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**The Effect of Irrigation Practice on Drainage and Solute Leaching**  
**Under Spray Irrigation on a**  
**Stony Soil**

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A Dissertation  
submitted in partial fulfilment  
of the requirements for the Degree of  
Bachelor of Science with Honours

at  
Lincoln University  
by  
Balin Burns Robertson

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Lincoln University

2016

Abstract of a Dissertation submitted in partial fulfilment of the requirements for the Degree of Bachelor of Science with Honours.

The Effect of Irrigation Practice on Drainage and Solute Leaching  
Under Spray Irrigation on a

Stony Soil

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Research was conducted to assist in the improvement of irrigation efficiency on the shallow stony soils of Canterbury and identify the effect of current irrigation practice on the redistribution of solute within the soil profile. Irrigation treatments were measured using twenty-four undisturbed monolith lysimeters containing a stony Eyre shallow silt loam soil. Treatments included 15/10, 15/15, 30/20, 30/30, 60/40 and 60/60, being the respective soil deficit irrigation trigger/irrigation depth combinations (mm). The trial was split into three experiments. Experiment 1 began with a surface application of bromide tracer before exposing the lysimeters to the irrigation treatments for three months. Experiment 2 and 3 were designed to examine how the bromide had been redistributed within the pores during Experiment 1. Experiment 2 irrigated 250 mm depth continuously at 50 mm/hr to drain bromide in the macropores, while Experiment 3 irrigated 500 mm depth continuously at 2 mm/hr to drain bromide in the soil matrix. Over the three experiments, leachate was collected regularly and analysed for bromide.

Preferential flow dominated solute leaching, occurring in the first drainage event irrespective of the application volume and frequency of irrigation, with leached bromide moving predominately through the macropore fraction of the soil. Treatments with greater irrigation quantities corresponded with more extensive preferential flow, drainage and for the most part, leaching in Experiment 1. Treatments irrigated to field capacity (FC) had greater leaching and drainage as well, as uniform irrigation of lysimeters in a treatment meant soil heterogeneity caused some lysimeters to exceed FC before others.

Generally, there were no significant treatment effects on the cumulative bromide leached across the experiments, reflecting the dominance of preferential flow under the irrigation conditions studied. There was evidence that bromide distribution in the profile at the end of Experiment 1 was affected by treatments, with moisture status after irrigation having an effect on the bromide peak mass

readings in Experiment 2, while the moisture deficit irrigation trigger influenced the bromide peak mass and cumulative mass readings in Experiment 3. However, effects were not consistent across treatments and experiments, making interpretations difficult.

The results indicate that irrigation practices on Eyre shallow silt loam soils at 50 mm/hr needs to be adjusted for preferential flow, which has a dominant influence on solute distribution within the soil profile. Results imply that the 15/10 treatment had the least leaching as less extensive preferential flow means solute remains within the profile and has a greater opportunity to be immobilised.

**Keywords:** Preferential flow, stony soil, solute leaching, solute distribution, bromide, spray irrigation.

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# Table of Contents

<b>Abstract .....</b>	<b>ii</b>
<b>Acknowledgements .....</b>	<b>iv</b>
<b>Table of Contents .....</b>	<b>v</b>
<b>List of Tables .....</b>	<b>vii</b>
<b>List of Figures .....</b>	<b>viii</b>
<b>Chapter 1 Introduction .....</b>	<b>1</b>
1.1 Aim and objectives of the study .....	2
<b>Chapter 2 Literature Review.....</b>	<b>3</b>
2.1 Quantifying drainage and solute transport behaviour .....	3
2.2 Modes of water flow and solute transport through soil .....	4
2.2.1 Diffusion .....	4
2.2.2 Matrix flow .....	4
2.2.3 Preferential flow .....	6
2.3 Importance of preferential flow to sustainable land management .....	8
2.3.1 Studies of preferential flow in New Zealand soils.....	8
2.4 Effect of irrigation practices on solute transport.....	9
2.4.1 Introduction .....	9
2.4.2 Initial soil water content .....	10
2.4.3 Influence of Irrigation rate and volume .....	10
2.4.4 Irrigation timing .....	11
2.5 Research gaps and the importance of the current study .....	12
<b>Chapter 3 Materials and Methods.....</b>	<b>14</b>
3.1 Soil description.....	14
3.2 Lysimeter installation.....	14
3.3 Lysimeter trials.....	16
3.3.1 Pre-wetting and establishment of antecedent moisture conditions.....	16
3.3.2 Bromide application .....	16
3.3.3 Irrigation season, Experiment 1 .....	17
3.3.4 50 mm/hr drainage period, Experiment 2 .....	18
3.3.5 2 mm/hr drainage period, Experiment 3 .....	18
3.4 Lysimeter measurements .....	18
3.4.1 Leachate collection and analysis.....	18
3.4.2 Pasture collection and analysis .....	19
3.5 Statistical analysis .....	19
<b>Chapter 4 Results.....</b>	<b>20</b>
4.1 Soil properties.....	20
4.2 Treatment application and wetting and drying cycles, Experiment 1 .....	21
4.3 Uniformity of drainage events .....	25
4.3.1 Experiment 2 .....	25
4.3.2 Experiment 3 .....	25

4.4	Bromide concentration .....	26
4.4.1	Experiment 1-3 overview .....	26
4.4.2	Experiment 1 peak concentrations .....	30
4.4.3	Experiment 2 peak concentrations .....	30
4.4.4	Experiment 3 peak concentrations .....	30
4.5	Bromide mass flux.....	31
4.5.1	Experiment 1-3 overview .....	31
4.5.2	Experiment 1 .....	35
4.5.3	Experiment 2 .....	35
4.5.4	Experiment 3 .....	36
4.6	Pasture analysis.....	38
4.6.1	Cumulative pasture yield .....	38
4.6.2	Cumulative pasture mass bromide .....	39
4.7	Bromide mass balance .....	40
<b>Chapter 5 Discussion.....</b>		<b>41</b>
5.1	Drainage.....	41
5.1.1	Effect of moisture status following irrigation .....	41
5.1.2	Effect of application volume .....	41
5.1.3	Effect on real world applications .....	42
5.2	Trends in leached bromide .....	43
5.2.1	Experiment 1 and 2, preferential flow .....	43
5.2.2	Bromide distribution in the soil matrix .....	45
5.2.3	Treatment effect on bromide flux .....	46
5.2.4	Soil heterogeneity .....	48
5.3	Plant yield and uptake .....	49
5.4	Bromide recovery.....	50
<b>Chapter 6 Conclusions .....</b>		<b>51</b>
6.1	Limitations and suggestions for further research.....	52
<b>References .....</b>		<b>54</b>
<b>Appendix A Eyre shallow silt loam soil profile.....</b>		<b>68</b>
<b>Appendix B Treatment blocking structure .....</b>		<b>69</b>
<b>Appendix C Field estimates of Eyre shallow silt loam profile. Sampled 13/6/13. Described by Sam Carrick. ....</b>		<b>70</b>
<b>Appendix D Modelled water content and conductivity relationships at different soil depths. ....</b>		<b>71</b>

