No*
c. Silage storage concrete pad	550	*No*
d. Concrete race with feeding troughs	900	*No*
e. Old farm dairy holding yard	350	*Potentially**
f. Old farm dairy additional yard	250	*Yes*
g. Old farm dairy roof	300	*Yes*
h. First FDE pond	700	*No*
i. Second FDE (storage) pond	1750	*No*
Total area prior to diversion:	**7300**	
Total area after diversion:	**6750**	

**Further research is required to identify fail-safe systems for diverting these areas.*

Data collected from the ultra-sonic pond level sensor was useful at demonstrating the impact that high rainfall events, falling on large rainfall catchment areas, can have on rapidly increasing the level of the storage pond. For example, over a two-day period, 7 to 9 January 2008, an 80 mm rainfall event at the case study farm rapidly increased the level of FDE in the second pond by 35 cm, reaching 5 cm below the over flow point (Figure 3.2). If the pond had been full at the time of the rainfall then as much as 600 m^3 of FDE would have overflowed from the pond over a two-day period. This highlights the need to maintain pond levels with sufficient freeboard to avoid pond overflow during high rainfall events. The size of the freeboard will depend on the area of rainfall catchment, the dimensions of the storage pond and the typical quantities of high rainfall over a 2-3 day period. The case study farm's storage pond requires a freeboard of about 40 cm. Daily pond level sensor data can be incorporated into a decision support management system (Figure 3.1) to provide farm staff with an alert when the level of FDE in the storage pond is within the freeboard zone.

The volume of $FDE_{stormwater}$ can be reduced through the use of stormwater diversion or by covering yards and feed pads. The critical time of year to minimise FDE generation is typically during winter and spring when soils are at or near field capacity. However, the potential for a farm to implement stormwater diversion will vary depending on a number of factors. On some farms, particularly those with fine textured soils and artificial drainage like the case study farm, there may be limited potential to divert storm water from concrete feed pads and yards due to the frequency these areas are used to stand cows off pasture to prevent pugging damage during wet soil conditions. At these times it may difficult to adequately clean these areas between uses to allow stormwater to be diverted. Therefore, where stormwater diversion is not practical, covering rainfall catchment areas may be required to reduce storm water entering FDE storage ponds.

An assessment of the potential for storm water diversion on the case study farm identified that storm water from only 550 m^2 (7.5%) of the catchment area could easily be diverted, which would decrease annual average FDE volume by an estimated 533 m^3 (Table 3.1). More substantive improvements in storm water diversion would require the development and evaluation of systems to prevent contaminated storm water being accidentally diverted to drains, rather than the FDE storage ponds. Further research is required to assess fail-safe systems that will allow greater use of storm water diversion, such as devices that automatic shut off storm water from yards when cows enter the area (e.g. using motion sensors).

Influence of evaporation from FDE storage ponds

Evaporation from the FDE storage ponds ($FDE_{evaporation}$) reduces the annual volume of FDE that needs to be irrigated. For an estimated annual average evaporation of 813 mm, the volume of evaporation from the case study farm's two FDE ponds is estimated to be 1992 m^3. Although evaporative loss can significantly reduce FDE volume annually, it has less impact on reducing FDE volume during winter and spring when maximum storage is required. For example, average evaporative loss from the FDE ponds on the case study farm during winter is estimated to be only 85 mm (10.5% of annual evaporation), which equates to an FDE volume of only 209 m^3.

Total net FDE generation

FDE_{net} for the case study farm is modelled to be 19,089 m^3 in a year with average annual rainfall, or as much as 21,863 m^3 in a high rainfall year. Annual figures are useful in demonstrating the relative contributions that various sources contribute to FDE volume. However, when determining FDE storage requirements, the quantity of FDE generated during winter and spring is of greater importance than annual figures. This is because winter and spring is typically the period when the soil is near or at field capacity, which limits opportunities to irrigate resulting in seasonally higher storage requirements.

Cumulative FDE_{net} generation on the case study farm over the six months during the winter and spring of 2008 was modelled as 11,160 m^3, which was over five times greater than the farm's FDE storage capacity of 2,000 m^3 at that time (Figure 3.3). If no irrigations were made during this period, the storage pond would have reached its capacity near the end of July. The amount of FDE volume generated up to the end of July was primarily from $FDE_{stormwater}$, which equated to about two-thirds of the pond's storage capacity to that point in time.

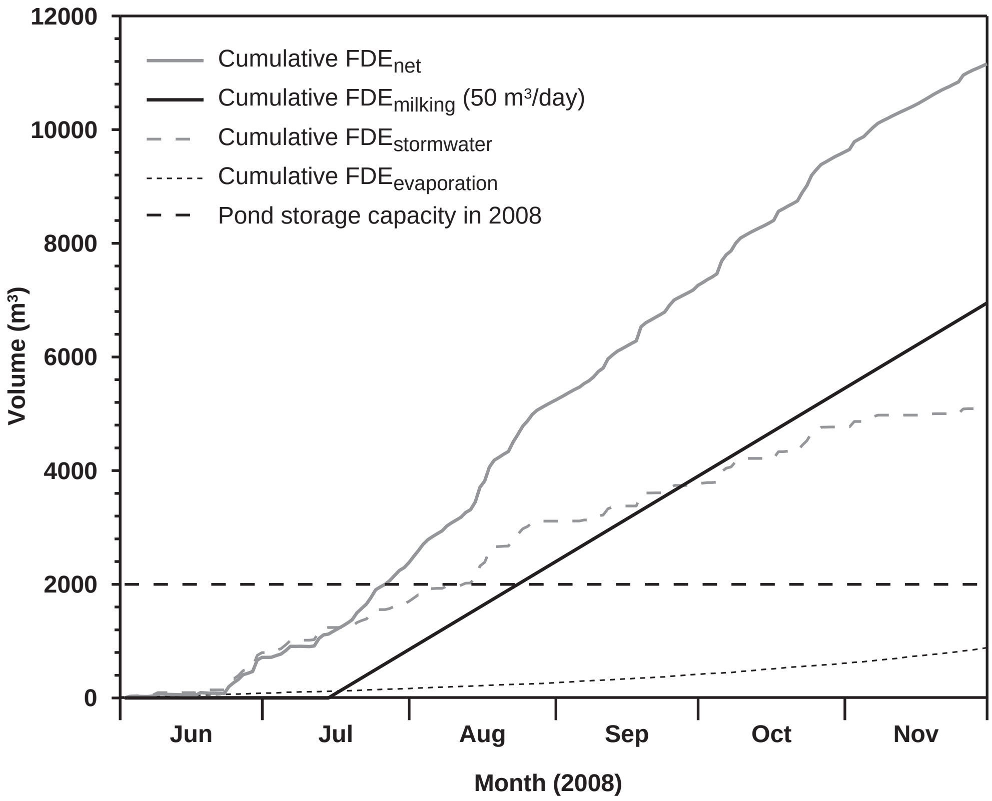

Figure 3.3 The contribution of different sources to FDE generation on the case study farm on during the winter and spring of 2008.

After the start of the lactation season in mid-July, the addition of FDE$_{milking}$ further increased the rate of FDE generation. FDE$_{stormwater}$ remained the largest contributor to FDE$_{net}$ until late September, after which time FDE$_{milking}$ became the greatest source of FDE. The month with the highest rate of FDE$_{net}$ generation was August, primarily due to it being the month with the highest rainfall during the milking season, therefore, the largest monthly FDE$_{stormwater}$ volumes.

Rate of FDE irrigation to land

In addition to the FDE generation rate, the other factor that influences FDE storage requirements is the irrigation rate. The rate of FDE irrigation is the volume of FDE applied per day and is dependent on the SWD and the irrigator type. The SWD determines the maximum application depth that can be applied. Further discussion on comparing methods for estimating the SWD is provided in Section 3.3.3. The irrigator type determines the minimum application depth achievable, which also influences the occurrence of irrigation days. The irrigator type also influences the area of land that can be practically irrigated in a single day.

Modelling FDE storage capacity for individual farms

FDE Storage Calculator

As outlined previously, a range of farm specific parameters are required to determine FDE storage requirements. To assist with this, the *FDE Storage Calculator* was developed by Massey University, in collaboration with Horizons Regional Council, to identify a farm's unique FDE storage requirements (Horne *et al.*, 2010). Documentation explaining how the *FDE Storage Calculator* works is provided in the Appendix. The basic principle behind the *Calculator* is that it uses farm-specific information and long-term daily climate data to model FDE generation. The *Calculator* also estimates the increase in FDE volume from rain falling on all catchment areas that drain storm water into the FDE ponds. The *Calculator* uses a daily soil water balance and a daily FDE irrigation model to estimate the quantity of FDE volume that can be irrigated each day.

The *Calculator* can be used to determine two different levels of storage capacity for a farm's FDE system, which are referred to here as 'adequate' and 'extended' storage capacities. 'Adequate' storage capacity is the storage volume required to avoid pond overflow in all years on the condition that a specified volume of FDE is irrigated on all days when there is a large enough SWD and when there is sufficient FDE in the storage pond. 'Extended' storage capacity also provides a storage capacity based on the criteria described for 'adequate' storage, but differs in that it allows a period to be specified when no irrigations need to be made.

Determining 'adequate' storage capacity for the case study farm

Under the case study farm's 'status quo' system (i.e. travelling irrigator, 100 L farm dairy water use/cow/day and 6750 m^2 of rainfall catchment area), the *FDE Storage Calculator* determined the maximum volume of storage required each year over a period of 30 years (1977-2006). There was a large variation in storage requirements between years, with the storage capacity ranging from 2,093 m^3, in 2006, up to 12,514 m^3, in 1996. The original capacity of the storage pond was only 2,000 m^3, therefore a 500 % increase in pond volume would be required to provide 'adequate' storage in the year with highest requirement. However, increasing storage pond size can require significant capital expenditure and does not reduce the amount of FDE that needs to be irrigated, with its associated labour, equipment and energy costs. Therefore, it is useful to assess how other system changes can be used to reduce both storage requirements and the volume of FDE generated.

Decreasing the case study farm's rainfall catchment area by 25%, to 5,063 m^2, would reduce the storage capacity requirement to 9,524 m^3, which is a 24% reduction, compared to the requirement for the 'status quo' system (Table 3.2). Alternatively, conserving water use by 25%, to 75 L/cow/day, lowers storage capacity requirements to 8,850 m^3 (29% reduction). The first two changes reduce both the storage requirements and the volume of FDE generated. Changing the irrigator type, from a travelling irrigator to a sprinkler system, would allow FDE to be applied on more days, which reduces the required storage capacity to 6,711 m^3 (46% reduction), however, this does not reduce that volume of FDE that must pass through the ponds and be pumped to the irrigation system.

Table 3.2 The influence of proposed system changes on FDE storage capacities required on the case study (highest storage capacity required in 30 years, 1977-2006).

System	**Irrigator Type**	**Farm dairy water use (L/cow/ day)**	**Rainfall catchment area (m^2)**	**Highest storage capacity required (m^3)**
Status quo	Travelling	100	6750	12514
Reduce rainfall catchment area by 25%	Travelling	100	**5063**	9524
Reduce water use by 25%	Travelling	**75**	6750	8850
Sprinkler irrigation (SI)	**Sprinkler**	100	6750	6711
SI + reduce FDWU by 10%	**Sprinkler**	**90**	6750	5979

Based on the assessments made in Table 3.2, the case study farm's FDE storage capacity was increased to 6,000 m^3 in autumn 2009 and a sprinkler irrigation system was purchased in the spring of 2009. For 6,000 m^3 to be 'adequate' storage capacity in the year with the greatest storage requirements, the farm would also required a reduction in farm dairy water use by 10%.

Determining 'adequate' storage requirements for five survey farms

Five dairy farms in the Manawatu-Wanganui region were surveyed to compare and contrast the impact of differing farm parameters on storage requirements, as determined by the *FDE Storage Calculator*. Two farms are located in the upper Manawatu river catchment, one farm is in the lower Manawatu river catchment and the remaining two farms are in the lower Rangitikei river catchment. Summary information for each farm is provided in Table 3.3.

The volume of FDE storage required by the five survey farms to practise *deficit irrigation* (e.g. 'adequate' storage), was determined by the *FDE Storage Calculator* in each of 12 years (1995-2006; Figures 3.4-3.8). These results demonstrate that the required volumes of storage varied considerably between farms and from year to year on the same farm. For example, in the year (1996) the highest storage requirement for the farms, ranged from 4,400 m^3 (*Farm 4*) to as much as 13,600 m^3 (*Farm 3*).

The required pond storage capacities predicted by the *FDE Storage Calculator* indicated that none of the case study farms had 'adequate' storage capacity to practice *deficit irrigation* (DI) in all 12 years analysed. *Farms 1* and *Farm 2* had close to 'adequate' storage in all years except for three, and additional storage volumes of 1,900 m^3 and 2,500 m^3, respectively, are required to have 'adequate' storage for the year with the highest storage requirement (Figures 3.4 and 3.5). Both of these farms, however, have a proportion of their effluent block areas on free draining soils, which provide areas where the use of *deficit irrigation* is less critical. Accordingly, during years when storage is insufficient, irrigations of FDE could be targeted more to the areas of free draining soils in winter and spring.

Table 3.3 Farm details for each of the five survey farms.

Farm details	**Case study dairy farms**				
	Farm 1	***Farm 2***	***Farm 3***	***Farm 4***	***Farm 5***
River catchment	Upper Manawatu	Upper Manawatu	Lower Rangitikei	Lower Rangitikei	Lower Manawatu
Dairy production system	Seasonal supply	Seasonal supply	Seasonal & winter milk supply	Seasonal supply	Seasonal supply
Effective farm area (ha)	170	330	440	250	403
Herd size (milking cows)	450	790	970	600	660
Milksolids production (kg/ha)	824	848	818	880	350
Annual average rainfall (mm)	1300	1300	1100	1100	1000
Farm dairy type	Herringbone	Herringbone	Rotary	Herringbone	Herringbone
Farm dairy yard wash	Manual hose	Manual hose	Automatic wash on backing gate	Manual hose	Manual hose
Farm dairy water use (FDWU):					
Total (m^3/day)	30	50	50	22	20
Per cow (L/cow/day)	67	63	52	37	30
Effluent block:					
Total area (ha)	34	48	56	26	110
Artificially drained area (%)	40	67	100	100	100
Predominant topography	Flat	Flat	Rolling	Flat	Flat
Effluent storage (m^3):					
Current	2900	5000	4600	1200	3600
'Adequate' for DI (in wettest of 12 years)	4800	7500	13600	4400	4300
*'Adequate' for DI (sprinkler irrigation)***	3300	5500	9600	2700	2130
'Extended' (No irrigation 1 Jul-31 Oct)	5700	8700	15300	5000	5100
Rainfall catchments areas (m^2):					
Yards	1100 (d)*	1000 (d)	1200	550	300
Feed pads	1050 (d)	-	1600	1000	1000
FDE Ponds	1250	2800	2700	600	1000
Shed roof	(d)	(d)	(d)	(d)	220
Irrigator type	1 x PTO pump 1 x SRTI$^{\Delta}$	1 x Electric pump 1 x SRTI 1 x Spitfire$^{\Delta\Delta}$	2 x Electric pumps 2 x SRTIs	1 x Electric pump 1 x SRTI	1 x Electric pump 1 x STRI

*(d) = diverted majority of time; **Storage if sprinkler irrigation used; $^{\Delta}$SRTI= small rotating travelling irrigator; $^{\Delta\Delta}$Spitfire = Spitfire irrigator; DI = Deficit Irrigation

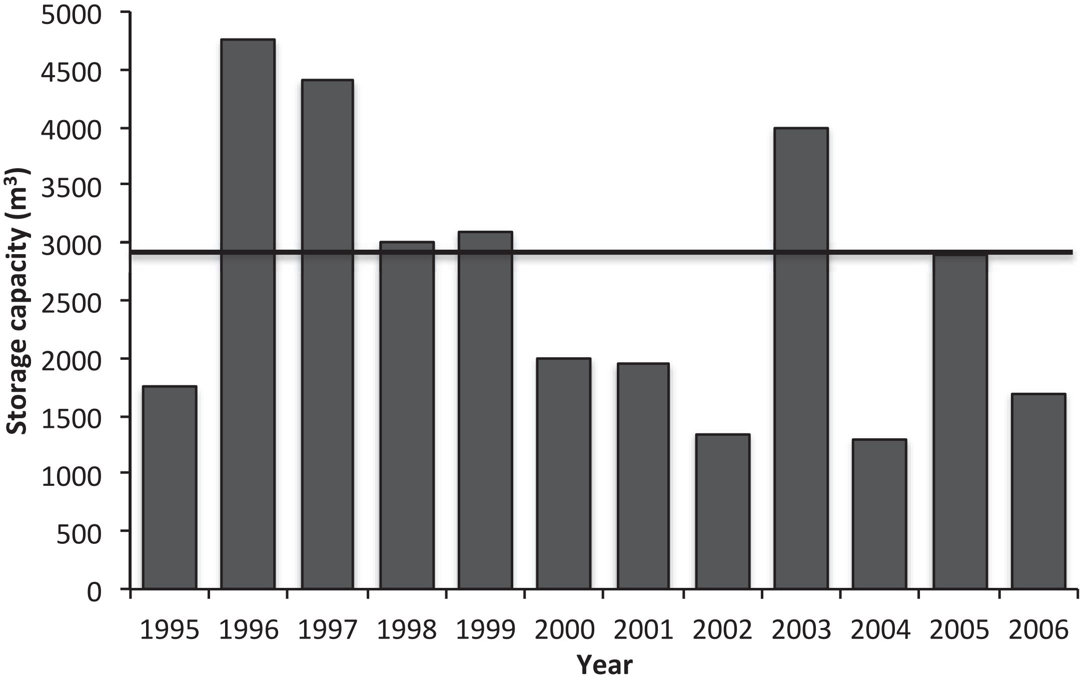

Figure 3.4 The volumes of storage required by *Farm 1* to practice *deficit irrigation* ('adequate' storage), as determined by the *FDE Storage Calculator*. *Horizontal line indicates current storage capacity*.

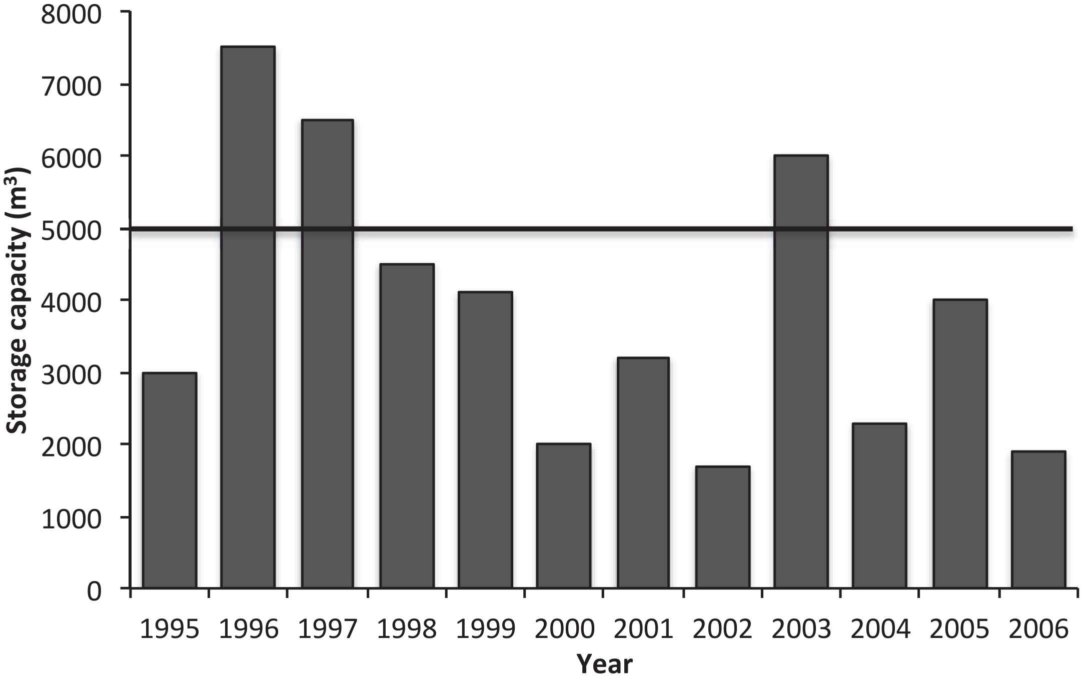

Figure 3.5 The volumes of storage required by *Farm 2* to practice *deficit irrigation* ('adequate' storage), as determined by the *FDE Storage Calculator*. *Horizontal line indicates current storage capacity*

Farms 3 and *4* have inadequate storage to practice *deficit irrigation* in most years (Figures 3.6 and 3.7). *Farm 3* has a particularly high storage requirement, which is primarily influenced by the practice of milking cows all year round and partly because it has a large amount of rainfall catchment area with limited ability to divert storm water. This farm requires an additional 9,000 m^3 (total storage requirement of 13,600 m^3) to practice *deficit irrigation* in the year with the highest storage requirement. If this farm replaced its two travelling irrigators with two sprinkler systems then FDE could be applied at lower application depths, which would allow applications on more days in winter and spring. For example, if sprinkler irrigators were used to apply FDE at an application depth of 5 mm, applying 275 m^3/day, then only 5,000 m^3 of additional storage (total storage requirement of 9,600 m^3) would be required in the year with the highest storage requirement.

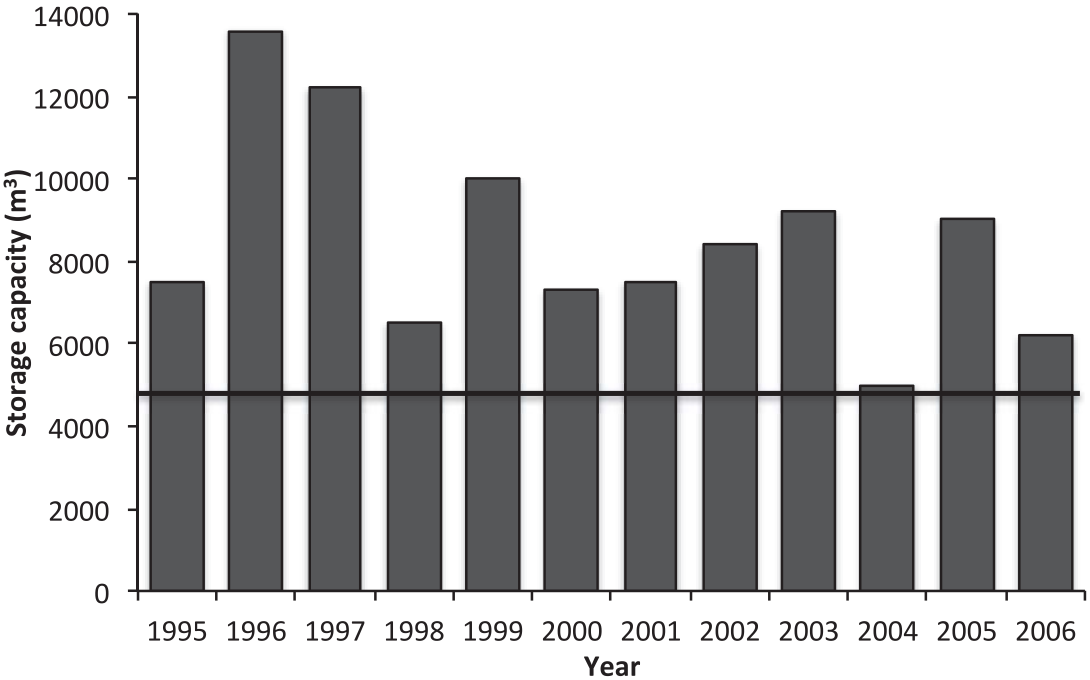

Figure 3.6 The volumes of storage required by *Farm 3* to practice *deficit irrigation* ('adequate' storage), as determined by the *FDE Storage Calculator*. *Horizontal line indicates current storage capacity*.

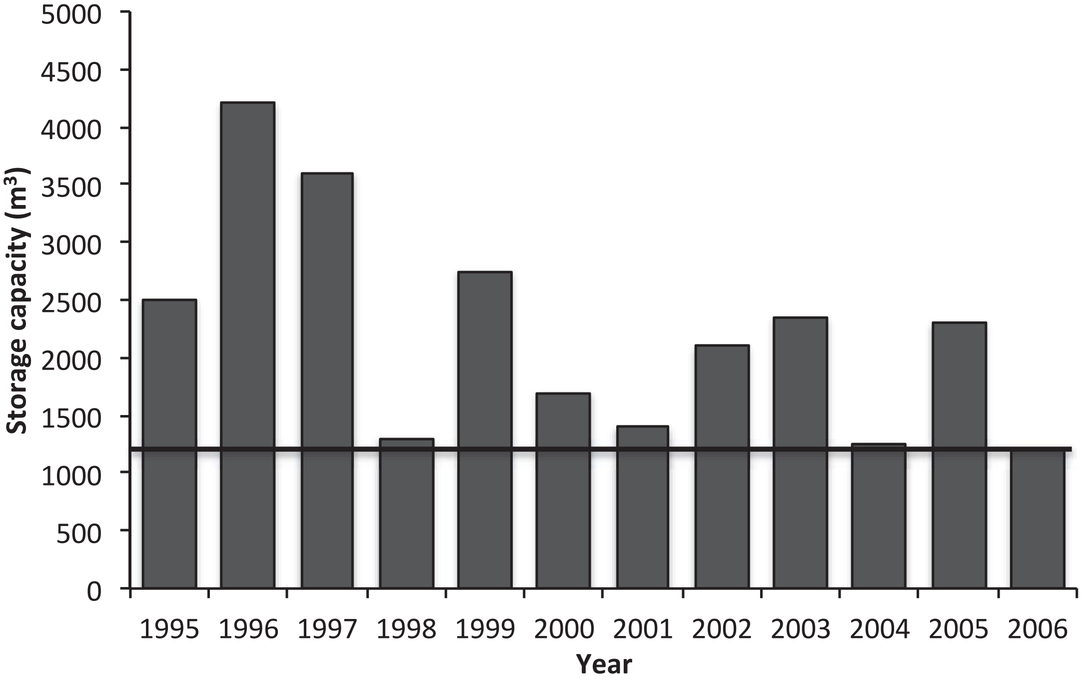

Figure 3.7 The volumes of storage required by *Farm 4* to practice *deficit irrigation* ('adequate' storage), as determined by the *FDE Storage Calculator*. *Horizontal line indicates current storage capacity.*

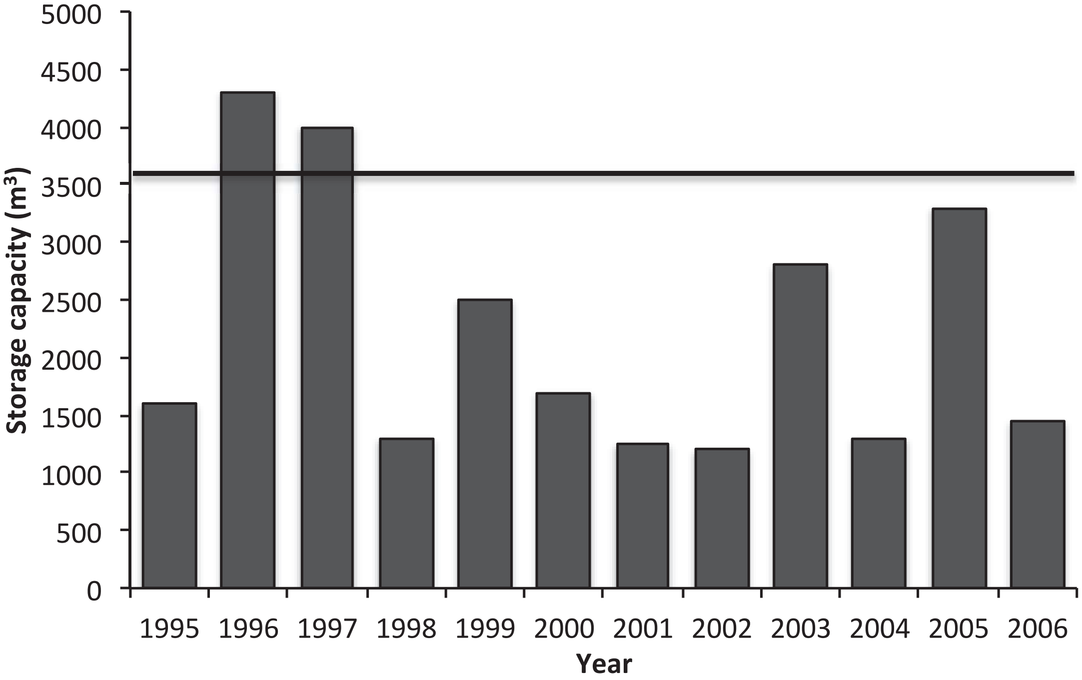

Figure 3.8 The volumes of storage required by *Farm 5* to practice *deficit irrigation* ('adequate' storage), as determined by the *FDE Storage Calculator*. *Horizontal line indicates current storage capacity.*

Farm 5 has 'adequate' storage for all except two years, but requires only an additional 700 m^3 (19% increase) of storage volume to have sufficient storage for the year (1996) with the highest storage requirement (Figure 3.8). However, this farm currently has small holding yards relative to the size of its milking herd, which results in cows being held on races prior to milking. To improve this situation, a larger yard is required, which would increase the FDE volume generated, from additional storm water and yard wash water. In turn, this increase in FDE volume will increase storage requirements. The *FDE Storage Calculator* can be used to assess how changes in yard areas and water use alter storage requirements.

To illustrate how the *Calculator* can be used to assess the impact of FDE system changes on storage requirements, the two case study farms (*Farms 3 & 4*) that required the greatest increase in storage capacity to achieve 'adequate' storage in the year with the highest requirement where assessed. For example, *Farm 3* needs to increase its current FDE storage pond capacity of 4,600 m^3 to 13,600 m3 to have an 'adequate' storage capacity. System changes that this farm could consider to reduce its storage requirement include reducing its farm dairy water use (e.g. 20% reduction), covering its 1,600 m^2 feed pad with a roof or changing to a irrigation system (e.g. sprinkler irrigation) that can apply smaller application depths (e.g. <5mm). The *Calculator* modelled that implementing these three system changes individually would reduce storage requirement to 12,300, 11,850 or 10,600 m3, respectively. Making all three changes together would reduce storage requirements to 7,900 m^3 (i.e. 42% reduction).

Farm 4 needs to increase its current FDE storage pond capacity of 1,200 m^3 to 4,400 m^3 to have adequate storage capacity in the year with the highest requirement. This farm already has a low farm dairy water use, therefore, the *Calculator* was used to just assess the impact of covering the feed pad and changing to a irrigation system that apply smaller application depths (e.g. < 5mm). Implementing these two system changes individually would reduce storage requirement to 3,200 or 3,900 m^3, respectively. Making both changes together would reduce storage requirement to 2,550 m^3 (i.e. 42% reduction).

Determining ‘extended’ storage requirements for the five survey farms

There can be further additional benefits for farms from having ‘extended’ FDE storage capacity, which provides additional storage so that no irrigations are required for a specified period each year (e.g. 1 July-31 October). The advantages of ‘extended’ FDE storage include:

- An extended period of time when irrigation of FDE is not required. Late winter and spring are a particularly busy time of the year on dairy farms, so not irrigating FDE at this time of year will reduce the work load on farm staff.
- The total amount of time spent moving irrigators each year can be reduced if irrigations are only made at a time of year when higher application depths can be used.
- Utilising more of the FDE as a source of irrigation water, if a larger proportion of the FDE volume is applied in summer, which can increase summer pasture growth.

In order to assess the value of ‘extended’ FDE storage, the cost of larger FDE storage facilities should be compared with the potential benefits. The *FDE Storage Calculator* can help with this analysis. Extended FDE storage was determined for each farm assuming the FDE would not be irrigated between 1 July and 31 October each year. Table 3.3 shows the difference between ‘adequate’ and ‘extended’ storage volumes for five case study farms as estimated by the *FDE Storage Calculator* for the year with the highest storage requirement. The increase in storage requirements from ‘adequate’ to ‘extended’ storage ranged from 600-1700 m^3 (12.5-19% increase) for the survey five farms. For some farms it may be more economic to make additional investments in storage capacity to gain the aforementioned benefits of ‘extended’ storage.

Managing FDE storage capacity for individual farms

The *FDE Storage Calculator* determines a farm’s required FDE storage capacity based on particular management criteria. For example, ‘adequate’ FDE storage capacity is the storage volume required to avoid pond overflow on the condition that a specified volume of FDE is irrigated on all suitable days. A ‘suitable’ day is when there is a large enough SWD to allow irrigation and when there is sufficient FDE in the storage pond. Therefore, the aspect of management that is important to avoid storage constraints is irrigating a specified volume of FDE on every ‘suitable’ day. Failure to do this can result in storage being inadequate at a later date, with the consequence of FDE having to be irrigated when soil conditions are too wet.

If a farm's FDE storage pond is not empty at end of the lactation season (typically late May), this indicate that FDE irrigations haven't been managed as specified. In 2011, the FDE level in the case study farm's storage pond was approximately two-thirds above the bottom of the pond at the end of May (Figure 3.9), which equates to about 2900 m^3 of FDE remaining in the pond at this time. The data from the ultra-sonic pond height sensor provided useful diagnostic information to allow identification of the periods of management that resulted in the pond not being emptied. The data presented in Figure 3.9 highlighted that there were an insufficient number of irrigations made during the late summer and autumn period, which is when there is typically the greatest opportunity to irrigate due to high SWDs. If FDE is applied at an application depth of 25 mm to an area of approximately 0.75 ha per irrigation, then only about 15 irrigations would have been required to empty the pond on the case study farm of its excess 2900 m^3 of FDE.

The largest drop in actual FDE level occurred during early March, which was when a contractor was hired to quickly reduce the pond level. A consequence of the pond not being empty at the end of May, will be that the farm is unlikely to have adequate storage capacity to practice *deficit irrigation* during the following late-winter/early spring period. This example demonstrates how farm mangers could use pond level sensor data to identify how historic management of FDE irrigations impact on storage constraints at a later date.

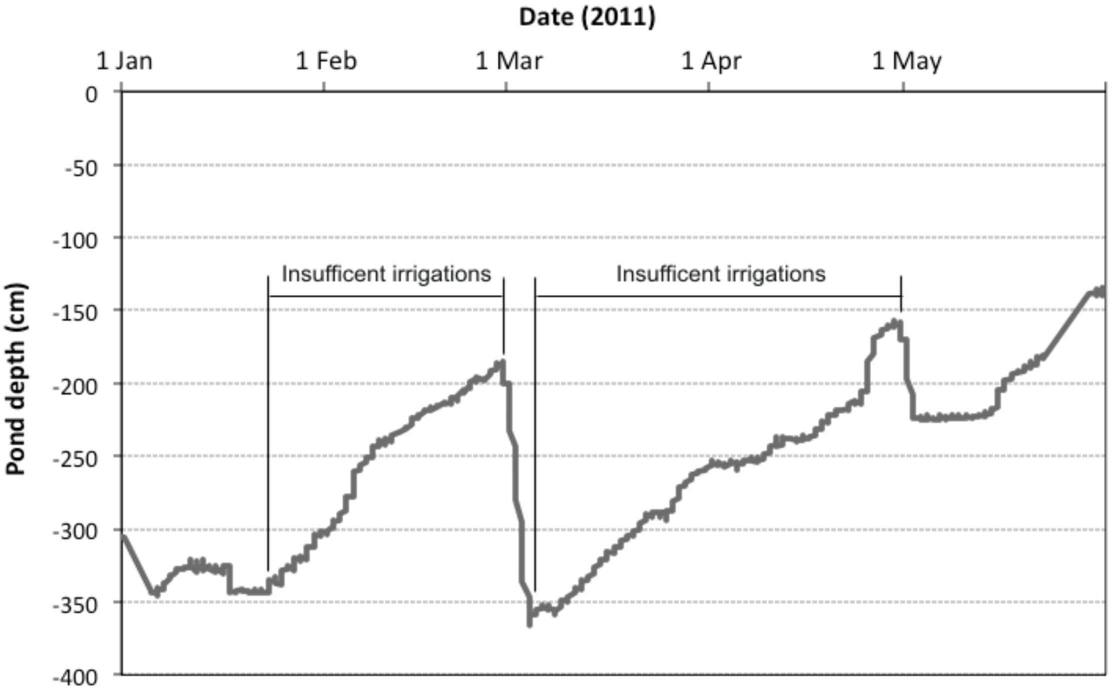

Figure 3.9 Change in FDE level of the case study farm's FDE storage pond, measured with an ultra-sonic pond level sensor from mid-summer to the end of autumn 2011.

3.3.3 Methods for providing farms with accurate daily SWD information

The provision of daily SWD information is important to guide when to schedule irrigations and to determine the application depth that should be used in order to practice *deficit irrigation*. The object of this section was to compare the various ways of providing soil moisture information, which include:

- Soil water balance modelling,
- On-farm soil moisture sensors, or
- Provision of a network of soil moisture monitoring sites across a region (Houlbrooke, 2008).

Both soil water balance modelling and a soil moisture sensor were assessed in this study to evaluate their ability to provide accurate SWD information for the specific purpose of guiding FDE application depth. Drainage data was collected on the case study farm, over a two-year period, to provide a measurement of drainage occurrence and to identify when the soil was likely to be at field capacity.

Rainfall and drainage 2006 and 2007

The annual quantities of rainfall at the case study farm during 2006 and 2007 were 1,146 and 733 mm, respectively. In comparison, the mean annual rainfall for Palmerston North is 970 mm. The quantity and occurrence of rainfall in 2006 resulted in a longer than average drainage season, with drainage events spread over a period of six months (Figure 3.10), and an above average quantity of drainage (394 mm). The length of the drainage season in the subsequent year (2007) was more typical, being about 4 months, however the drainage quantity was well below average (117 mm; Figures 3.11).

Soil water balance modelling

A soil water balance provides an estimate of the SWD based on climate data and soil water holding characteristics (Scotter *et al.*, 1979). The climate data required to produce a soil water balance are daily rainfall and daily evapotranspiration (ET). Evapotranspiration is estimated from daily maximum and minimum air temperature, daily sunshine hours and daily cumulative wind speed. The FAO equations were used to calculate ET (Allen *et al.* 1998) for the soil water balance modelling used in this study.