## List of Tables

Table 1 Irrigation treatments and associated moisture status. ....	17
Table 2 Average hydraulic soil properties. Values in brackets were the calculated standard deviation. Soil properties to the depth of 40 cm were measured from 10x7.5 cm soil cores using pressure plate and tension table apparatus (Carrick, 2009). Soil properties below 40 cm were measured in the field using the volume replacement method (Hedley et al., 2012).....	21
Table 3 Experiment 1 irrigation applied and drainage for the different treatments. Drainage values represent the average of the lysimeter reps within a treatment, whilst values in brackets represent the treatment range, and application efficiency is the proportion of irrigation that wasn't lost as drainage (average of the lysimeter reps). ....	22
Table 4 Treatment average bromide recovery. ....	40
Table 5 Characteristics of pores estimated to be responsible for 90% of drainage. ....	45

## List of Figures

Figure 1 Schematic concepts contributing to mechanical dispersion; a) pore wall frictional drag, b) pore size effect on mean solute velocity, c) pore tortuosity, d) solute convergence/divergence (Leij & Van Genuchten, 2001).....	5
Figure 2 Descriptive diagram of the dispersal of a band of solute during convective transport through a soil (Carey, 1993). .....	6
Figure 3 Lysimeter TDR distribution.....	15
Figure 4 Experiment 1, wetting and drying cycles for deficit-irrigated treatments. Top graph: 15/10 treatment; middle graph: 30/20 treatment; bottom graph: 60/40 treatment.....	23
Figure 5 Experiment 1 wetting and drying cycles for the field capacity-irrigated treatments. Top graph: 15/15; middle graph: 30/30; bottom graph (60/60).....	24
Figure 6 Experiment 2 cumulative drainage. Number labels refer to the lysimeter where drainage results were collected from.....	25
Figure 7 Experiment 3 cumulative drainage. Number labels refer to the lysimeter where drainage results were collected from.....	26
Figure 8 Bromide concentration breakthrough for deficit-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). C is the concentration of bromide in the soil leachate. $C_0$ is the concentration of the bromide solution that was initially applied to soil. Treatments shown are 15/10 (Top graphs); 30/20 (middle graphs); 60/40 (bottom graphs). .....	28
Figure 9 Bromide concentration breakthrough for field capacity-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). C is the concentration of bromide in the soil leachate. $C_0$ is the concentration of the bromide solution that was initially applied to soil. Treatments shown are 15/15 (Top graphs); 30/30 (middle graphs); 60/60 (bottom graphs). .....	29
Figure 10 Treatment average peak concentrations for Experiment 3. C is the concentration of bromide in the soil leachate. $C_0$ is the concentration of the bromide solution that was initially applied to soil. Vertical bars represent standard error of the mean. ....	31
Figure 11 Bromide mass breakthrough for deficit-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). Treatments shown are 15/10 (Top graphs); 30/20 (middle graphs); 60/40 (bottom graphs).....	33
Figure 12 Bromide mass breakthrough for field capacity-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). Treatments shown are 15/15 (Top graphs); 30/30 (middle graphs); 60/60 (bottom graphs).....	34
Figure 13 Treatment average peak mass readings for Experiment 2. Vertical bars represent standard error of the mean. ....	36
Figure 14 Treatment average cumulative mass bromide for standardised drainage in Experiment 3. Vertical bars represent standard error of the mean. ....	37
Figure 15 Treatment average peak mass readings for Experiment 3. Vertical bars represent standard error of the mean. ....	38
Figure 16 Treatment average, cumulative dry matter yield for three pasture cuts (20/4/16; 15/6/16 and 12/7/16). Vertical bars represent standard error of the mean.....	39
Figure 17 Treatment average, cumulative bromide uptake for three pasture cuts (20/4/16; 15/6/16 and 12/7/16). Vertical bars represent standard error of the mean.....	39

# Chapter 1

## Introduction

The area of irrigated land in New Zealand is rapidly increasing, being strongly linked to intensive land use, in particular dairy farming. It is well established that irrigation can have significant benefits to agriculture, increasing plant yield and allowing previously unproductive land to be of economic benefit. However, current environmental research has shown these practices can have detrimental effects, by promoting solute transport and the leaching of nutrients like nitrate (Di & Cameron, 2002b; Heckrath et al., 1995). In light of this issue, it is necessary to understand how irrigation affects solute leaching and hence how specific management practices may enhance or mitigate leaching losses.

In recent years, the risk of enhanced solute transport in the Canterbury region has increased over significant areas, considering the region represents approximately 60% of New Zealand's irrigated land area, with recent land conversions to dairy (and irrigation) situated predominately on stony soils (Cichota et al., 2016). Such soils are characterised by low water holding capacity, and considered vulnerable to nutrient leaching losses and preferential flow (Carrick et al., 2013). Current literature has predicted that the adoption of irrigation on these soils will induce nutrient leaching, especially under poor irrigation practice and high application rates (Carrick et al., 2014; Di & Cameron, 2002a). However, the actual dynamics of solutes within these soils under different irrigation regimes is poorly understood or quantified, especially the effects of soil antecedent conditions, irrigation rate and irrigation frequency (Cichota et al., 2016; Lilburne et al., 2010).

Quantification of these processes has become of increasing importance in New Zealand, especially with the implementation of the National Policy Statement for Freshwater Management (NPS-FM) in 2011. Growing public demands for sustainability, and a necessity to maintain the country's 'clean green' image, made it necessary to develop enforceable limits of water quality and quantity. Under the NPS-FM, regional councils are required to develop regional plans that detail rules on land and water use as directed by national bottom lines and compulsory water values (Ministry for the Environment, 2014). In Canterbury, this is seen in the form of the Land and Water Regional Plan (LRWP), which specifies maximum annual amounts of nutrients (such as nitrate) that can be lost from a system (Environment Canterbury, 2015). In light of this, it is necessary to determine best management strategies for irrigation that can be used to minimise leaching, so farms don't exceed nutrient caps. However, current research on solute dynamics under irrigation has not caught up to policy or sustainable management requirements, with a deficit in knowledge of how solute is distributed through the profile under current irrigation practices.

## 1.1 Aim and objectives of the study

The main aim of the project is as follows:

- To assist in the improvement of irrigation efficiency on the shallow stony soils of Canterbury and identify the effect of current irrigation practice on the redistribution of solute within the soil profile.

To achieve this goal, the main objectives of the study were as follows:

- To quantify different drainage and solute losses under varying irrigation return intervals.
- To quantify different drainage and solute losses that occur when soils are irrigated to field capacity or a determined moisture deficit.
- To quantify the redistribution of solute in the soil profile with variation in irrigation practice.

The hypotheses of the project were as follows:

- Irrigation to refill a greater soil moisture deficit will increase the rate of drainage and solute leaching.
- Drainage and solute leaching will be less when a soil is not irrigated back up to field capacity.