The advantage of using a soil water balance for scheduling FDE irrigations, is that a soil water balance provides an estimate of the size of the SWD, which can be used to directly determine FDE application depth. Also, soil water balance calculators are relatively easy to construct. The challenge for applying soil water balance modelling for FDE irrigation scheduling is the need to accurately estimate the SWD on a daily basis for individual farms. Inaccurate SWD information, when used to schedule FDE applications to ‘high risk’ soils and landscapes, can result in substantial losses of FDE contaminated water to surface water bodies. For example, a SWD inaccuracy of 10 mm can result in as much as 100 m^3 of FDE being applied per hectare in excess of the SWD, from a single paddock run with a travelling irrigator.

A soil water balance model, using rainfall measured on the case study farm and ET values estimated from other district climate data, was used to provide daily SWD values for the winter/spring period of 2006 and 2007 (Figures 3.10 and 3.11, respectively). Soil water balance modelling indicated that there were less ‘irrigation days’ during the winter/spring period in 2006, compared to 2007. From May to November, the SWD was < 10 mm on 157 days in 2006, compared with only 87 days in 2007. The variation between years provides a challenge with managing FDE irrigation and highlights the importance of accounting for this variation in system design.

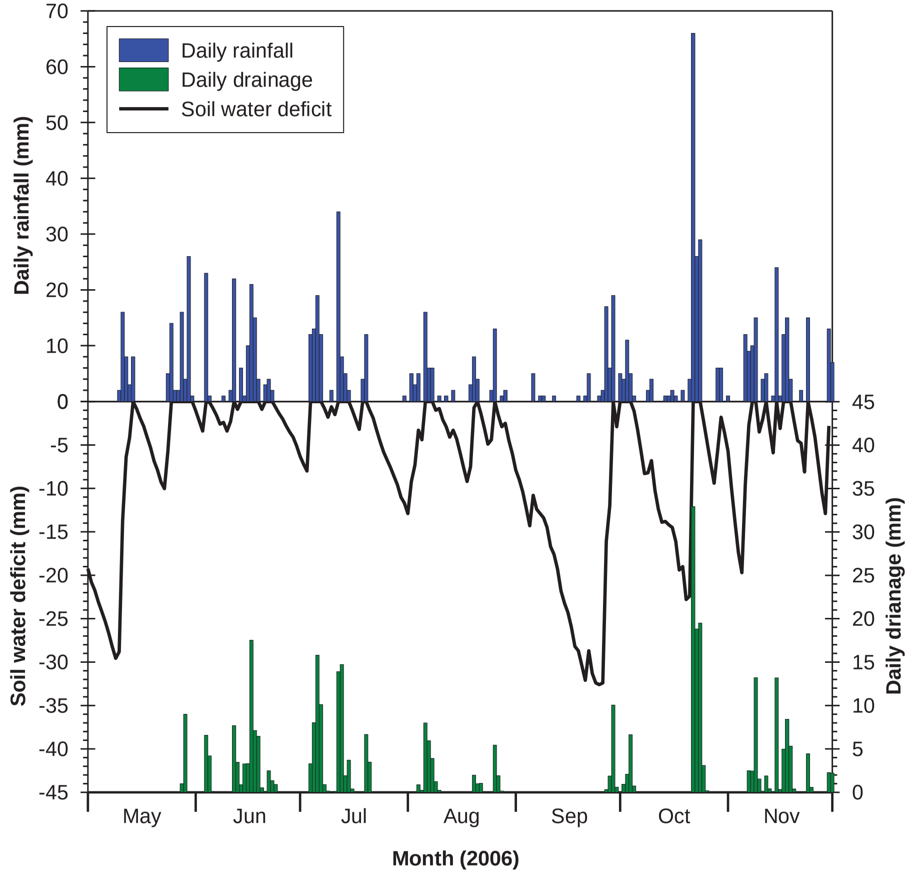

Figure 3.10 Daily rainfall and drainage measured at Massey University's No.4 Dairy Farm and SWD estimated using a soil water balance model (SWD restricted to 75 mm) during 2006.

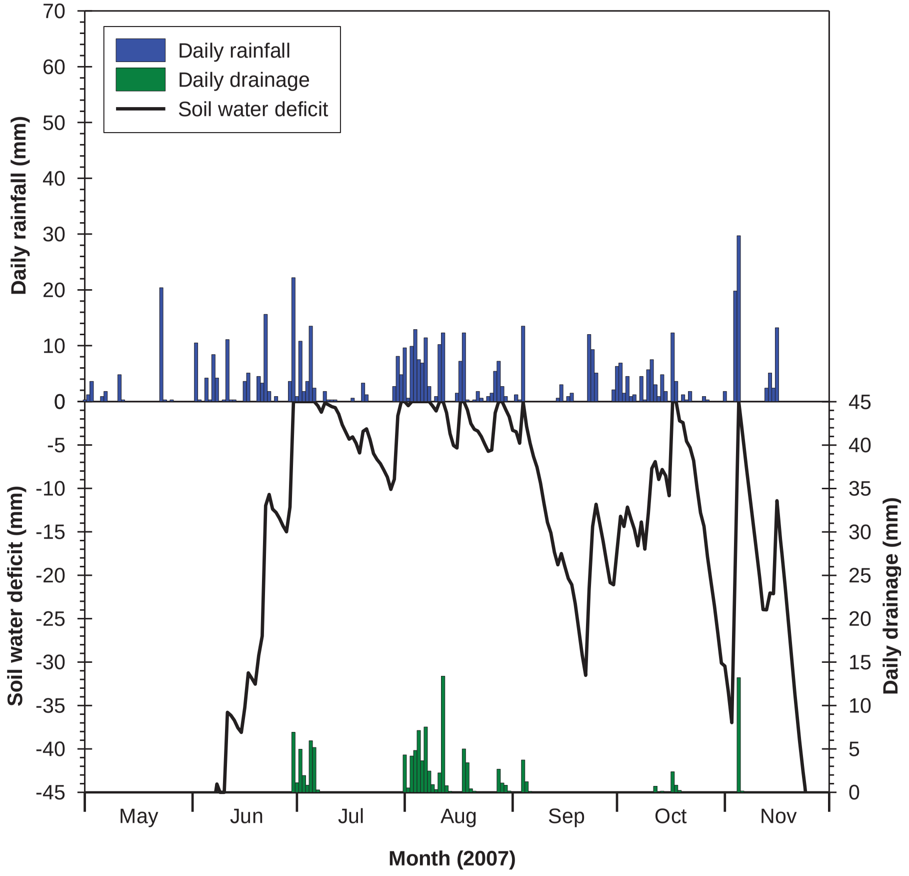

Figure 3.11 Daily rainfall and drainage measured at Massey University's No.4 Dairy Farm and SWD estimated using a soil water balance model (SWD restricted to 75 mm) during 2007.

In both years, the occurrence of drainage on the case study farm consistently coincided with modelled SWD values at or near zero. This result supports the view that the use of SWD modelling using actual farm rainfall has potential to provide the level of accuracy required to schedule FDE irrigations adhering to *deficit irrigation* criteria. However, further research is needed to assess whether this approach can consistently provide reliable SWD information under a range of different soil type and climate combinations.

Farm rainfall vs district rainfall

Another way to provide farmers with SWD information is to use a district soil water balance using entirely district climate data, which is currently available in some districts. Although it would be relatively easy to make this information available to farmers on a daily basis via the Internet or text messages, it is also important to assess whether this approach would be sufficiently accurate for FDE irrigation scheduling.

Soil water deficit values for the case study farm in 2007 estimated using a soil water balance model based on rainfall recorded on the farm (SWB_{farm}) were compared with values calculated using district rainfall ($SWB_{district}$), recorded at a weather station 8 km from the farm (Figure 3.12). District estimated ET was used in both SWB models. During the winter period, both soil water balance models provided similar SWD values. However, during spring the SWB_{farm} model provided a better estimate of when the soil was at field capacity, compared to the $SWB_{district}$ model. Below average spring rainfall in 2007 meant that both soil water balance models did not often return to field capacity. This meant that there were few opportunities for any differences between the two models to equalise. Consequently, there were occasions when drainage occurred when the $SWB_{district}$ model was estimating the SWD to be >10 mm. Therefore, scheduling irrigations based on the $SWB_{district}$ model could have resulted in FDE being applied in excess of the SWD in 2007, with the potential for generating FDE contaminated drainage.

The impact that using district rainfall will have on reducing the accuracy of the soil water balance will depend on the frequency and degree to which rainfall varies across a district. However, rainfall is typically highly variable over relatively short distances in many districts of New Zealand. Therefore, the accuracy of a soil water balance using district rainfall for guiding FDE irrigations should be assessed for individual farms.

Rainfall can be measured on farm with a manual gauge or an automated tipping bucket rain gauge, which is a relatively inexpensive instrument that provides sufficiently accurate data once calibrated.

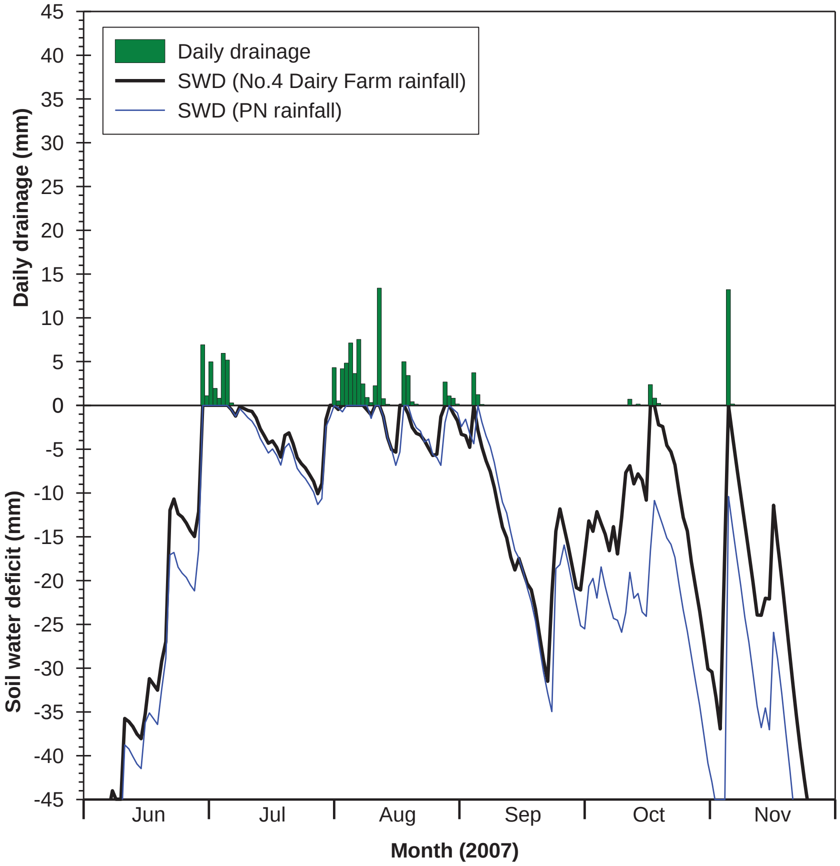

Figure 3.12 Measured daily drainage and estimated SWD using rainfall measured at Massey University No.4 Dairy Farm and at a Palmerston North (PN) weather station (8 km from the farm), during winter and spring 2007.

Actual district ET vs long-term average district ET

In order to create a daily farm-specific soil water balance, the logistics of combining real-time daily farm rainfall and district ET values on a daily basis need to be considered. One approach could be for district ET values to be made available to farmers via the Internet or as a daily text message, where cellular phone reception is adequate. The farmer can then use this daily ET value each day to create a simple manual daily soil water balance model.

For farms where daily district ET values aren't available, the use of long-term ET rates for each calendar day could be an alternative. Again, it is important to assess whether the use of long-term average daily ET values would provide information that is sufficiently accurate for FDE irrigation scheduling.

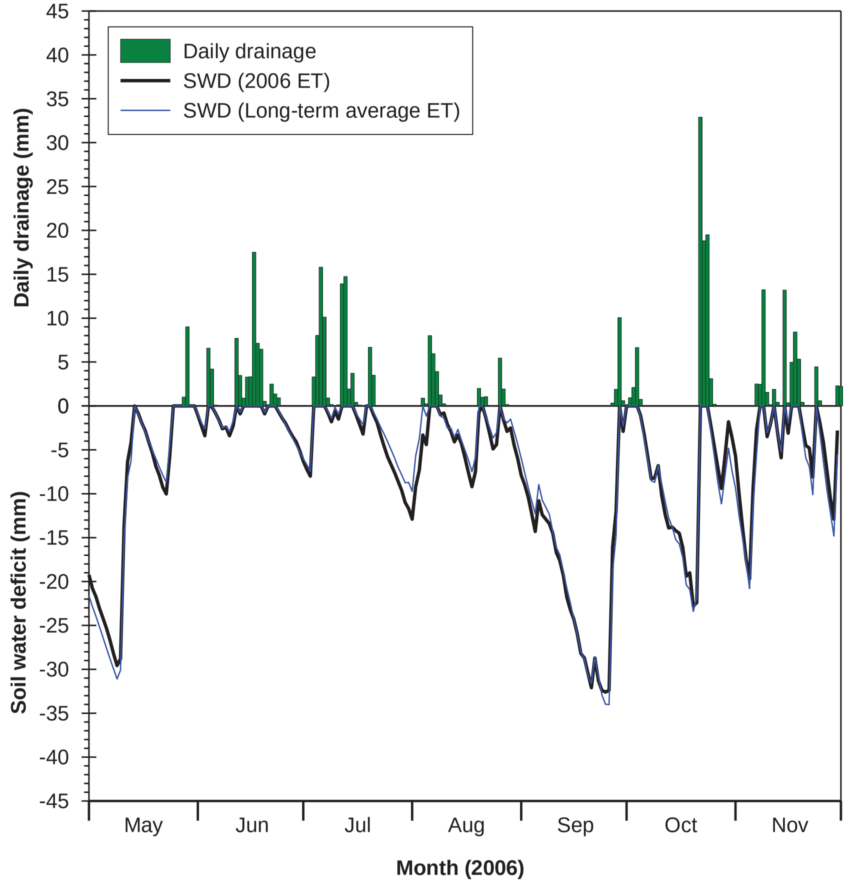

Figure 3.13 Daily drainage measured at Massey University No.4 Dairy Farm and SWD values estimated using farm rainfall and either 2006 district ET rates or long-term average district ET rates (10 years; 1996-2005) for each calendar day.

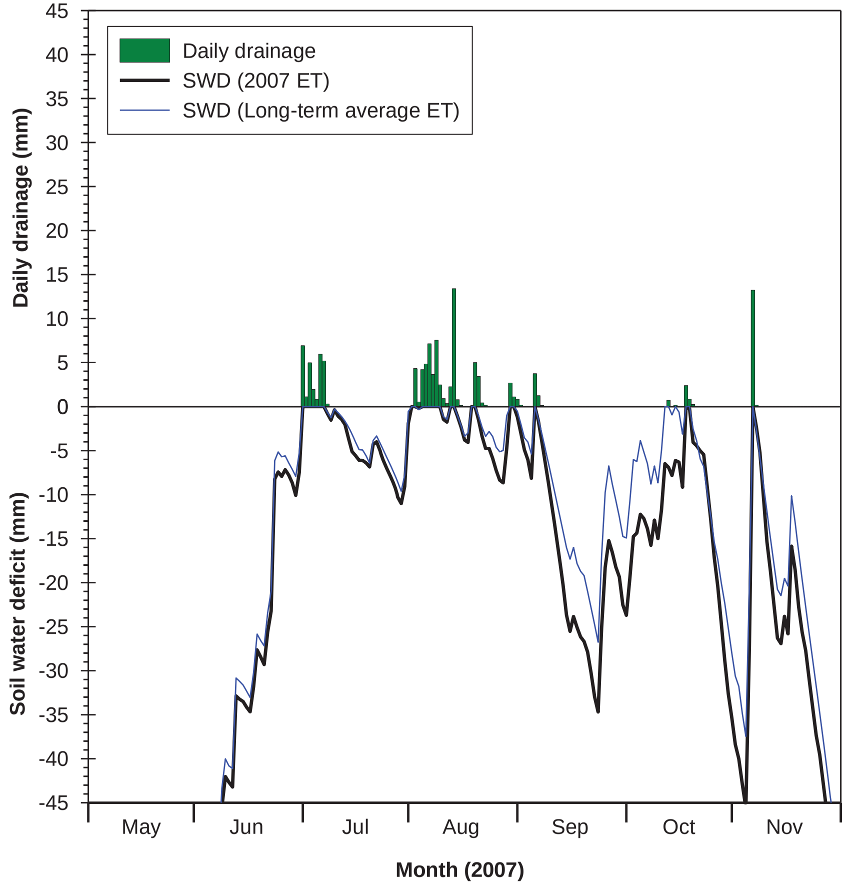

Figure 3.14 Daily drainage measured at Massey University No.4 Dairy Farm and SWD values estimated using farm rainfall and either 2007 district ET rates or long-term average district ET rates (10 years; 1996-2005) for each calendar day.

A comparison of SWD values derived from a soil water balance model, using either actual district ET values ($SWB_{actualET}$) and a model using long-term average (10 year average; 1996-2005) district ET values ($SWB_{averageET}$), are provided for the winter and spring period in 2006 and 2007 in Figures 3.13 and 3.14, respectively.

Throughout the 2006 winter and spring period the $SWB_{averageET}$ model provided SWD values that were very close to the values derived from the $SWB_{actualET}$ model. In 2007, the SWD values from the two models were also similar during winter but differed by up to 9 mm in spring. These differences in spring resulted from the 2007 ET values being generally higher than long-term average ET values, therefore, when variation did occur the $SWB_{averageET}$ generally provided smaller SWD values than the $SWB_{actualET.}$ Consequently, in both years the use of the long-term district ET values would not have increased the risk of FDE being applied in excess of the SWD. However, further comparisons with a larger number of years and across a range of regions is needed to assess the robustness of this approach for informing FDE irrigations.

Soil moisture sensors

Soil moisture sensors provide a direct measurement of soil moisture content. However, they also require calibration (Plauborg *et al.*, 2005) to identify the moisture content that corresponds to field capacity, and an algorithm to convert sensor readings to SWD values. The type of information an Aquaflex sensor provides prior to calibration is presented in Figure 3.15.

A soil water balance or knowledge of when drainage occurs can be used to identify the soil moisture content reading corresponding with field capacity (Figure 3.16). The advantage of calibrating the sensor with a soil water balance is that it allows sensor readings to be converted to SWD values. For example, the Tokomaru silt loam soil at this site provided a sensor reading of 36% when the soil was at field capacity (e.g. 0 mm SWD) and a reading of 28% when the SWD was 45 mm.

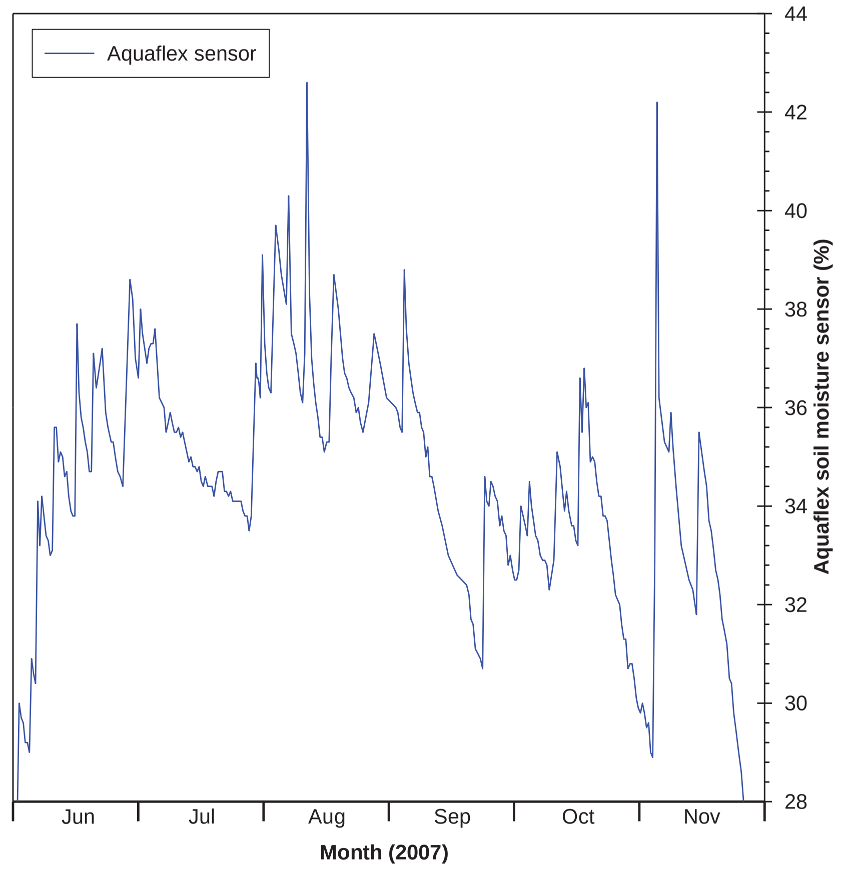

Figure 3.15 Aquaflex soil moisture sensor readings from a mole and pipe drained soil at Massey University's No.4 Dairy Farm, during winter and spring 2007.

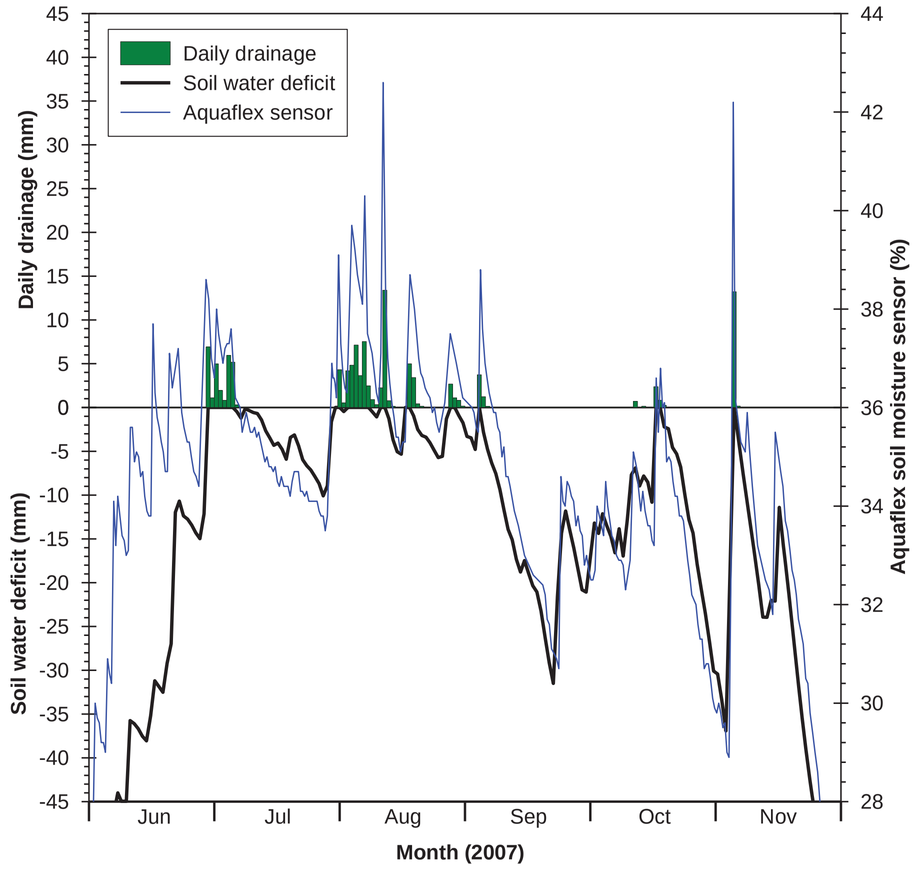

Figure 3.16 Measured daily drainage, soil water balance and Aquaflex soil moisture sensor readings on a mole and pipe drained soil at Massey University's No.4 Dairy Farm, during winter and spring 2007.

Field capacity can also be determined by identifying the Aquaflex reading that coincides with the end of a drainage event (Figures 3.17 and 3.18). This approach also identified that field capacity occurred at a sensor reading of 36% during 2007 (Figure 3.18).

An important consideration with using soil moisture sensors, for accurately assessing SWD values in winter and spring, is that sensor readings for field capacity may vary from year to year (i.e. drift in reading) in some case. For example, field capacity was identified at a sensor reading of 36% in July 2007, and 38% in July 2006. This variation is equivalent to a SWD difference of approximately 10 mm. Therefore, annual recalibration of the sensor may be required to gain the level of accuracy needed to schedule FDE applications using *deficit irrigation* criteria.

Farm vs district soil moisture sensors

As with the soil water balance modelling approach, the ability for a district soil moisture sensor to provide an accurate assessment of SWD for an individual farm will depend on the frequency and degree to which rainfall, an key determinant of soil moisture, varies across a district. As previously stated, rainfall is typically highly variable over relatively short distances in many districts of New Zealand. As a consequence, the use of an on-farm soil moisture sensor is likely to be required to provide the level of accuracy needed.

Assessment

This study compared several methods for providing farmers with soil moisture information to guide the scheduling of FDE irrigations. A soil water balance, updated daily with farm-specific rainfall, was shown to have potential to provide the level of accuracy required to schedule FDE irrigations adhering to *deficit irrigation* criteria, particularly in winter and spring when the risk and consequence of over application is higher. However, further research is needed to assess whether this approach can consistently provide reliable SWD information under a range of different soil types and climate combinations to determine it applicability to other regions of New Zealand. Also, research is required to determine the most effective way to provide farmers with daily farm-specific soil water balance information.

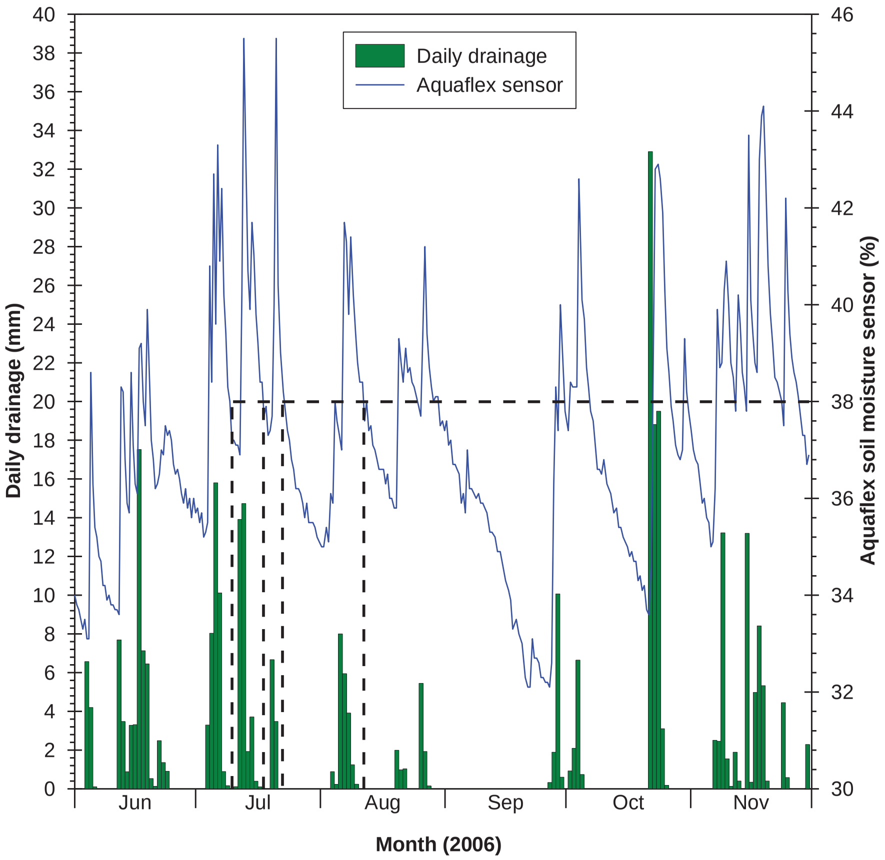

Figure 3.17 Measured daily drainage and Aquaflex soil moisture sensor readings on a mole and pipe drained soil at Massey University's No.4 Dairy Farm, during winter and spring 2006.

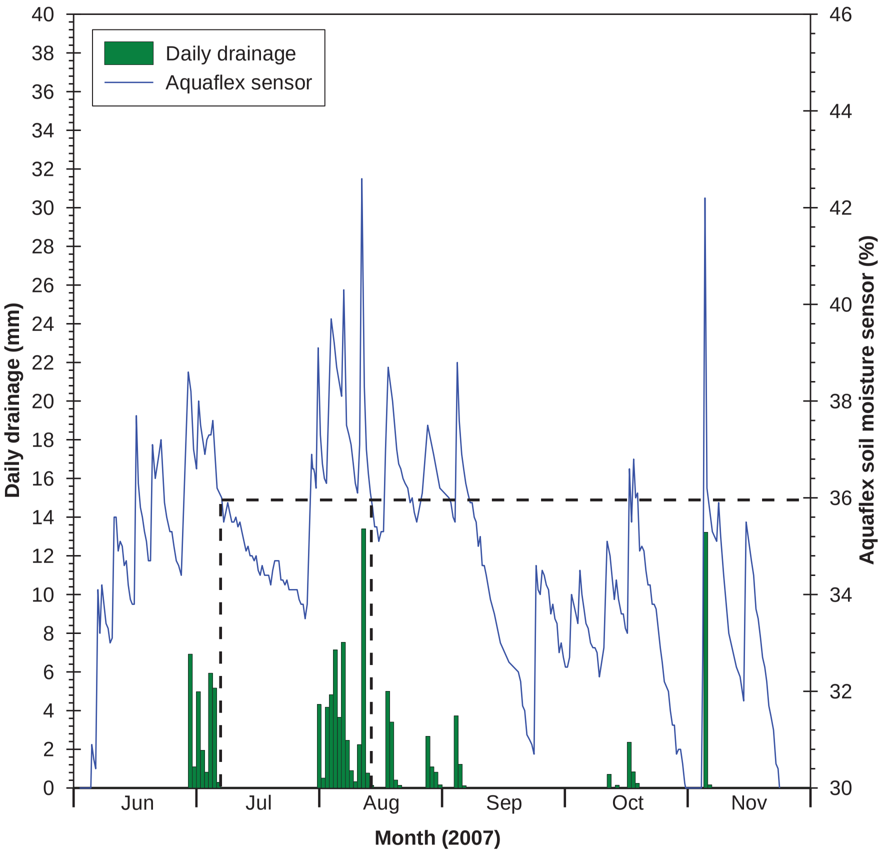

Figure 3.18 Measured daily drainage and Aquaflex soil moisture sensor readings on a mole and pipe drained soil at Massey University's No.4 Dairy Farm, during winter and spring 2007.

3.3.4 FDE travelling irrigator reliability and recording

Remote sensing (GPS and wheel movement sensing) was used to track a small rotating travelling irrigator on the case study farm, during the 2007/08 lactation season. The tracking data demonstrated that irrigator stoppages were a regular occurrence due to a range of causes, which included: mechanical breakdowns, broken/kinked drag hoses, the irrigator anchor point breaking or the irrigator finishing a paddock run sooner than the farm staff had anticipated. A travelling irrigator stoppage creates a runoff risk when the irrigator stops travelling while the irrigation pump is still running.

When a stoppage occurs, the travelling irrigator applies FDE to a single area, of approximately 170 m^2, resulting in extremely high application depths at a rate of about 70 mm/hour. During an irrigator stoppage the SWD in the soil depth (0-450 mm) above the mole channels is likely to be exceeded within the first hour, depending on the SWD. During the 2007/08 season, irrigator stoppages occurred for periods of up to 12 hours. In a 12-hour irrigator stoppage approximately 140 m^3 of FDE is applied, of which greater than 90% is likely to be applied in excess of the SWD. This can result in substantial proportions of the FDE nutrients being lost to surface water in surface runoff and/or drainage (Houlbrooke *et al.*, 2004b). For FDE with an N concentration of 110 mg N/L (refer to Section 3.3.6) the quantity of N applied in 140 m^3 is 15.4 kg N, which during an irrigator stoppage is applied to an area less than 2% of a hectare. To put this in perspective, this rate of applied N is equivalent to 906 kg N/ha on average.

While some causes of irrigator stoppages can be avoided, for example through irrigator maintenance or checking the strength of irrigator anchor points, other causes of irrigator stoppage would be difficult to prevent without constant monitoring of the irrigator. As it is not practical for farm staff to continually watch a travelling irrigator, the use of an automated system to eliminate stoppages is recommended.

Tools for improving travelling irrigator reliability

Automatic irrigator monitoring equipment has the potential to provide fail-safe capability and several different levels of decision support information to assist with management. These levels are:

- Level 1 - Irrigator stoppage alert and automatic shut-off.
- Level 2 – Level 1 plus automatic feedback on the correct application depth.

- Level 3 – Level 2 plus automatic record of FDE placement across the farm.

Irrigator stoppage alert and automatic shut off (Level 1)

An initial irrigator alert system was developed as part of this study with the assistance of DataCarter Ltd in 2007 (Hanly *et al*., 2008; Plate 3.3). The initial prototype system had the following attributes:

- Irrigator wheel movement and FDE pressure inputs.
- Pre-programmed alert criteria to determine when an irrigator stoppage occurred. These criteria identified an alert as being when FDE pressure is present within the irrigator and there is no wheel movement for a period of 10 minutes.
- An alert was sent as a cellular phone text message to designated farm staff.

Evaluation of this system indicated that it did not consistently prevent irrigator stoppages because staff did not always immediately see the text message alert. In order to address this problem, a switch was installed on the FDE pump that enabled the irrigator to automatically turn off the pump via a text message when an irrigator stoppage occurred. This automation of pump shut-off detected most irrigator stoppages, but stoppages caused by broken FDE irrigation pipelines could not be detected due to a limitation in the original alert criteria. When a pipeline is broken, FDE does not reach the irrigator and, therefore, no pressure is registered within the irrigator by the alert system. The criteria were modified to improve communication between the irrigator and the pump, which has enabled broken or kinked irrigation pipelines to be identified by the alert system. This modification has enabled further causes of stoppages to be detected and rectified.

The irrigator remote monitoring system also enabled farm staff to turn the irrigator on or off remotely using their cellular phones, which is useful when troubleshooting problems with the irrigator or checking that the irrigator is working at the start of a new irrigator run. The automatic shut-off capability of the irrigator has also given the farm staff the flexibility to operate the irrigator through the night, providing more time to irrigate.

The irrigator alert system is powered by a lead-acid battery (12 volt, 7 amp hour), charged from a solar panel installed on the irrigator, which was adequate to keep the battery charged year-round. The solar panel only requires cleaning once every few months. However, the use of a solar panel may not be practical in the cases where raw FDE is irrigated directly from a sump, because higher concentration of solids may dirty the solar panel quickly, which may reduce its effectiveness.

Automatic feedback and recording of application depth (Level 2)

In order to follow *deficit irrigation* criteria, FDE application should be set at a depth that is less than the SWD. A conceptual application depth alert system is proposed that could be included as part of the irrigator monitoring package. This feature would inform farm staff, via a cellular phone text message, when the application depth is set too high, which provides feedback to improve irrigator management. The average application depth can be estimated from the travelling irrigator's groundspeed, which is measured using a wheel sensor. GPS information or manual measurements can be used to calibrate the wheel sensor to convert wheel revolutions over a period of time into groundspeed. Using GPS to accurately estimate groundspeed over relatively short periods of time may be difficult due to drift in GPS readings and the relatively slow groundspeeds of the travelling irrigator. Therefore, calibration of the wheel sensor should be assessed using a full paddock run (i.e. >150 m) when the irrigator is set to its fastest groundspeed.

Wheel sensor information can be sent via a cellular phone network to a remote host server, where the calibration data can be used to determine groundspeed. Values for the relationship between groundspeed and application depth for travelling irrigators can be measured on farm or be obtained from manufacturers. The application depth can be automatically compared with the SWD and a text message alert can be sent to farm staff if the irrigator application depth is set too high. Application depth information can also be used in conjunction with FDE nutrient concentrations to provide farm staff with feedback on the amount of nutrients applied in each application and the area of land receiving these nutrients.

Automatic record of FDE placement across a farm (Level 3)

Farm dairy effluent irrigators need to be moved progressively around the effluent block to ensure a relatively even annual load of applied nutrients. However, in practice this may not always occur due to a range of reasons, including; some paddocks may not be available for irrigation at certain times because of paddock grazings, or, because they are 'closed-up' for growing forage crops or harvesting pasture for supplementary feed. Also, there may be a tendency for farm staff to use the longer paddocks more frequently to reduce the number of irrigator shifts required, particularly during winter and spring when smaller application depths are required. GPS data can be used to determine how much FDE is applied to each paddock progressively over a season. This information then allows paddocks that have received less FDE to be identified and targeted for more applications later in the season.

An example of GPS tracking over a one-month period is presented in Plate 3.5. This image shows 17 irrigator runs over a one-month duration. In general, the travelling irrigator was moved around this part of the effluent block relatively evenly over this period. Only two irrigator runs, in Paddock D, were made over the same area. The two irrigator runs in Paddock B were made at a slower ground speed (i.e. higher application depth) compared with all the other runs made that month. The groundspeed data from these runs can be used to estimate the application depth and the quantity of nutrients applied.

Plate 3.5 Travelling irrigator GPS tracks that were recorded between 12 February and 11 March 2008 at Massey University's No.4 Dairy Farm.

The GPS data also highlights where potential improvements to irrigator runs can be made. For example, some irrigator runs in Paddock C were relatively short, which require greater labour inputs compared to longer paddock runs (e.g. Paddocks A and B). Changing the layout of paddocks to increase run length may be one option to improve efficiency of irrigations. Also, the pattern of some irrigator runs in Paddock A would have caused FDE applications to overlap toward the end of the run, which can result in higher applications depths than intended. This pattern may have been caused by a lack of anchor posts at each end of the paddock, which can be corrected by installing additional posts.

Estimating farm-specific average FDE nutrient concentrations

OVERSEER® Nutrient Budgets model is a useful tool for determining the area of the effluent block required for land application. This model estimates, from farm input parameters, the annual quantity of nutrients deposited as dairy cow dung and urine in the farm dairy, on stock holding yards and on feed pads, contributing to FDE. This estimate for the annual quantity of nutrients in FDE can then be used to guide the selection of the size of the effluent block in order to achieve recommended annual nutrient loadings, primarily N, phosphorus (P) and potassium (K) loadings.

Farm dairy effluent land treatment consent requirements, in some regions of New Zealand, also require that the amount of N applied in a single application of FDE should not exceed a specified value (e.g. 50 kg N/ha/24 hours; Horizons Regional Council). For farmers to determine the rate of N being applied during a single application they first need to know the N concentration of the FDE. The nutrient concentration of FDE is typically determined by collecting a sample of FDE and having it analysed by a commercial laboratory. However, FDE concentration can vary throughout the year due to variation in cow diet, the amount of storm water entering storage pond and losses of nutrients in storage. Consequently, multiple samples collected throughout the year may be required to determine the variation in nutrient concentrations of a farm's FDE. Farm dairy effluent nutrient concentrations can also change from year to year, depending on a range of factors including; stocking rate, cow diet and climate.