## Chapter 2

### Literature Review

#### 2.1 Quantifying drainage and solute transport behaviour

Quantification of soil drainage and solute leaching is a notoriously difficult task. Undisturbed soil can cause issues due to the inherent soil heterogeneity, while factors such as measurement scale and labour restraints cause some methods to become unsuitable. Of the many methods that have been developed, lysimeters have been found to be highly versatile and accurate for free draining soils. Capable of using both repacked and undisturbed soil, lysimeters can be engineered to specific measurement requirements or be used to reproduce soil field conditions. Lysimeters also have a significant advantage to field studies, whereby it is possible to collect lysimeters from different locations and transport them back to a research facility, where it is possible to better control variables such as rainfall or irrigation.

As with any method, lysimeters have their restrictions. Repacked lysimeters have been criticised for the alteration of water flow paths and the formation of artificial soil systems (Cassel et al., 1974). This has caused significant over estimation of drainage and nitrogen flux, with a study by Pakrou and Dillon (2000) over estimating drainage in an irrigated paddock by 78%. The use of undisturbed monolith lysimeters allows a more natural quantification of solute and water flux. However, issues have been raised with collection techniques as a result of soil compaction due to friction between the soil and the walls of the lysimeter (Klocke et al., 1993). Developments in lysimeter extraction, with a focus on supporting soil pedestals has meant monolith lysimeters can be collected without alteration of physical properties (Bowman et al., 1994). While the application of liquefied petrolatum can fill the gap between the monolith and lysimeter casing, preventing preferential edge flow (Cameron et al., 1992). However, considering a limited volume of soil is removed from the field, it must be determined whether the volume measured is representative of the variability of the studied soil or parameter.

Multiple studies have demonstrated that significant soil heterogeneity can exist within small areas of land (Hbirkou, 2011; Hillel, 1998), with even small variations in soil properties resulting in significant differences in the leaching characteristics of a soil (Lilburne & Webb, 2002). As a result, soil physics research studies need to take into account the potential effect of the representative elementary volume (REV), which is the smallest volume required to represent the variation in element forms and proportions within a given system (Bear, 1972). The size of the REV varies spatially and depends on the quantity being represented, where a 10 cm sample may encompass all the variation that is important for a homogenous soil, however the REV may also exceed 10 m when involving macropores (Al-Raoush

& Papadopoulos, 2010; Richard & Steenhuis, 1988). Li et al. (2009), found for a cracked clay soil, an REV of width 0.29 m could be used for determining water movement. While Lauren et al. (1988) estimated an REV with a representative area of 0.5 m<sup>2</sup> is necessary. These studies demonstrate that a lysimeter with conventional dimensions (50 cm width by 70 cm depth, and 0.2 m<sup>2</sup> area) may have issues in capturing the REV for leaching studies through soils that have significant macropore flow. As a result, this may be a source of variation in the leaching behaviour between replicate lysimeters in a trial, and needs to be considered when interpreting trial results.

## **2.2 Modes of water flow and solute transport through soil**

When soil moisture content exceeds field capacity (FC) (-5 to -20 kPa suction, depending on soil physical properties), the soil is unable to store water, causing water to drain through the profile. Solutes in the soil solution (such as bromide and nitrate) can be mobile, and are therefore leached when drainage occurs (Malcolm, 2013). Due to this, the movement of water significantly affects how solutes are transported through the soil. When there is negligible water movement, diffusion is the governing mechanism of solute transport. As water movement becomes more significant, solutes move in relation to convective and hydrodynamic dispersion (matrix flow) or preferential flow.

### **2.2.1 Diffusion**

Diffusion is the dominant spreading mechanism under low flow rates or for short travel distances (Flury & Gimmi, 2002). Its importance in solute investigations is generally negligible, as project conditions are commonly saturated or continuous unsaturated flow. However, in investigations involving intermittent water application such as irrigation, with periods of no drainage and soil drying by evapotranspiration and low water flux, diffusion can have a significant effect on solute movement (Gerke & Kohne, 2004).

The underlying method of transport occurs as a result of Brownian motion, where repeated deflections and collisions of molecules in fluid cause solutes to equalise in terms of spatial distribution (Hillel, 2003). Therefore, solutes move in response to a concentration gradient and can be described by Fick's Law:

$$J_d = -D_s \frac{dc}{dx} \quad (1)$$

where  $J_d$  is the rate of diffusion,  $D_s$  is the diffusion coefficient of the solute in soil as determined by soil moisture content and  $dc/dx$  is the solute concentration gradient (McLaren & Cameron, 1996).

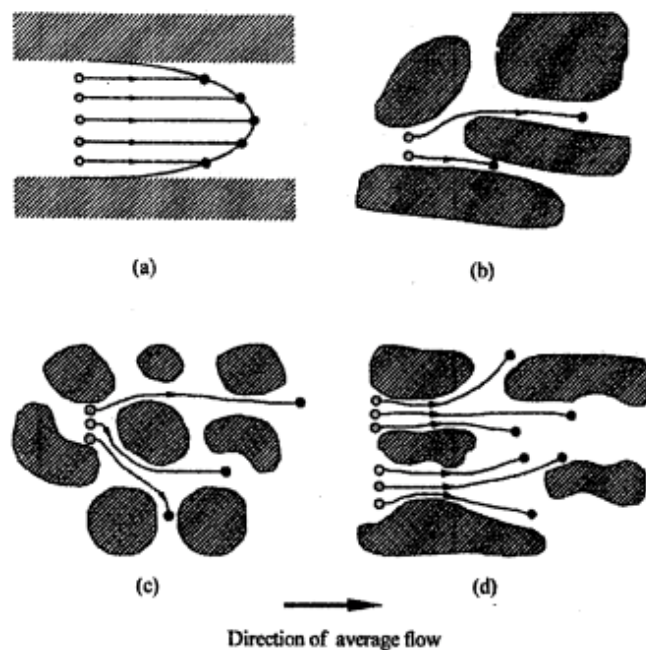
### **2.2.2 Matrix flow**

As water flux increases, the mechanisms of convection and hydrodynamic dispersion dominate solute transport. Convective transport, sometimes called Darcian flow, describes the flux of solutes that

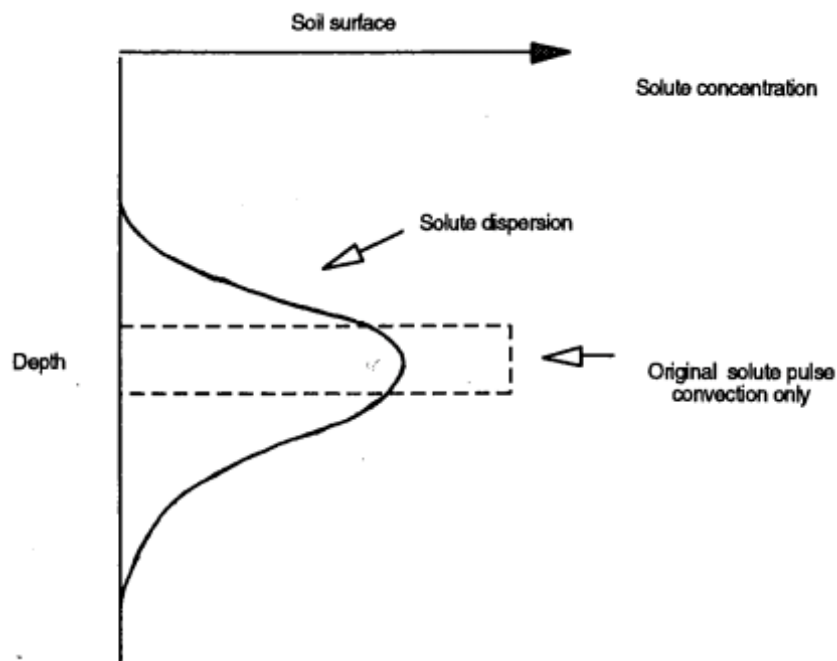
occurs with a mass flow of water through soil (Hillel, 2003). Darcy's Law, with an additional solute concentration function  $c$ , describes this transport (Hillel, 2003):