The development of the *FDE Storage Calculator* provides another way for farmers to determine the nutrient concentrations of their FDE. The *Calculator* estimates the annual average volume of FDE produced, which can be combined with the amounts of nutrient applied to land in FDE per annum, as estimated by the OVERSEER® Nutrient Budgets model, to calculate the average nutrient concentrations. For example, OVERSEER® estimated that annually an average of ~2,100 kg N is applied to the effluent block each year on the case study farm. The *Calculator* estimated that the annual average volume of FDE generated is 19,089 m^3. Accordingly, the average total N concentration of FDE is estimated to be 110 mg N/L, which is similar to the concentrations measured in the case study farm's storage pond (Houlbrooke *et al*., 2004b). At the travelling irrigator's highest application depth setting of 35 mm, which could be used in summer and autumn when there is an adequate SWD, the amount of N applied would be 38.5 kg N/ha. Therefore, it can be determined that even at the travelling irrigators highest application depth/pass the average N application rate is unlikely to be greater than 50 kg N/ha/pass (i.e. consent requirement per day) on this farm.

Another purpose for knowing the N concentration of FDE is for estimating the amount of strategic N applied in winter and spring, to guide how much urea application can be substituted with FDE N. For example, the average ground speed of the travelling irrigator in Paddock B was 12 m/hr, which provided an average application depth of 30 mm. Using the estimated average N concentration in FDE of 110 mg/L, this would equate to 33 kg N/ha. In comparison, the average ground speed of the travelling irrigator in Paddock A was 43 m/hr, which provided an average application depth of 8.5 mm (9.4 kg N/ha). Not all of FDE-N is in the plant-available mineral form (e.g. ammonium and nitrate). For example, based on Houlbrooke *et al.* (2004b), about 60 % of the two-pond treated FDE at the case study farm was mineral N. Therefore, every 8.5 mm of FDE applied to a hectare would provide about 5.6 kg of mineral N/ha.

3.4 Conclusions

Until recently, little attention has been paid to the need to equip farmers with the knowledge and tools that they need to successfully manage FDE land treatment. This study has demonstrated how decision support tools can provide information and fail-safe automation to assist with the design and management of FDE land treatment systems, particularly on 'high risk' soils where the use of *deficit irrigation* is required to minimise the risk of FDE losses to surface waters.

Storage capacity plays a crucial role in determining whether or not *deficit irrigation* can be successfully practiced on a farm. The *FDE Storage Calculator* uses farm and climate information to capture the influence that FDE generation and irrigation rates have on storage requirements. One of the key factors influencing storage requirements on the case study farm was the relatively high FDE generation rates, which during winter and spring was influenced by the significant contribution of stormwater coming from the farm’s large rainfall catchment areas.

Pond storage requirements need to be specifically designed for individual farms to minimise the adverse environmental consequences of undersized capacity. The storage requirements of five survey farms in the Manawatu-Wanganui Region (Table 3.3), also determined using the *FDE Storage Calculator*, varied from 4,400 to 13,600 m^3 (or 6.5 to 10.7 m^3 storage/cow) demonstrating the large variation in storage requirements between farms. The ability to determine farm-specific storage will also help farms avoid being required to have excess storage capacity, reducing capital costs. The *Calculator* also provides the ability to compare various FDE system changes to allow the costs and benefits of alternatives to be assessed during the design process.

Farms practicing *deficit irrigation* of FDE also require accurate, daily, farm-specific SWD information to schedule irrigations. A customised soil water balance, using farm-specific daily rainfall, has potential to provide the level of accuracy required to schedule FDE irrigations adhering to *deficit irrigation* criteria. However, further research is needed to assess this approach under a range of different soil type and climate combinations.

Remote sensing of the small rotating travelling irrigator on the case study farm demonstrated that irrigator stoppages were a regular occurrence, due to a range of causes. The resulting excessive applications of FDE resulted in direct surface runoff and mole and pipe drainage of FDE to surface waters. The development and use of the a travelling irrigator breakdown alert and automatic shut-off system was effective at substantially reducing the risk of further irrigator stoppages on the case study farm.

3.5 References

Allen RG, Pereira LS, Dirk R, Smith M (1998). Crop evapotranspiration: guidelines for computing crop water requirements. Rome, FAO, Irrigation and Drainage Paper 56.

Collins R, McLeod M, Hedley M, Donnison A, Close M, Hanly J, Horne D, Ross C, Davies-Colley R, Bagshaw C, Matthews L (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research*, 50, 267-278.

Davies A, Kaine G and Lourey R (2007). *Understanding Factors Leading to Non-compliance with Regulations by Dairy Farms*. Environment Waikato Technical Report 2007/37 (www.ew.govt.nz).

Dexel (2007). *A guide to managing farm dairy effluent (Manawatu/Wanganui).* http://www.dairynz.co.nz/. 40 pages.

Hanly JA, Horne DJ, Hedley MJ (2008). Implementing deferred dairy effluent irrigation: new technologies. New Zealand Land Treatment Collective Annual Conference Proceedings (16-18 April 2008), Queenstown.

Hanly JA, Horne DJ, Hedley MJ (2010). Sustainable Systems for Land Treatment of Farm Dairy Effluent. Part 2: Tools for management. New Zealand Land Treatment Collective Annual Conference Proceedings (17-19 March 2010), Dunedin.

Haynes RJ and Williams PH (1993). Nutrient Cycling and Soil Fertility in the Grazed Pasture Ecosystem. Advances in Agronomy, 49, 119-199.

Hewitt, A.E. 1998. *New Zealand soil classification 2nd ed*. Manaaki Whenua - Landcare Research New Zealand Ltd Press, Lincoln, New Zealand.

Horne DJ, Hanly JA, Bretherton MR, Roygard JKF (2010). Sustainable Systems for Land Treatment of Farm Dairy Effluent. Part 1: Tools for system design. New Zealand Land Treatment Collective Annual Conference Proceedings (17-19 March 2010), Dunedin.

Houlbrooke DJ (2008). Best practice management of Farm Dairy Effluent in the Manawatu-Wanganui region. Report prepared for Horizons Regional Council (February 2008). 44 pages.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA (2004a). The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research*, 47, 587-596.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR (2004b). Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deficit irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research*, 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA (2008). Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research*, 46, 45–52.

Houlbrooke DJ, Monaghan R (2010). Land application of farm dairy effluent: development of a decision framework for matching management practice to soil and landscape risk. In: *Farming's future: minimising footprints and maximising margins* (Eds L.D. Currie and C.L. Lindsay). Occasional Report No. 23. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. *In press*.

Humphrey MD, Istok JD, Lee JY, Hevesi JA, Flint AL (1997). A new method for automated dynamic calibration of tipping-bucket rain gauges. *Journal of Atmospheric and Oceanic Technology* 14, 1513-1519.

Ministry of Agriculture and Forestry (2009). The Dairying and clean streams accord: snapshot of progress 2007/2008. Published in March 2009 by Ministry of Agriculture and Forestry (www.maf.govt.nz). 12 pages.

Monaghan RM, Smith LC (2004). Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research* 47, 417–428.

Plauborg F, Iversen BV, Lærke PE (2005). In situ comparison of three dielectric soil moisture sensors in drip irrigated sandy soils. *Vadose Zone Journal*, 4, 1037-1047.

Scotter DR, Clothier BE, Turner MA (1979). The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research*, 17, 455–465.

Vanderholm, DH (1984). *Agricultural waste manual*. NZAEI Project report 32. Lincoln College, Canterbury, Agricultural Engineering Institute.

CHAPTER 4:
Implementing deficit irrigation of farm dairy effluent at a farm scale - a Manawatu case study

Chapter's context: The previous Chapter evaluated the capability of a range of decision-support and fail-safe tools to assist farmers with the design and management of *deficit irrigation* FDE land treatment systems. In order to determine the value of implementing improved FDE systems it is also necessary to quantify the impact of system and management changes on reducing the risk of FDE losses to surface water at a farm scale. Chapter 4 demonstrates, using a case study farm, the use of remote-sensing methods to quantify the potential for farm-scale FDE losses to surface water and show how system constraints and improvements influence the risk of these losses.

4.1 Introduction

The Dairying and Clean Streams Accord focuses on reducing the impacts of dairying on the quality of New Zealand surface water. One of the key priorities of the Accord is to ensure that FDE is appropriately treated, with a target of 100% of FDE discharges to immediately comply with resource consents and regional plans. Assessments of FDE management on individual farms are currently obtained from visual farm inspections, used to determine whether farms are complying with regional council rules and consent conditions. This data has shown that nationally the level of full compliance dropped from 64% in the 2007/08 season to 60% in the 2008/09 season (Ministry of Agriculture and Forestry, 2009). In part, this decrease in compliance reflects increased compliance monitoring and the inclusion of feed pads and other rainfall catchment areas in monitoring, previously limited to farm dairies. However, the relatively high levels of continued non-compliance demonstrates that a significant proportion of dairy farms continue to have problems with FDE management.

Although information on non-compliance provides a general indication of the challenges that many farmers have with adhering to regional council rules, it does not provide a quantitative assessment of FDE-associated losses from farms, which is required to determine the scale of the environmental impacts. Quantifying the influence that current practice has on the FDE losses from individual farms is also important for determining the potential improvements that can be gained from changes to the design and management of FDE land treatment systems. If current assessments underestimate these losses then there will be less incentive to make changes. Conversely, if losses are overestimated then needless expense may be incurred.

Previous approaches used to quantify the impacts of FDE management on the loss of FDE in surface runoff and/or drainage water have included modelling losses at a regional or national level. Using such an approach, Flemmer and Flemmer (2008) concluded that an annual average volume of 960 million m^3 of ‘effluent water’ was produced on dairy farms nationally, of which an average of 59% went to surface water (the remaining 41% to ground water). However, these conclusions are easily misinterpreted and based on a model with significant fundamental errors. Firstly, the conclusions are open to misinterpretation because the term ‘effluent’ is used by the authors to describe both FDE and the additional surface runoff and drainage water from paddocks resulting from either FDE or water irrigation (termed ‘effluent water’ by Flemmer and Flemmer, 2008). As a consequence, their estimated volumes of ‘effluent water’ are open to be mistaken for FDE, an example of which is in Shams *et al.* (2010). In the Flemmer and Flemmer (2008) study, less than 5% of the additional surface runoff and drainage water generated (i.e. ‘effluent water’) was estimated to have resulted from modelled FDE irrigation, with the majority coming from modelled water irrigation.

Secondly, the volumes of additional surface runoff and drainage water generated from irrigation, are derived by Flemmer and Flemmer (2008) using a model that has fundamental errors with its water balance (Houlbrooke *et al*., 2010). The most significant error is the failure to account for the impact that irrigation has on increasing the quantity of soil limited evapotranspiration. As a consequence, the calculated volumes of additional surface runoff and drainage water generated are overestimated, particularly in regions where water irrigation is common because of low summer rainfall (e.g. Canterbury). Ultimately, quantifying the impact of farm FDE management on FDE losses in surface runoff and drainage at a regional level is problematic because it cannot account for the many factors that impact on the effectiveness of FDE land treatment systems at the farm level.

An approach widely used in New Zealand to model the impacts of farm nutrient management, including FDE management, on the losses of nutrients from farm systems is the OVERSEER® Nutrients Budgets model (Wheeler *et al.*, 2006). OVERSEER® is an annual average model, which assumes that the use of nutrients on farms follow best management practices. OVERSEER® is a useful tool for estimating farm-specific quantities of nutrients transferred around a farm in FDE. However, as discussed previously, many dairy farms continue to have problems with FDE management, due to either system or management constraints, therefore, the assumption of best management practices cannot be assumed on these farms. Accordingly, OVERSEER® does not model the direct losses of nutrients caused by the immediate generation of FDE-induced surface runoff and/or drainage from poorly managed individual FDE irrigation events. As a consequence, actual losses of FDE may be underestimated by OVERSEER® for individual farms.

Houlbrooke *et al*. (2004b) provides quantitative data on the impacts of FDE irrigation management on the direct losses of FDE in surface runoff and drainage water. In this study, a single 25-mm FDE irrigation was applied to a mole and tile drained soil with a 6 mm soil water deficit (SWD). This FDE irrigation event resulted in the direct generation of 8 mm of surface runoff and 10 mm of drainage, which when combined contained the equivalent of 42% and 23% of the quantity of TN and TP, respectively, present in the applied FDE. This study demonstrated the significant impact that poorly managed FDE irrigation events can have on the losses of FDE and the need for best management practices to be implemented.

For ‘high risk’ soils, like mole and pipe drained soils, the use of a more strict form of ‘deferred irrigation’ criteria, called *deficit irrigation*, has been advocated, as it has been shown to minimise the losses of nutrients and pathogens applied to land in FDE (Houlbrooke *et al.*, 2004b; Collins *et al.*, 2007). *Deficit irrigation* involves the storage of FDE when the SWD is smaller than the minimum application depth of the irrigation system, as operated by the farmer. The minimum application depth achievable with small rotating travelling irrigators is typically 8-10 mm, whereas sprinkler irrigation systems can achieve smaller application depths.

Although *deficit irrigation* has been researched at the paddock scale (i.e. proof of concept; Houlbrooke *et al.,* 2004b), and modelled at the farm scale (Houlbrooke, 2005), its actual implementation at a farm scale has not been researched. It is necessary to study the implementation of *deficit irrigation* at the farm scale because its adoption and success can be constrained by a number of critical factors. Some of these factors can be modelled, such as climate, rate of FDE generation, FDE storage capacity and type of irrigation system. However, the influence of other key aspects of management, such as labour availability and skills, and access to decision support information (Hanly *et al.*, 2008), cannot be accounted for in a model. Therefore, an overall assessment of how well a farm implements *deficit irrigation* requires daily monitoring of various aspects of the FDE system.

The aim of this investigative case study was to use a combination of modelling and on-farm remote sensing to:

- Identify the system constraints that limit the implementation of *deficit irrigation* at a farm scale,
- Quantify the potential volumes of land applied FDE that are at risk of being lost annually in surface runoff and/or drainage from current practice, and
- Explore changes to system design that would enable *deficit irrigation* to be successfully implemented and managed.

4.2 Materials and methods

4.2.1 The case study farm

The case study farm used for this research is Massey University's No.4 Dairy Farm located near Palmerston North, Manawatu. Details of this farm are provided in Section 3.2.1 in Chapter 3.

4.2.2 Monitoring and measurement

Monitoring equipment was installed on the case study farm between 2006 and 2009 to provide continuous measurement of the following aspects of the FDE land treatment system:

Rainfall and soil moisture

Rainfall was monitored using a tipping bucket rain collector (Davis Rain Collector II) and soil moisture was estimated using a soil water balance (Scotter *et al.*, 1979).

FDE height in storage pond

The height of FDE in the storage pond was monitored using an ultra-sonic pond level sensor (EchoSonic LU05), which was installed in 2007 and provided a height recording every 10 minutes. In autumn of 2009 the storage pond was deepened, which required the installation of a replacement ultra-sonic sensor (EchoSonic LU13) with a longer range of measurement. Data from the ultra-sonic pond height sensors were sent wirelessly, via the cellular network, to a remote host server where the data was made accessible via the Internet.

The height of FDE in the pond each day was used to estimate the volume of stored FDE volume (FDE_{stored}; m^3) using the following equation, which is used to calculate the volume of a rectangular pond with sloping sides:

$$FDE_{stored}=(1/6)*(2h[x + (2hb)][y + (2hb)]+ yh[x + (2hb)] + xh[y + (2hb)] + 2xyh)$$

Where, b = is the batter of the pond walls, h = height of FDE in the pond each day, x = length of pond base, and y = width of pond base.

Travelling irrigator tracking

A custom built irrigator tracking device (DataCarter Ltd), which incorporated both Global Position System (GPS) and wheel movement sensors (magnetic reed), was installed on the farm’s travelling irrigator in 2007 to record irrigator use, location and groundspeed. This data, in conjunction with the irrigator’s application distribution patterns (Houlbrooke *et al*. 2004a), was used to estimate FDE application depths and the area of land receiving irrigation each day.

The daily application depth information was used with the area of land irrigated each day to determine the volumes of FDE that were applied. Potential losses of FDE in surface runoff and/or drainage were estimated for each irrigation event by comparing the application depth with the soil water deficit (SWD), as determined by a soil water balance. When the application depth exceeded the SWD the magnitude of surface runoff and/or drainage was given by the difference between the application depth and the SWD.

4.2.3 Model parameters

The parameters used to model net FDE generation, daily volumes of FDE irrigated and daily volumes of FDE irrigated in excess of the SWD, were:

The net volume of FDE generated each day (FDE_{net}, m^3/day) is calculated as:

$$FDE_{net} = FDE_{milking} + FDE_{stormwater} - FDE_{evaporation}$$

Where, $FDE_{milking}$ is the daily volume of FDE produced from washing of the milking plant, farm dairy and the farm dairy yards after milking (m^3/day),

$FDE_{stormwater}$ is the daily storm water volume that comes from the rainfall catchment areas (e.g. concrete yards and feed pads) into the storage ponds (m^3/day),

$FDE_{evaporation}$ is the daily volume of evaporative losses from the FDE storage ponds (m^3/day).

The volume of FDE irrigated each day ($FDE_{irrigated}$; m^3/day) is calculated as:

$$FDE_{irrigated} = FDE_{depth} \text{ x } FDE_{area}$$

Where, FDE_{depth} is the daily average FDE application depth (mm) each day, which is determined from irrigator ground speed.

FDE_{area} is the estimated area (ha) receiving an FDE application each day, which is determined from irrigator swath width, ground speed and duration of operation.

When $FDE_{depth} > SWD$, the volume of irrigated FDE that exceeds the SWD ($FDE_{>SWD}$; m^3/day) is calculated as:

$$FDE_{>SWD} = FDE_{irrigated} - [SWD \text{ x } FDE_{area}]$$

Where, SWD is the daily soil water deficient (mm), which is determined using the procedure described by Scotter *et al.* (1979).

4.3 Results and discussion

4.3.1 Rainfall 2008 and 2009

The annual quantities of rainfall at the case study farm during 2008 and 2009 were 1,135 and 1,253 mm, respectively. In comparison, the mean annual rainfall for Palmerston North is 970 mm. The quantity and occurrence of rainfall in 2008 was above the mean monthly figures during the winter and early spring period, and was particularly high in August (Figure 4.1). In 2009, rainfall tended to be higher than the mean figures during the late spring and summer period, with rainfall in February being almost four times greater than the mean monthly value. During the winter and spring period, FDE land treatment is typically more difficult to schedule due to the soil being near or at field capacity. Over the six-month period from June-November the quantity of rainfall for 2008 and 2009 was 47 and 27% higher than the mean monthly value, respectively. This indicates that managing *deficit irrigation* during these two years is likely to have been more difficult than in an average year.

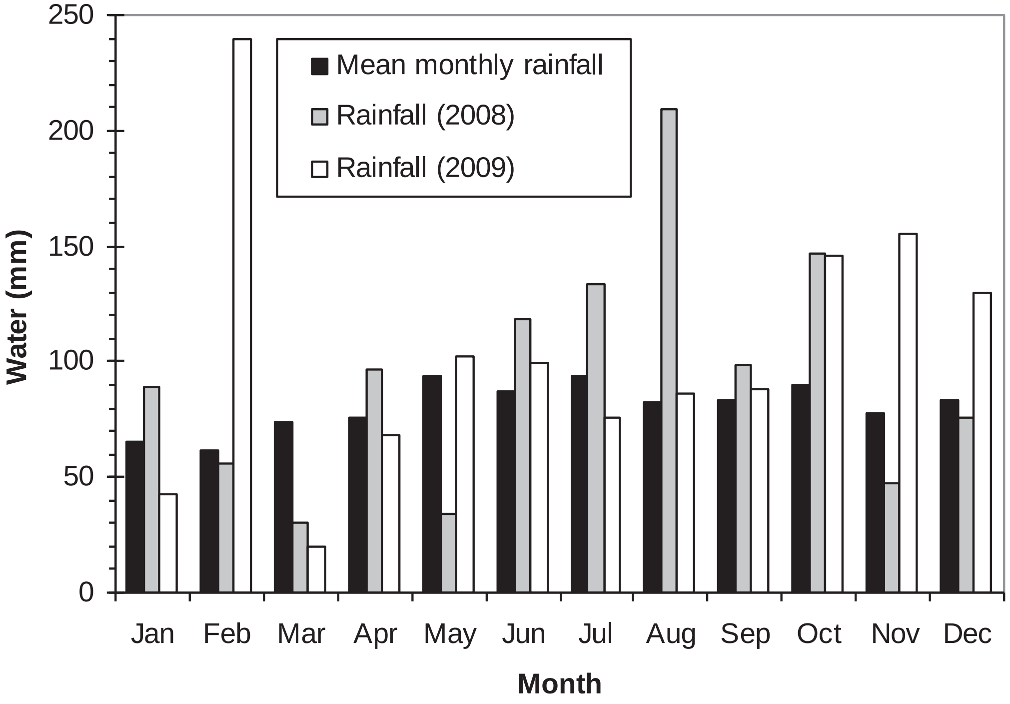

Figure 4.1 Mean monthly rainfall for Palmerston North and monthly rainfall or the case study farm during 2008 and 2009.

4.3.2 System constraints

Monitoring of the case study farm's FDE land treatment system identified that the main system constraints to the implementation of *deficit irrigation*, were inadequate FDE storage capacity and the minimum application depth of the irrigator. Scenarios of either actual or modelled management are used in the following sections to demonstrate how each of these system constraints influenced the effectiveness of the FDE land treatment system.

Inadequate FDE storage capacity

The impact of inadequate FDE storage capacity on irrigation management was quantified on the case study farm by assessing the interaction between the key components of a FDE land treatment system. These components include net FDE generation rate, storage capacity, irrigation system type and soil moisture status.

Scenario 1: Actual farm practice (winter and spring 2008)

Scenario 1 describes the actual FDE irrigation as it was practiced on the farm during the winter and spring of 2008. In this scenario, the FDE storage pond was 40% full at the start of winter (June 2008) and farm staff realised that to avoid FDE pond overflow, frequent FDE irrigations would be required at times when the SWD was at or near field capacity. Data from the irrigator remote sensing equipment was used to estimate the quantity of FDE that was applied in excess of the SWD and, therefore, the quantity of FDE that was likely to cause direct surface runoff and/or drainage enriched in nutrients and faecal microorganisms.

The estimated volume of FDE irrigated on the case study farm, during the winter and spring of 2008, was approximately 11,500 m^3, of which an estimated 7,890 m^3 (69%) was applied in excess of the SWD (Figure 4.2). Therefore, significant proportions of the nutrients applied in the FDE were at risk of being lost in surface runoff and/or mole and pipe drainage (Houlbrooke *et al.*, 2004b). Based on the case study farm's average FDE nutrient concentrations (150 mg TN/L, 25 mg TP/L; Houlbrooke *et al.*, 2004b), the quantity of total nitrogen (TN) and total phosphorus (TP) in 7,890 m^3 of FDE is estimated to be 1184 kg TN and 197 kg TP. These values represent a theoretical maximum quantity of nutrients that are at risk of being lost to surface waters. However, the actual quantity of FDE-derived nutrients reaching fresh surface water systems will depend on a range of mitigating factors, including: FDE application rate and depth, SWD, soil drainage properties and land slope. These factors influence the quantities and relative proportions of FDE lost via surface runoff versus drainage and the amount of attenuation in the soil (Houlbrooke *et al.*, 2004b).

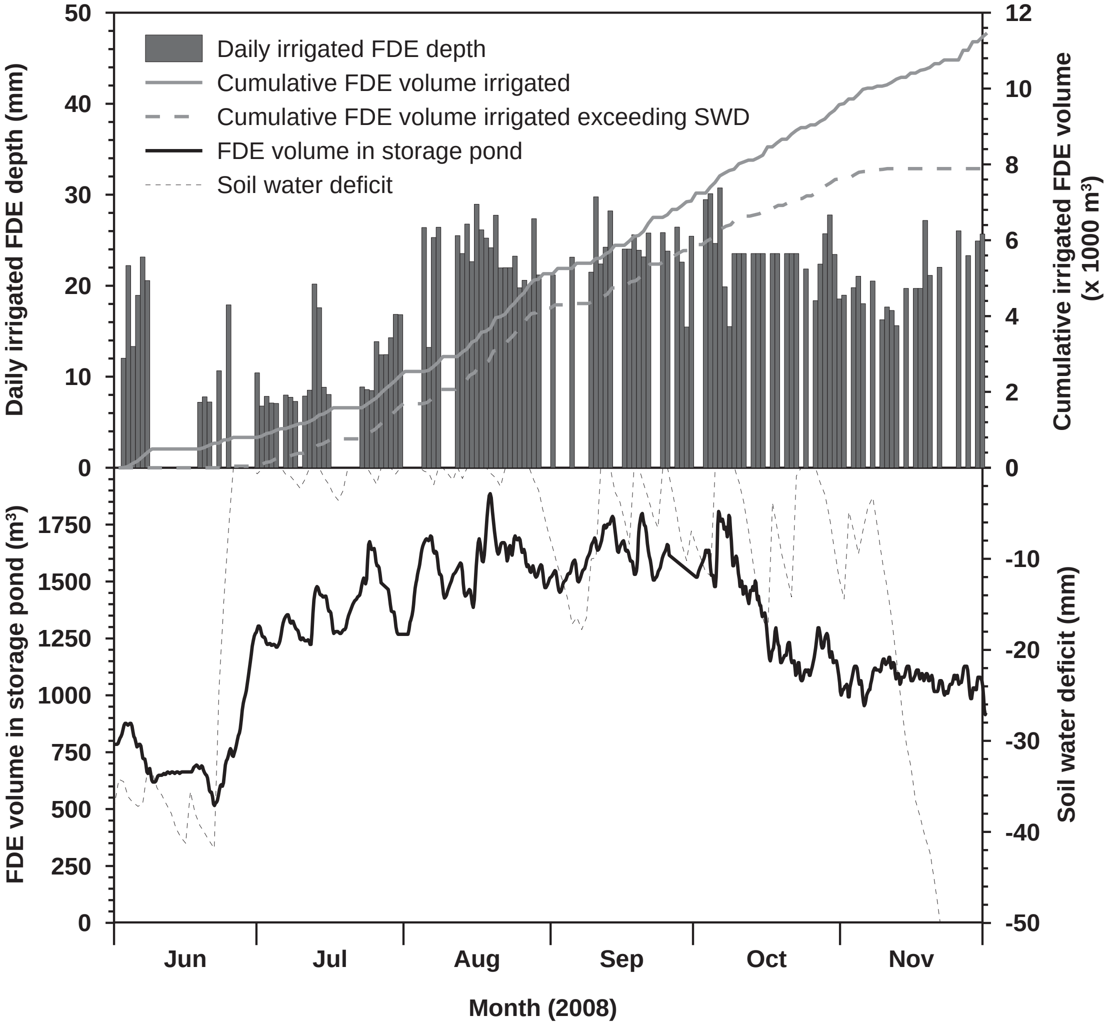

Figure 4.2 The key features of FDE land treatment system, as practiced on the case study farm during winter and spring of 2008 (*Scenario 1*), and in relation to soil moisture conditions (pond maximum storage capacity = 2,000 m^3).

When application depths of FDE exceed the SWD on soils with a high degree of preferential flow, the attenuation of applied nutrient (N and P) concentrations has been reported to be 10-58% (Houlbrooke *et al.*, 2006; Houlbrooke *et al.*, 2004b; Monaghan & Smith, 2004). Although the values given for percentage attenuation are for the total applied volume, they have been used in this study for the volume applied in excess of the SWD in 2008, which provides a relatively conservative estimate of losses to surface water. Therefore, of the 1,184 kg TN and 197 kg TP calculated to have been applied in FDE at application depths in excess of the SWD, an estimated 497-1,067 kg TN and 83-177 kg TP could have been lost to surface water, depending on the level of attenuation. To put this in perspective, if it is assumed that the average annual total farm losses of N and P in rainfall-induced surface runoff and drainage are c. 16 kg TN/ha (Overseer estimate; Chapter 6, Table 6.3) and c. 1.3 kg TP/ha (Houlbrooke, 2005), then the 196 ha case study farm would loss 3,136 kg TN and 255 kg TP annually, excluding FDE losses. It then follows that the estimated quantities of N and P lost to surface waters in over-applied FDE, during the winter and spring of 2008, are equivalent to increases in total farm losses of 16-34% TN and 33-69% TP.

During 2008, FDE was applied in excess of the SWD as a result of both system constraints and management decisions, such as using application depths that were greater than the SWD. Accordingly, it is useful to quantify the contribution that system constraints made to FDE being over applied, in order to assess the benefits of system improvements. This was determined by modelling the 2008 winter and spring period using ‘optimal’ management criteria, which is described in *Scenario 2*.

Scenario 2: Modelled ‘optimal’ management criteria for existing infra-structure (winter and spring 2008)

In *Scenario 2* the storage pond was assumed to be empty at the start of winter. Also, FDE irrigation scheduling in the model was determined by the availability of FDE to irrigate and by the following criteria:

When SWD ≤ 10 mm and remaining pond storage capacity > 500 m^3, then no irrigation.

When SWD ≤ 10 mm and remaining pond storage capacity < 500 m^3, then irrigate at an application depth of 8 mm (120 m^3).

When SWD = 10-20 mm, then irrigate at an application depth of 8 mm (120 m^3).

When SWD > 20 mm, then irrigate application depth of 16 mm (120 m^3).

The two application depths used in the model correspond to the fastest and second fastest travel speeds (i.e. two lowest application depth settings) of the travelling irrigator used on the case study farm. The SWD values used for determining when to irrigate were set higher than the application depth to partly accommodate for the non-uniform application distribution pattern of the travelling irrigator (Houlbrooke *et al.*, 2004a).

Farm dairy effluent was also irrigated at a depth of 8 mm on all days when the model predicted that there was less than 500 m^3 of storage capacity available before overflow commenced. This irrigation trigger volume, which equates to a pond level of approximately 30 cm below the overflow point, was used to apply FDE irrespective of the SWD in order to minimise the risk of pond overflow. On every day that FDE was irrigated, the model assumed that 120 m^3 was applied. This volume was determined as being the approximate volume of FDE applied at an 8 mm application depth in two irrigator runs, with an average run length of 210 m, or at a 16 mm application depth in a single run. The outputs from this model are presented in Figure 4.3.

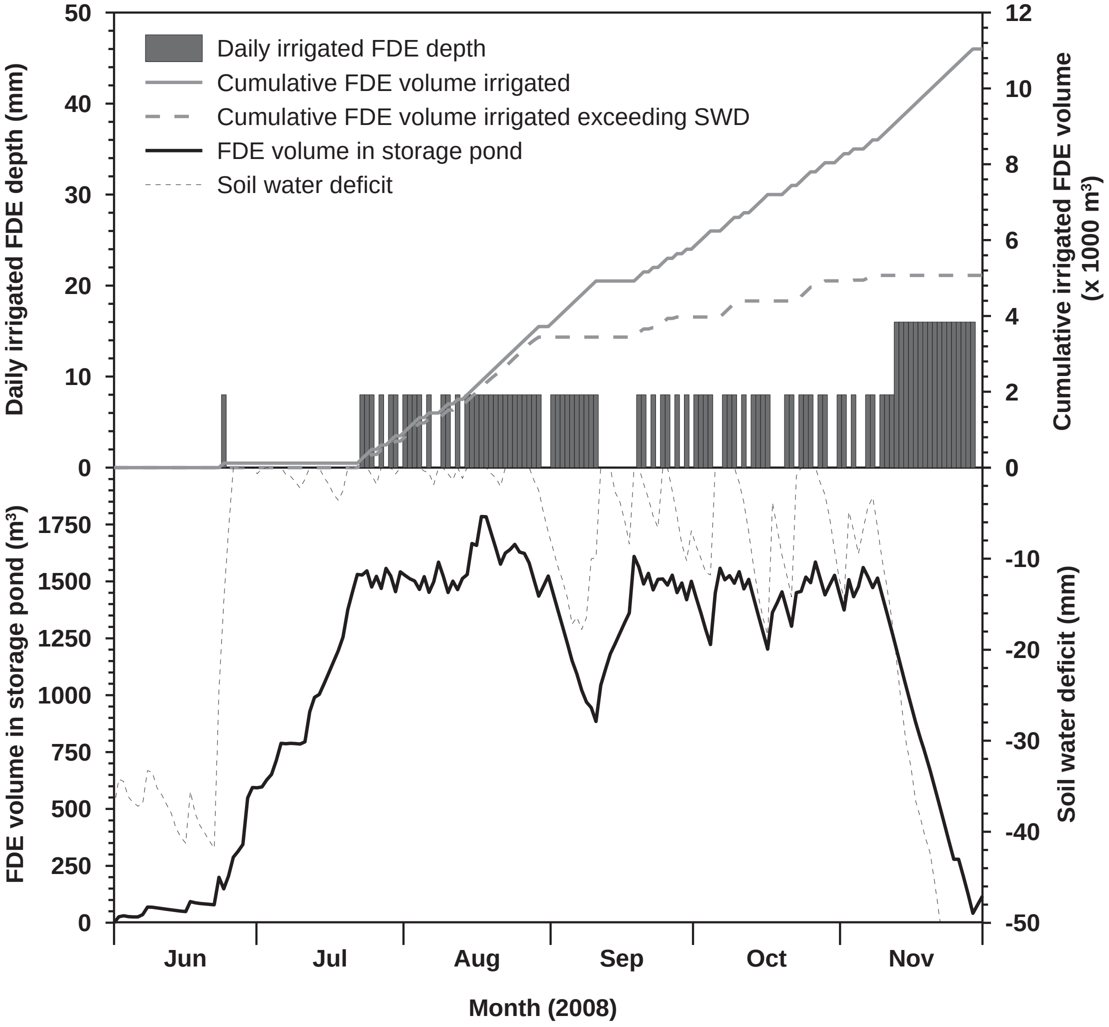

Figure 4.3 Modelled components of the FDE land treatment system for the case study farm, during the winter and spring of 2008, using the 'optimal' management criteria outlined in *Scenario 2* (pond maximum storage capacity = 2,000 m^3).

The pond level remained below the over flow point throughout the entire winter and spring period in *Scenario 2*, reaching its highest point (215 m^3 from overflow point) in August, which was the month with the highest rainfall (Figure 4.1). However, in order to avoid pond overflow, it was estimated that significant volumes of FDE would still have to be applied at application depths greater than the SWD, particularly during August. Consequently, the model estimated that of the 11,040 m^3 of FDE that needed to be irrigated to minimise the risk of pond overflow, an estimated 5,070 m^3 (45.9%) would still have been applied in excess of the SWD. This represents about two-thirds of the FDE actually applied in excess of the SWD in 2008, which demonstrates that inadequate FDE storage capacity was the largest contributor to FDE being over applied in that year. The estimated quantities of N and P contained in 5,070 m^3 of FDE are provided in Table 4.1.

To enable farm staff to strictly follow the criteria in *Scenario 2,* the number of irrigator shifts would need to be increased. This is because for a given volume of FDE applied, a lower application depth can only be achieved by increasing the area of application, which increases labour requirements. A total of 81 irrigator runs were made during the winter and spring of 2008. However, this number would need to more than double, to 167 runs, to adhere to the criteria described in *Scenario 2*. Assuming the amount of time required to move the irrigator between runs is between 0.5-1 hour/run, the additional time required for ‘optimal’ management is estimated to be between 43 and 86 hours.

If this scenario is modelled with the actual pond level at the start of winter (e.g. 40% full) this would not have influenced the results in *Scenario 2* as there was adequate SWD and very little FDE generation during the first three weeks of June 2008. Even if the pond had been full at the start of June, there would have still been sufficient SWD to empty the pond by 18 June. Therefore, in 2008 the pond level at the start of the winter was not an important factor influencing FDE management.

Scenario 3: Actual farm practice (winter and spring 2009)

During autumn 2009, the FDE storage pond on the case study farm was enlarged to a capacity of 6,000 m^3 to improve the ability of the farm to practice *deficit irrigation*. The *FDE Storage Calculator* was used to establish that this storage capacity would be adequate, in the years with the highest storage requirements, if the farm also changed to using a sprinkler irrigation system, instead of the travelling irrigator, and reduced farm dairy water use by 10% (Chapter 3). During the winter and spring of 2009, the farm’s FDE system was again monitored to assess the influence of increased storage capacity on FDE management and to identify any other system constraints. The small travelling irrigator was used up until mid-September, after which time the farm purchased a sprinkler irrigation system with the capability of irrigating at application rates of 1.5 mm/hour to a single area of approximately 1.2 ha.

Scenario 3 describes the efficiency of FDE land treatment resulting from actual farm practice during the winter and spring of 2009 (Figure 4.4). Over the assessment period a total of 6,050 m^3 was irrigated, of which an estimated 1,560 m^3 (25.8%) was applied in excess of the SWD.