$$J_c = qc = -c(k \frac{dH}{dx}) \quad (2)$$

where  $J_c$  is the convective solute flux,  $c$  is the solute concentration,  $q$  is water flux,  $K$  is the hydraulic conductivity and  $dH/dx$  is the hydraulic gradient (McLaren & Cameron, 1996). By this mechanism alone, a band of solute would move as a single wetting front, as dictated by the average pore velocity (McLaren & Cameron, 1996). However, due to soil heterogeneity, solute breakthrough undergoes mechanical mixing known as hydrodynamic dispersion. This mixing is a function of the varying pore sizes, lengths and tortuosity found within a soil (Figure 1). Some solute moves rapidly through large pores, while other solute moves slower through smaller pores (Dennis, 2009). Even within a pore, solute is prone to a velocity gradient due to frictional drag between the pore wall and moving soil water (Carey, 1993). Pore pathways may also be tortuous, with some pathways being longer than others to cover the same distance down the soil (Dennis, 2009). As a result, some solute tends to drain faster and/or slower than other solute, causing solute breakthrough to become dispersed, even with a uniform wetting front (Figure 2).



**Figure 1** Schematic concepts contributing to mechanical dispersion; a) pore wall frictional drag, b) pore size effect on mean solute velocity, c) pore tortuosity, d) solute convergence/divergence (Leij & Van Genuchten, 2001).



**Figure 2 Descriptive diagram of the dispersal of a band of solute during convective transport through a soil (Carey, 1993).**

### **2.2.3 Preferential flow**

Preferential flow is defined as “all phenomena where water and solutes move along certain pathways, while bypassing other volume fractions of the porous soil matrix” (Gerke, 2006). These phenomena result in a spatially irregular wetting of the soil profile, as water moves faster and with higher quantity at certain locations of the soil (Šimůnek et al., 2003). These flows commonly develop into “finger”-like flow patterns, representing the channels of concentrated water flow through the soil (Rezanezhad et al., 2006). Quantification of this phenomenon is difficult as it is affected by many factors and can exist in multiple forms. In general, preferential flow is classified into three differing categories: macropore flow, unstable flow and funnel flow (Gerke, 2006).

#### **Macropore flow**

Macropore flow is described as rapid non-equilibrium channel flow through structural pores in the soil (Šimůnek et al., 2003). The definition of macropore flow is flexible, with flow paths varying from individual pores of different size to highly connected pore networks (Gerke, 2006). The significance of preferential flow to solute leaching can vary depending on macropore continuity, tortuosity and density (Jarvis, 2007). Macropores with the greatest leaching potential are generally surface connected and have a low tortuosity in the case of sorbed solutes (Allaire et al., 2002). These pores become active in response to a prevailing pressure potential gradient (Jarvis, 2007). When the application of water exceeds the rate with which the finer pore fraction of the soil can conduct, water moves into larger pores as the water entry potential of macropores is exceeded (Hendrickx & Flury, 2001). A wide range of soil formations have been included under the term macropore, and include biotic pores formed by

plant roots or earthworms, cracks produced by shrinkage of clay soils, chemical weathering of bedrock material, freeze-thaw cycles and soil cultivation (Beven & Germann, 1982). The presence of rock fragments has also been shown to influence macropore flow, causing an increase in the mean radius of macropores (Shi et al., 2012), producing voids along soil-stone interfaces in shrinking-swelling soils (Sauer & Logsdon, 2002) and influencing the direction of root growth (Schwärzel et al., 2012).

### **Unstable flow**

Unstable flow generally occurs in the matrix of coarse textured soils as a result of instabilities in the waterfront (Larsson et al., 1999). Instabilities develop from perturbations in the wetting front caused when the matric potential behind the front opposes the flow (Wang et al., 2003). The mechanism for water front perturbation can vary between soils and includes air pressure build-up ahead of the wetting front (Hill & Parlange, 1972), water repellency (Wang et al., 2000) and at fine-over-coarse textural layers (Dobrovolskaya et al., 2014). As a result of water front perturbation, wetting fronts are refined to small areas of infiltration. Redistribution of water creates a matric potential reversal, causing flow to move preferentially through these infiltrating areas to form 'fingers' of rapid water flow (Wang et al., 2003).

### **Funnel flow**

Funnel flow refers to situations where parts of the soil behave like the wall of a funnel, deflecting unsaturated flow into spatially concentrated columns of rapid water movement (Nimmo, 2005). The concentration of water corresponds with an increase in hydraulic conductivity and is commonly associated with contrasting soil layers or lenses (Kung, 1990b). In a lab study, Kung (1993) found that funnel flow would occur along an inclined boundary when there is a macroscopic Haines jump (a high-speed pore scale event (Armstrong et al., 2015)) across the boundary and water application rates were smaller than a certain critical rate.

The effect of these phenomena on solute transport can vary. Many studies observe preferential flow causing rapid movement of solute through the soil profile leading to enhanced solute leaching (Blackwell, 2000; Reichenberger et al., 2002; Tyner et al., 2007). Alternatively, a few studies have observed solute leaching had reduced as a result of preferential flow (Cote et al., 2000; Dennis, 2009; Larsson & Jarvis, 1999). From these studies, solute placement appears to govern whether preferential leaching or preferential bypass occurs (Dennis, 2009). If the solute is located near macropores it will be prone to leaching, while solute found in the less permeable region of the soil matrix is protected (Cote et al., 2000).

## **2.3 Importance of preferential flow to sustainable land management**

The importance of preferential flow has increased over time as old perceptions of soil homogeneity and solute transport by matrix flow has changed. Reliance on lab studies developed a perception of a strong interaction of drainage with the soil matrix, and hence many solutes were thought to have negligible leaching due to soil sorption (Flury, 1996). However, increasingly studies have found preferential flow can significantly affect solute losses and land management (Anyusheva et al., 2016). Everts and Kanwar (1990) observed preferential flow transported as much as 24% of the bromide and 20% of the nitrate that leached into a subsurface drain, while contributing to only 2% of the total drainage. Shipitalo et al. (1990) found similar results, with a small fraction of the soil accounting for 70% of the total leaching from a 60 mm water application.