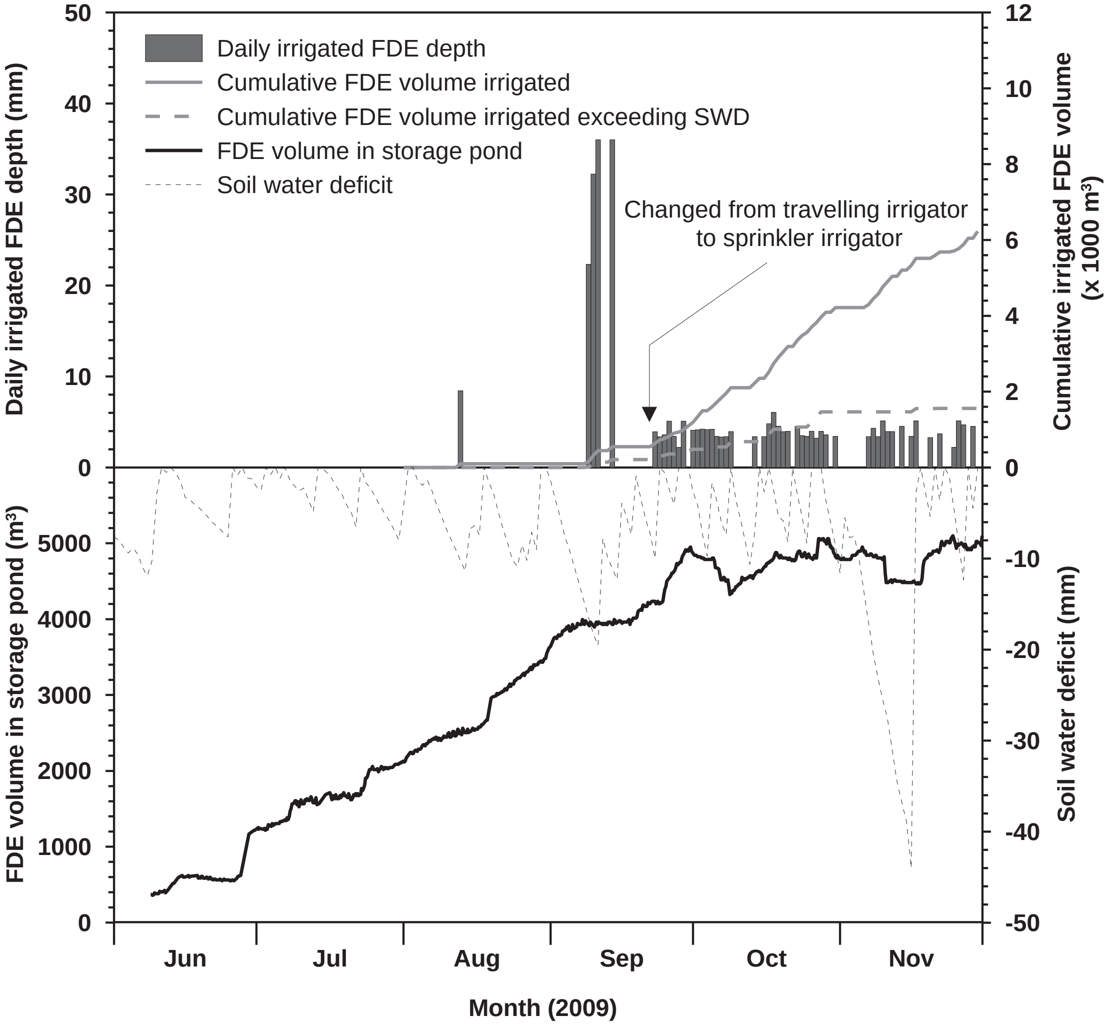

Figure 4.4 The key features of FDE land treatment system, as practised on the case study farm during winter and spring of 2009 (*Scenario 3*), following an enlargement of pond to a maximum storage capacity of 6,000 m^3, and in relation to soil moisture conditions. The irrigation system was changed from a travelling irrigator to a sprinkler irrigator in mid-September.

The volume of over-applied FDE in 2009 was substantially lower than the quantity of FDE applied above the SWD in 2008. This difference, while largely due to the 200% increase in storage capacity, was also influenced by differences in rainfall between the two years, with 2008 having higher winter and early spring monthly rainfall. As with the previous year, it was also useful to quantify the contribution that system constraints made to FDE being over-applied in 2009. To achieve this, the use of 'optimal' management criteria was again modelled for the winter and spring period of 2009 in *Scenario 4*.

Scenario 4: Modelled 'optimal' management criteria (winter and spring 2009) using a travelling irrigator

Scenario 4 assumes 6,000 m^3 of storage capacity was used with a small travelling irrigator, to demonstrate whether *deficit irrigation* of FDE could be implemented in 2009 without changing the irrigation system. The model criteria used were the same as those described previously for *Scenario 2*. The pond level came within about 200 m^3 of pond overflow at its highest two points toward the end of October and again at the end of November (Figure 4.5).

An estimated 590 m^3 would have been applied in excess of the SWD, under 'optimal' management, which is about one-third of the actual FDE volume applied above the SWD in 2009. The modelled results show that when a travelling irrigator is used for the entire winter and spring period in 2009, then a storage capacity of 6,000 m^3 was not quite adequate to avoid FDE being applied in excess of the SWD (Figure 4.5), however, only a further 10% increase in capacity would be required.

Irrigator minimum application depth

Eliminating the need to apply FDE in excess of the SWD in 2009 would have required a further increase in storage capacity, changing the farms irrigator to a system with lower minimum application depths, reducing FDE generation or a combination of these improvements. The purchase of a sprinkler irrigator in September 2009 provided a greater number of irrigation days due to its ability to apply FDE at lower application depths, compared to a travelling irrigator. Therefore, it was useful to assess the potential influence of the sprinkler irrigation system if it had been available for the entire winter and spring period in 2009.

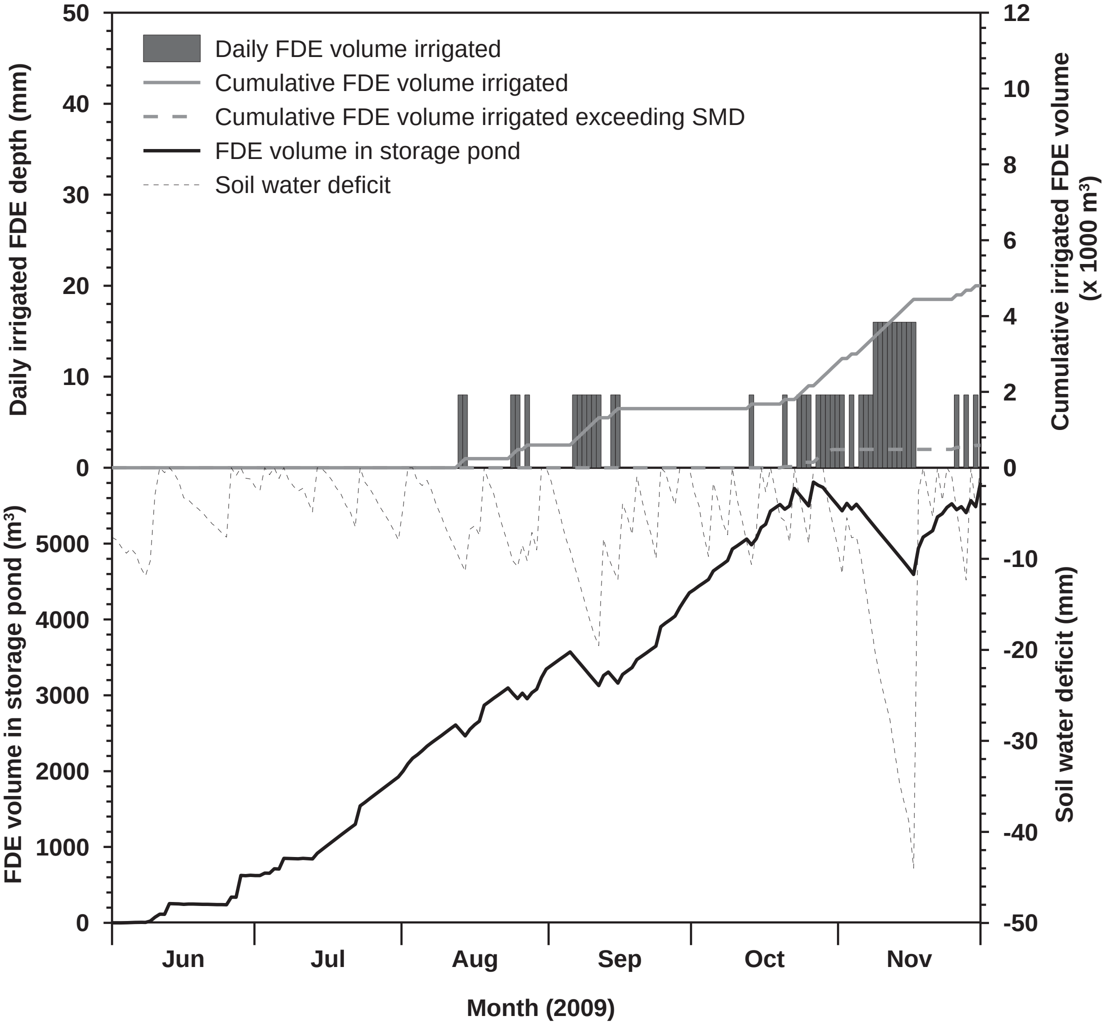

Figure 4.5 Modelled components of the FDE land treatment system for the case study farm, during the winter and spring of 2009, using the 'optimal' management criteria outlined in *Scenario 4*. This scenario models the impact of the enlarged storage capacity of 6,000 m^3 storage capacity combined with use of a rotating travelling irrigator.

Scenario 5: Modelled 'optimal' management criteria using a sprinkler irrigation system (winter and spring 2009)

Scenario 5 models the use of greater storage capacity (6000 m^3) with a sprinkler irrigation system, instead of a travelling irrigator, during the winter and spring of 2009.

The criteria used in this simulation were:

When SWD ≤ 5 mm and available storage capacity > 500 m^3, then no irrigation.

When SWD ≤ 5 mm and available storage capacity < 500 m^3, then irrigate at an application depth of 4.5 mm depth (108 m^3).

> *When SWD = 5-10 mm, then irrigate at an application depth of 4.5 mm (108 m*^{3}*).*
>
> *When SWD > 10 mm, then irrigate at an application depth of 9 mm (108 m*^{3}*).*

An FDE volume of 108 m^3 was irrigated on each irrigation day, which is the approximate volume applied over two sprinkler locations (1.2 ha per location) at a 4.5 mm application depth or a single location at a 9 mm application depth.

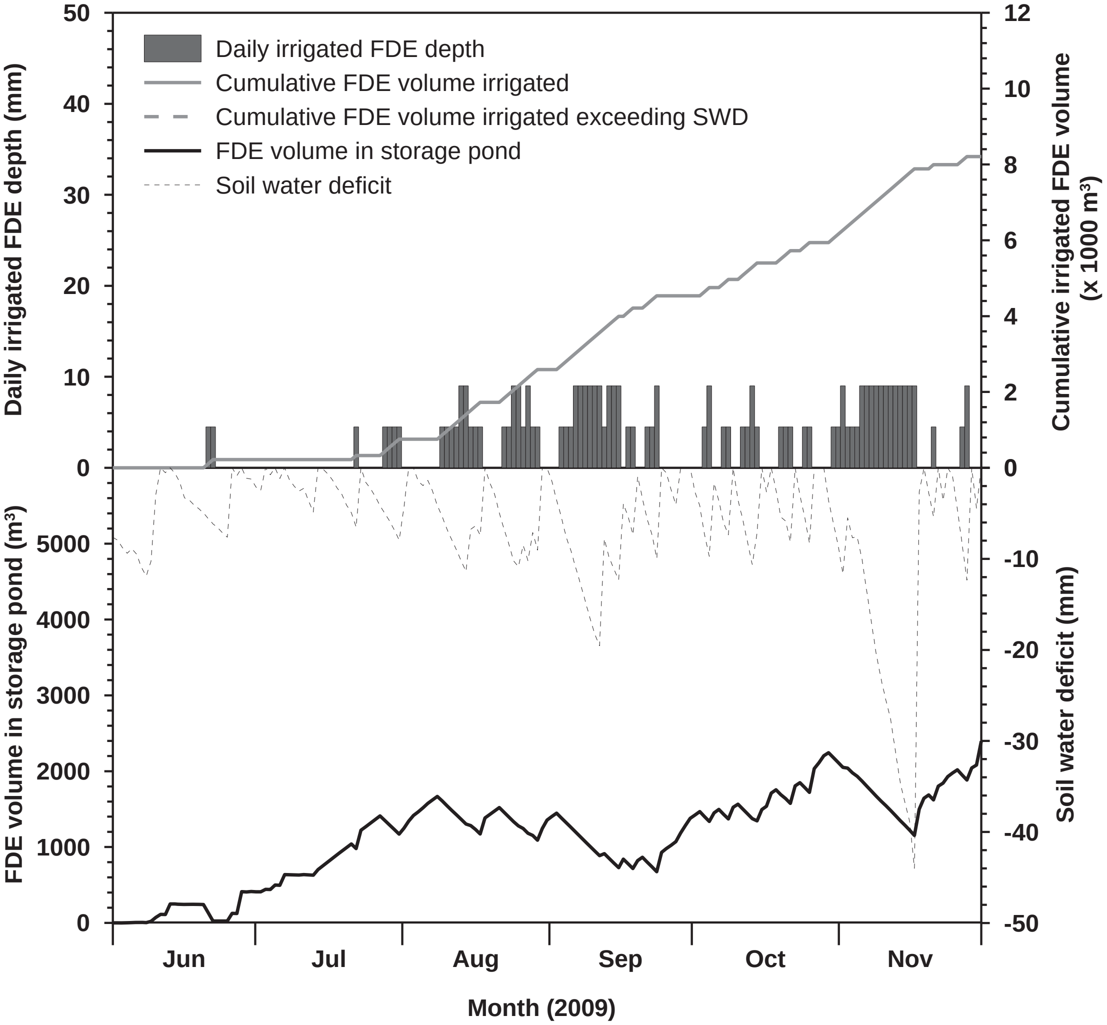

Figure 4.6 Modelled components of the FDE land treatment system for the case study farm, during the winter and spring of 2009, using the 'optimal' management criteria outlined in *Scenario 5*. This scenario models the impact of the enlarged storage capacity of 6,000 m^3 storage capacity combined with use of a sprinkler irrigator.

The use of the sprinkler irrigation system, during winter and spring 2009, is estimated to have allowed the application of 8,200 m^3 of FDE at application depths less than the

SWD and without the risk of pond overflow (Figure 4.6). The lower irrigator application depths achievable with the sprinkler irrigation system, compared to the travelling irrigator, would allow more irrigation days, resulting in lower pond levels being maintained. The ability to achieve lower pond levels in winter and spring further reduced the risk of pond over-flow and provides greater flexibility with timing of irrigations. A summary of the five scenarios compared in this section is provided in Table 4.1.

Table 4.1 Summary of the five scenarios comparing the estimated volumes of FDE applied in excess of the SWD and the estimated quantities of TN and TP contained in each of the volumes.

Scenario	**Estimated volume of FDE applied in excess of the SWD (Jun-Nov) (m^3)**	**Estimated quantity of nutrient contained in FDE volume**	
		Total N (kg)	**Total P (kg)**
Scenario 1: *Actual management 2008* *(2000 m^3 FDE storage, travelling irrigator)*	7,890	1,184 (781)*	197 (130)
Scenario 2: *Modelled management 2008* *(2000 m^3 FDE storage, travelling irrigator)*	5,070	761 (502)	126 (83)
Scenario 3: *Actual management 2009* *(6000 m^3 FDE storage, travelling irrigator [Jun-Aug] sprinkler irrigator [Sep-Nov])*	1,560	234 (154)	39 (26)
Scenario 4: *Modelled management 2009* *(6000 m^3 FDE storage, travelling irrigator)*	590	89 (59)	15 (19)
Scenario 5: *Modelled management 2009* *(6000 m^3 FDE storage, sprinkler irrigator)*	0	-	-

*Value in parenthesis is quantity of TN or TP that is estimated to have been lost in drainage and surface runoff during FDE irrigation, assuming an average attenuation of these nutrients in the soil of 34% (10-58% attenuation; Houlbrooke *et al.*, 2006; Houlbrooke *et al.*, 2004b; Monaghan & Smith, 2004).

The 2008 winter and spring period was also modelled with the system improvements implemented in 2009 (e.g. 6,000 m^3 of storage capacity and a sprinkler irrigation system, data not presented). These changes would have also allowed *deficit irrigation* to be successfully practiced in 2008, without FDE needing to be applied in excess of the SWD.

4.4 Conclusions

The remote sensing and modelling methods used in this study were effective at assessing the ability of the case study farm to implement *deficit irrigation* and also for estimating the potential FDE losses. Monitoring of the farm's FDE pond level, FDE travelling irrigator groundspeed and soil moisture conditions enabled the potential volumes applied in excess of the soil water deficit to be estimated. During the winter and spring of 2008 it was estimated that as much as 7,890 m^3 FDE was applied in excess of the SWD. The quantities of N and P calculated to have been lost to surface waters from this over-applied FDE are equivalent to increases in total farm losses of 16-34% TN and 33-69% TP, depending on the level of attenuation. The use of modelling was used to identify that approximately two-thirds of the over-applied FDE was due to system constraints. The main two system constraints were the farm's inadequate FDE storage capacity, of 2,000 m^3, and the inability of the farm's irrigator to apply FDE at application depths less than 8 mm.

Modelling the 2008 and 2009 winter and spring periods using a FDE storage capacity of 6,000 m^3 and a low application depth sprinkler irrigation system estimated that *deficit irrigation* could have been implemented in both years successfully with these two system changes. The monitoring and modelling approaches developed and evaluated in this study have potential for use on other farms to quantify the benefits of improved system design and management.

4.5 References

Collins R, McLeod M, Hedley M, Donnison A, Close M, Hanly J, Horne D, Ross C, Davies-Colley R, Bagshaw C, Matthews L (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research*, 50, 267-278.

Flemmer CL, Flemmer RC (2008). Water effluent from New Zealand dairy farms from 1997 to 2000. *New Zealand Journal of Agricultural Research*, 51(2), 181-189.

Hanly JA, Horne DJ, Hedley MJ (2008). Implementing deferred dairy effluent irrigation: new technologies. *Proceedings from the Land Treatment Collective Conference*, Queenstown (16-18 Apr 2008). p 202-209.

Houlbrooke DJ (2005). *A Study of the Quality of Artificial Drainage Under Intensive Dairy Farming and the Improved Management of Farm Diary Effluent Using 'Deferred Irrigation'*. PhD Thesis, Massey University, Palmerston North. p 211.

Houlbrooke D, Hanly J, Monaghan R, Hedley M, Horne D (2010). Letter to the Editor. *New Zealand Journal of Agricultural Research*, 53, 407-409.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA (2004a). The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research*, 47, 587-596.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR (2004b). Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deficit irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research*, 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA (2008). Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research*, 46, 45–52.

Houlbrooke DJ, Monaghan RM, Smith LC and Nicolson C (2006). Reducing contaminant losses from land applied farm dairy effluent using K-line irrigation systems. In: Implementing sustainable nutrient management strategies in agriculture (Eds L.D. Currie and J.A. Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 290-300.

Livestock Improvement Corporation (LIC) (2009). New Zealand Dairying Statistics 2008/09. Prepared by LIC and Dairy NZ. www.lic.co.nz. p7.

Ministry of Agriculture and Forestry (2009). The Dairying and clean streams accord: snapshot of progress 2007/2008. Published in March 2009 by Ministry of Agriculture and Forestry (www.maf.govt.nz). 12 pages.

Monaghan RM, Smith LC (2004). Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research*, 47, 417–428.

Scotter DR, Clothier BE and Turner MA (1979). The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research*, 17, 455–465.

Shams DF, Singhal N, Elefsiniotis P, Johnson A (2010). Treatment of farm dairy effluent with hybrid upflow multilayer bioreactor and activated sludge module. *Water Science & Technology*, 61(7), 1683–1690.

Wheeler D, Ledgard SF, Monaghan RM, McDowell R, and DeKlien C (2006). OVERSEER® Nutrients Budgets Model – What is it, what it does? In *Implementing sustainable nutrient management strategies in agriculture.* (Eds. L.D. Currie and J.A. Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 231-236.

CHAPTER 5:
Evaluation of tephra for removing phosphorus from dairy farm drainage waters

Publication arising from this Chapter:

Hanly JA, Hedley MJ and Horne DJ, 2008. Evaluation of tephra for removing phosphorus from dairy farm drainage waters. *Australian Journal of Soil Research*, 46, 542–551.

Chapter's context: Chapters 3 and 4 focused on evaluating decisions-support tools and quantifying the influence of FDE system changes on the implementation of *deficit irrigation* of FDE at a farm scale. This research was targeted at reducing the risk of N and P losses in surface runoff and drainage at the time FDE is being applied to land. Chapter 5 also investigates methods of reducing P losses in drainage waters from land treated with FDE, but focuses on P losses in rainfall-induced drainage rather than drainage caused directly by FDE irrigations. The hypothesis that forms the basis for this Chapter is that P levels in drainage waters can be reduced by filling mole and pipe drainage systems with materials that have a high P adsorption capacity.

5.1 Introduction

Phosphorus (P) enrichment of freshwater systems can stimulate increased growth of aquatic plants and algae, leading to accelerated eutrophication, when P is the main growth limiting nutrient (Sharpley & Syers, 1979). Improvements in the treatment of point-source pollution have led to an increase in the relative importance that non-point source pollution has on declining surface water quality in New Zealand (Scarsbrook, 2006). Consequently, resource managers from regulatory authorities (Regional councils) are placing greater emphasis on the control of non-point source pollution associated with intensive agriculture.

Increased stocking rates on pastoral farms contribute to increased transfer of nitrogen (N) and P from grazed pastures to surface water bodies (Monaghan *et al.*, 2006). Accelerated P loss in surface runoff and in mole and pipe drainage from dairy farms has been reported and quantified in a number of research studies (Sharpley & Syers, 1979; Nash & Murdoch, 1997; Monaghan *et al.*, 2002; Houlbrooke *et al.*, 2003). These P losses can be particularly large from land where farm dairy effluent (FDE) is applied (Houlbrooke *et al.*, 2004b). When FDE is irrigated to artificially drained soils there is the risk that FDE will move rapidly through preferential flow paths in the soil to mole channels and then to drainage pipes discharging to surface waters (Houlbrooke *et al.* 2004a). Phosphorus losses in rainfall-induced winter drainage have also been shown to be higher from dairy farm areas receiving FDE compared to non-effluent areas (Houlbrooke *et al*., 2003). Presumably this due the FDE increasing accumulation of P near or adjacent to macro-pore preferential pathways in the soil.

Mole and pipe drainage systems are commonly employed by intensive agriculture in temperate regions of the world to overcome the imperfect drainage caused by fine textured subsoils. In New Zealand, mole and pipe drainage systems are widely used, including for intensive dairying in the Manawatu, Northland, Southland and Otago regions. In situations where drainage waters are excessively enriched in P, it has been suggested that the use of high P adsorbing materials, as fill in drainage ditches or in underground mole and pipe drainage networks, could be effective in trapping P before it can enter surface waters (Heal *et al.*, 2004; Monaghan *et al.*, 2005).

Much of the research conducted on the capacity of P adsorbing materials to remove P from water has focused on their use in constructed wetland systems (Mann, 1997; Sakadevan & Bavor, 1998; Tanner *et al.*, 1999; Brix *et al.*, 2001; Gruneberg and Kern 2001; Pant *et al.*, 2001; Naylor *et al.*, 2003; Heal *et al.*, 2005; Drizo *et al.*, 2006; Ballantine & Tanner, 2010). Constructed wetlands, with subsurface flow, are widely used throughout the world to treat a wide variety of wastewaters (Del Bubba *et al.*, 2003). However, constructed wetlands generally have a greater potential to remove N, by biological denitrification, than they do P (Arias *et al.*, 2001). The main methods of P removal from wastewaters in constructed wetlands are plant uptake, assimilation by micro-organisms and physico-chemical processes. Among the physico-chemical processes, P adsorption by soil/media and precipitation reactions play an important role (Del Bubba *et al.*, 2003). Research has also focused on using P adsorbing materials for reducing P losses in surface runoff from critical source areas (CSA) on farms (McDowell & Nash, 2012).

Phosphorus removal efficiency is often high initially and then decreases after some time as the P adsorption capacity of the media is exhausted. Accordingly, it is important to select a media with a high P adsorption capacity for sustained P removal over the long term (Arias *et al.,* 2001). The material properties important for influencing P adsorption include the presence of minerals with reactive iron (Fe) or aluminium (Al) hydroxide or oxide groups on their surfaces, and calcareous materials, which can promote calcium (Ca) phosphate precipitation (Zhu *et al.*, 1997; Drizo *et al.*, 1999). Also, adsorption is controlled by the material's pH dependent surface charge and adsorptive surface area. Materials with small particle size have large surface areas for a given volume and, therefore, the potential to enhance P adsorption capacity (Zhu *et al.*, 1997). However, materials with smaller particles size, when packed in beds, also have lower hydraulic conductivity, which can lead to the occurrence of either restricted flow or by-pass flow. The latter can result in insufficient contact between the wastewater and the media within the constructed wetland (Drizo *et al.,* 1999). Anion competition, such as the competitive adsorption of phosphate (PO_4^{3-}) and sulphate (SO_4^{2-}), is another factor that needs consideration when evaluating the effectiveness of media to adsorb P from drainage or wastewaters (Parfitt, 1982; Ryden *et al*., 1987).

New Zealand has abundant naturally occurring materials with high P adsorption capacities, such as soils and moderately weathered materials derived from volcanic tephra. Moderately weathered materials that contain the mineral allophane, show particular promise for removing P from wastewater. Ryden and Syers (1975) demonstrated that of the tephra materials they studied, moderately weathered andesitic tephra had the greatest potential for removing P from effluent. They found that andesitic tephra from Taranaki, New Zealand, was capable of removing between 80% and 97% of P from a synthetic P solution containing 5 mg P/g tephra.

The aim of this study was to evaluate the effectiveness of one particular type of tephra (Papakai tephra) as a P adsorbing material for removing P from dairy farm drainage water when used in mole and pipe drainage systems.

5.2 Materials and methods

5.2.1 Laboratory study

Materials

The tephra used in this study, Papakai tephra, was collected from the Mangatoetoenui Quarry, which is located beside where the Mangatoetoenui Stream crosses State Highway 1 (NZMS 260, T20, 460 152) on the Tongariro Volcanic Centre (TgVC). This material was selected because it is andesitic tephra subsoil with a high P-retention value and because of is locatation in a quarry, allowed for easy excavation. The Papakai tephra (ash and lapilli) was taken from a depth of c. 345-375 cm and represents the lowest strategraphic layer of the Papakai Formation, which is dated c. 9790-2500 yr BP (Donoghue *et al.* 1995).

The Papakai tephra has an average pH of 6.3, an extractable sulphate (Blakemore *et al.* 1987) level of 19.5 mg S/kg, an Olsen extractable P (Olsen *et al.,* 1954) value of 0.9 mg P/L and P retention (Saunders, 1965) value of 83%. Table 5.1 shows the particle size distributions of the 'as received' tephra and the corresponding P retention values.

Patua fine sandy loam soil (0-100 mm soil depth; Acidic Orthic Allophanic Soil: Hewitt, 1998) was used as a comparison in this study as it has a high P adsorption capacity. The soil was collected from the Northern side of Mt Taranaki, alone side Carrington road. This soil had an average pH of 5.5, an Olsen extractable P value of 6.7 mg P/L and P retention value of 94%.

Table 5.1 Particle size distribution and P retention of Papakai tephra.

Particle size fractions	**Papakai tephra (c. 345-375 cm depth)**	
	Particle size distribution (%, by weight)	P retention (%)
*<2 mm**	21.1	88
2-4 mm	29.6	85
4-8 mm	27.9	82
8-15 mm	17.0	70
>15 mm	4.4	51

* The <2 mm particle size fraction, which contributed 21.1% to the total sample weight, consisted of 3.1% in the < 1 mm size range and 18% in the 1-2 mm size range.

Flow rate potential determination

A series of tests were conducted on various particle size fractions of tephra to assess their flow rate potentials when used to fill mole channels. In each test, perspex tubes were used to simulate mole channels. The tubes measured 1200 mm long and each had an internal diameter of 45 mm. Each tube was filled with one of three different particle size fractions (1-2 mm, 2-4 mm and 4-8 mm) and flow rates of water through the filled tubes were determined using a 20 cm standing head of water. Flow rate potentials for in-field mole channels, which have an internal diameter of c. 50 mm, were estimated by applying a 23% increase (increase in channel cross-sectional area) to the values obtained with the 45 mm diameter perspex tubes.

Phosphorus adsorption characteristics

The P adsorption characteristics of Papakai tephra were evaluated using a series of column experiments. The flow rates used in these experiments were designed to simulate the relatively short average residence time of drainage water in mole channels and back-fill. The dissolved reactive phosphorus (DRP) concentrations of the influent solutions, fed into the columns, were typical of those found either in rainfall-induced drainage or two-pond treated FDE.

Column experiment 1

Column experiment 1 was a study involving three air-dried materials of particular sieve size ranges; 1-2 mm tephra, 0.25-1 mm tephra and 1-2 mm Patua soil. Each treatment was replicated twice. The tephra sieve size ranges consisted of all individual particles, while the Patua soil size range contained both particles and aggregates. In this experiment the tephra particle size fractions were sieved from “as received” Papakai tephra. However, the 1-4 mm tephra used in the second column experiment and in the field trial was achieved by sieving a combination of “as received” Papakai tephra and larger particle size fractions of Papakai tephra that had been crushed to reduce their size.

The columns used were 400 mm long with an internal diameter of 27 mm. The internal volume of each column was 0.23 L, which contained 0.2 kg of 1-2 mm Papakai tephra, 0.18 kg of 0.25-1 mm Papakai tephra and 0.15 kg of the 1-2 mm Patua soil. Each column was fixed on a horizontal incline with their entrance end positioned below the exit to ensure that the influent solution came into contact with all the material within the column. The influent solution DRP concentration was 12 mg P/L, which was within the range of DRP concentrations measured in FDE (4.6-17.1 mg P/L; Hickey *et al.* 1989). Solution flow rate into each column was 0.0035 L/min, which provided an average residence time in the column of c. 35 minutes. In comparison, a standard mole channel (c. 50 mm diameter, 40 m length) would have an internal volume of 78.5 L, which is 341 times greater than the volume of the column used in this experiment. Therefore, the residence time used in this experiment would be comparable to the residence time of drainage water flowing at a rate of 1.19 L/min in an individual mole channel (mole channel flow rates discussed in Section 5.3.1). This experiment was run continually for 214 hours.

Samples of treated solution exiting each column were collected at regular time intervals and analysed for DRP. The difference in the quantity of P entering the column and that exiting the column was assumed to have been adsorbed by column media. Dissolved reactive phosphorus analysis was conducted on a Technicon segmented flow auto analyser using the colorimetric reagents described by Murphy and Riley (1962).

Column experiment 2

Column experiment 2 was an evaluation of the effect of contrasting influent P concentrations on the P adsorption characteristics of Papakai tephra (1-4 mm sieve size range), which is the same material used in the field study described below. Each column contained 0.25 kg of tephra. The four influent solution treatments were; 12 mg P/L, 12 mg P/L + 10 mg SO_4^{2-}-S/L, 0.25 mg P/L (increased later to 0.75 mg P/L) + 10 mg SO_4^{2-}-S/L, and two-pond treated FDE containing 18 mg DRP/L. Each treatment was replicated twice. The lowest P concentration influent solution treatment started with a P concentration of 0.25 mg P/L, which was within range for dairy pasture drainage water (0.02-0.45 mg P/L; Houlbrooke *et al.*, 2003). However, this influent solution treatment was increased, from 0.25 to 0.75 mg P/L, part way though the experiment due to time constraints of the study. Sulphate, at a concentration typical of drainage water (10 mg SO_4^{2-}-S/L; Heng *et al.*, 1991), was added to some influent solutions to assess whether its presence would decrease P removal efficiency of the tephra, through anion competition for absorption sites. Also, a FDE solution treatment was used to determine whether P removal efficiency from a real wastewater would be different to that from a synthetic P solution.

Column size and setup, and the solution flow rate were the same as those described in the first column experiment. The lowest P concentration influent solution was run for a total duration of 847 hours, initially with 0.25 mg P/L solution for 415 hours followed by a 0.75 mg P/L solution for 432 hours. Both influent solutions also contained 10 mg SO_4^{2-}-S/L. This treatment was stopped on four occasions, for periods ranging from 65 hours to 475 hours. These stoppages where made to assess whether resting the tephra from influent solution inflow, as would occur in between natural drainage events, could influence its P removal efficiency. The other three influent solutions were run continually for 49 hours. Samples of treated solution exiting each column were collected at regular time intervals and analysed for DRP as described for column experiment 1.

5.2.2 Field Study

Trial site and drainage treatments

A field research site was established in January 2005 on a mole and pipe drained Tokomaru silt loam soil, a Fragic Perch-gley Pallic Soil (Hewitt 1998) or Typic Fragiaqualf (Soil Survey Staff, 1998) on Massey University’s No. 4 dairy farm near Palmerston North, Manawatu, New Zealand (NZMS 260, T24, 312867). A further description of the farm system is provided in Section 3.2.1 (Chapter 3).

The research area consisted of six plots (each 25 × 40 m), each with an isolated mole and pipe drain system. Mole channels were installed at 2 m intervals at a depth of 0.45 m. A mole-plough, pulling a steel torpedo-shaped plug with a diameter of 65 mm, was used to form mole channels with internal diameters after installation of c. 50 mm. Drainage from the mole channels were intercepted by a perforated pipe drain (110 mm diameter), which was installed perpendicular to the moles at a depth of 0.60 m. Three drainage system treatments, each replicated twice, were used in this study; a Control treatment, a tephra filled mole channel treatment (hereafter ‘Mole-fill’) and a treatment where tephra was placed as back-fill over the intercepting pipe (hereafter ‘Back-fill’). Treatments were randomly allocated to drainage plots.

The Control treatment was a standard mole and pipe drainage system with open mole channels and greywacke gravel back-fill over the pipe. For the Mole-fill treatment, a modified mole plough (Plate 5.1), specially designed as part of this study, was developed to fill mole channels with 1-4 mm sized Papakai tephra, which drained into greywacke gravel back-fill over the receiving pipe. The Back-fill treatment had open mole channels, but had 'as received' Papakai tephra back-fill above the receiving pipe instead of greywacke (refer to Table 1 for the particle size distribution of the 'as received' Papakai tephra). The amount of tephra used for both tephra treatments was c. 8 t dry weight/ha.

Plate 5.1 Modified mole plough, with the added hopper and delivery chute, used to install tephra into mole channels.

Drainage water volume measurements and phosphorus analysis

At the corner of each drainage plot, a pit was excavated and a tipping-bucket flow meter placed at the exit of the drainage pipe to monitor drainage flow rates. Each tipping bucket was calibrated dynamically to account for the influence that flow rate has on tip volumes. When a tipping bucket starts tipping there is a brief time when additional water can still enter the full side of the bucket. This additional water volume increases with flow rate, which can result in an underestimation of tip volume, known as 'undercatchment', at higher flow rates (Humphrey *et al*., 1997). All tipping buckets were instrumented with data loggers to provide continuous measurements of flow rate. During each drainage event, a proportion (c. 0.1%) of the drainage water from every second tip of the tipping bucket flow meter was automatically collected to provide a volume-proportioned mixed sample for water quality analysis. Drainage was monitored for the entire 2005 drainage season.

Drainage water samples were analysed for DRP and total phosphorus (TP). All measures of DRP were determined on samples that had been passed through a 0.45 µm filter. Analyses were carried out colorimetrically on a Technicon Auto Analyser II using the following methods: Murphy and Riley (1962) for analyses of DRP and the Vanadomolybdate method (AOAC 1975) for determining TP, after a Kjeldahl acid digest as described by McKenzie and Wallace (1954). Soil water deficits for Tokomaru silt loam were predicted using the soil water balance model and parameters of Scotter *et al*. (1979). To estimate the occurrence of drainage the maximum SWD was constrained to 95 mm.

The drainage water mean DRP and TP concentrations for the entire drainage season were calculated by dividing the total DRP and TP loads, measured in drainage water over the entire season (summed from individual drainage events), by the measured annual drainage volumes from each drainage plot.

Statistical analysis

SAS (Statistical Analysis Systems, Version 9.1, SAS Institute Inc.) was used to conduct statistical analyses. Data from the field trial were analysed using an Analysis of Variance (ANOVA) test and the Least Significant Difference (LSD) test was used to group treatment means.

5.3 Results and discussion

5.3.1 Flow rate potential of tephra filled mole channels

Tephra particle size had a large influence on flow rates of water through perspex tubes (simulated mole channels) filled with tephra. Water flow rate potentials for mole channels (50 mm diameter) filled with 1-2, 2-4 or 4-8 mm tephra were estimated to be 0.44, 0.95 and 3.20 L/min, respectively. These flow rate potentials were compared with the actual flow rates of drainage from 40 m long mole channels without fill (e.g. open channels; Control treatment plots) from the 2005 field study described in this chapter. In 2005, 90% of winter drainage volume occurred at average individual mole channel flow rates of 7.10 L/minute or less, while the remaining 10% of drainage occurred at flow rates between 7.10 and 14.25 L/min. Only 26% of the total winter drainage volume occurred at mole channel flow rates lower than 0.44 L/min (corresponding to the flow rate of 1-2 mm tephra), 47.6% lower than 0.95 L/min (2-4 mm tephra) and 73.5 % lower than 3.20/L min (4-8 mm tephra). Therefore, with standard mole channel diameter, length and spacing, all three particle size fractions are likely to limit mole channel flow rates, compared to open channels.

Increased surface runoff may occur if filling mole channels with tephra restricts drainage flow rates. More surface runoff can result in greater losses of P to surface waters, as the concentration of P in surface runoff is typically higher than in drainage water (Nash & Murdoch 1997; Houlbrooke, 2005; McDowell *et al.*, 2006). In order to minimise the risk of surface runoff caused by filling mole channels, alterations can be made to standard mole channel systems to increase flow rate potentials, including; using mole channels with larger diameters and installing more channels closer together. However, the use of more intensive tephra filled mole channels will increase the cost of installation. If the cost of more intensive drainage systems is too prohibitive for use across whole farms, then they could be used more specifically on FDE blocks. Poorly-timed FDE applications can cause high drainage water P concentrations (Houlbrooke *et al.*, 2004a). Also, areas irrigated with FDE tend to have higher winter drainage water P concentrations, compared to non-effluent areas (Houlbrooke *et al*., 2008).

5.3.2 Column experiment 1 – phosphorus adsorption capacity of materials

The aim of the first column experiment was to assess whether ash sized tephra (0.25-1 mm and 1-2 mm sieve size ranges) is an effective material for installing into mole and pipe drainage systems for removing P from dairy farm drainage water, particularly from areas used for land application of FDE. Patua soil (sieved to 1-2 mm) was also used in this experiment as a comparison as it was known to have a high P retention.

The P adsorption curves (Figure 5.1) show that the 0.25-1 mm tephra treatment was the most effective material at lowering the solution final DRP concentration, during the early part of the experiment. For the first 1 mg P adsorbed/g tephra, this treatment maintained solution final DRP concentrations below 0.010 mg DRP/L, which is considered to be the threshold concentration above which aquatic weed growth in lowland streams is stimulated (ANZECC 2000).

Based on the fitted Freundlich equations (Kinniburgh, 1986), the predicted maximum P adsorption capacities were 7.9, 3.1 and 1.9 mg P/g material for the Patua soil, 0.25-1 mm tephra and the 1-2 mm tephra, respectively. However, caution needs to be exercised with the estimate for the Patua soil treatment for two reasons. Firstly, it appears that the curve was only just starting to plateau at the end of the experiment, and secondly, the step in the curve may indicate some disaggregation of soil aggregates creating increased sorption surfaces later in the experiment.

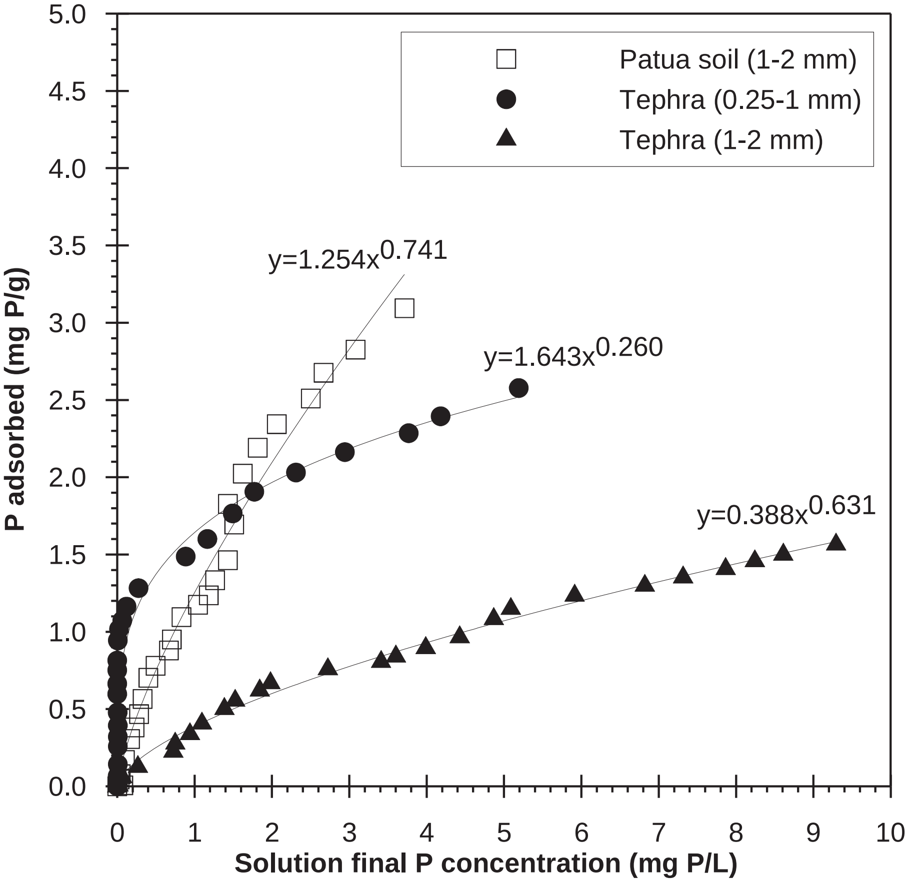

Figure 5.1 Mean estimated P adsorption by 0.25-1 mm Papakai tephra, 1-2 mm Papakai tephra, and 1-2 mm Patua soil, compared with solution final P concentration (12 mg P/L influent solution concentration, c.35 minute residence time within the column). Lines are fitted Freundlich equations.

The efficiencies of P removal from solution were high for both the Patua soil and the 0.25-1 mm tephra. By the end of the experiment, the Patua soil had adsorbed 3.1 mg P/g soil (SEM ± 0.045) at an average removal efficiency of 86 % (Figure 5.2). The finer tephra (0.25-1 mm) adsorbed less P (2.6 mg P/g tephra; SEM ± 0.171), compared to the soil treatment, but had the same average P removal efficiency. The bulk density of the Patua soil in the columns was less than for the tephra, and therefore, the amount of P added per unit weight of filter media was highest for the Patua soil (refer to Section 5.2.1).

The 1-2 mm tephra had the lowest P adsorption (1.6 mg P/g tephra; SEM ± 0.076) and removal efficiency (58%). The Patua soil adsorbed more P than both tephra treatments even though its size of aggregate was greater than the particle size of the 0.25-1 mm tephra treatment. One reason for the better performance of the Patua soil is that, although it was sieved to 1-2 mm, some of the sieved material included aggregates of much finer sand, slit and clay particles and, consequently, had a greater total surface area than individual 1-2 mm sized particles. As expected, the 0.25-1 mm Papakai tephra achieved higher P adsorption than the coarser 1-2 mm Papakai tephra, indicating that surface area of the material was likely to have been an important factor in its sorption capacity (Zhu *et al*., 1997).

5.3.3 Column experiment 2 - factors affecting phosphorus adsorption efficiency

The second column experiment was used to assess whether P removal efficiency was influenced by influent solution characteristics, which would vary under field conditions. The characteristics investigated were solution P concentration, the presence of SO_4^{2-} as a competing anion and the use of a real wastewater (FDE).

Phosphorus adsorption of 1-4 mm tephra

The amount of P removed by the 1-4 mm tephra from the 12 mg P/L influent solution treatment was 0.20 mg P/g tephra (SEM ± 0) (Figure 5.3). This P removal represented 40% of the 0.50 mg P/g tephra added to the column in the influent solution. This level of P removal was substantially lower than that measured in the previous experiment using finer tephra (Figure 5.2).

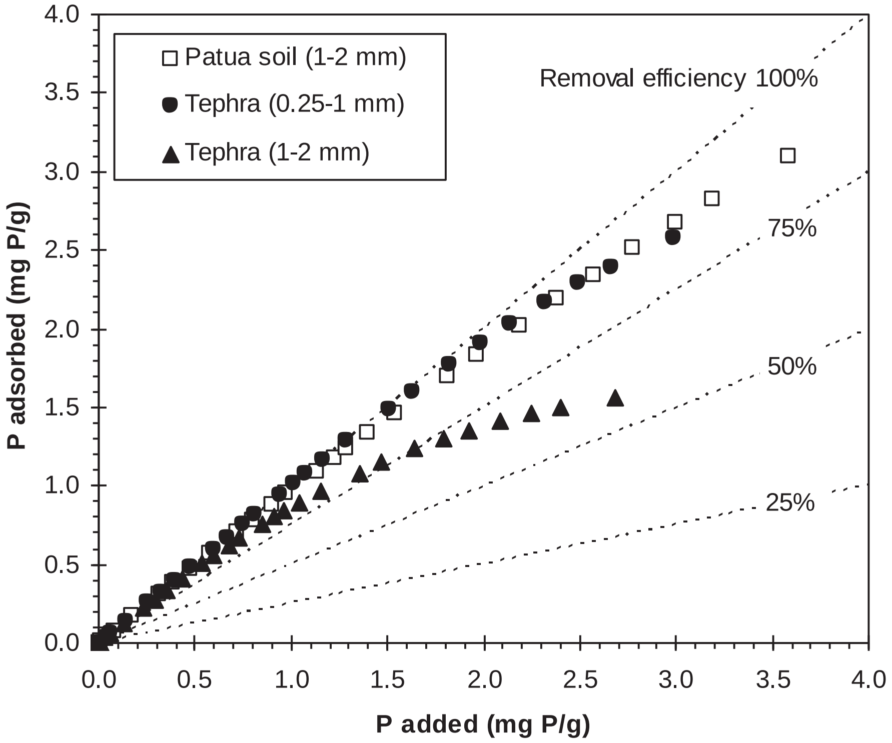

Figure 5.2 Mean estimated P adsorbed by 0.25-1 mm Papakai tephra, 1-2 mm Papakai tephra and 1-2 mm Patua soil, compared to the quanitity of P added to the column (12 mg P/L influent solution concentration, c. 35 minute residence time within the column).

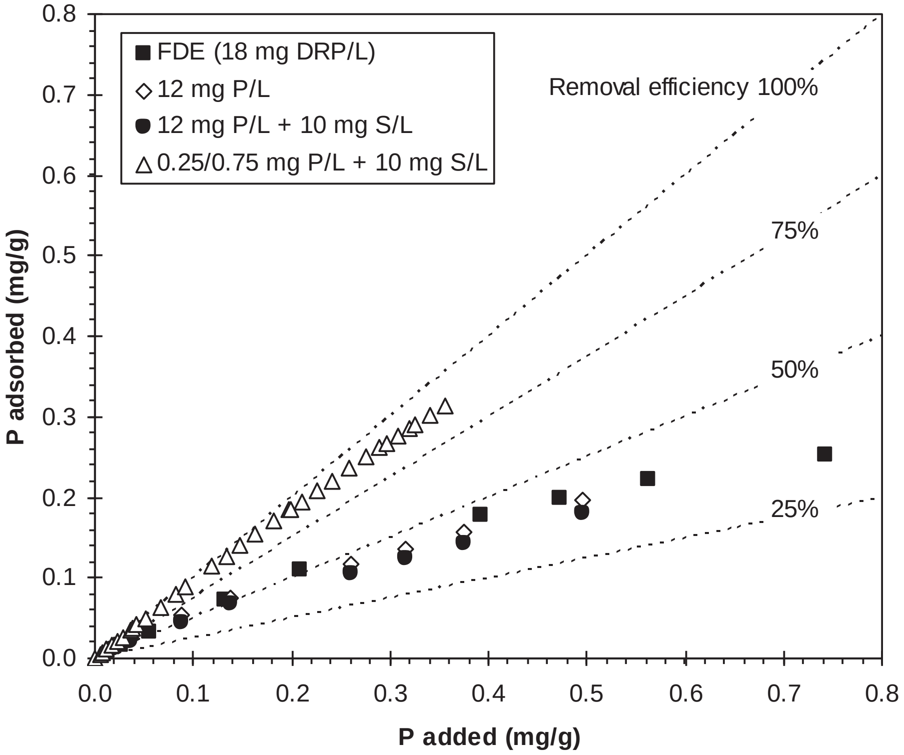

Figure 5.3 Mean estimated P adsorbed by 1-4 mm Papakai tephra from four different influent solutions, compared to the quantity of P added to the column.

A reason for the lower removal efficiency of the 1-4 mm tephra, compared to the 1-2 mm tephra used in the first experiment, is that the 1-4 mm tephra has a lower total particle surface area for a given volume of tephra. In addition, a portion of 1-4 mm tephra was obtained by crushing larger particle sizes of tephra. While this would have increased surface area of the particles, the newly exposed surfaces may not have had the same P adsorbing capacity as the original weathered surfaces.

Effect of sulphate and FDE on P adsorption

The amount of P adsorbed by the 1-4 mm tephra from the 12 mg P/L + 10 mg SO_4^{2-}-S/L influent solution was 0.18 mg P/g tephra (SEM ± 0.017), which was 36% of the 0.50 mg P/g tephra added. Phosphorus removal from this influent solution was similar to the 12 mg P/L influent solution without SO_4^{2-}, which indicates that there was negligible influence of SO_4^{2-} competing with PO_4^{3-} for adsorption sites on the tephra. This result is not unexpected because PO_4^{3-} is generally known be adsorbed onto allophanic soils more strongly than SO_4^{2-} (Bolan *et. al*, 1988).

The amount of P adsorbed by the 1-4 mm tephra from the FDE influent solution was 0.25 mg P/g tephra (SEM ± 0.019), which was 34% of the 0.74 mg P/g tephra added. When the P removal efficiency by tephra from the FDE is compared with the 12 mg P/L influent solution, at the same level of added P (0.50 mg P/g tephra), then the amount of P removed was the same. This result indicated that the P removal efficiency of tephra was not influenced by the use of two-pond treated FDE compared to a synthetic P solution.

Effect of influent solution P concentrations

Most of the influent solution P concentrations used in this study have been at levels similar to the DRP concentrations of FDE. However, dairy farm winter drainage water typically has DRP concentrations less than 0.45 mg P/L (Houlbrooke *et al.*, 2003). When influent solution concentration was 0.25 mg P/L, P removal efficiency by the 1-4 mm tephra was 96% for the first 0.09 mg P/g tephra added to the column. This compares with a P removal efficiency of only 51% for the 12 mg P/L influent solution. Subsequently, the 0.25 mg P/L influent solution was increased to 0.75 mg P/L. By the end of the experiment, 0.36 mg P/g tephra had been added to the column of which 0.32 mg P/g tephra (SEM ± 0.006) had been adsorbed by the tephra (P removal efficiency of

88%). At the same level of P added, the 12 mg P/L treatment achieved an average removal efficiency of only 38%, demonstrating the influence of influent solution P concentration on P removal efficiency. These results suggest that the P removal efficiencies for the first column experiment could have been higher if lower influent solution P concentrations, similar to levels in dairy farm drainage water, had been used. There was some evidence that the four resting periods also improved the P removal efficiency by the tephra from the 0.25/0.75 mg P/L solution treatment, however, these improvements trended to be small and short lived. For example, during a period when the influent solution concentration was 0.75 mg P/L and the effluent solution concentration was an average of 0.17 mg P/L, the columns were rested from influent solution for a period of 4 days. When the inflow of influent solution resumed the effluent solution concentration had decreased to 0.125 mg P/L. However, after 24 hours of continuous influent flow the effluent concentration returned to 0.17 mg P/L.

The amounts of P removed from solution by tephra in both column experiments compare favourably with the performance of a range of other P adsorbing materials evaluated in other studies. For example, Mann (1997) demonstrated in a column study that steel industry slags, using an influent solution P concentration of 10 mg P/L and residence time of 48 hours, could adsorb 0.09 mg P/g material, which represented only 32.6% of the P added to the column. In another column study (Drizo *et al.*, 1999), the P adsorbing properties of bauxite, shale, burnt oil shale, limestone, zeolite, lightweight expanded clay aggregates, and fly ash were investigated using synthetic wastewater with P concentrations ranging from 5 – 45 mg P/L and a residence time of c. 12 hours. Shale achieved the highest P removal of 0.73 mg P/g shale; however, this represented only 11.7% of the P added to the column. Arias *et al.* (2001) studied the P adsorbing capacity of a range of sands, also in column experiments. Influent solution P concentration was 10 mg P/L and residence time was 12-14 hours. By the end of the study only 0.20 mg P/g material had been loaded into the columns of which Darup sand, the best performing sand in this study, was still removing 80% of P from solution.

In the second column experiment of the current study, the 1-4 mm tephra adsorbed an estimated 0.32 mg P/g tephra from the lower P solution at an average P removal efficiency of 88%. The amount of tephra installed into a standard mole channel system (50 mm diameter, 2 m spacing) is equivalent to c. 8 t/ha. Accordingly, these results indicate that this tephra, when inserted into mole channels, has potential to remove more than 2.5 kg P/ha from drainage water. Houlbrooke *et al*. (2008) reported that the annual drainage water DRP losses from mole and pipe drainage were 0.77 or 0.14 kg P/ha from effluent and non-effluent areas, respectively. Based on these values the 1-4 mm tephra would have the potential to remove the majority of DRP from drainage water for more than 3 or 17 years for the effluent and non-effluent areas, respectively. However, greater longevity would be expected from ‘as received’ 1-4 mm tephra. This tephra is likely to have a higher P removal capacity than the 1-4 tephra used in the current study, which was achieved by crushing larger particle sizes.

In the first laboratory experiment, the uncrushed 1-2 mm tephra removed 1.6 mg P/g tephra at a removal efficiency of 58%. At a tephra installation rate of c. 8 t/ha, the 1-2 mm tephra could remove more than 12 kg P/ha. At this level of P removal this tephra has the potential to remove P from drainage water for more than 15 or 85 years when used in either FDE or non-effluent areas, respectively. Installing 1-2 mm material is likely to reduce the flow rate of water in mole channels. As noted above, the use of larger diameter mole channels or a greater number of mole channels for a given area are methods of improving the flow rate of drainage.

5.3.4 Field Trial

Drainage quantity

The annual rainfall in 2005 was 885 mm, which was well below the mean annual rainfall of 968 mm for Palmerston North. For seven consecutive months (February-August), monthly rainfall was below mean monthly rainfall (Figure 5.4). As a consequence, the start of season drainage didn’t delayed until early July (Figure 5.5). Most drainage occurred during two main periods; 7th July to 16th August, and 22nd September to 23rd October 2005. Rainfall intensity and volumes were highest in October with the largest drainage events also occurring in this month. However, total drainage volumes for the year were low, reflecting the low rainfall for most months. By the end of the drainage season, the three drainage treatments; Control, Mole-fill and Back-fill, had similar average drainage depth of 124, 111 and 109 mm of drainage, respectively.

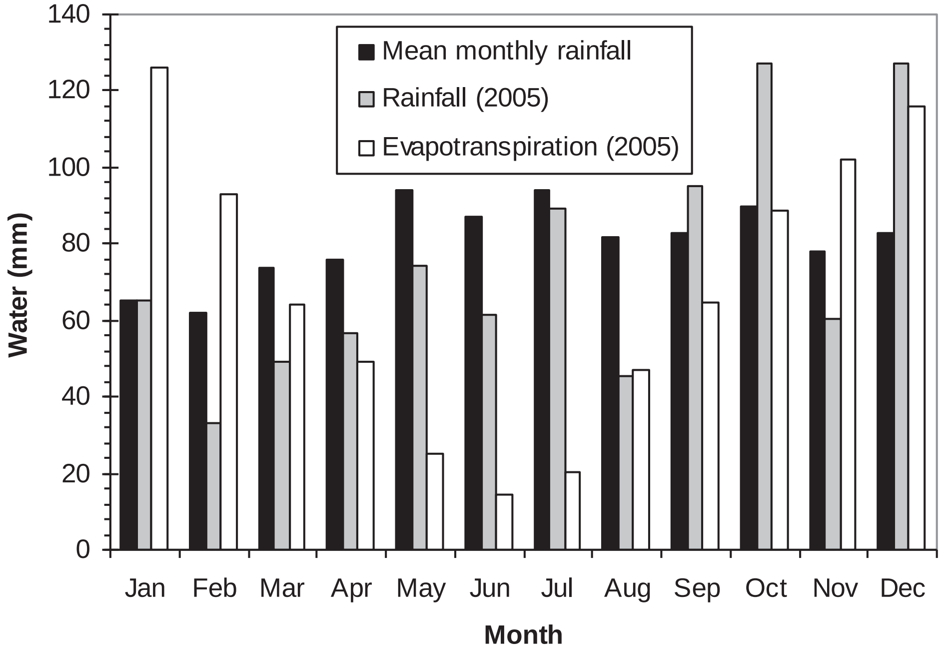

Figure 5.4 Palmerston North mean monthly rainfall (30 year means;1971-2000) and monthly rainfall and estimated evapotranspiration for the field trial site during 2005.

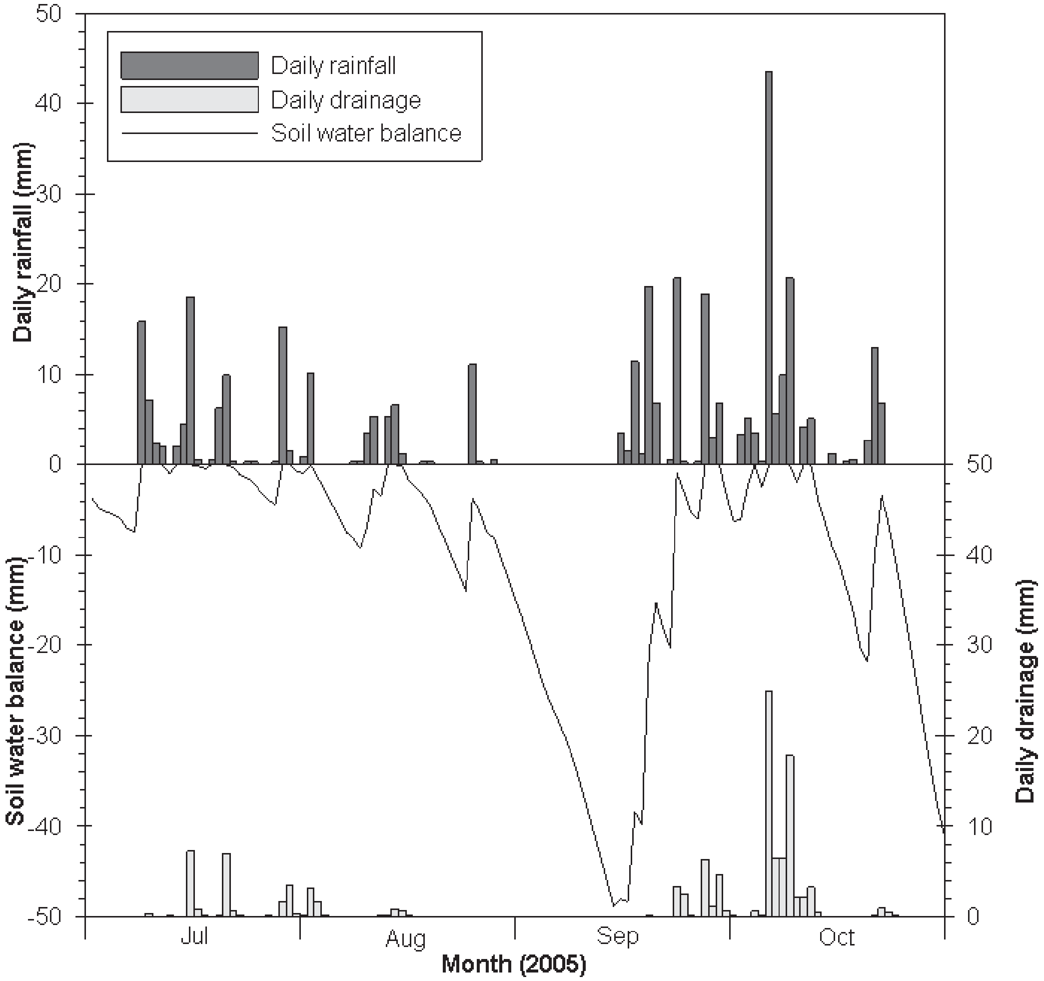

Figure 5.5 Daily rainfall, daily drainage and predicted soil water balance for the field trial site during the 2005 drainage season.

Phosphorus in drainage

In 2005, the average DRP (0.07 mg P/L) and TP (0.24 mg P/L) concentrations of drainage water from the Control treatment plots were considerably higher than the levels (0.010 mg DRP/L, 0.033 mg TP/L; ANZECC 2000) considered likely to promote aquatic weed growth in lowland streams. These Control treatment drainage P concentrations were similar to those measured two years previously in a study at the same site (Houlbrooke *et al.*, 2008). However, the total quantity of DRP (0.09 kg P/ha) and TP (0.30 kg P/ha) lost in drainage water from the Control treatment plots in 2005 were approximately half of the losses measured in the 2003 study, which was a reflection of drainage volumes in 2005 being about half of those recorded in 2003.

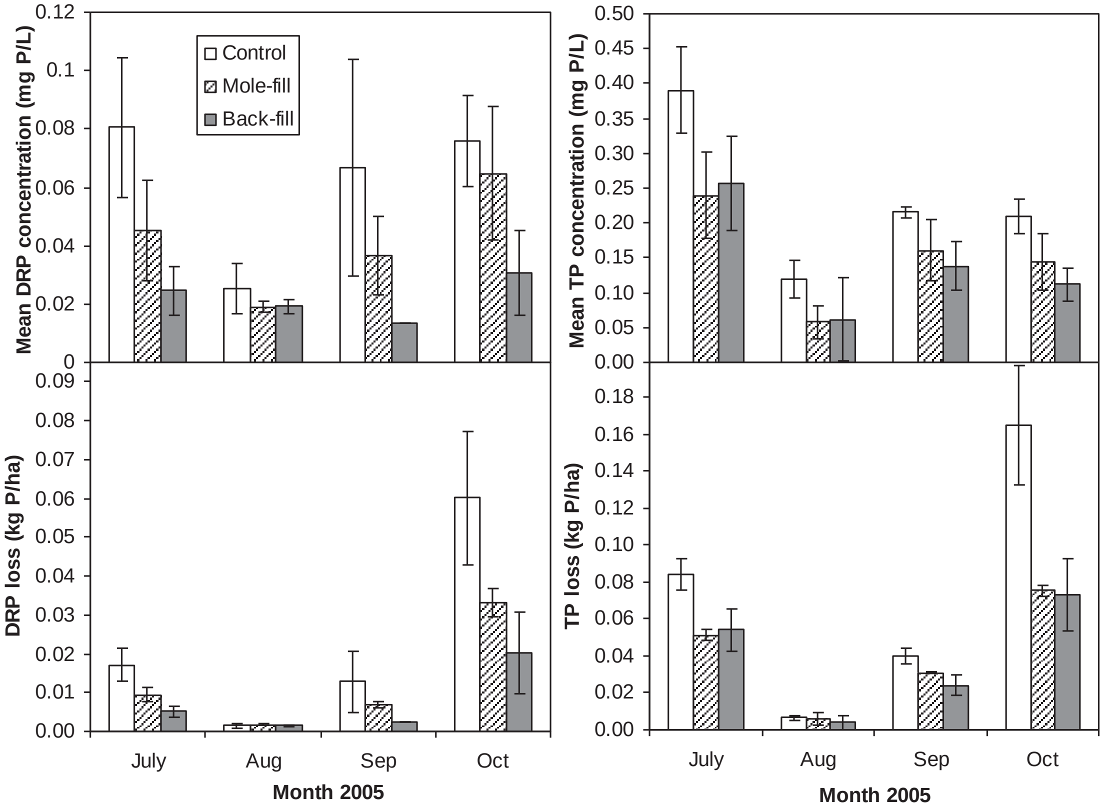

Figure 5.6 Mean monthly DRP and TP concentrations and losses in drainage water from the three drainage treatments in 2005 (error bars represent ± standard error of means).

In both years, DRP represented 30% of the TP lost in drainage water. The highest monthly DRP (0.08 mg P/L) and TP (0.39 mg P/L) drainage water concentrations for the Control treatment plots occurred in July (Figure 5.6). These higher monthly mean P concentrations were strongly influenced by plots being grazed by dairy cows on a day that coincided with rainfall and drainage. This caused the Control treatment drainage

DRP concentrations to increase from a pre-grazing level of 0.01 up to 0.98 mg P/L after grazing. Over the same period, the mean Control treatment TP concentration increased from 0.29 to 4.12 mg P/L. However, the greatest quantity of monthly DRP and TP losses were in October, reflecting the high drainage volumes occurring in this month.

Effect of drainage system treatments on phosphorus loss

During 2005, both tephra drainage treatments (Mole-fill and Back-fill) had lower drainage water TP losses (Table 5.2) compared to the Control treatment. The average TP losses for the Mole-fill and the Back-fill treatments were 45% and 47% lower than the Control treatment, respectively. The P losses from the tephra treatments were at levels similar to those from some less intensive farming systems (Monaghan *et al.*, 2002).

Table 5.2 Effect of drainage treatments on mean DRP and TP concentrations and accumulated losses during the 2005 winter drainage season. The 10% LSD and *P*-value are presented for comparison between treatment means (*ns*, not significant).

Treatment	**Mean DRP concentration (mg P/L)**	**DRP loss (kg P/ha)**	**Mean TP concentration (mg P/L)**	**TP loss (kg P/ha)**
Control	0.073 (0.062, 0.085)*	0.092 (0.071, 0.112)	0.239 (0.232, 0.245)	0.296 (0.267, 0.324)
Mole-fill	0.051 (0.033,0.069)	0.051 (0.045, 0.057)	0.160 (0.119, 0.201)	0.163 (0.161, 0.065)
Back-fill	0.026 (0.016, 0.036)	0.029 (0.018, 0.041)	0.139 (0.105, 0.173)	0.156 (0.116, 0.196)
LSD$_{10\%}$	-	-	-	*0.095*
P-value	*ns*	*ns*	*ns*	*P=0.0665*

* Values in parenthesis are for individual treatment replicates.

There was insufficient statistical evidence to support a significant treatment affect on DRP drainage losses (Table 5.2). This was also the case for monthly DRP and TP losses (Figure 5.6). Large plots (each 1000 m^2) were used in this study to better represent whole paddock drainage P losses. However, the large size of the plots also constrained the number of plots available for replication. Accordingly, the use of only two replicate plots per treatment was a factor influencing the ability to obtain significant treatment affects in the field study.

Of the two tephra drainage treatments, the Mole-fill treatment was expected to have the lowest DRP losses, due to it having the longer contact time between drainage water and the tephra. However, there was no evidence of it performing better than the Back-fill treatment. At the end of the 2005 winter drainage season, two tephra filled mole channels were excavated. This investigation revealed that the mole channels had a tear-drop shape with a wedge-shaped air space above the tephra. This space resulted from the use of a tephra delivery chute that was 40 mm wider than the mole plough blade (Plate 5.1). The air space had potential to allow drainage to by-pass the tephra and, therefore, lower the effectiveness of the treatment at removing P from drainage water. For future installations, the risk of by-pass flow occurring could be minimised by using additional tephra to fill both the mole channel and the wedge shaped area above the channel or by redesigning the equipment.

It is unlikely that P adsorption capacity of the tephra was the factor limiting the performance of the Mole-fill treatment. This is because the second column study indicated that the 1-4 mm tephra, used in the field study, was capable of adsorbing more than 2.5 kg P/ha, which is many times greater than the amount of DRP and TP measured in drainage water from the Control treatment (Table 5.2). The flow rate used in the column studies was estimated to be equivalent to an individual mole channel flow rate of 1.19 L/min. During 2005, 46% of drainage volume occurred at mole channel flow rates higher than 1.19 L/min. Consequently, drainage residence times in the field mole channels would have been shorter than in the column studies for almost half of the drainage volume occurring in 2005. Shorter residence times could have been another factor reducing the efficiency of the tephra at removing P from drainage water.

The tephra in the pipe Back-fill treatment also had a higher capacity to remove P than was evidenced in the field trial. The distance that drainage water passes through the tephra back-fill, between leaving the mole channel and entering the drainage pipe, may not have been long enough to allow sufficient residence time for efficient P removal over the range of drainage flow rates measured in the field study. Because the pipe Back-fill treatment is easier and potentially cheaper to install than the Mole-fill treatment, further work is required to determine how important the drainage water residence time is at influencing the P removal efficiency of pipe back-fill.

5.4 Summary and conclusions

The aim of this study was to evaluate the effectiveness of Papakai tephra for removing P from dairy farm drainage water when used as fill in mole and pipe drainage systems. Ash sized Papakai tephra is an effective P adsorbent, comparable to industrial furnace ashes and slags that have been evaluated by other researchers. Laboratory simulated mole channels packed with ash sized tephra were capable of removing P, from high P solutions, to a point where the treated solutions P concentrations were below the threshold values for stimulating aquatic weed growth. The presence of sulphate in the influent solution or the use of FDE as an influent solution did not appear to influence the effectiveness of P adsorption by the tephra.

Filling standard mole channels with fine materials can reduce their hydraulic conductivity and increase the risk of surface runoff. Increasing mole channel diameter or the number of mole channels used, for a given area, can increase drainage rate and lower the surface runoff risk. If these modifications are uneconomic for use across whole farms, then they could be targeted for use on high P loss risk areas, such as paddocks receiving irrigated FDE or paddocks designated for grazing while rainfall and drainage are occurring.

When used in paddock drainage systems, as fill in mole channels or as back-fill over drainage pipes, tephra appeared to reduce TP losses in drainage. The removal of DRP by tephra from the drainage water in the Mole-fill and Back-fill treatments was less efficient than that observed in the laboratory simulations. It is possible that some drainage water travelled in an air gap above the tephra in the Mole-fill treatment. In the Back-fill treatment relatively short drainage/tephra contact times may have caused the reduced P removal efficiency. Further research is required to improve the process of filling mole channels with tephra and to determine the optimal mole channel size and spacing for this application. The ability of the field study to clearly demonstrate the effectiveness of the tephra treatments at removing P was hindered by limited treatment plot replication. The use of greater replication in a longer-term field study, which covers a range of climatic conditions, is recommended to help establish the full benefits of tephra filled drainage systems to mitigate P loss from intensive pastoral farms.

5.5 References

ANZECC (2000) Australian and New Zealand guidelines for fresh and marine water quality. Vols 1 and 2. Australian and New Zealand Environment and Conservation Council, Canberra, ACT, Australia.

AOAC 1975: *Association of official agricultural chemists, official analysis. 12th Ed*. Washington DC.

Arias CA, Del Bubba M, Brix H (2001) Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. *Water Research,* 35, 1159-1168.

Ballantine DJ, Tanner CC (2010) Substrate and filter materials to enhance phosphorus removal in constructed wetlands treating diffuse farm runoff: a review, *New Zealand Journal of Agricultural Research*, 53:1, 71-95

Blakemore LC, Searle PL, Daly BK (1987) Methods for chemical analysis of soils. *NZ Soil Bureau Scientific Report* 80, 94-96.

Bolan NS, Syers JK, Tillman RW, Scotter DR (1988). Effect of liming and phosphate additions on sulphate leaching in soils. *Journal of Soil Science*, 39, 493-504.

Brix H, Arias CA, Del Bubba M (2001) Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. *Water Science and Technology,* 44, 47-54.

Del Bubba M, Arias CA, Brix H (2003) Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. *Water Research*, 37, 3390-3400.

Donoghue SL, Neall VE, Palmer AS (1995) Stratigraphy and chronology of late Quaternary andesitic tephra deposits, Tongariro Volcanic Centre, New Zealand *Journal of The Royal Society of New Zealand*, 25, 115-206.

Drizo A, Forget C, Chapuis RP, Comeau Y (2006) Phosphorus removal by electric arc furnace steel slag and serpentinite. *Water Research,* 40, 1547-1554.

Drizo A, Frost CA, Grace J, Smith KA (1999) Physico-chemical screening of phosphate-removing substrates for use in constructed wetland systems. *Water Research,* 33, 3595-3602.

Gruneberg B, Kern J (2001) Phosphorus retention capacity of iron-ore and blast furnace slag in subsurface flow constructed wetlands. *Water Science and Technology,* 44, 69-75.

Heal KV, Dobbie KE, Bozika E, McHaffie H, Simpson AE, Smith KA (2005) Enhancing phosphorus removal in constructed wetlands with ochre from mine drainage treatment. *Water Science and Technology*, 51, 275-282.

Heal KV, Smith KA, Younger PL, McHaffie H, Batty LC (2004) Removing phosphorus from sewage effluent and agricultural runoff using recovered ochre. In *Phosphorus in Environmental Technology: Principles and Applications*, ed. V.-J. E., IWA Publishing. London, pp. 321-335.

Heng LK, White RE, Bolan NS, Scotter DR (1991) Leaching losses of major nutrients from a mole-drainage soil under pasture. *New Zealand Journal of Agricultural Research,* 34, 325-334.

Hewitt AE (1998) *New Zealand soil classification 2nd ed*. Manaaki Whenua - Landcare Research New Zealand Ltd Press, Lincoln, New Zealand.

Hickey CW, Quinn JM, Davies-Colley RJ (1989) Effluent characteristics of dairy shed oxidation ponds and their potential impacts on rivers. *New Zealand Journal of Marine and Freshwater Research,* 23, 569-583.

Houlbrooke DJ (2005). *A Study of the Quality of Artificial Drainage Under Intensive Dairy Farming and the Improved Management of Farm Diary Effluent Using 'Deferred Irrigation'*. PhD Thesis, Massey University, Palmerston North. p 211.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO (2004a) Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research*, 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2004b) A review of literature on the land treatment of farm-dairy effluent in New Zealand and its impact on water quality. *New Zealand Journal of Agricultural Research,* 47, 499-511.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2003) The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association,* 65, 179-184.

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA (2008) Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research,* 46, 45–52.

Humphrey MD, Istok JD, Lee JY, Hevesi JA, Flint AL (1997) A new method for automated dynamic calibration of tipping-bucket rain gauges. *Journal of Atmospheric and Oceanic Technology,* 14, 1513-1519.

Kinniburgh DG (1986). General purpose adsorption isotherms. *Environmental Science Technology,* 20, 174-178.

McDowell RW, Muirhead RW, Monaghan RM (2006) Nutrient, sediment, and bacterial losses in overland flow from pasture and cropping soils following cattle dung deposition. *Communications in Soil Science and Plant Analysis,* 37, 93-108.

McDowell RW, Nash D (2012) A Review of the Cost-Effectiveness and Suitability of Mitigation Strategies to Prevent Phosphorus Loss from Dairy Farms in New Zealand and Australia. *Journal of Environmental Quality,* 41, (special submission).

McKenzie HA, Wallace HS (1954) The Kjeldahl determination of nitrogen – a critical study of digestion conditions – temperature, catalyst and oxidising agent. *Australian Journal of Chemistry*, 7, 55–77.

Mann RA (1997) Phosphorus adsorption and desorption characteristics of constructed wetland gravels and steelworks by-products. *Australian Journal of Soil Research,* 35, 375-384.

Monaghan RM, Paton RJ, Drewry JJ (2002) Nitrogen and phosphorus losses in mole and tile drainage from a cattle-grazed pasture in eastern Southland. *New Zealand Journal of Agricultural Research,* 45, 197-205.

Monaghan RM, Paton RJ, Smith LC, Drewry JJ, Littlejohn RP (2005) The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. *New Zealand Journal of Agricultural Research,* 48, 227-240.

Monaghan RM, Wilcock RJ, Smith LC, Tikkisetty B, Thorrold BS, Costall D (2006) Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems & Environment,* 118, 211-222.

Murphy J, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta,* 27, 31-36.

Nash D, Murdoch C (1997) Phosphorus in runoff from a fertile dairy pasture. *Australian Journal of Soil Research,* 35, 419-429.

Naylor S, Brisson J, Labelle MA, Drizo A, Comeau Y (2003) Treatment of freshwater fish farm effluent using constructed wetlands: the role of plants and substrate. *Water Science and Technology*, 48, 215-222.

Olsen SR, Cole VV, Watauable FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *United States Department of Agriculture Circular*, 939, 1-9.

Pant HK, Reddy KR, Lemon E (2001) Phosphorus retention capacity of root bed media of sub-surface flow constructed wetlands. *Ecological Engineering*, 17, 345-355.

Parfitt RL (1982) Competitive adsorption of phosphate and sulphate on goethite (-FeOOH): a note. *New Zealand Journal of Science,* 25, 147–148.

Ryden, JC, Syers, JK (1975) Use of tephra for the removal of dissolved inorganic phosphate from sewage effluent. *New Zealand Journal of Science,* 18, 3-16.

Ryden JC, Syers JK, Tillman RW (1987) Inorganic anion sorption and interactions with phosphate sorption by hydrous ferric oxide gel. *Journal of Soil Science,* 38, 211–217.

Sakadevan K, Bavor HJ (1998) Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. *Water Research*, 32, 393-399.

Saunders WMH (1965) Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter and other soil properties. *New Zealand Journal of Agricultural Research,* 8, 30-57.

Scarsbrook M (2006) *State and Trends in the National River Water Quality Network (1989–2005)*. Report published by the Ministry for the Environment, Wellington, NZ, pp 48.