Even pesticides, thought to be strongly sorbed to the soil and of low leaching susceptibility have been lost from systems in significant quantities due to preferential flow (Flury, 1996). Wettstein et al. (2016) found rapid breakthrough of thiamethoxam, and three other highly sorbed pesticides even though the first drainage event didn't occur until 15 days after application. While Flury et al. (1995) found that three pesticides with varying sorption strengths moved to the same maximum depth due to preferential flow. Although preferential flow may only equate to small annual pesticide loss rates, which can range from 0.1% to several percent (Flury, 1996; Wettstein et al., 2016), even small proportions of leached pesticide can have significant effects on ecosystem or human health (Klaus et al., 2014).

It can be gathered from the literature that when preferential flow is present, it can account for substantial leaching losses from a soil. The frequency with which it occurs is in some debate however, due to the highly variable nature of the phenomena. Graham and Lin (2011) found in 175 rainfall events, preferential flow occurred at 17 to 54% of the events at each of the 10 sites monitored in the study. However, when viewed holistically, preferential flow occurred in at least one site during 90% of the rainfall events (Graham & Lin, 2011). Wiekenkamp et al. (2016) had similar results in a catchment scale study, with preferential flow occurring in 7 to 51% of the measured rainfall events. It was found that preferential flow could be highly uniform during large storm events (>25 mm), but was otherwise governed by small scale soil and biological features (Wiekenkamp et al., 2016). This indicates the difficulty in developing management practices to reduce forms of preferential flow, as the phenomena are variable over space and time, with the parameters governing preferential flow still understudied.

### **2.3.1 Studies of preferential flow in New Zealand soils**

In New Zealand, studies have been aimed at identifying soils susceptible to preferential flow. A few soils have demonstrated low susceptibility to preferential flow including Allophanic soils and Pumice

soils (Aislabie et al., 2001; Pang et al., 2008). This was generally attributed to the soils having a fine uniform soil structure that kept the soils well-drained and minimised preferential flow (Aislabie et al., 2001). However, even these soils could demonstrate preferential flow under the right conditions with multiple studies demonstrating the development of funnel flow in volcanic soils as a result of hydrophobicity (Barkle et al., 2014; Muller et al., 2010). Well-drained silt loam soils, such as Waikiwi and Templeton silt loams demonstrated higher susceptibility to preferential flow, however soils that were poorly drained or stony are found to be the most susceptible (McLeod et al., 2003; McLeod et al., 1998; Pang et al., 2008). Poorly drained soils such as Gley soils are generally associated with cracking and a soil matrix of low hydraulic conductivity, causing water and solute to move preferentially down macropores (Li et al., 2009). For stony soils, susceptibility to preferential flow is commonly attributed to a low water holding capacity and a moderate to rapid permeability (Carrick et al., 2014). However, solute dynamics in these soils is understudied. Most research is confined to constant saturated or unsaturated conditions (Cichota et al., 2016; Pang et al., 2008), which indicate strong preferential flow, however may be biased due to unnatural wetting conditions. Transient condition studies have more variable results. Carrick et al. (2014) observed preferential flow in a Selwyn stony soil in a periodic irrigation experiment even though the trial followed best management practices in terms of irrigation rate (35-40 mm/hr) and application volume (12-18 mm). In contrast, Close et al. (2010) on a Lismore stony soil, found low faecal coliform leaching under a travel irrigator which applied 55 mm of irrigation. However, when irrigation application increased to 80 mm, leaching became more apparent (Close et al., 2010). Thus, stony soils may be susceptible under some conditions, but can have negligible preferential flow in others. This demonstrates an important area of research to be studied, as no papers can be found that have done systematic trials on stony soils, to see how solute transport is affected by different irrigation practices and antecedent soil moisture conditions. As a result, the effectiveness of current irrigation practices can only be assumed, with little research to be found for an informed judgement.

## **2.4 Effect of irrigation practices on solute transport**

### **2.4.1 Introduction**

Irrigation is now an intrinsic part of agriculture in New Zealand and generally signifies an increase in productivity and land-use intensification. The method of application can vary but is progressively becoming dominated by spray systems in the form of centre pivots (Statistics New Zealand, 2012). Older methods of flood irrigation are being replaced over time by centre pivots due to the need for greater water-use efficiency and nutrient management (Cichota et al., 2016). Centre-pivot systems are considered to have a greater control over the water that is applied, allowing a wider range of irrigation management strategies in terms of rate, volume and timing. The effect this may have on drainage and

solute leaching from a soil is still uncertain however, as patterns in water movement can vary significantly with differing soils, boundary conditions and plant cover.

#### **2.4.2 Initial soil water content**

The initial saturation of the soil prior to irrigation can significantly influence the hydrological properties of the soil. At high initial water saturation, pulses of solute tend to bypass a greater proportion of the smaller pores, which when filled with water have low conductivity (Hamlen & Kachanoski, 2004). As a result, water and solute tend to flow preferentially down macropores with high conductivity (Lewan et al., 2009; Schaetzl & Thompson, 2015; Vereecken, 2005). Quisenberry and Phillips (1976) observed this, with 20% of a 42 mm water application penetrating below the 90 cm depth immediately after application, even though initial soil moisture was below FC.

Alternatively, dry soil conditions can cause preferential flow due to the presence of hydrophobicity and soil cracking (Barkle et al., 2014; Bronswijk, 1991; Ritsema et al., 1998). Ritsema et al. (1998) identified the formation of a non-uniform wetting front in a dry soil due to lateral transport of water. This occurred under extreme conditions, as the dry soil was water repellent, resulting in wetting fronts infiltrating deeper in areas of the soil with higher antecedent water content. It has also been found that drier soils may enhance preferential flow by reducing the lateral losses from preferential flow paths (Jarvis, 2007). Multiple studies have demonstrated initially dry soils as having more rapid and significant preferential flow to soils of higher water content (Babel et al., 1995; Merdun et al., 2008; Shipitalo & Edwards, 1996). However, the requirement of dry soils (c. 11% water content; [Merdun et al., 2008; Shipitalo & Edwards, 1996]) may mean preferential flow maybe less likely to arise from this phenomena in irrigated pasture. However, Kung et al. (2006) had variable results, as application of bromide to dry soil caused leaching to reduce. It was speculated that the dry surface conditions would result in many small pores near the soil surface with negative matric potentials. This would cause bromide to infiltrate into the small pore fraction, causing bromide to be less susceptible to macropore flow (Kung et al., 2006).

#### **2.4.3 Influence of Irrigation rate and volume**

The quantity and intensity of irrigation can strongly affect water and solute transport. High irrigation volumes generally correspond with a greater leaching depth; however, results vary pending on irrigation rate (Yang, 2014). If the rate is lower than the maximum infiltration rate of the soil matrix, water flow occurs predominately by uniform matrix flow (Schaetzl & Thompson, 2015). As a result, draining water only reaches a depth relative to the volume of infiltrating water. When irrigation rate exceeds the infiltration capacity of the soil matrix, water tends to flow through macropores forming preferential flow, causing drainage to reach a greater depth than the volume of irrigation would imply

(Dennis, 2009). On a stony Lismore soil, Cichota et al. (2016) was able to observe this relationship, with preferential solute transport seen to be greater at 20 mm/hr compared to 5 mm/hr. Gray et al. (2016) found a similar effect in a transient moisture study on an Eyre shallow silt loam, with increased cumulative drainage when irrigation rate increased from 12 to 50 mm/hr irrigation. However, the rate effect on phosphorus leaching was marginal, and indicates that irrigation rate may not be a dominant influence on leaching in the studied stony soil (Gray et al., 2016).