Scotter DR, Clothier BE, Turner MA (1979) The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research*, 17, 455-465.

Sharpley AN, Syers JK (1979) Loss of nitrogen and phosphorus in tile drainage as influenced by urea application and grazing animals. *New Zealand Journal of Agricultural Research*, 18, 183-187.

Soil Survey Staff (1998) *Keys to soil taxonomy 8th ed*. United States Department of Agriculture, Washington DC.

Tanner CC, Sukias JPS, Upsdell MP (1999) Substratum phosphorus accumulation during maturation of gravel-bed constructed wetlands. *Water Science and Technology,* 40, 147-154.

Zhu T, Jenssen PD, Maehlum T, Krogstad T (1997) Phosphorus sorption and chemical characteristics of lightweight aggregates (LWA) - Potential filter media in treatment wetlands. *Water Science and Technology*, 35, 103-108.

CHAPTER 6:
Effect of cultivating long-term dairy pasture, summer forage cropping and autumn pasture renewal on nitrate leaching in the Manawatu

Chapter's context: The previous Chapter developed and evaluated an active filtering drainage system technology for reducing P losses in rainfall-induced drainage waters from land treated with FDE. Another nutrient management issue that can develop on land receiving FDE applications is the excessive accumulation of potassium (K). While summer forage cropping is a useful practice for accumulating summer fed for live-stock, it has also been shown to be a useful strategy for reducing excessive soil K levels. Because summer forage cropping is widely practiced by farmers, it is important to determine the effect this cropping has on the accelerated loss of other nutrients (e.g. N & P) in drainage waters. The hypothesis of Chapter 6 is that the cultivation of long-term pasture for summer forage cropping increases the risk of nitrate losses in drainage water.

6.1 Introduction

Long-term (>10 years) pastures, grazed in situ, provide the main source of livestock feed on most dairy farms in New Zealand. In the Manawatu region, it is common practice for dairy farmers to cultivate an area of long-term pastoral land each year for growing summer forage crops (e.g. turnips or green feed maize), which allows the pasture to be renovated with new, more productive ryegrass and white clover cultivars. Summer forage crops are a valuable component of seasonal feed supply, as they accumulate larger quantities (e.g. >two-fold) of forage dry matter (DM) compared with pasture, which can be grazed in summer when plant growth is often limited by inadequate soil moisture.

Summer forage crops are also a useful strategy for reducing excessive levels of potassium (K) that can accumulate in soils receiving K-rich farm dairy effluent (FDE) (Longhurst *et al*., 2000; Houlbrooke *et al*., 2004; Salazar *et al*., 2010). Above optimal soil K levels are undesirable as they increase the risk of metabolic disorders in dairy cows, such as hypocalcaemia (milk fever) and hypomagnesaemia (grass staggers).

When the turnips are grazed by dairy cows for short durations (i.e. 4 hours) each day, before being moved to other parts of the farm, then net removals of K from turnip areas can be achieved (Salazar *et al*., 2010).

While there are the aforementioned benefits of growing summer forage, the cultivation of soil under long-term pasture also increases the risk of nutrient losses (Shepherd *et al*., 2001; Monaghan *et al*., 2002; Smith *et al*., 2008). Under long-term pastures, considerable quantities of soil organic N can accumulate (Haynes 2000); while, cultivation of these pastures can result in net N mineralisation from pasture residues and soil organic matter (Francis *et al*., 1995; Davies *et al*., 2001; Eriksen & Jensen, 2001, Eriksen *et al*., 2008). These elevations in soil mineral N are beneficial for supplying N to subsequent crops (Eriksen *et al*., 2008), however, they can also contribute to increased NO_3^- leaching if NO_3^- accumulates in the soil immediately prior to a period of drainage (Shepherd *et al*., 2001; Di & Cameron, 2002).

There is mounting concern in New Zealand that pollutants from dairy farms, particularly nitrogen (N) and phosphorus (P), are degrading the quality of surface and ground waters in many areas of New Zealand. Mole and pipe drained soils allow direct connectivity between excess soil water and surface water bodies. The transfer of nutrients in drainage water to surface waters is rapid in these soils. In New Zealand, the use of mole and pipe drained soils for dairy farming has increased over the last fifteen years, as a result of the rapid expansion of dairying into regions with soil types (e.g. Pallic Soils) that require artificial drainage to accommodate dairying (e.g. Southland).

The timing of long-term pasture cultivation is known to have a significant influence on the potential for NO_3^- leaching from soils. In general, autumn cultivation is expected to result in higher NO_3^- leaching losses compared to spring cultivation, as there is a shorter period after autumn cultivation for a crop to take up soil NO_3^- before the winter drainage season begins (Francis, 1995; Djurhuus & Olsen, 1997; Shepherd *et al*., 2001). The quantity of NO_3^- leached from autumn cultivation can also be influenced by the type of cover crop grown over winter and the timing of drainage in relation to crop development (McLenaghen *et al*., 1996; Francis *et al*., 1998). Winter cover crops are most effective when they are sown early in autumn and take up a large proportion of soil NO_3^- before drainage occurs (Francis, 1995).

When soil under long-tem pasture is cultivated in spring for summer forage cropping and autumn re-grassing, there are a range of factors that impact on subsequent NO_3^- leaching, which include the:

i. Amount of N released from mineralisation of cultivated pasture soil
ii. N fertiliser policy for growing the forage crop
iii. Proportion of soil mineral N taken up by the forage crop (McLenaghen *et al*., 1996; Francis *et al*., 1998)
iv. Quantity of dairy cow excretal N returned during grazing (Silva et al., 1999; Ledgard, 2001; Lindsay *et al.*, 2009; Christensen *et al*., 2011; Gourley *et al*., 2011).
v. Timing of autumn cultivation and resowing of the new pasture (McLenaghen *et al*., 1996).
vi. The proportion of soil mineral N taken up by the new pasture prior to the start of winter drainage (Francis, 1995).

Determining the relative importance of each of these factors requires the use of component studies. However, because NO_3^- leaching is influenced by various interactions between management, soil properties and climate, it is also useful to assess the combined impact of the aforementioned factors. Also, pasture renewal results in changes to soil properties and pasture botanical composition that may influence NO_3^- leaching in subsequent seasons. However, there is limited information from field-scale studies assessing the influence of these practices over a number of years. In particular, information is required to determine the contribution that forage cropping makes to overall farm NO_3^- leaching on mole and pipe drained soils in New Zealand pastoral based dairy systems.

The aim of this study was to quantify the effects of cultivating long-term pasture, summer forage crop management and autumn regrassing on N and P losses in drainage water from a mole and pipe drained dairy pasture soil over three years in the Manawatu region of New Zealand.

6.2 Material and methods

6.2.1 Trial site, treatments and grazing management

A three-year (2006-2008) field trial was conducted on Massey University's No. 4 dairy farm near Palmerston North, Manawatu, New Zealand (NZMS 260, T24, 312867). The site is located in a flat to easy rolling landscape (c. 3% slope) on the Tokomaru silt loam soil, a Fragic Perch-gley Pallic Soil (Hewitt, 1998) or Typic Fragiaqualf (Soil Survey Staff, 1998). For the first two years (2006, 2007), the experiment consisted of four plots (40 × 40 m), each with an isolated mole and pipe drain system. In the third year (2008) of the trial all the plots were divided in half to provide a total of eight drainage plots (20 x 40 m). In each plot, mole channels (40 m long) were installed at 2 m intervals at a depth of 0.45 m. Drainage from the mole channels was intercepted by perforated collecting pipe drains (0.11 m diameter) that were installed at the edge of each plot, perpendicular to the moles at a depth of 0.60 m. Prior to commencement of this trial, all plots were managed under long-term pasture (>10 years) grazed by dairy cows. A further description of the farm system is provided in Section 3.2.1 (Chapter 3).

The trial design consisted of two treatments; the first treatment (hereafter, called *'LP'* treatment) was a continuation of long-term pasture (>10 years), which was grazed as part of the farm's grazing rotation. With the second treatment (hereafter, called *'CP'* treatment), long-term (>10 years) pasture was cultivated in spring, sown into turnips and used as a summer forage crop for dairy cows (Figure 6.1). In the subsequent autumn the *CP* treatment plots were cultivated again and sown into new pasture. The limited availability of large drainage plots for this study meant that treatments were replicated twice. The general N fertiliser policy for pasture on this farm is approximately 125 kg N/ha/year, applied as urea in 4-5 applications during late winter and spring.

In the Manawatu region, cultivation of pastoral soils for summer forage cropping occurs as soon as the soil moisture conditions are suitable for ploughing, which is typically in mid-late spring. Following current practice, the long-term pasture in the *CP* plots was sprayed with glyphosate, a non-selective herbicide, on 17 October 2006 and then cultivated with a mouldboard plough on 6 November 2006 (see crop calendar, Figure 6.1). Due to very wet soil conditions during late spring, cultivation was not completed until 14 December 2006. At this time the plots were prepared for sowing using power harrows and ‘Dutch’ harrows (Figure 6.1) and basal fertiliser (95 kg N/ha as urea; 31 kg P/ha and 34 kg S/ha as single superphosphate) was applied by hand to the *CP* plots and incorporated into the soil with chain harrows. On 15 December 2006 turnip seed (v. Barkant) was sown at a rate of c. 3 kg/ha using a Duncan vee-ring roller drill.

From 74 to 78 days after sowing (DAS; 28 February - 3 March 2007) the turnip crop on the *CP* treatment plots was strip grazed (c. 640 m^2/day) by 85 lactating dairy cows for two hours each day over five consecutive days (Plate 6.2). The area allocated per day was based on offering a diet of c. 4 kg DM turnips/cow/day. For the entire duration of the trial the *LP* treatment plots were grazed as part of the farm’s normal grazing rotation.

Plate 6.1 Preparation of the soil using ‘Dutch’ harrows prior to sowing turnips on the *CP* treatment plots (14 December 2006).

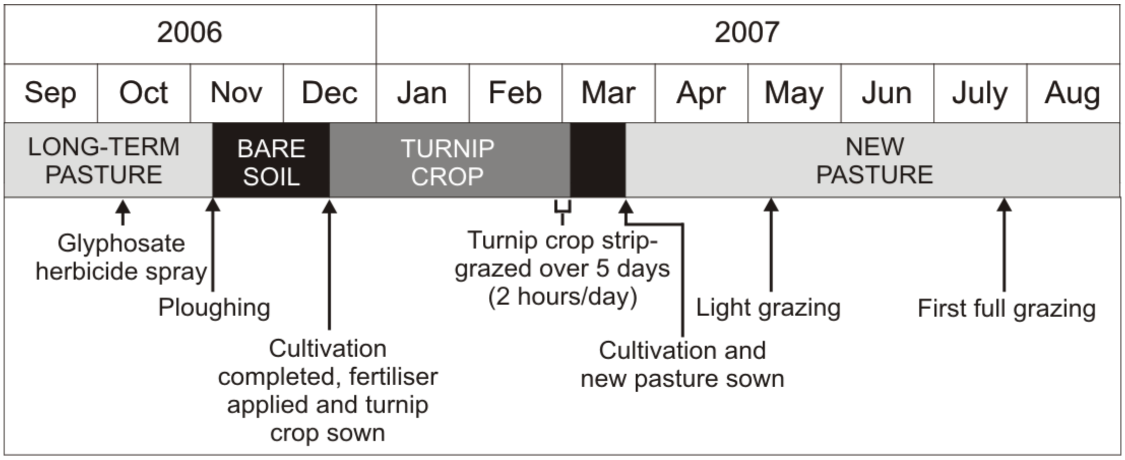

Figure 6.1 Crop calendar for the *CP* treatment plots.

New grass was sown into the grazed *CP* plots on 23 March 2007 after cultivation with a mouldboard plough, power harrows and Dutch harrows. A pasture mix of 26 kg/ha Bealey tetraploid perennial ryegrass and 4 kg/ha white clover was sown using a Duncan vee-ring roller drill. The new pasture plots were lightly grazed on 7 May 2007 to encourage tillering.

Plate 6.2 Dairy cows strip-grazing turnips on the *CP* treatment plots.

On 19-20 July 2007 pasture covers on the *CP* and *LP* treatment plots were determined using a rising plate meter. Mobs of non-lactating cows, on 24-hour grazing intervals, were allocated to each plot (275 cows/ha on *CP* plots and 94 cows/ha on *LP* plots). The average estimated pasture on offer was c. 8 kg DM/cow/day. Each day cows were allocated c.1 kg pasture hay DM/cow/day prior to grazing of the *CP* plots to minimise the risk of NO_3^- poisoning. At all subsequent grazing times, dairy cows grazed all plots from both treatments at the same time and stocking rate.

6.2.2 Herbage sampling and analysis

Turnip dry matter (DM) accumulation and plant population densities were assessed on five occasions (40, 47, 54, 61 and 73 days after sowing - DAS), using six quadrat measurements on each *CP* treatment plot. At the first four samplings times, a 0.32 m^2 quadrat was randomly placed on an area of turnip crop and the numbers of turnips within the quadrat were counted. Nine turnip plants (leaf, stem and bulb) were randomly sampled from each quadrat for DM weight determination. At the fifth and final sampling time (73 DAS) a 1 m^2 quadrat was used. All turnip plants within each quadrat area were collected by hand and weighed fresh. The above ground components (leaf and stem) of the turnip samples were sub-sampled for DM determination. All bulbs from each quadrat were used for DM determination. Herbage samples were oven dried at 65 ºC and weighed to determine DM content.

Utilisation of the turnip crop by cows was assessed by collecting all crop residues (leaf, stem and bulb) from an area of 1 m^2 at five locations within each plot (Plate 6.3). The turnip crop residues were washed, to remove soil and cow dung, oven dried at 65 ºC and weighed to determine DM content.

Plate 6.3 Turnip crop residues sampled within a 1 m^2 quadrat to assess turnip utilisation by dairy cows on a *CP* treatment plot.

On 16 July 2007, five quadrats (0.25 m^2) of pasture were cut from each trial plot using an electric trimmer. Samples were dried at 65 ºC and weighed to determine DM content. In addition, a sample containing 20 pasture grab samples was randomly collected from each plot for NO_3^- analysis.

6.2.3 Drainage water flow rate and volume measurements

At the corner of each drainage plot, a pit was excavated and a tipping-bucket flow meter was installed at the end of the drainage pipe to monitor drainage flow rates (refer to Plate 3.1 in Chapter 3). Each tipping bucket was calibrated dynamically to account for larger tip volumes at higher flow rates (Humphrey *et al*., 1997). All tipping buckets were instrumented with data loggers to provide continuous measurements of drainage flow rate. During each drainage event a proportion (c. 0.1%) of the drainage water from every second tip of the tipping bucket was automatically collected to provide a volume-proportioned mixed sample for water quality analysis. Drainage was monitored for the entire 2006, 2007 and 2008 drainage seasons. Soil water deficits were predicted using the soil water balance model and parameters described by Scotter *et al*. (1979).

6.2.4 Drainage water nitrogen and phosphorus analysis

Drainage water samples were analysed for NO_3^-, total N (TN), dissolved reactive phosphorus (DRP) and total phosphorus (TP). Nitrate and DRP were determined on filtered (0.45 µm filter) samples, while TN and TP were determined following acid persulphate digestion of unfiltered water samples (Hosomi & Sudo, 1986). All N and P analyses were conducted colorimetrically using a Technicon Auto Analyser (Blackmore *et al*., 1987).

6.2.5 Statistical analysis

Data from the field trial were statistically analysed using an Analysis of Variance (ANOVA) test to determine the level of statistical significance for a treatment effect. The standard errors of the means were used to provide a measure of the variation between treatment replicates. The 2007 drainage water NO_3^- and TN data (concentration and quantity) where analysed, after log transformation, using regression analysis against cumulative drainage. This analysis was conducted on the 2007 data because in this year there was a clear trend of variance increasing with drainage water N values.

6.2.6 Rainfall and drainage

The annual quantities of rainfall at the trial site during 2006, 2007 and 2008 were 1146, 733 and 1117 mm, respectively. In comparison, the mean annual rainfall for Palmerston North is 968 mm. Of the three study years, 2006 had the highest late spring and early summer (Oct-Dec) rainfall, while 2008 had the highest winter and early spring rainfall (Jun-Sep), which influenced soil water deficits (Figures 6.2 & 6.3).

The 2006 year had a longer than average drainage season, with drainage events occurring over a period of six months (Figure 6.4). Drainage season length in 2007 and 2008 were more typical, being approximately 4 months in duration. Average drainage quantities in 2006, 2007 and 2008 were 394, 117 and 353 mm, respectively. The low drainage quantity in 2007 resulted from lower winter and spring rainfall and not a shortening of the drainage season.

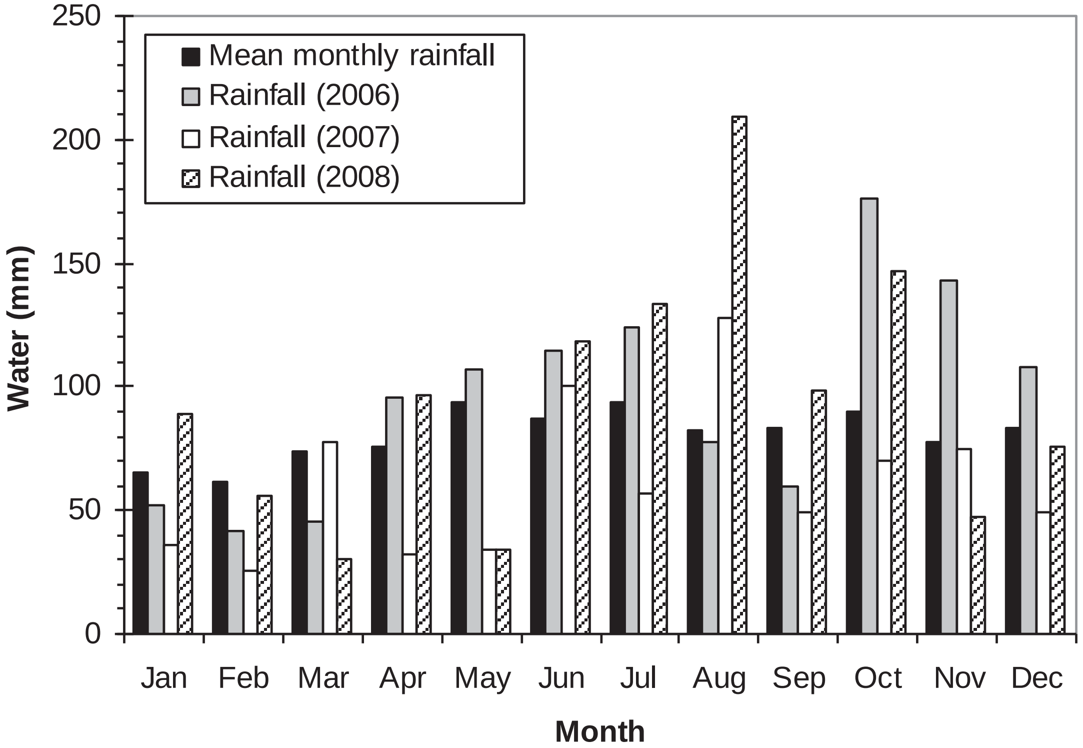

Figure 6.2 Mean monthly rainfall for Palmerston North and monthly rainfall for the trial site during 2006, 2007 and 2008.

During the 2006 drainage season, the average quantity of drainage occurring after treatment commencement (17 October 2006) was 153 mm for the *LP* treatment plots and 188 mm for the *CP* treatment plots. The higher drainage volumes measured for the *CP* treatment plots could be due to lower evapotranspiration rates from no crop cover being present during most of this period. It could also be due to lower surface runoff from the *CP* plots due to plough furrows improving infiltration.

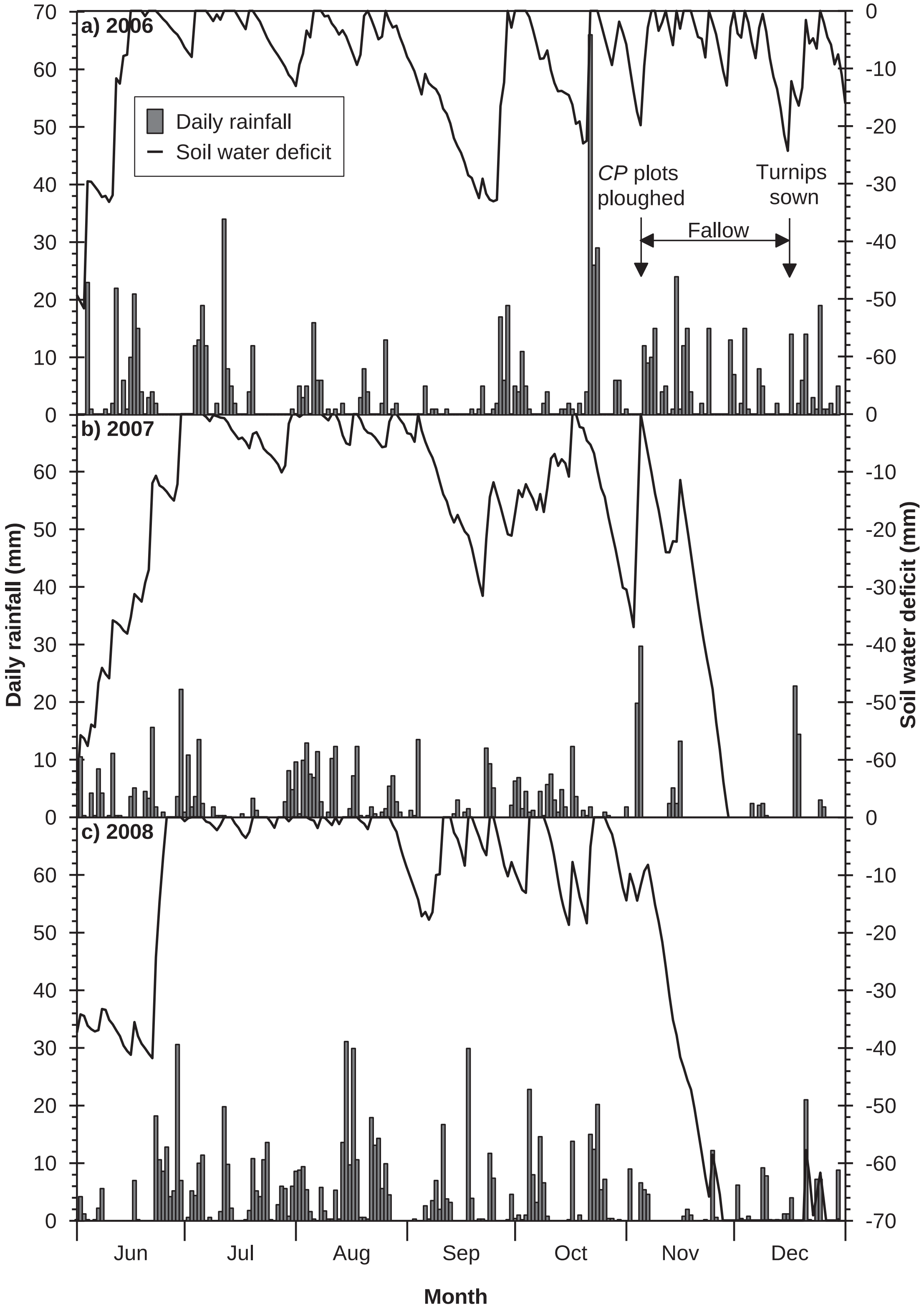

Figure 6.3 Daily rainfall and estimated soil water deficits at the field trial site during the 2006, 2007 and 2008 drainage seasons.

6.2.7 Turnip crop yield and grazing utilisation

The turnip crop (leaf, stem and bulb) yield on the *CP* treatment plots was an average of 6.9 T DM/ha on the day prior to strip grazing of the crop commenced (28 February 2007; 74 DAS). At this time, the bulb comprised 29% of total yield, with leaf and stem comprised the remaining biomass. This turnip yield is similar to average yields for v. Barkant turnips grown in the Manawatu region (Daniels, 1995).

Average turnip crop utilisation by grazing dairy cows was 75%. Utilisation of the turnip bulb was 82%, compared with 72% for the above-ground herbage. Turnip intakes by cows were estimated to be an average of 3.9 kg DM/cow/day.

6.2.8 Nitrogen losses in drainage water

2006 drainage season

Prior to treatment commencement in 2006, drainage NO_3^- concentrations were highest at the start of the drainage season and decreased with successive drainage events, reaching the lowest concentrations toward the end of August (Figure 6.4a). This trend of drainage water NO_3^- concentrations declining over the winter months has been observed in other studies at this site (Houlbrooke *et al*., 2003; Lindsay *et al*., 2009) and at other sites with mole and pipe drainage systems under grazed pasture (Monaghan *et al*., 2002).

Between *CP* treatment commencement and the end of the drainage season there were a further 10 drainage events. During this period, average drainage NO_3^- concentrations from the *LP* treatment plots remained low (<3 mg NO_3^--N/L). In contrast, following ploughing on 6 November 2006, average NO_3^- concentrations of drainage water from the *CP* treatment plots increased with successive drainage events for much of November and then remained relatively constant at c. 11 mg NO_3^--N/L during the first half of December. These higher drainage NO_3^- concentrations are likely to have resulted from a combination of increased soil organic N mineralisation, caused by cultivation, and the absence of plant N uptake.

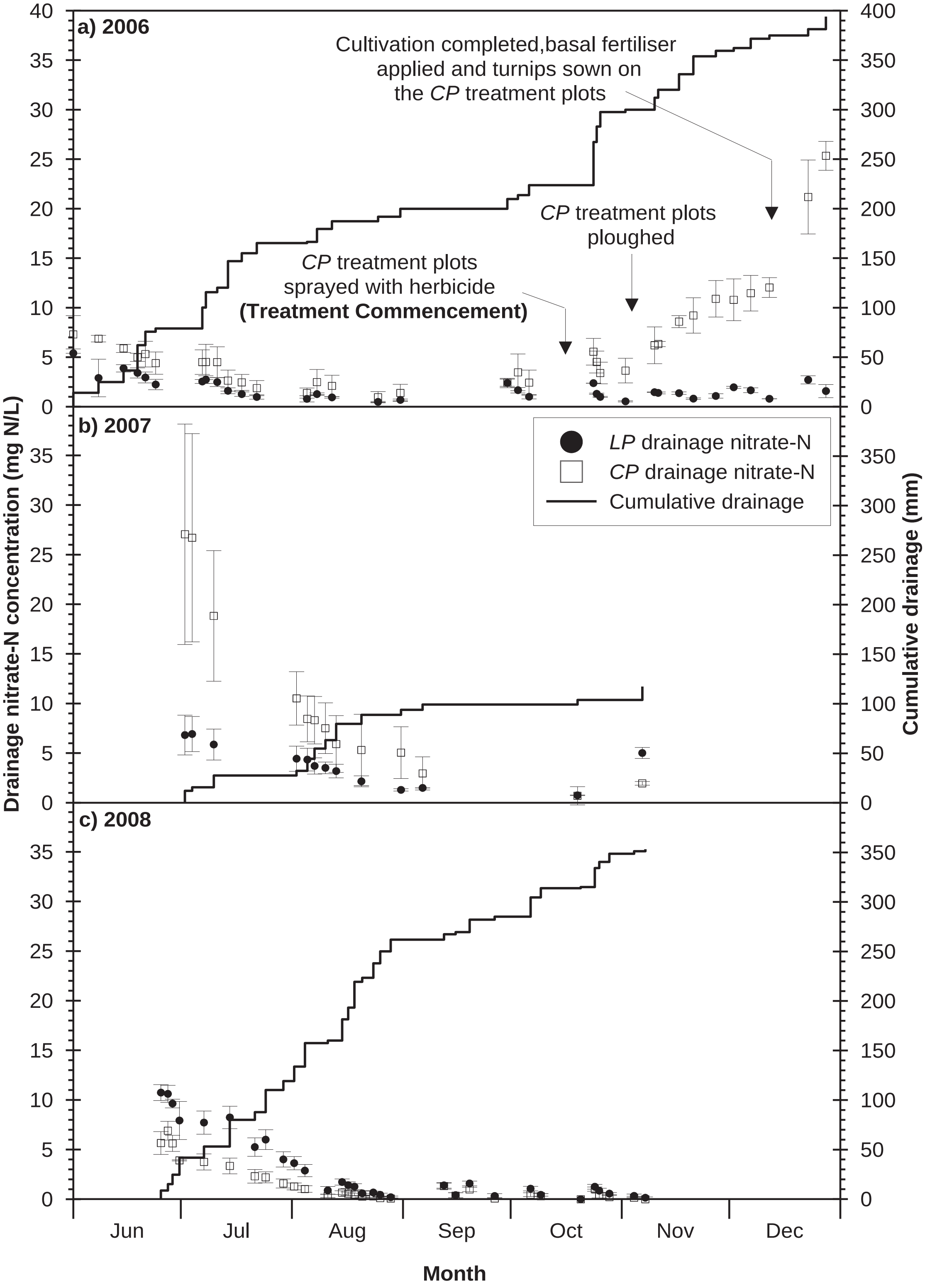

Figure 6.4 Mean measured cumulative drainage and drainage NO_3^--N concentrations for the *LP* and *CP* treatments during the 2006, 2007 and 2008 drainage seasons (*error bars represent ± standard error of mean*).

Following completion of cultivation, basal fertiliser application and sowing of the turnip crop (14-15 December 2006) there were two further drainage events (totalling 19 mm) in which drainage water NO_3^- concentrations from the *CP* treatment plots increased up to 25.3 mg NO_3^--N/L. These increases in NO_3^- concentrations are likely to have resulted from fertiliser N addition and further soil N mineralisation, coinciding with a period of nil plant N uptake (Gill *et al.*, 1995).

During the 2006 drainage season, the quantities of TN measured in drainage water from the *CP* treatment plots (32 kg N/ha) were c. 3-fold higher than the *LP* treatment value of 11.3 kg N/ha (Table 6.1). Nitrate accounted for the majority of N measured in drainage water, being 67% and 77% of the TN losses for the *LP* and *CP* treatments, respectively.

Table 6.1 Average losses of N and P (kg/ha) measured in drainage from the *LP* and *CP* treatment plots during the 2006, 2007 and 2008 drainage seasons.

Treatment	**TP (kg P/ha)**	**NO_3^--N (kg N/ha)**	**TN (kg N/ha)**
a) 2006			
LP	0.30 (0.16)*	7.6 (2.5)	11.3 (3.9)
CP	0.43 (0.23)	25.3 (16.2)	32.8 (20.0)
P-value	*0.0227 (0.1600)*	*0.0629 (0.0247)*	*0.0964 (0.0500)*
b) 2007			
LP	0.11	4.7	6.4
CP	0.26	12.0	14.7
P-value	*0.0414*	-**	-**
c) 2008			
LP	0.20	11.2	14.6
CP	0.34	6.2	11.2
P-value	*0.0640*	*0.0713*	*0.1997*
c) 2006-08 post-treat.*			
LP	0.47	18.4	24.9
CP	0.83	34.4	45.9
P-value	*0.0720*	*0.0369*	*0.0441*

* Values in parenthesis are for post-treatment commencement (17 October 2006).

** The effect of treatments on drainage water NO_3^- and TN values in 2007 were assessed using a separate regression analysis (refer Section 6.2.5). The results from this statistical analysis are discussed in the text.

Following treatment commencement, the average amount of TN lost in drainage water from the *CP* treatment was 16.1 kg N/ha higher than from the *LP* treatment (Figure 6.5). About half of this additional TN loss occurred between initial cultivation (November ploughing) and mid-December, when fertiliser N was applied. As stated above, the intial higher TN losses from the *CP* treatment plots are likely to have resulted from increased soil mineral N, caused by cultivation, coinciding with a period of zero plant uptake and reoccurring drainage events. Fertiliser N addition is likely to have contributed to TN losses occuring in drainage water after mid-December, when urea fertiliser was applied.

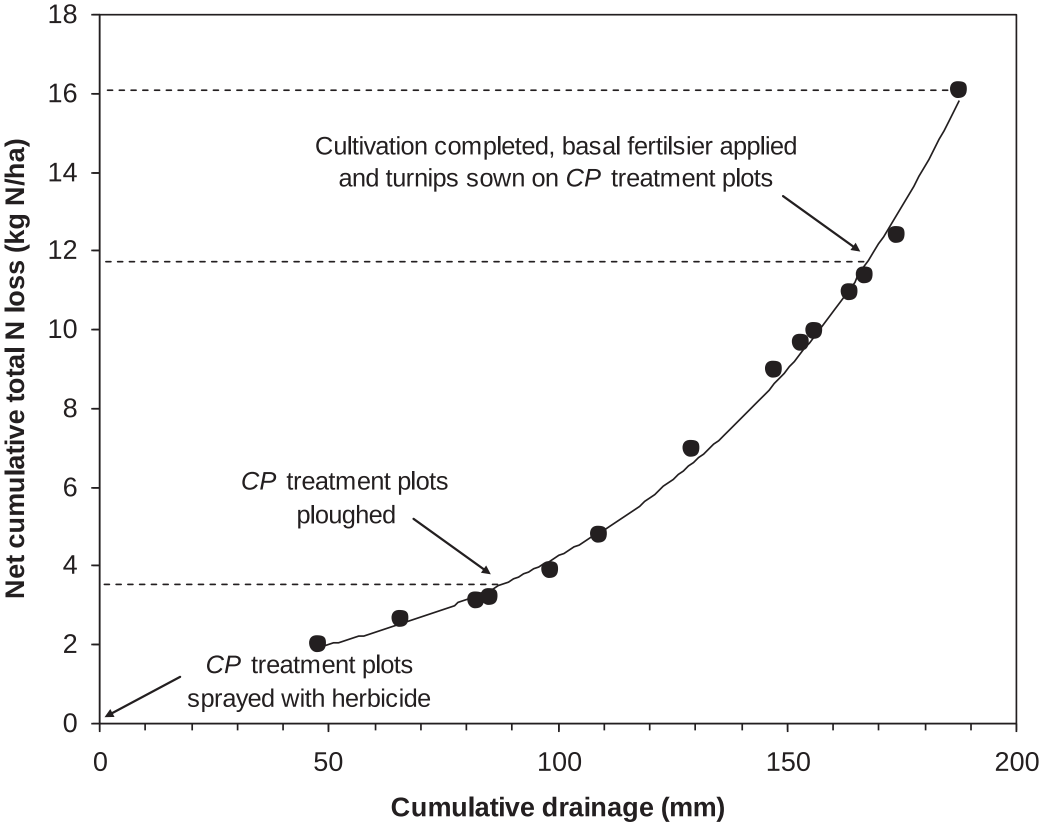

Figure 6.5 Net cumulative total N loss (*CP* treatment minus *LP* treatment values) in cumulative drainage following treatment commencment (17 October 2006), during the 2006 drainage season.

Because the quantity of drainage following spring pasture cultivation had an influence on the amount of N lost in drainage from the *CP* treatment during 2006, it was important to estimate how typical this drainage quantity was. A daily soil water balance model was used to estimate the quantity of drainage occurring after mid-October in each of the past 30 years (1978-2007). This analysis indicated that only 3 out of the 30 years assessed, including 2006, had >100 mm of cumulative drainage after mid-October (Table 6.2). In addition, the average quantity of drainage water occurring after mid-October, over the 30 years assessed, was only c. 25 mm. Therefore, if the amount of cumulative drainage that occurred after treatment commencement in 2006 had ceased after 25 mm (i.e. average year) then the additional quantity of TN lost from the *CP* treatment is estimated to have only been c. 1 kg N/ha, rather than 16.1 kg N/ha measured (Figure 6.5). In other words, losses of N in drainage following mid-spring cultivation of pasture are likely to be relatively low on average at this site.

Table 6.2 Measured net cumulative total N losses (*CP* treatment values minus *LP* treatment values) in drainage after treatment commencement (17 October 2006).

	Quantity of cumulative drainage (mm) and total N losses (after 17 October 2006)				
	0	**1-50**	**51-100**	**101-150**	**151-188**
Total N (kg N/ha)	0	0-2.0	2.0-4.2	4.2-9.0	9.0-16.1
Number of years*	***11***	***11***	***5***	***1***	***2***

*Estimated number of years, in the period 1978-2007, that were within each range of cumulated drainage after 17 October.

2007 drainage season

The 2007 drainage season average drainage water NO_3^- concentrations showed the normal trend of starting high for early-season drainage events (early July) and decreasing with successive drainage events over the winter months (Figure 6.4b). Average NO_3^- concentrations at the start of the drainage season were substantially higher (27.1 mg NO_3^--N/L) on *CP* treatment plots than for the *LP* treatment (7.9 mg NO_3^--N/L). Nitrate concentrations reached their lowest levels in October, at c. 0.7 mg NO_3^--N/L for both treatments, after c. 100 mm of cumulative drainage. The statistical analysis (refer Section 6.2.5) confirmed that the *CP* treatment had significantly ($P<0.001$) higher drainage water NO_3^- & TP values (concentrations and quantities) over the drainage season, compared to the *LP* treatment. In total over the duration of the drainage season the quantity of TN lost in drainage water from the *CP* treatment plots averaged 14.7 kg N/ha, which was more than double the 6.4 kg N/ha lost from the *LP* treatment plots.

Urine patches, deposited over multiple grazings during the months preceeding the start of winter drainage, are typically a major source of N leached in mole and pipe drained pastoral soils at this site (Lindsay *et al.*, 2009, Shepherd *et al.*, 2011). Estimates of grazing time and stocking rates were used to determine the relative amounts of urine N deposited on both treatments to assess whether this source could have been a factor influencing the differences in early season drainage water NO_3^- concentrations between the two treatments. The number of cow hours/ha over the summer and autumn period for the *CP* treatment was estimated to be approxiately half that for the *LP* treatment.

Therefore, the higher NO_3^- concentrations from the *CP* treatment plots at the start of the 2007 drainage season are unlikely to be attributable to higher uninary N inputs. A combination of higher soil mineral N, from mineralised soil organic N and fertiliser N, and lower N plant uptake during autumn are likely to be the main causes of higher NO_3^--N concentrations in early season drainage water for the *CP* treatment.

As previously discussed, the duration between autumn sowing of a crop and the start of the winter drainage season can influence the amount of NO_3^- that accumulates in the soil and, therefore, is susceptible to leaching (Francis, 1995). In general, the later a crop is sown in autumn, the less time there is for crop establishment and uptake of soil NO_3^- prior to the commencement of the drainage season. However, the timing of when new grass can be sown, following a summer forage crop, will be influenced by when soil moisture conditions are suitable for cultivation and germination.

An analysis using a daily soil water balance, modelled over a 30 year period (1978-2007), was used to assess how typical the autumn cultivation date in this study was and how variable this may be from year to year. In the model it was assumed that autumn cultivation could start following 25 February once 30 mm of soil moisture had accumulated in the topsoil (Pers. com. D. Horne). Using these criteria, the theoretical cultivation date varied from as early as 26 February to as late as 21 May. The average theoretical cultivation date was 27 March, which was only five days later than when autumn cultivation was carried out in this study. This analysis indicates that the potential autumn cultivation date is highly variable; however, the actual cultivation date in this study was close to the average for this site.

2008 drainage season

In contrast to the previous season, NO_3^- concentrations in drainage water during the 2008 season were mostly lower for the *CP* treatment compared to the *LP* treatment (Figure 6.8c). The average load of NO_3^--N measured in drainage from *CP* treatment plots was 23 % lower than the *LP* treatment value of 14.6 kg NO_3^--N/ha (Table 6.1). These results indicate that during the second drainage season, following the establishment of new grass, there is likley to be greater immobilisation of mineral N (i.e. less net-mineralsation) on the *CP* treatment plots, compared to permanent pasture.

2006-2008 drainage summary

The average cumulative quantities of TN measured in drainage water between trial commencement (17 October 2006) and the end of the 2008 drainage season for *CP* treatment was 45.9 kg N/ha, which was 84% (21 kg N/ha) higher than the *LP* treatment value of 24.9 kg N/ha (Table 6.2). Nitrate accounted for the majority of N measured in drainage water, being about 75% of the TN losses for both treatments. As discussed earlier, a large proportion of the additional drainage TN losses from the *CP* treatment occurred during the 2006 drainage season as a result of an atypically long drainage season. If the study had commenced in a more typical year, with 25 mm of drainage occurring after the 17 October (refer to Figure 6.5 & Table 6.2), then the additional TN losses from the *CP* treatment, over the three drainage seasons studied, is estimated to have only been about 5.9 kg N/ha (i.e. +1 kg N/ha, 2006; +8.3 kg N/ha, 2007; -3.4 kg N/ha, 2008), which represents a 23.7% increase above the losses from the *LP* treatment.

6.2.9 Phosphorus losses in drainage water (2006-2008)

The quantities of total P (TP) lost in drainage were generally low (<0.5 kg P/ha/year) during all three drainage seasons (2006-2008) (Table 6.1). The magnitude of these losses was similar to values reported for this site in other studies (Chapter 3; Houlbrooke *et al*., 2008). In all three drainage seasons there was some evidence of a small increase in TP drainage water losses from the *CP* treatment, compared to the *LP* treatment. During the period from treatment commencement (17 October 2006) to the end of the 2008 drainage season the *CP* treatment plots lost 0.83 kg of TP, which was 77% higher than the *CP* treatment average value of 0.47 kg P/ha. The losses of dissolved reactive P (DRP), which were measured in the first two seasons only (data not shown), were approximately one-third of TP losses for both treatments in 2006 and only about one-tenth of TP in 2007. Accordingly, DRP was not the main form of P lost in drainage water during these two seasons, which was also the observation of Houlbrooke *et al.* (2008).

6.2.10 Comparisons with whole-farm N leaching and OVERSEER® Nutrient Budgets model

To put into perspective the increase in N leaching losses, caused by growing a forage crop as part of a farm's normal regrassing (renovation) strategy, it is useful to evaluate the significance of the N losses in the context of a farm's whole grass-crop regrassing cycle. When spring cultivation occurs in an average year (i.e. with no more than 25 mm of cumulative drainage after mid-October) then the additional TN losses in drainage water for the *CP* treatment was estimated to be 5.9 kg N/ha. When this value is added to the annual average N loss from the *LP* treatment, of 10.8 kg N/ha/year, then the annualised N drainage losses from forage cropped areas would be an average of 16.7 kg N/ha/year. If forage cropping is used in conjunction with pasture renovation every 10 years, then in any one year c. 10% of the farm is cropped for forage. Based on these results, foraging cropping is estimated to increase whole-farm drainage water N losses by c. 0.6 kg N/ha/yr (5.6%), compared to a farm with only long-term pasture.

Table 6.3 Estimated contribution turnip forage blocks to whole-farm average drainage water N losses.

Farm block (% of farm area)	**Annual N losses (kg N/ha/yr)**	
	Measured in field study	**Predicted by OVERSEER®**
Pasture (90%)	10.8	15.0
Turnip forage (10%)	16.7	23.0
Weighted farm average	11.4	15.7
*Turnip forage contribution to farm av.**	0.6 (5.6%)	0.7 (4.7%)

*Compared to a farm with 100% long-term pasture.

The farm system was also simulated using the OVERSEER® Nutrient Budgets model, which is a long-term annual average model currently used by the dairy industry to estimate the impacts of nutrient management on nutrient losses from individual farms (Version 5.4.9; Wheeler *et al.*, 2006). OVERSEER® estimated that a pasture block would loose 15.0 kg N/ha and a turnip forage block would loose 22.0 kg N/ha. Although these values are higher, than those measured in the current study, the difference may partly be due the surface runoff N losses not being measured in this study. In 2003, Houlbrooke (2005) quantified surface runoff N losses of 3 kg N/ha/year at this site, which would mostly account for the above differences.

Overall, the OVERSEER® estimates agreed well with the results measured in this study. Foraging cropping and pasture renewal increased whole-farm annual drainage water N losses by c. 5%, when 10% of a farm's area is cultivated each year.

6.2.11 Nitrate concentrations in re-sown ryegrass-clover pastures

When the new pasture on the *CP* treatment plots were first fully grazed in July 2007, the average NO_3^- concentration in the new pasture was 4,085 mg NO_3^--N/kg DM, compared with only 139 mg NO_3^--N/kg DM for *LP* treatment plots on average. At this time the average pasture covers were 3,354 kg DM/ha for the *CP* treatment and 1,814 kg DM/ha for the *LP* treatment, which resulted in above-ground pasture NO_3^- accumulation of 13.7 and 0.25 kg NO_3^--N/ha, respectively. The high pasture NO_3^- concentrations in the new pasture was at a level considered to be a high risk of causing NO_3^- toxicity to grazing stock (Stoltenow & Lardy, 1998) and reflects the higher availability of soil NO_3^- in the *CP* treatment plots during autumn 2007. This result highlights the importance of managing the grazing of new pastures carefully to minimise the risk of NO_3^- toxicity.

6.2.12 Mitigating N leaching from forage cropping

The contribution that cultivating long-term pasture, for summer forage cropping and autumn regrassing, makes to increasing whole-farm N leaching losses is relatively small due to these cropped areas comprising only about 10% of a farm’s area in any one year. However, because these are likely to be the areas with the highest farm per hectare N leaching losses, efforts to reduce farm N leaching should target these areas. To reduce the risk of NO_3^- leaching following autumn cultivation, management should focus on practices that minimise excess accumulation of soil NO_3^- prior to the start of the subsequent drainage season. The application of a nitrification inhibitor has potential to reduce the accumulation of soil NO_3^-, following autumn cultivation, by inhibiting the nitrification of ammonium to NO_3^- in the soil. Francis (1995) measured reductions in NO_3^- leaching (24-46%) following March cultivation of pasture when DCD was surface applied as an aqueous solution the day before ploughing. Reducing NO_3^- accumulation in the soil, by modifying soil processes, can also reduce plant uptake of NO_3^-, which has potential to reduce the risk of NO_3^- N toxicity of livestock grazing new pastures.

6.3 Conclusions

The turnip summer forage crop was an effective method of accumulating relatively large quantities of standing feed, which was well utilised by grazing dairy cows. The cultivation of long-term pastures elevated drainage water N concentrations immediately following spring cultivation and again during the subsequent drainage season, after autumn regrassing. The effect of spring cultivation on N drainage water losses, however, is dependent on the timing and quantity of drainage in the first few months following cultivation. Normally the drainage season has typically finished near the time of spring cultivation at this site and, therefore, any direct NO_3^- leaching losses from spring cultivation are likely to be minimal in most years. Following grazing of the forage crop and establishment of new pasture, in the subsequent autumn, the drainage water NO_3^- concentrations were also elevated.

The quantity of TN measured in drainage water over the duration of this study was 84% (21 kg N/ha) higher for the *CP* treatment, compared to the *LP* treatment. If this study had commenced in a more typical year, this increase is estimated to have only been about 23.7% or 5.9 kg N/ha. Based on these results, foraging cropping is estimated to increase whole-farm drainage water N losses by about 5%, when 10% of a farm's area is cultivated each year.

The greatest potential to mitigate NO_3^- leaching losses measured in the *CP* treatment, will be from strategies that can minimise the accumulation of soil NO_3^- following autumn cultivation and prior to the start of the subsequent drainage season. Future research should focus on the use of nitrification inhibitors, applied during autumn cultivation, to reduce the accumulation of soil NO_3^- and subsequent NO_3^- leaching. This also has potential to decrease the risk of NO_3^- toxicity of livestock grazing new pastures.

The cultivation of long-term pasture and summer forage cropping did result in an increase in TP losses in drainage, however, overall losses of TP were low for both treatments during the years of the study.

6.4 References

Blakemore LC, Searle PL, Daly BK (1987). *Methods for chemical analysis of soils*. New Zealand Soil Bureau Scientific Report 80.

Christensen CL, Hedley MJ, Hanly JA, Horne DJ (2011). Nitrate leaching and pasture accumulation during two years of duration-controlled grazing in the Manawatu. In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C.L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Accessed 6/7/2011.

Daniels N (1995). Summer forage crop survey. *Dairy Farming Annual*, 47, 32-40.

Davies MG, Smith KA, Vinten AJA (2001). The mineralisation and fate of nitrate following ploughing of grass and grass-clover swards. *Biology and Fertility of Soils*, 33, 423-434.

Di HJ, Cameron KC (2002). Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, 46, 237-256, 2002.

Djurhuus J, Olsen P (1997). Nitrate leaching after cut grass/clover leys as affected by time of ploughing. *Soil Use and Management*, 13, 61-67.

Eriksen J, Askegaard M, Søegaard K (2008). Residual effect and nitrate leaching in grass-arable rotations: effect of grassland proportion, sward and fertiliser history. *Soil Use and Management*, 24, 373–382.

Eriksen J, Jensen LS (2001). Soil respiration, nitrogen mineralization and uptake in barley following cultivation of grazed grasslands. *Biology & Fertility of Soils*, 33, 139-145.

Francis GS (1995). Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand. *Journal of Contaminant Hydrology*, 20, 313-327.

Francis GS, Bartley KM, Tabley FJ (1998). The effect of winter cover crop management on nitrate leaching losses and crop growth. *Journal of Agricultural Science*, 131, 299-308.

Francis GS, Haynes RJ, Williams PH (1995). Effects of timing of ploughing in temporary leguminous pastures and two winter cover crops on nitrogen mineralization, nitrate leaching an spring wheat growth. *Journal of Agricultural Science*, 124, 1-9.

Gourley CJP, Aarons SA, Dougherty WJ, Weaver DM (2011). Nitrogen and phosphorus balances and efficiencies on contrasting dairy farming in Australia. In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C.L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Accessed 6/7/2011.

Gill K, Jarvis SC, Hatch DJ (1995). Mineralisation of nitrogen in long-term pasture soils: effects of management. *Plant and Soil*, 172, 153-162.

Haynes RJ (2000). Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biology & Biochemistry,* 32, 211-219.

Hewitt AE (1998). *New Zealand soil classification 2nd ed*. Manaaki Whenua - Landcare Research New Zealand Ltd Press, Lincoln, New Zealand.

Hosomi M, Sudo R (1986). Simultaneous determination of total nitrogen and total phosphorus in freshwater samples using persulphate digestion. *International Journal of Environmental Studies*, 27, 267-275.

Houlbrooke DJ (2005). *A Study of the Quality of Artificial Drainage Under Intensive Dairy Farming and the Improved Management of Farm Diary Effluent Using 'Deferred Irrigation'*. PhD Thesis, Massey University, Palmerston North. p 211.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO (2004). Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research,* 47, 405-415.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Snow VO (2003). The impact of intensive dairy farming on the leaching losses of nitrogen and phosphorus from a mole and pipe drained soil. *Proceedings of the New Zealand Grassland Association,* 65, 179-184

Houlbrooke DJ, Horne DJ, Hedley MJ, Snow VO, Hanly JA (2008). Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research*, 46, 45–52.

Humphrey MD, Istok JD, Lee JY, Hevesi JA, Flint AL (1997). A new method for automated dynamic calibration of tipping-bucket rain gauges. *Journal of Atmospheric and Oceanic Technology*, 14, 1513-1519.

Lindsay CL, Hanly JA, Hedley MJ, Horne DJ (2009). Controlling nitrogen and phosphorus loss from dairy farms using restricted grazing practices. In *Nutrient Management in a Rapidly Changing World* (Eds. L D Currie and C L Lindsay), Occasional Report No. 22, Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 295–302.

Ledgard S (2001). Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil*, 228(1), 43-59.

Longhurst RD, Roberts AHC, O'Connor MB (2000). Farm dairy effluent: a review of published data on chemical and physical characteristics in New Zealand. *New Zealand Journal of Agricultural Research*, 43:7-14.

McLenaghen RD, Cameron KC, Lamkin NH, Daly ML, Deo B (1996). Nitrate leaching from ploughed pasture and effectiveness of winter catch crops in reducing leaching losses. *New Zealand Journal of Agricultural Research*, 39, 413-420.

Monaghan RM, Paton RJ, Drewry JJ (2002). Nitrogen and phosphorus losses in mole and tile drainage from a cattle-grazed pasture in eastern Southland. *New Zealand Journal of Agricultural Research*, 45, 197–205.

Salazar ME (2006). *Use of turnips to reduce potassium accumulation on areas receiving farm dairy farm effluent*. M.Appl.Sc. thesis. Massey University.

Salazar ME, Hedley MJ, Horne DJ (2010). Can turnips be used to reduce soil K loading on the effluent block? Grasslands Conference

Scotter DR, Clothier BE, Turner MA (1979). The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research,* 17, 455-465.

Shepherd MA, Hatch DJ, Jarvis SC, Bhogal A (2001). Nitrate leaching from reseed pasture. *Soil Use and Management,* 17, 97-105.

Shepherd M, Phillips P, Snow V (2011). The challenge of late summer urine patches in the Waikato region. In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C.L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Accessed 6/7/2011.

Silva RG, Cameron KC, Di HJ, Hendry T (1999). A lysimeter study of the impact of cow urine, dairy shed effluent, and nitrogen fertiliser on nitrate leaching. *Australian Journal of Soil Research,* 37, 357–369.

Smith LC, de Klein CAM, Monaghan RM, Catto WD (2008). The effectiveness of dicyandiamide in reducing nitrous oxide emissions from a cattle-grazed, winter forage crop in Southland, New Zealand. *Australian Journal of Experimental Agriculture*, 48(1-2), 160-164.

Soil Survey Staff (1998). *Keys to soil taxonomy 8th ed*. United States Department of Agriculture, Washington DC.

Stoltenow C, Lardy G (1998). Nitrate Poisoning of Livestock. North Dakota State University. Available at: http://www.ag.ndsu.edu/pubs/ansci/livestoc/v839w.htm. Accessed 29/11/2010.

Wheeler D, Ledgard SF, Monaghan RM, McDowell R, and DeKlien C (2006). OVERSEER® Nutrients Budgets Model – What is it, what it does? In *Implementing sustainable nutrient management strategies in agriculture.* (Eds. L.D. Currie and J.A. Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 231-236.

CHAPTER 7: Summary

7.1 Introduction

Increased nutrient losses from dairy farms to surface and ground water have been associated with a decline in the quality of the country’s fresh water resource. In particular, many farmers have had difficulty complying with regional council regulations for the management of farm dairy effluent (FDE).

Land application is the preferred method used for treating FDE in most regions of New Zealand. However, poorly managed FDE land treatment systems continue to contribute to the eutrophication of fresh water rivers and lakes. As a consequence, much effort has focused on research to improve FDE land treatment systems (Houlbrooke *et al.*, 2004a; Houlbrooke *et al.*, 2004b; Monaghan & Smith, 2004). A key outcome of this work has been to establish the need for improved management of land application of FDE onto ‘high risk’ soils and landscapes, which allow a high degree of connectivity between drainage water and surface water bodies. On mole and pipe drained soils, the use of *deficit irrigation* has been shown to minimise the losses of nutrients and pathogens from land applied FDE. However, there has been limited research conducted to determine what assistance farmers need to implement these practices effectively.

Furthermore, there are a number of other nutrient management issues that can also develop in soils receiving FDE. These issues include elevated P losses in winter mole and pipe drainage water and the accelerated accumulation of soil potassium (K). In situations where seasonal drainage waters are excessively enriched in P, it has been suggest that the use of high P adsorbing materials, as fill in drainage ditches or in underground mole and pipe drainage networks, could be effective in trapping P before it can enter surface waters. For soils with excessive levels of K, summer forage cropping has been shown to be a useful strategy for reducing this accumulation. However, the cultivation of long-term pasture also has the potential to increase the loss of NO_3^- leaching.

The principal aim of this thesis was to evaluate farm management practices and decision-support tools with potential to reduce the losses of N and P from mole and pipe drained dairy pasture soils, with a focus on soils used for FDE land treatment. This thesis had the following research objectives:

- To evaluate decision support and fail-safe tools for informing the design and management of land treatment systems for *deficit irrigation* of FDE at a farm scale.
- To quantify the impact of system design changes on the practice of *deficit irrigation* at a farm scale, using a case study farm.
- To develop a novel drainage treatment system, using andesitic tephra, and evaluate its effectiveness at removing P from drainage water from soils used for FDE land treatment.
- To quantify the effects of cultivating long-term pasture soils, summer forage crop management and autumn regrassing on N and P losses in drainage water from a mole and pipe drained dairy pasture soil.

7.2 Tools for informing the design and management of deficit irrigation FDE land treatment systems (Chapter 3)

The key aspects of FDE system design and management that are critical to the successful operation of *deficit irrigation* are determining adequate farm-specific storage requirements, the provision of accurate real-time soil water deficit information, and preventing the occurrence of irrigator stoppages.

This study showed that the *FDE Storage Calculator* is an effective tool for estimating the storage capacity a farm requires to practice *deficit irrigation* of FDE. The Calculator uses farm and climate information to capture the influence that FDE generation and irrigation rates have on storage requirements. Having a storage requirement specifically designed for individual farms helps to minimise the environmental consequences of undersized storage capacity. The ability to determine farm-specific storage will also help farmers avoid being required to have excess storage capacity, reducing capital costs. The *Calculator* also provides the ability to compare various FDE system changes to allow the costs and benefits of alternatives to be assessed during the design process.

In addition to adequate FDE storage capacity, dairy farms practicing *deficit irrigation* of FDE also require accurate, daily farm-specific SWD information to schedule irrigations.

In both years of this study, the occurrence of drainage on the case study farm consistently coincided with modelled SWD values at or near zero. This result demonstrated that soil water balance modelling, using actual farm daily real-time rainfall, has the potential to provide the level of accuracy required to schedule FDE irrigations adhering to *deficit irrigation* criteria.

Remote sensing of the small rotating travelling irrigator on the case study farm demonstrated that irrigator stoppages were a regular occurrence and lasted for up to 12 hours at a time. In a 12-hour stoppage the case study farm's irrigator applied approximately 140 m^3 of FDE, of which most is likely to have been applied in excess of the SWD, causing direct surface runoff and/or drainage of FDE. While some causes of irrigator stoppage can be avoided, for example through irrigator maintenance or checking the strength of irrigator anchor points, other causes of irrigator stoppage would be difficult to prevent without constant monitoring of the irrigator. As it is not practical for farm staff to continually watch a travelling irrigator, the use of an automated system to eliminate stoppages is recommended. A travelling irrigator breakdown alert and automatic shut-off system was developed as part of this study and its effectiveness at preventing further irrigator stoppages was demonstrated.

Overall, this study demonstrated that the design and management of FDE land treatment systems could be improved through the use of decision-support and fail-safe tools.

7.3 Implementing deficit irrigation of farm dairy effluent at a farm scale – a Manawatu case study (Chapter 4)

Although *deficit irrigation* has been researched at the paddock scale (i.e. proof of concept; Houlbrooke *et al.* 2004b), and modelled at the farm scale (Houlbrooke, 2005), its actual implementation at a farm scale has not been researched. It is necessary to study the implementation of *deficit irrigation* at the farm scale because this will help to identify how key factors and system constraints influence its adoption and success. Some of these factors can be modelled, such as climate, rate of FDE generation, FDE storage capacity and type of irrigation system. However, the influence of other key aspects of management, such as labour availability and skills, and access to decision support information, cannot be accounted for in a model. Therefore, an overall assessment of how well a farm implements *deficit irrigation* requires daily monitoring of key components of the FDE system.

The aim of this investigative case study was to use a combination of modelling and on-farm remote sensing to:

- Identify the system constraints that limit the implementation of *deficit irrigation* at a farm scale,
- Quantify the potential volumes of land applied FDE that are at risk of being lost annually in surface runoff and/or drainage from current practice, and
- Explore changes to system design that will enable *deficit irrigation* to be successfully implemented and managed.

The remote sensing and modelling methods used in this study were effective at assessing the ability of the case study farm to implement *deficit irrigation* and also for estimating the potential FDE losses. Monitoring of the farm's FDE pond level, FDE travelling irrigator groundspeed and soil moisture conditions enabled the potential volumes applied in excess of the SWD to be estimated.

During the winter and spring of 2008 it was estimated that as much as 7,890 m^3 FDE was applied in excess of the SWD. The quantities of N and P estimated to have been lost to surface waters from this over applied FDE are equivalent to increases in farm losses of 16-34% TN and 33-69% TP. The use of modelling identified that about two-thirds of this was due to the system constraints of inadequate FDE storage capacity and the irrigator's minimum application depth. In the subsequent year, after the FDE storage capacity was increased, it was estimated that 1,560 m^3 was applied in excess of the SWD. The improvements in FDE land application in 2009, compared to 2008, were due to both the increases in storage capacity and to lower winter and spring rainfall in 2009. Modelling the 2008 and 2009 winter and spring periods using both a 6,000 m^3 storage capacity and a low application depth sprinkler irrigation system showed that *deficit irrigation* could have been implemented in both years successfully if both of these changes had been made.

The use of the remote sensing approach used this study, was an effective method for evaluating the implementation of *deficit irrigation* at a farm scale and to test the impact of system constraints predicted with modelling.

7.4 Evaluation of tephra for removing phosphorus from dairy farm drainage waters (Chapter 5)

Phosphorus losses in rainfall-induced winter drainage have also been shown to be higher from dairy farm areas receiving FDE compared to non-effluent areas (Houlbrooke *et al*., 2003). The aim of this study was to use a P adsorbing material in mole and pipe drainage systems to remove P from dairy farm drainage water.

Research was conducted in the Manawatu region, New Zealand, to evaluate the effectiveness of an andesitic tephra subsoil (Papakai tephra) at removing P from dairy farm mole and pipe drainage waters from effluent block soils. The capacity of this tephra to adsorb P was quantified in the laboratory using a series of column experiments and was further evaluated in a field study.

Laboratory simulated mole channels packed with ash sized tephra were capable of removing P from water at rates comparable to industrial furnace ashes and slags, that have been evaluated by other researchers. The 0.25-1 mm tephra removed an estimated 2.6 mg P/g tephra from a 12 mg P/L influent solution at an average P removal efficiency of 86%. The 1-2 mm tephra removed 1.6 mg P/g tephra at an average removal efficiency of 58%. The presence of sulphate in the influent solution or the use of FDE as an influent solution did not appear to influence the effectiveness of P adsorption by the tephra.

In the field study, the two tephra treatments involved filling mole channels with 1-4 mm tephra (Mole-fill treatment) or filling the trench above intercepting drainage pipes with ‘as received’ tephra (Back-fill treatment). Over an entire winter drainage season, the quantity of total phosphorus (TP) lost from the Control treatment drainage system was 0.30 kg P/ha. The average TP losses for the Mole-fill and the Back-fill treatments were 45% and 47% lower than the Control treatment, respectively. The removal of DRP by tephra from the drainage water in the Mole-fill and Back-fill treatments was less efficient than that observed in the laboratory simulations. It is likely that some drainage water travelled in an air gap above the tephra in the Mole-fill treatment. In the Back-fill treatment relatively short drainage/tephra contact times may have caused the reduced P removal efficiency.

The ability of the field study to demonstrate the effectiveness of the tephra treatments at removing P was hindered by limited treatment plot replication. The use of greater replication in a longer-term field study, which covers a range of climatic conditions, is recommended to help establish the full benefits of tephra filled drainage systems to mitigate P loss from intensive pastoral farms. Further research is also required to improve the process of filling mole channels with tephra and to determine the optimal mole channel size and spacing for this application.

7.5 Effect of cultivating long-term dairy pasture, summer forage cropping and autumn pasture renewal on nitrate leaching in the Manawatu Region (Chapter 6)

In the Manawatu region, it is common practice for dairy farmers to cultivate an area of long-term pastoral land each year for growing summer forage crops, which allows pasture to be renovated with new, more productive ryegrass and white clover cultivars. The use of summer forage cropping also provides a useful strategy for reducing excessive levels of K that can accumulate in soils receiving K-rich farm FDE. However, the cultivation of soil under long-term pasture also increases the risk of NO_3^- leaching, when this practice results in more NO_3^- accumulating in the soil immediately prior to a period of drainage.

A three-year field study was conducted to quantify the effects of long-term dairy pasture cultivation, summer forage cropping and autumn regrassing on drainage water N and P losses from a mole and pipe drained soil. The study consisted of two treatments; a continuation of long-term grazed pasture (called '*LP*' treatment), and long-term pasture that was cultivated in spring 2006, sown into turnips as a summer forage for dairy cows, followed by autumn regrassing in 2007 (called '*CP*' treatment).

The turnip summer forage crop was an effective method of accumulating relatively large quantities of standing feed, which was well utilised by grazing dairy cows. However, the cultivation of long-term pastures increased TN and TP losses in drainage water. The cumulative quantity of TN measured in drainage water between trial commencement (October 2006) and the end of the 2008 drainage season (November 2008) for *CP* treatment was 45.9 kg N/ha, which was 84% higher than the *LP* treatment losses of 24.9 kg N/ha. Approximately half of this increase in N losses from the *CP* treatment occurred during the first few months following spring cultivation, due to an atypically long drainage season in 2006. Normally the drainage season has typically finished near the time of spring cultivation, and therefore, any direct N leaching loss immediately following spring cultivation are likely to minor in most years.

Drainage water NO_3^- concentrations were also higher for the *CP* treatment, compared to the *LP* treatment, at the start of the subsequent drainage season (2007); following establishment of new grass on the *CP* treatment plots. The higher losses of N from the *CP* treatment did not continue into the third drainage season (2008). Although the *CP* treatment also increased TP losses in drainage water, in all three seasons studied, the quantities of TP in drainage were low for both treatments.

To put into perspective the increased N leaching losses, caused by growing a forage crop as part of a farm’s normal regrassing strategy, it is useful to considered these losses in context of a farm’s whole grass-crop regrassing cycle. On average, foraging cropping and pasture renovation on 10% of a farm’s area each year is estimated to increase farm annual N leaching losses by c. 5%, compared to a farm comprising all permanent pasture. Although this is a relatively small increase, cultivated areas are likely to be the parts of the farm with the highest N leaching losses; therefore, efforts to reduce farm N leaching should target these areas. Further research should focus on management practices that have potential to minimise excessive accumulation of soil NO_3^- between autumn sowing of new pastures and immediately prior to the start of the subsequent drainage season. Reducing soil NO_3^- accumulation in autumn also has the potential to reduce the risk of NO_3^- toxicity of livestock grazing new pastures.

7.6 Potential for management of the effluent block to influence whole-farm N and P losses in surface runoff and drainage

This thesis investigated three areas of practices and/or technologies (i. changes to the FDE system infrastructure, ii. introduction of P adsorbing material into the drainage system and iii. timing of summer forage cropping) with potential to influence N and P losses in surface runoff and drainage from mole and pipe drained dairy pasture soils irrigated with FDE. In this section these three areas are ranked for their potential to reduce whole farm N and P losses.

Inadequate FDE system infrastructure in the 2008 season was estimated to have caused 5,070 m^3 of FDE to be applied in excess of the SWD. This was estimated to have caused as much as 502 kg TN and 83 kg TN to be lost in surface runoff and drainage (Table 4.1). This would equate to an increase in total farm annual losses of 16.5 and 33% for TN and TP, respectively (Table 7.1). The two main system constraints were the farm's insufficient FDE storage capacity (2,000 m^3) and, relatedly, the inability of the farm's irrigator to apply small application depths (<8 mm). Changes in FDE system infrastructure on the case study farm were required to facilitate the implementation of *deficit irrigation* of FDE (i.e. the prevention of direct runoff and drainage). One such scenario for improvements would be the introduction of a low rate irrigation system and the expansion of the storage capacity to 4,000 m^3.

Papakai tephra was installed into mole and pipe drainage systems to remove P from drainage waters. The tephra reduced TP losses in drainage by about 50% (c. 0.14 kg P/ha; Table 5.2) over a drainage season, which equated to a 2.8 kg P reduction for a 20 hectare effluent block. This quantity of P loss accounts for only about 1.1% of total farm P loss in surface runoff and drainage (Table 7.1).

The practice of spring cultivating long-term dairy pasture, summer forage cropping and autumn regrassing increased the quantity of TN measured in drainage water over three drainage seasons (2006 to 2008) by 84% (21 kg N/ha; Table 6.1), compared to long-term pasture. If this study had commenced in spring with a more typical pattern of rainfall and drainage, this increase is estimated to have only been about 23.7% (5.9 kg N/ha) or a total of 112 kg N if an area of 20 ha is cropped each year. Based on these results, summer foraging cropping is estimated to increase whole-farm N losses in drainage by about 5%, when 10% of a farm's area is cultivated each year. This equates to a 3.7% increase when compared to whole-farm N losses in both surface runoff and drainage (Table 7.1).

Table 7.1 The comparison of management practices, assessed in this study, to influence whole-farm N and P losses in surface runoff and drainage.

	Total farm annual losses in surface runoff and/or drainage	
	Total N (kg)	**Total P (kg)**
Case study farm's estimated total annual surface runoff and drainage N & P losses (farm area of 194 ha):	3,046*	252*
(i) Potential increase in N & P losses caused by FDE system constraints (Table 4.1, Scenario 2; effluent block area of 20 ha):	+502 (16.5%)**	+83 (33%)
(ii) Measured reduction in drainage P losses from effluent block soils from tephra filled mole and pipe drainage systems (effluent block area of 20 ha):	-	-2.8 (1.1%)
(iii) Measured increase in N drainage water losses caused by summer forage cropping (forage crop area of 20 ha):	+112 (3.7%)	-

*Farm TN losses based on OVEERSEER® (15.7 kg N/ha; refer to Table 6.3) and TP losses based on Houlbrooke (2005) (1.3 kg P/ha).
**Values in parentheses are a percentage of farm total annual losses.

Of the management practices and technologies studied, the greatest opportunity, by far, to reduce the losses N and P to surface water from the case study farm's effluent block, is through investment in FDE system infrastructure, particularly adequate storage capacity, to allow the implementation of *deficit irrigation* of FDE.

7.7 Further research

This section describes areas of research relating to this thesis that would benefit from further study:

- The studies described in Chapters 3 and 4 demonstrated how decision support and fail-safe tools, and remote sensing technologies provide information and automation to assist with the design and management of *deficit irrigation* FDE land treatment systems. Further research is required to assess how these technologies can best be made available to famers. This may involve aspects of farmer participatory research to identify the forms of information delivery or interfaces that are most useful to famers.
- The research reported in Chapter 5 highlighted that further research is required to improve the process of filling mole channels with andesitic tephra subsoils and also determining the optimal mole channel size and spacing for this application. The evaluation of tephra installed in filter trenches for removing P from runoff water from farm critical source areas (e.g. races/underpasses, winter forage crops) also warrants researching.
- Chapter 6 quantified the effect of forage cropping on increased N leaching. Further research is required under a range of climatic conditions on the effect of nitrification inhibitors, applied during autumn cultivation, on reducing both nitrate ($NO_3^{-)}$ leaching and the risk of NO_3^- toxicity in autumn sown pasture.
- The use of cow housing and other forms of stand-off facilities are becoming increasing common in New Zealand. Drivers for this change include the need to improve winter management to protect pastures from pugging damage, increase feed and nutrient use efficiency, and reduced environmental impacts, namely N leaching and P run-off. The use of duration control grazing practices, which involves only keeping cows on pastures about eight hours (2 x 4-hours grazings) per day, throughout the entire year, has shown to significantly reduce N leaching by decreasing the quantity of N returned to pastures in urine spots (Christensen *et al.*, 2011). However, a consequence of this practice is a substantial increase in the proportion of nutrients recycled on dairy farms that need to be applied back to land as an effluent, rather than directly by cows in excreta. While this has the advantage of reducing the spatial variation in nutrient returns, it also raises the influence that FDE

management has on overall farm nutrient use efficiency and pasture production. Cow housing also influences the composition of effluents, with a greater proportion of captured excreta being collected as slurries and manures, which have high total solids and nutrient concentrations. Further research is required to determine the optimal timing, rates and forms of nutrients returned to pastures in these effluents to maximise pasture production and minimise nutrient losses. In particular, research should focus on how to maximise the strategic N value of applied effluents to optimise spring pasture growth, which is a time when plant availability soil N is a main growth limiting factors.

7.8 References

Christensen CL, Hedley MJ, Hanly JA, Horne DJ (2011). Nitrate leaching and pasture accumulation during two years of duration-controlled grazing in the Manawatu. In: *Adding to the knowledge base for the nutrient manager*. (Eds L.D. Currie and C L Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA (2004a). The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research* 47, 587-596.

Houlbrooke DJ, Horne DJ, Hedley MJ, Hanly JA, Scotter DR, Snow VO (2004b) Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research* 47, 405-415.

Monaghan RM, Smith LC (2004). Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research* 47, 417–428.

APPENDIX:
The farm dairy effluent storage calculator –
Identifying the storage volume required to practise deferred irrigation of FDE

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(Envirolink Medium Advice Grant 529-HZLC58)

June 2009

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A.1 Executive Summary

Deferred irrigation (DI) of farm dairy effluent (FDE) is widely recognised as best management practise in a number of situations including but not necessarily limited to;

- Mole and pipe drained soils,
- Soils with impeded drainage,
- Soils with a rising (or ground) water table,
- Very shallow, stony soils, and
- Sloping soils.

Adequate storage is the basis for sustainable and successful implementations and practise of DI. If a farm does not have sufficient storage, then no amount of good intention or technological innovation will allow successful practise of DI at all times.

To date, there is no accurate way for regional council personnel, farmers or their advisors to determine the storage that is required to practise DI. Typically, recommendations for FDE storage requirements are based on the duration (e.g. weeks) that storage is required and the amount of storage volume is calculated using industry averages (Dexel, 2007; Houlbrooke, 2008). However, it is important to appreciate that each farm will require a unique storage volume to practise DI. Recognising this, Massey University and Horizons Regional Council collaborated in the development of a ‘FDE Pond Storage Calculator’ that uses long-term daily climate data and individual farm details to provide recommendations customised for each farm to inform decision making around FDE storage requirements. Horizons commissioned this project (with funding from the FRST Envirolink fund) and Horizons and Massey University staff have worked together to produce the calculator.

The volume of storage required is essentially the difference between the rate that FDE is generated and the rate that it can be irrigated to land.

The quantity of FDE produced depends on:

- Water use in the farm dairy, principally water used to clean the milking plant and to wash the yard,

- The rainfall catchment area which includes; shed roves, yards, feed pads, the ponds themselves, and any other hard, impervious area that drains storm water to the FDE pond,
- Rainfall, and
- Diversion of storm water away from the ponds when catchment areas are not in use.

The rate that FDE can be irrigated to land depends on:

- The soil moisture deficit (as driven by rainfall and evaporation), and
- The type of irrigator

The ‘FDE Pond Storage Calculator’ has been developed to account for the impact of each of the aforementioned factors on the quantity of storage required on a dairy farm to successfully practise DI of FDE. The Calculator uses climate data to simulate the fluctuations in pond volume on a daily basis for the past thirty years. For each year, it identifies the maximum quantity of FDE in the pond and hence the maximum storage capacity required to practice DI that year: this value varies form year to year depending on the rainfall. As an output, the Calculator states the maximum storage required over the thirty year period. If the farm currently has ponds, this storage capacity is compared with the required value as predicted by the Calculator.

A.2 Introduction to the Calculator

Land application of FDE is now standard practice on most dairy farms in New Zealand. There are four main contexts where a storage facility for FDE is needed. Firstly, emergency storage will be required as a contingency for a major pump or irrigator breakdown. Secondly, storage is required on less permeable soils, or soils with a rising water table and/or sloping soils where there will be times of the year when the soil is wet and the risk that irrigated FDE will run off the soil surface. Thirdly, very shallow, stony soils may not provide sufficient treatment if FDE is irrigated when these soils are wet. Fourthly, FDE should not be irrigated to soils with mole-pipe drainage systems when soil moisture conditions are at or near field capacity if surface runoff and preferential flow of FDE through the soil is to be avoided. Preferential flow is flow directly through the very large pores of the soil. When FDE preferentially drains through a soil there is much less treatment occurring. Use of a storage pond at such times avoids runoff and rapid drainage of FDE into surface waters. The ‘FDE Pond Storage Calculator’ estimates the required size of such a storage pond.

The volume of storage required is essentially the difference between the rate that FDE is generated and the rate that it can be irrigated to land.

The quantity of FDE produced depends on:

- Water use in the farm dairy, principally water used to clean the milking plant and to wash the yard,
- The rainfall catchment area, which includes; shed roves, yards, feed pads, the ponds themselves, and any other impervious area that drains storm water to the FDE pond,
- Rainfall, and
- Diversion of storm water away from the ponds when catchment areas are not in use.

The rate that FDE can be irrigated to land depends on:

- The soil moisture deficit (as driven by rainfall and evaporation), and
- The type of irrigator.

A.3 The FDE Pond Storage Calculator

The Calculator has been developed to quantify the impact of the aforementioned factors on the storage required to successfully practise DI. The Calculator simulates the change in pond volume on a daily basis over a thirty-year period. The Calculator uses climate data to predict FDE generation and the scheduling of FDE irrigation via a soil water balance. The change in volume in the storage pond is given by the following relationship

$$VP_n = VP_{n-1} + FDE_{generated} - FDE_{irrigated}$$

Where - VP_n is the volume of FDE in the pond on day n (m^3),

- VP_{n-1} is the volume of FDE in the pond on day n-1 (m^3),
- $FDE_{generated}$ is the total volume of FDE generated each day (m^3), and
- $FDE_{irrigated}$ is the volume of FDE irrigated each day (m^3)

It is important to note that it is assumed that irrigation of FDE takes place on every suitable day, unless otherwise specified (the ‘extended’ storage option).