If irrigation is of a great enough volume, preferential flow can also be induced as infiltration rates decline with the filling up of soil pores, causing water to preferentially move down macropores (Kohne & Gerke, 2005; Kung et al., 2006; Schaetzl & Thompson, 2015). Kohne and Gerke (2005) observed this, with a rate of only 7 mm/hr causing preferential flow in a tile drained field soil. Non-uniform wetting fronts can also be developed as a result of water ponding and micro topography. Cook (1983) observed high rate irrigation could facilitate the preferential infiltration of water at micro-topographical depressions on the soil surface. Clothier and Heiler (1983) had similar results, however rate did not appear to be a major influence, with a significantly higher fraction of water infiltrating at the low points in the micro-relief at rates as low as 4.1 mm/hr.

#### **2.4.4 Irrigation timing**

Irrigation timing has complicated effects on drainage and solute movement. Firstly it affects the initial water content of the soil prior to irrigation, influencing properties such as infiltration and matric potential. Frequent irrigation is likely to result in a soil with a relatively high water content, while the longer the between irrigation period, the greater the opportunity for hydrophobicity and soil cracking to occur (the effect of which is described in section 2.4.2 Initial soil water content).

Secondly, it affects the dynamics of solute and water. Under saturated flow, the hydraulic head or gravitational potential is the primary driver of the downward flow of water (Nimmo, 2005). Alternatively, in unsaturated conditions, water movement is driven by differences in water potential (Nimmo, 2005). This causes water to move in variable directions, which can be lateral, downward, or even upward in response to evaporation (Schaetzl & Thompson, 2015). The effect of this is a redistribution of solute in the soil profile, which can have variable effects on solute leaching. Some studies have seen a significant increase in solute leaching as a result of transient soil moisture conditions (Lewan et al., 2009; Meyer-Windel et al., 1999). Cote et al. (1999); (2000) found that flow interruptions and the development of transient conditions caused bromide leaching to increase by 10-20% compared to continuous flow leaching. Alternatively, other studies have found transient conditions to have a retarding effect on solute leaching (Gerke & Kohne, 2004; Sambale et al., 2000).

Effects seem to depend on the severity of the transient conditions. At short intervals, interruption in flow allows solute to diffuse from less permeable regions of the soil matrix to the boundary of preferential flow paths. As a result, solute is prone to leaching with a continuation in water flow. This can lead to the enhanced leaching found by Cote et al. (2000), however, if preferential flow does not occur (matrix flow instead), a reduction in leaching occurs (Meyer-Windel et al., 1999).

Under more severe transient conditions, the process of drying causes the redistribution of bromide from larger pores to smaller pores. Sambale et al. (2000) observed bromide under very dry conditions, moving from macropores into the finer pore fraction. In these smaller pores, pore water velocity was low, thus reducing the amount of leaching. However, over multiple wetting events, bromide remobilised and was again susceptible to leaching (Sambale et al., 2000).

The limitation with current literature is that studies have focused on the extremities of antecedent conditions. As such, the 'antecedent conditions' that have been researched are either developed over the soil draining from saturated flow to FC (Cote et al., 2000), or over months without water (Sambale et al., 2000). As a result, the redistribution of solute that would occur under conventional irrigation practice is still relatively unknown.

## **2.5 Research gaps and the importance of the current study**

It was detailed in the Introduction that there is a practical demand for transient irrigation studies to determine practices with the lowest leaching risk, as required by new legislation on water management. In Canterbury, studies on stony soils are of significant interest, as they dominate the irrigated land area in the region and are still relatively understudied in terms of solute and drainage dynamics. From the literature, preferential flow appears to be a major contributor to the mobility of solute within a soil, with the proportion of the active pore volume in this phenomenon being small relative to the quantity of leaching it can cause. However, it has been shown that preferential flow can be initiated by a number of mechanisms and have varying effects on leaching depending on a number of conditions such as soil type, initial soil moisture content, application volume, application rate and strength of antecedent conditions. Limitations in research surrounding the effect of these factors in relation to the transient moisture conditions expected under 'real' irrigation practice, means there is a deficit in knowledge to back up best management practices for reducing leaching from irrigation.

This dissertation aims to assist in the improvement of irrigation efficiency on shallow stony soils by researching the following knowledge gaps:

- There is little experimental research on how solute is redistributed within the soil as a result of transient conditions caused by irrigation. This could have significant implications to the susceptibility of solute to leach over time, determining what pore fraction the solute is found

in and hence its susceptibility to different forms of water movement. Two drainage events are used in this study to explore the effect of different irrigation practices on the locality of solute in the soil profile.

- Stony soils have been classed as susceptible to preferential flow and solute leaching. However, the conditions that govern the initiation or extent of this phenomenon in these soils are not well understood. Using different irrigation practices, this study explores how preferential flow maybe influenced by variation in application volume, antecedent conditions and the moisture status the soil is irrigated to.

# Chapter 3

## Materials and Methods

### 3.1 Soil description

Solute leaching measurements were made on 24 undisturbed soil monolith lysimeters. Lysimeters (50 cm diameter by 65 cm depth) were collected during a previous 2013 project from an irrigated sheep grazed pasture at the AgResearch Research Farm, Canterbury (43.62 °S, 172.47 °E). The soil was a free-draining Eyre shallow silt loam (Orthic Recent soil [Hewitt, 2010]) with four distinct layers, including a stoneless topsoil and B-horizon overlying two very stony horizons, one with a silt loam matrix and the other a sand matrix (Appendix A). Soil physical properties are described in Table 2 (Section 4.1 Soil properties), based on soil samples collected in undisturbed soil adjacent to the lysimeter collection pit. For the stone free layers (0 – 40 cm depth) undisturbed soil cores (10 cm diameter x 7.5 cm depth) were hand carved from each depth increment to measure soil bulk density, porosity, water release and hydraulic conductivity at the Landcare Research soil physics lab. In the stony horizons it is not possible to collect soil cores, so a volume replacement method (Hedley et al., 2012) was used to calculate stone content, bulk density and porosity. Water holding porosity and unsaturated conductivity were not measured on the gravelly horizons.