A.4 The generation of FDE

The FDE generated each day is given by:

$$FDE_{generated} = FDE_{wash} + FDE_{yard} + FDE_{shed} + FDE_{feedpad} + FDE_{pond}$$

Where – $FDE_{generated}$ is the total FDE produced each day (m^3),

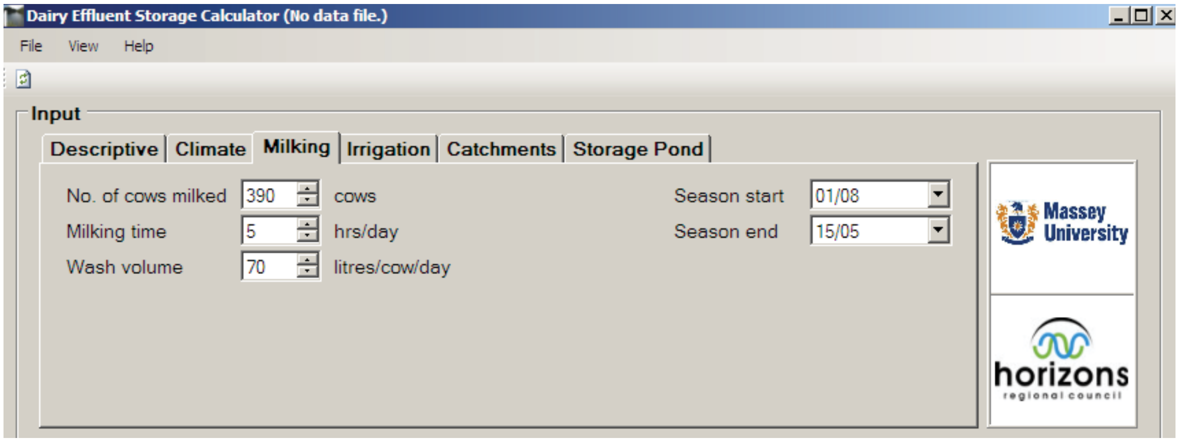
- FDE_{wash} is the volume of FDE produced when yards are washed after milking (m^3),
- FDE_{yard} is the volume of rainfall that runs off the yard to the pond each day (m^3),
- FDE_{shed} is the volume of rainfall from the shed roof that goes to the ponds each day (m^3),
- $FDE_{feedpad}$ is the volume of rainfall that runs off the feedpad to the ponds each day (m^3), and
- FDE_{pond} is the daily volume of rainfall minus the volume of evaporation from the ponds (m^3).

A.4.1 FDE_{wash}

Each day of the milking season, the quantity of water produced in the washing of the yards is calculated as follows:

$$FDE_{wash} = \text{number of cows x wash water used per cow per day}$$

The milking season is defined in the ‘Season start’ and ‘Season end’ tabs (Figure A.1). The user also specifies the volume of wash water used per cow in the farm dairy and as yard wash. The default setting is 70 litres/cow/day (this includes both daily milkings). This is the industry standard that is currently used by Horizons Regional Council.



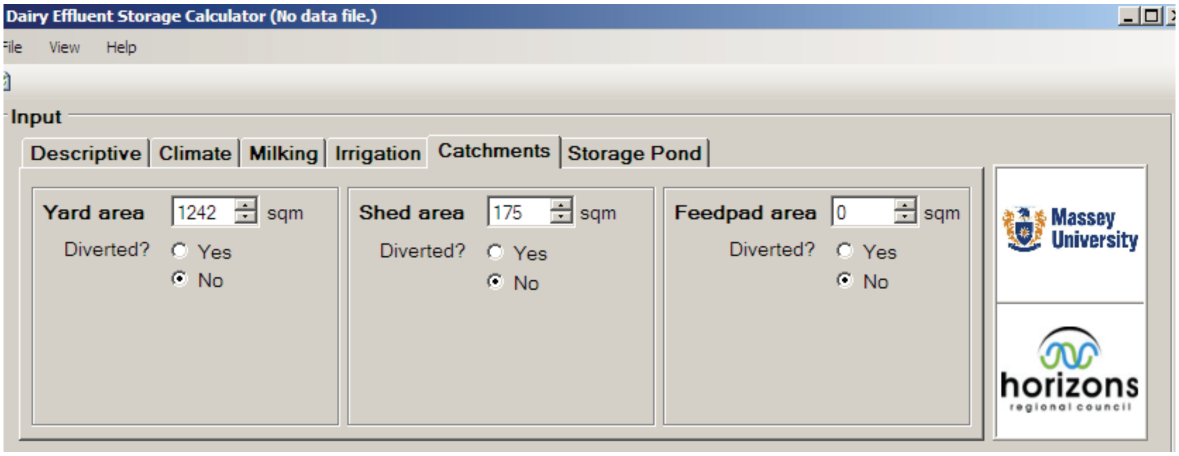
No. of cows milked 390 cows
Milking time 5 hrs/day
Wash volume 70 litres/cow/day
Season start 01/08
Season end 15/05

Figure A.1 Input data required for Calculator to predict the volume of FDE produced each day due to washing of yards. The ‘milking time’ is required to calculate the reduction on FDE generated from the yards where diversion is practised.

A.4.2 FDE_{yard}

$$FDE_{yard} = (\text{rainfall x yard area}) - (\text{hours of diversion}/24 \text{ x rainfall x yard area})$$

If there is no facility to divert storm water, the second term in the above expression disappears. If there is diversion capability then storm water can be diverted from the yards at all times except when milking is taking place (hence the tab to specify ‘milking duration (hours per day)’. In the non-milking season, diversion can be practised 24 hours a day and the above expression will then equal 0. If the farmer has the facility to divert runoff from the yards, yet is in the habit of standing cows in the yards for long periods to protect soil and pasture in wet conditions then consideration should be given to leaving the diversion tab set in the “no” setting.



Yard area 1242 sqm
Diverted? ○ Yes ● No

Shed area 175 sqm
Diverted? ○ Yes ● No

Feedpad area 0 sqm
Diverted? ○ Yes ● No

Figure A.2 The input information required to predict the FDE generated from rainfall catchment on hard surfaces.

A.4.3 FDE$_{shed}$

If the storm water from the shed roof goes to the ponds then:

$$FDE_{shed} = \text{area of roof x rainfall}$$

If storm water from the shed roof is diverted away from the ponds then it obviously does not contribute to FDE generation.

A.4.4 FDE$_{feedpad}$

If storm water from a feedpad enters the pond then:

$$FDE_{feedpad} = \text{area of feedpad x rainfall}$$

Some farmers use their feedpads for only part of the year. If they clean the pad after they have finished using it, they can divert the storm water away from the pond when the feedpad is not in use. This diversion feature for feedpads has been incorporated into the Calculator (Figure A.2).

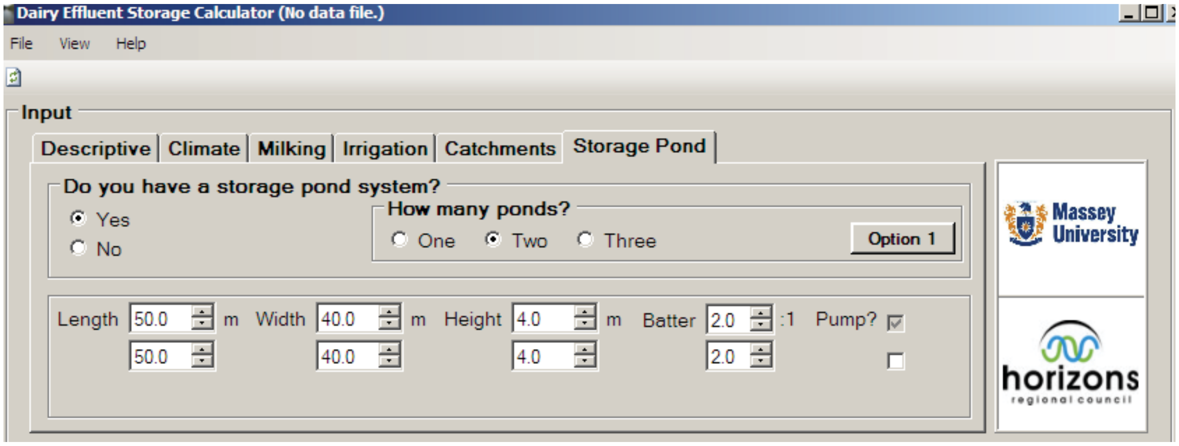
A.4.5 $\mathrm{FDE}_{\mathrm{ponds}}$

$$\mathrm{FDE}_{\mathrm{ponds}} = (\text{pond surface area x rainfall}) – (\text{pond surface area x evaporation})$$

Where the farm has ponds, their dimensions must be specified so that the total surface area of the ponds can be determined.

Where the farm does not have ponds, the surface area (SA) is given by;

$$\text{Pond SA} = \text{number of cows x } 5.1\ (\mathrm{m}^2/\text{cow})$$



Do you have a storage pond system?
● Yes
○ No

How many ponds?
○ One ● Two ○ Three

Length 50.0 m Width 40.0 m Height 4.0 m Batter 2.0 :1 Pump? ☑
50.0 40.0 4.0 2.0 ☐

Figure A.3 Input information required to determine the surface area and the storage volume of current ponds on the farm.

A.4.6 Emergency storage

The Calculator has an extra ‘seven days’ of storage built in for contingencies that would prevent the irrigation of FDE such as breakdown of equipment or staff illness. This emergency storage is calculated as follows

$$\mathrm{ES} = (7^*\mathrm{FDE}_{\mathrm{wash}}) + (\ 7/31 * \mathrm{AR} * \mathrm{CA})$$

Where ES = emergency storage (m^3)

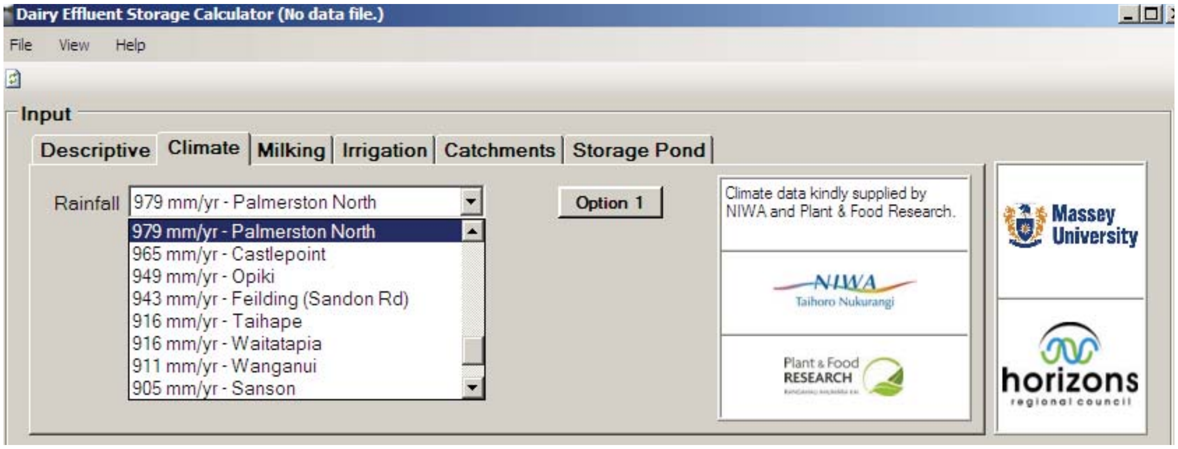
AR = August rainfall

CA = catchment area (yard, feedpad, ponds etc)

A.5 Irrigating FDE

The soil water balance (Scotter *et al.*, 1979) is run for each day for the 30 year period between 1975/1976 (the dairy season from June to June) to 2005/2006 (June to June). The Calculator has a library of daily rainfall data for 37 locations in and around the ‘Horizons’ region. The user selects the closest site for climate data from a ‘drop down’ menu (Figure A.4a). Site locations are displayed over a rainfall map (Figure A.4b).

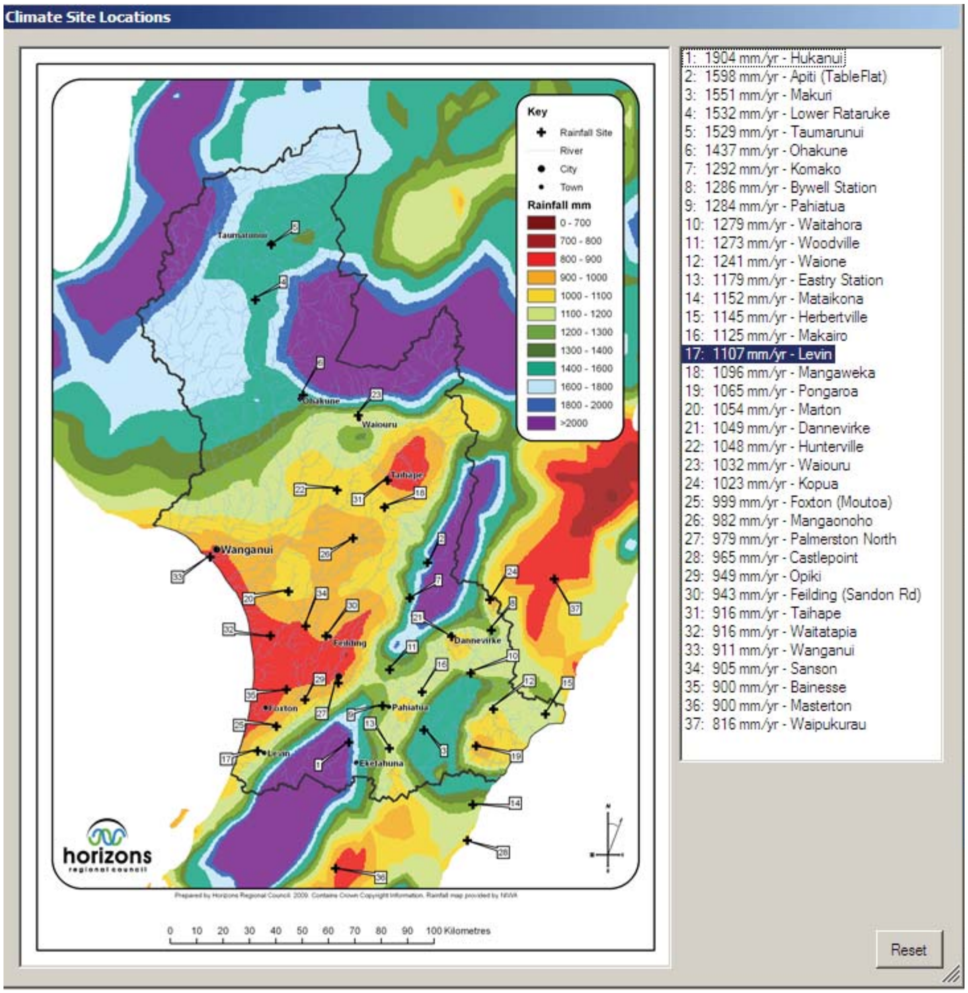
The value for ‘available water’ in the soil water balance is set at 50 mm. As the storage volume that the Calculator is seeking to identify is determined, amongst other things, by the soil moisture deficit pattern in spring (i.e. relatively small deficits), the output from the Calculator is not that sensitive to the value used for available water. Therefore there is little advantage to asking the user to input a unique value for available water, particularly when it is likely that this value will not be known.



Rainfall: 979 mm/yr - Palmerston North

Climate data kindly supplied by NIWA and Plant & Food Research.

Figure A.4a Selection of site for the 30 years of rainfall data for daily soil water balance.



1: 1904 mm/yr - Hukanui
2: 1598 mm/yr - Apiti (TableFlat)
3: 1551 mm/yr - Makuri
4: 1532 mm/yr - Lower Rataruke
5: 1529 mm/yr - Taumarunui
6: 1437 mm/yr - Ohakune
7: 1292 mm/yr - Komako
8: 1286 mm/yr - Bywell Station
9: 1284 mm/yr - Pahiatua
10: 1279 mm/yr - Waitahora
11: 1273 mm/yr - Woodville
12: 1241 mm/yr - Waione
13: 1179 mm/yr - Eastry Station
14: 1152 mm/yr - Mataikona
15: 1145 mm/yr - Herbertville
16: 1125 mm/yr - Makairo
17: 1107 mm/yr - Levin
18: 1096 mm/yr - Mangaweka
19: 1065 mm/yr - Pongaroa
20: 1054 mm/yr - Marton
21: 1049 mm/yr - Dannevirke
22: 1048 mm/yr - Hunterville
23: 1032 mm/yr - Waiouru
24: 1023 mm/yr - Kopua
25: 999 mm/yr - Foxton (Moutoa)
26: 982 mm/yr - Mangaonoho
27: 979 mm/yr - Palmerston North
28: 965 mm/yr - Castlepoint
29: 949 mm/yr - Opiki
30: 943 mm/yr - Feilding (Sandon Rd)
31: 916 mm/yr - Taihape
32: 916 mm/yr - Waitatapia
33: 911 mm/yr - Wanganui
34: 905 mm/yr - Sanson
35: 900 mm/yr - Bainesse
36: 900 mm/yr - Masterton
37: 816 mm/yr - Waipukurau

Figure A.4b Map in the Calculator showing the location of the 37 sites. The user selects one of these sites by clicking on it.

FDE is irrigated at a set depth on days when the soil moisture deficit is greater than a specified (i.e. trigger) value. There is scope to set two trigger deficit values and two irrigation depths. In spring, farmers are likely to irrigate smaller depths at lower trigger deficits: In summer when soils are drier they may irrigate larger depths.

If $D < T_1$ then $FDE_{irrigated} = 0$

If $T_2 > D \geq T_1$ then $FDE_{irrigated} = IV_1$

If $D \geq T_2$ then $FDE_{irrigated} = IV_2$

Where D = the soil moisture deficit,

T_1 = the smaller trigger deficit,

T_2 = the larger trigger deficit,

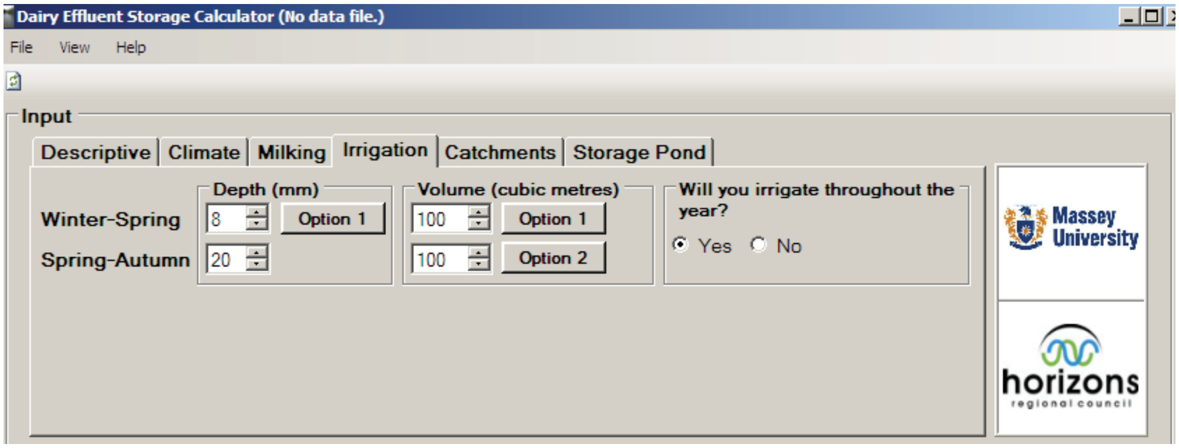
IV_1 = the smaller irrigation volume (associated with FDE irrigation when the soil moisture deficit is between T_1 and T_2, and

IV_2 = the larger irrigation volume (associated with FDE irrigation when the soil moisture deficit is equal to or greater than T_2)

A.5.1 T_1 and T_2

The irrigation trigger deficits (T_1 and T_2) will be selected according to a number of factors, not least of all, the type of irrigator used. Where a farmer with a travelling irrigator is endeavouring to reduce storage requirement, he will select the quickest travel speed (i.e. smallest application depth) for T_1 in the winter-spring seasons. As the soil profile dries in the latter part of spring and greater soil moisture deficits accrue, a larger depth of FDE can be applied. Therefore, once the soil has dried, farmers often set their irrigator to slower travel speeds and, therefore, greater application depths. Irrigating greater depths of FDE reduces the labour required to shift irrigators and helps empty the storage pond in summer and autumn period. The second trigger deficit T_2 in the Calculator is included to reflect this practise. The value of T_2 has little bearing on the size of the required storage volume predicted by the Calculator but its incorporation does allow the calculator to check that the ponds can be emptied between lactation seasons (Figure A.5).

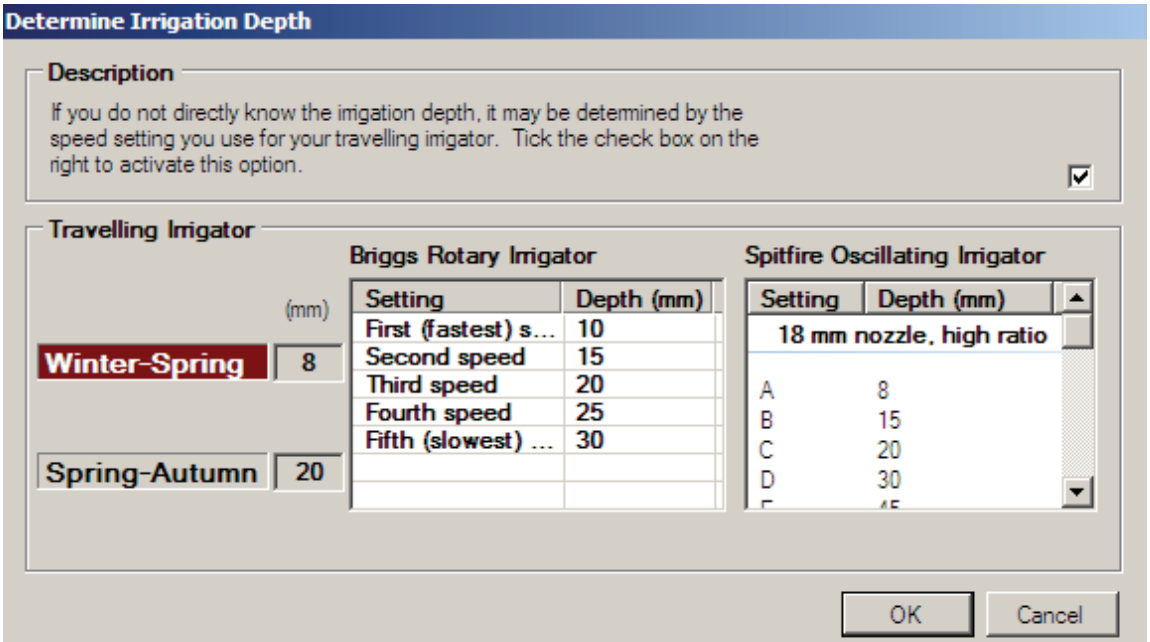
If the user does not know the application depths of the irrigator then a series of 'look up' tables for the range of travel speeds and application depths for the rotating boom (Briggs machine) and Spitfire travelling irrigators can be consulted (Figure A.6). The values used in the Calculator for the rotating boom irrigator are shown in Figure A.6.



	Depth (mm)		Volume (cubic metres)	
Winter-Spring	8	Option 1	100	Option 1
Spring-Autumn	20		100	Option 2

Will you irrigate throughout the year? ● Yes ○ No

Figure A.5 Input information related to irrigation of FDE, including the critical deficits at which irrigation(s) commence. The daily irrigation volumes are also entered here. If the critical deficits and irrigated volume are not unknown, the "help" tabs take the user to a series of look-up tables for assistance. The tab which activates the 'extended' storage option (i.e. no irrigation of FDE in the early part of the milking season) is also shown.



If you do not directly know the irrigation depth, it may be determined by the speed setting you use for your travelling irrigator. Tick the check box on the right to activate this option. ☑

	(mm)
Winter-Spring	8
Spring-Autumn	20

Briggs Rotary Irrigator

Setting	Depth (mm)
First (fastest) s...	10
Second speed	15
Third speed	20
Fourth speed	25
Fifth (slowest) ...	30

Spitfire Oscillating Irrigator

Setting	Depth (mm)
18 mm nozzle, high ratio	
A	8
B	15
C	20
D	30

Figure A.6 The look-up tables that help the user identify the critical deficits T_1 and T_2 for the small rotating boom and Spitfire travelling irrigators.

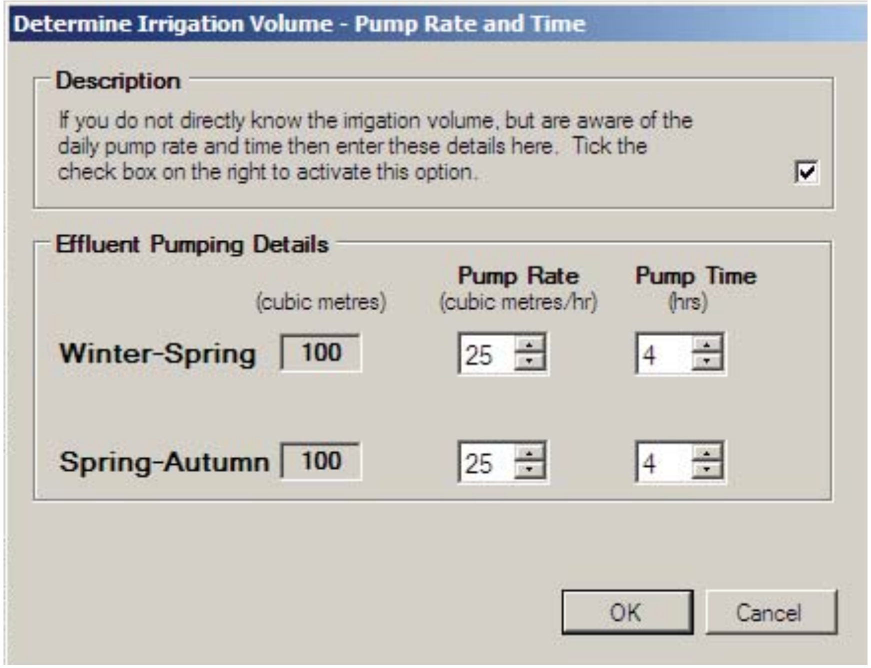
A.5.2 IV_1 and IV_2

IV_1 is the volume of FDE applied each day when the soil moisture deficit is between T_1 and T_2. IV_2 is the daily irrigated volume when the deficit is greater than T_2 (providing that there is sufficient FDE in the pond). If known, the daily irrigation volume is inputted (Figure A.5). Where the irrigation volume is not known, the user is presented with two options to calculate this value. If the pumping rate and time are known then these can be entered and the product of these two factors provides the volume of irrigated FDE (Figure A.7).

IV = pump rate * pump time

Alternatively, if the dimensions of the irrigated area (i.e. wetted width and length of irrigation run) and number of runs each day are entered then these may be multiplied together along with the application depth to give the volume of FDE applied (Figure A.8).

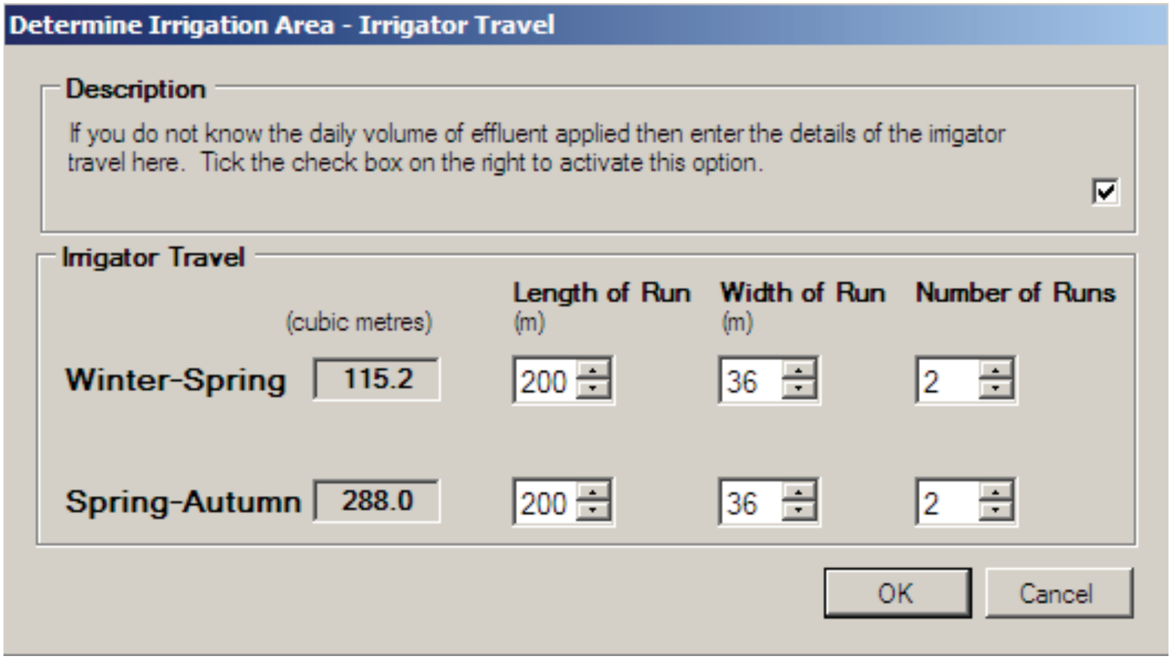
IV = wetted width * length or run * number of runs * application depth



If you do not directly know the irrigation volume, but are aware of the daily pump rate and time then enter these details here. Tick the check box on the right to activate this option. ☑

	(cubic metres)	Pump Rate (cubic metres/hr)	Pump Time (hrs)
Winter-Spring	100	25	4
Spring-Autumn	100	25	4

Figure A.7 Identifying the irrigated volume using the pump rate and pumping time.



If you do not know the daily volume of effluent applied then enter the details of the irrigator travel here. Tick the check box on the right to activate this option. ☑

	(cubic metres)	Length of Run (m)	Width of Run (m)	Number of Runs
Winter-Spring	115.2	200	36	2
Spring-Autumn	288.0	200	36	2

Figure A.8 Determining the volume of irrigated FDE using the dimensions of the irrigated area (i.e. the length of the run multiplied by the width of the wetted area) the number of runs and the irrigation depth (T_1 and T_2 from Figure A.5).

A.5.3 Current storage

In order to calculate the maximum storage volume required each year, the Calculator assumes that the storage ponds are very (‘infinitely’) deep. However, if the farm currently has ponds, the storage capacity of the pond system is calculated for comparison with the volume required to practise deferred irrigation of FDE.

If the farm currently has ponds then the dimensions of these ponds are entered including the slope of the battered pond sides (Figure A.3). The surface area of all the ponds is important as ponds both catch rainfall and loose FDE volume as evaporation.

Storage ponds are defined as those ponds which can be pumped to the irrigator. This is denoted in the Calculator by ‘ticking’ the ponds that can be pumped (Figure A.9). The storage volume of these ponds is calculated using the following relationship.

$$V = (h/6) * (2ab + ay + bx + 2xy)$$

Where - V = volume,
- a = length of top,
- b = width of top,
- x = length of base, and
- y = width of base and h = height.

Where ponds have a different shape (i.e. they are neither rectangular nor square), then their surface area and volume must be calculated manually and inserted into the Calculator.

Where a farm pumps from the second (aerobic) pond of a traditional two pond system and extra storage is required, then, where practicable, consideration should be given to shifting the pump and extracting FDE from the first pond at key times. This measure could negate the need for earth works to enlarge the second pond. This will be most advantageous where a travelling irrigator is employed to apply FDE.

A.5.4 Extended storage

There may be additional benefits to having 'extended' (i.e. greater) FDE, storage, so that irrigation of FDE is confined to summer and autumn and the application of FDE is not necessary in winter and spring. The advantages of 'extended' FDE storage are discussed by Hanly *et al.* (2009).

The potential use and value of the 'extended storage' option can be explored using the Calculator (Figure 5). For farms where there is little difference between 'adequate' and 'extended' storage requirements, the farmer may choose to spend a little more to gain 'extended' storage, which provides the benefit of knowing that irrigation doesn't need to start until a specific date each year, irrespective of how wet the winter and spring are.

A.6 The output screen

The results window shows a graph of the maximum storage volume required to practise DI of FDE for each year for the past 30 years. The maximum value for this period is also stated. If the farm currently has storage ponds then this volume is also depicted on the graph.

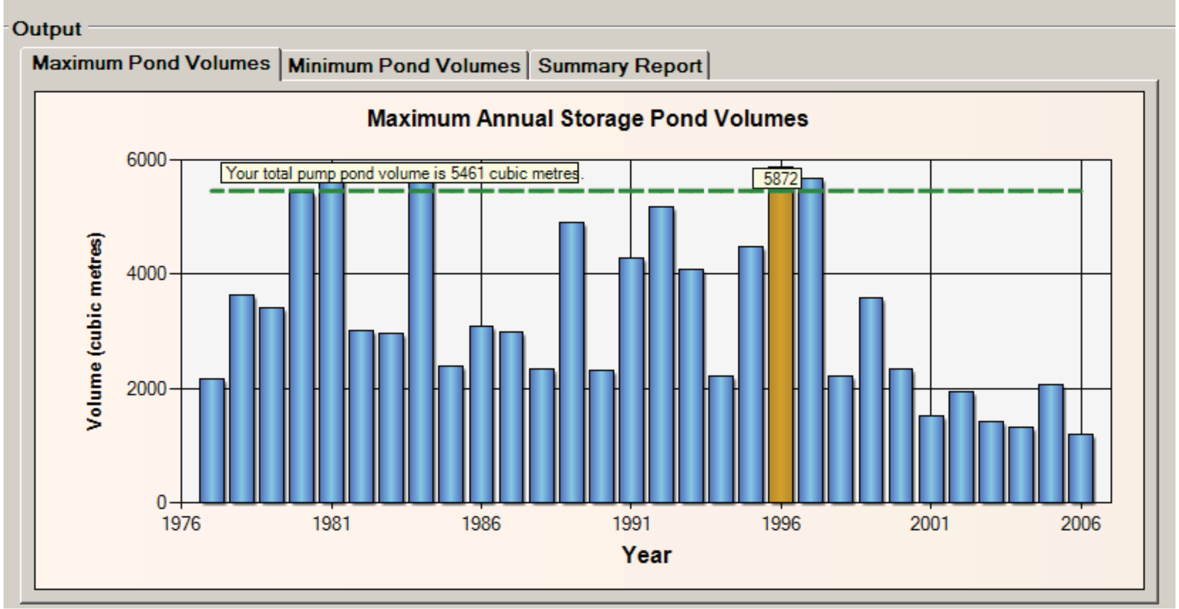


Figure A.9 The output window showing the maximum storage required for each of the milking seasons from 1976-77 to 2006-07 and the maximum storage for the period. If the farm has existing storage then it is also shown as a line for comparative purposes.

There is the facility to print a summary page which includes the most important input information and a copy of the graph showing maximum storage required for each of the past 30 years.

A.7 Some important provisos

The Calculator is only as good as the information that is put into it. For example, it is important to note that the storage volume that the Calculator estimates as being ‘adequate’ to practice DI, assumes that irrigations of a specified volume of FDE will take place on **every** day when there is sufficient soil moisture deficit. Failure to irrigate on every suitable day and/or apply the nominated volume of FDE (e.g. fewer shifts of the irrigator) in early lactation will result in a greater storage requirement than that predicted by the Calculator.

It is important to realise that the Calculator is a guide: it does not give a definitive storage volume. There may be other factors to consider when selecting the final dimensions of a storage pond. For example, the Calculator predicts the ‘raw’ storage volume required. No allowance is made for solids that might accumulate at the bottom of the storage pond (where there is only one pond). Neither has any buffer been included to ensure that the pond’s sides and bottom are not damaged during cleaning. In other words, the final volume of the storage pond may need to be larger than the volume given by the Calculator to facilitate cleaning etc.

A.8 Future work on the Calculator

The Calculator could be improved by including a number of features in future versions.

a) Winter milking

Currently, the Calculator can cope with only one milking season (i.e. one herd). However, some farms have two herds; one herd calving in spring and the other in autumn. The Calculator needs to be modified so that milking cow numbers can be entered on a monthly basis.

b) Mean annual irrigation depth to FDE block and the quantity of nutrients added

In addition to giving the storage volume required to practise DI, the mean average irrigation depth of FDE applied to the effluent block will also be provided in future versions of the Calculator. If the total annual quantity of nutrients applied to the FDE block are estimated using OVERSEER® Nutrient Budgets model, the Calculator will be able use these values to estimate the average nutrient concentrations of FDE and therefore the amounts of nutrients applied at each irrigation.

c) Include a ‘Smart farm’ option

Where the soil deficit is monitored on a daily basis, as for the ‘Smart Farm’ (Hanly et al., 2009), there may be scope to change the application depth (speed setting) of a travelling irrigator on a routine basis to ensure a better match between the soil moisture deficit and the depth, and therefore volume, of irrigated FDE (rather than the simple two tiers or settings i.e. T_1, T_2, IV_1 and IV_2 employed above). An increased number of application depths and volumes could be incorporated into the Calculator easily. As the size of required storage volume is most sensitive to T_1 and IV_1, additional application depths and volumes, in all likelihood, will make only a small difference to the required storage. This point notwithstanding, this feature should enhance the fit or connection between the Calculator and the rest of the ‘Smart Farm’ package.

d) Cost/benefit analysis

In future versions of the Calculator, it will be possible to include some simple financial analysis of costs and benefits associated with changes to the FDE system on a farm. For example, a commonly asked question is; will the cost of extra storage be recouped in labour savings and extra pasture growth?

A.9 References

Dexel (2007). *A guide to managing farm dairy effluent (Manawatu/Wanganui)*. http://www.dairynz.co.nz/. 40 pages.

Hanly JA, Horne DJ, Roygard JFK (2009). Smart farming: using technology to support best management practise of farm dairy effluent. Report prepared for Horizons Regional Council (October 2009). 47 pages.

Houlbrooke DJ (2008). *Best practice management of Farm Dairy Effluent in the Manawatu-Wanganui region*. Report prepared for Horizons Regional Council (February 2008). 44 pages.

Scotter DR, Clothier BE and Turner MA (1979). The soil water balance in a Fragiaqualf and its effect on pasture growth in central New Zealand. *Australian Journal of Soil Research*, 17, 455–465.