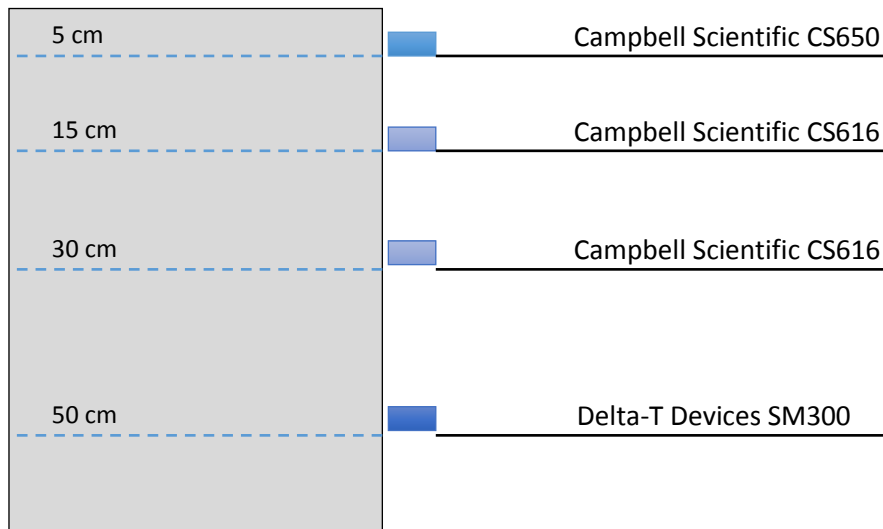
Based on this measured data, an average pore volume (PV) was estimated at approximately 249 mm for the soil volume within the lysimeters. Total porosity averaged 50% in the top 40 cm (fine earth fraction) while stone content reached 71% at the base of the lysimeters, reducing the porosity of the gravel layers down to 18-25%.

### 3.2 Lysimeter installation

Collection of lysimeters followed the procedure given in Cameron et al. (1992). This involved working a metal cylinder casing (50 cm diameter by 70 cm depth) into the soil while carefully digging around the casing to minimise disturbance of soil structure, and leaving an undisturbed soil monolith with an actual soil column length of 65 cm within the casing. To prevent preferential edge flow down the casing wall, lysimeters were sealed using petroleum jelly. The lysimeters are then separated from the underlying gravels using a hydraulic ram to insert a cutting plate at the bottom of the lysimeter. Following this, the cutting plate is replaced with a drainage base that collects lysimeter drainage through a centre drainage hole.

Plastic tubing connected to the base of each lysimeter directed any drainage or solute to a tipping spoon set above a drainage collection vessel. Each lysimeter included four soil moisture sensors (

Figure 3), which were used to determine the soil water deficit for each lysimeter, and consequently the timing of irrigation. A CR1000 Campbell Scientific data logger recorded soil moisture sensors and tipping spoon drainage data at 10-minute intervals.



**Figure 3 Lysimeter TDR distribution.**

Herbage on the lysimeters was a mixed sward dominated by rye grass, and was allowed to grow to enhance soil moisture loss through evapotranspiration. Herbage growth rate was maintained by applying 250 kg/ha of superphosphate and 100 kg/ha urea prior to the start of the experiment (22/12/15), and 50 kg N/ha as calcium ammonium nitrate fertiliser on the 15<sup>th</sup> April 2016, to ensure herbage growth was not nutrient limited during the experiment. Lysimeters were located at the Plant and Food Research lysimeters facility at Lincoln, which included a rain out shelter (Plate 1). The rain out shelter was a cover that automatically moved over the lysimeters during rain, but otherwise left lysimeters exposed to climatic conditions.



**Plate 1 Plant and Food Research lysimeter facility.**

### **3.3 Lysimeter trials**

Lysimeters were irrigated by an automated sprinkler system that was driven by a CR 3000 Campbell Scientific data logger. Irrigation was applied by Fulljet FL-5VC spray nozzles mounted directly over top of each of the lysimeters. Each nozzle was individually controlled by a solenoid, which pulsed irrigation to a determined rate and depth. To account for nozzle heterogeneity, each nozzle was individually calibrated, with a single pulse applying 0.23-0.29 mm depending on the nozzle. The individual irrigation pulse duration was the same for all nozzles, at 2 seconds length, but to achieve the different application rates the interval between pulses was varied.

#### **3.3.1 Pre-wetting and establishment of antecedent moisture conditions**

To negate the effect of previous moisture content artefacts developed during the preceding spring and summer, lysimeters were fully wetted by 120 mm of irrigation on the 19<sup>th</sup> February and left to drain. To establish antecedent moisture conditions, lysimeters were exposed to their individual treatments (refer to section 3.3.3 Irrigation season, Experiment 1), for a month before the experiment began. The number of irrigations ranged from zero for the high moisture deficit treatments to four for the lowest moisture deficit treatments.

#### **3.3.2 Bromide application**

Solute transport was measured using a bromide tracer (KBr), which was applied at a rate equivalent to 100 kg Br/ha (1.963 g Br per lysimeter) on the 18<sup>th</sup> of March. The date of application coincided with a day where all treatments had reached their moisture deficit irrigation trigger (refer to section 3.3.3 Irrigation season, Experiment 1). KBr was applied as a dissolved solution (equivalent to 2.5 mm) using a hand-held spray bottle at a rate equivalent to 50 mm/hr. To do this, lysimeters were exposed to pulsed bromide application over 9 minutes. Tracer application was followed immediately by an application of irrigation at a volume determined by the lysimeters set treatment (refer to section 3.3.3 Irrigation season, Experiment 1), but deducting the 2.5 mm of irrigation that was applied in the tracer application. The process was repeated for all twenty-four lysimeters used in the trial. To improve uniformity, tracer was applied under the rain out shelter to minimise spray drift (Plate 2).



**Plate 2 Bromide tracer application.**

### **3.3.3 Irrigation season, Experiment 1**

The experiment was set as a complete randomised block design. This design was made up of six treatments, involving three different soil deficits to trigger irrigation and six different irrigation volumes that equated to two moisture statuses following irrigation (Table 1). Lysimeters were irrigated at a rate of 50 mm/hr, which is a common rate applied by centre pivot irrigators, as well as roto-rainer and gun type irrigators (Powers, 2012).

Each treatment was replicated four times to give a total of twenty-four lysimeters. Considering potential legacy effects (as lysimeters had been used in a previous experiment), two blocks were dedicated to the lysimeters that received urine in the previous experiment, the remaining two blocks being dedicated to the lysimeters that did not receive urine. Blocking structure can be seen in Appendix B.

**Table 1 Irrigation treatments and associated moisture status.**

Treatment	Soil deficit irrigation trigger	Depth irrigated	Moisture status following irrigation
15/10	15 mm	10 mm	5 mm deficit
15/15	15 mm	15 mm	Field capacity
30/20	30 mm	20 mm	10 mm deficit
30/30	30 mm	30 mm	Field capacity
60/40	60 mm	40 mm	20 mm deficit
60/60	60 mm	60 mm	Field capacity

The treatment plan was first initiated on the 18<sup>th</sup> March and continued until the 16<sup>th</sup> June 2016. Irrigation timing was controlled by treatment soil moisture averages, so that all lysimeters within a

treatment were assumed to have negligible differences in moisture content and thus irrigated at the same time. This assumption was deemed acceptable, as it represents common irrigation practice, where irrigation is triggered based on the average moisture content of a field or farm. The moisture content averages were based on the readings from sixteen soil moisture sensors, which represent the four sensors found in each of the four lysimeters within any single treatment. For each depth, the average soil moisture content was calculated, and these were then summed over the depth of the lysimeter.

### **3.3.4 50 mm/hr drainage period, Experiment 2**

On the 16th of June, all lysimeters were subject to 250 mm of continuous irrigation (equivalent to approximately one PV). Irrigation was applied at the same rate as during the irrigation season (50 mm/hr) to leach out bromide residing in the macropores. Considering discrepancies in moisture content between lysimeters of varying treatments, all lysimeters were irrigated to FC the day before (15 June) to improve the uniformity of drainage sampling. The infiltration rate of lysimeter twenty-one was found to be half the rate of the irrigation (50 mm/hr) and the other lysimeters. As a result, this lysimeter had to be leached for twice as long to allow comparable drainage samples.

### **3.3.5 2 mm/hr drainage period, Experiment 3**

Following completion of Experiment 2, the lysimeters were allowed to drain for *c.* 24 hours, upon which drainage had largely ceased. All lysimeters were then subject to a further 500 mm of continuous irrigation (equivalent to approximately two PV). Irrigation was applied at a rate of 2 mm/hr to leach out bromide located within the soil matrix. The irrigation period extended from the 17<sup>th</sup> to the 29<sup>th</sup> of June.

## **3.4 Lysimeter measurements**

### **3.4.1 Leachate collection and analysis**

Drainage water from lysimeters was quantified using tipping spoon data and regular drainage sampling. Sampling involved measuring the volume of drainage water and taking a 50 mL sample for chemical analysis.

For Experiment 1, drainage weights were taken at daily intervals following an irrigation event and continued until drainage had stopped. Sub samples for chemical analysis were taken whenever the drainage exceeded 50 mL.

The target for Experiments 2 and 3, was to sample leachate at intervals of 25mm. Experiment 2 required drainage weights and sub samples to be taken every thirty minutes over the five-hour

irrigation period, as a result of the continual high intensity (50 mm/hr) irrigation. Experiment 3, had drainage weights and sub samples taken every twelve hours (7:30 am and 7:30 pm).

Considering the number of samples collected across treatments and experiments, only a selection were analysed for bromide using ion chromatography. From Experiment 1, samples were taken at times that represented significant drainage for a treatment.

Experiment 2 had 11 samplings over the whole drainage event. Initially, approximately 5 mm of drainage was analysed (samples 1-5); thereafter, drainage was analysed at c. 50 mm intervals (sample 7, 9 and 11) to determine the shape of the solute breakthrough curve.

Experiment 3 had 24 samplings. Samples were analysed at c. 25 mm drainage intervals (for samples 1-3), then at c. 100 mm drainage intervals (samples 5, 9, 13, 17, 21) and finally sample 24. As with Experiment 2, this frequency allowed the shape determination of the solute breakthrough curve.

### **3.4.2 Pasture collection and analysis**

Over the course of the investigation, pasture was cut three times as required to prevent significant disruption to irrigation uniformity on lysimeters. Cuts were made using electric hand shears, and herbage on all lysimeters was harvested to a standard height of approximately 5 cm (1500 kg DM/ha residual). Herbage dry weights were measured before removing a subsample for each lysimeter that incorporated all three pasture cuts. Subsamples were ground and exposed to a water-methanol extraction before analysis by ion chromatography for bromide.

### **3.5 Statistical analysis**

All data sets were statistically analysed to test for significant treatment effects by conducting an analysis of variance (ANOVA) using Genstat 13.

Lysimeter 19 (60/60) was not included in the results, as for unknown reasons, herbage died off, and drainage patterns were peculiar compared to all other lysimeters.

## Chapter 4

### Results

#### 4.1 Soil properties

Soil properties are displayed in Table 2. Total porosity and available water capacity were greatest in the top 7.5 cm of the soil profile and generally reduced with depth. A significant decrease in hydraulic conductivity is also apparent with greater soil depth, with an observed 10-fold reduction between the 0-7.5 cm and the 30-40 cm depths under 0.1 and 0.4 kPa suction. Conductivity decreases as suction increases, which corresponds to the change in active water transmitting pores. Estimates on the maximum pore size full of water indicate that at 0.1 kPa, water is moving through pores of 3 mm diameter, decreasing to 0.7 mm under a suction of 0.4 kPa, and down to 0.3 mm under 1 kPa suction.

Using the measurements of total porosity for each depth increment, an estimate of 249 mm was calculated as the average pore volume (PV) for the 50 cm diameter by 65 cm deep lysimeter soil columns.

Variability in soil parameters was generally quite low for the examined samples, however, hydraulic conductivity, especially under low suction, had quite high variability. The standard deviation for the  $K^{0.1}$  estimates were almost half the average for the top three sample depths. Variability was observed in the  $K^{0.4}$  and  $K^{0.1}$  as well, especially for the top two sample depths.

**Table 2 Average hydraulic soil properties. Values in brackets were the calculated standard deviation. Soil properties to the depth of 40 cm were measured from 10x7.5 cm soil cores using pressure plate and tension table apparatus (Carrick, 2009). Soil properties below 40 cm were measured in the field using the volume replacement method (Hedley et al., 2012).**

Depth cm	Stone %	Bulk density g cm <sup>-3</sup>	Total porosity %	Volumetric water content				Hydraulic conductivity (K)		
				@1 kPa %	@10 kPa %	@1500 kPa %	AWC %	K <sup>0.1 kPa</sup> mm/h	K <sup>0.4 kPa</sup> mm/h	K <sup>1 kPa</sup> mm/h
0-7.5	0 (±0)	1.08 (±0.04)	58 (±1.65)	47 (±1.32)	38 (±1.78)	14 (±1.84)	24	120.22 (±57.00)	30.09 (±13.40)	1.42 (±0.61)
7.5-15	0 (±1)	1.33 (±0.04)	49 (±1.55)	40 (±1.59)	34 (±1.53)	16 (±2.46)	18	33.78 (±12.90)	9.58 (±3.28)	1.27 (±0.55)
15-30	0 (±0)	1.36 (±0.07)	48 (±2.38)	38 (±3.48)	31 (±3.00)	15 (±2.34)	16	24.91 (±11.31)	5.8 (±1.79)	0.93 (±0.35)
30-40	2 (±3)	1.47 (±0.04)	44 (±1.17)	35 (±1.56)	29 (±2.17)	16 (±3.04)	13	10.04 (±1.99)	3.06 (±1.17)	0.9 (±0.31)
40-50	60 (±4)	1.99 (±0.09)	25 (±3.23)		10* (± 1.07)	4#	6			
50-65	71 (±1)	2.17 (±0.05)	18 (±1.99)		6* (± 0.72)	2#	4			

\*At the 40 – 65 cm depths the 10 kPa measurement was not directly measured, but is estimated by the volumetric water content directly measured when the soil was wet to field capacity (Refer to section 3.1 Soil description).

# not measured at this site, but estimated from similar stony soil layers elsewhere.

## 4.2 Treatment application and wetting and drying cycles, Experiment 1

Experiment 1 wetting and drying cycles are presented in Figure 4 for deficit-irrigated treatments and Figure 5 for field capacity (FC) treatments. Depth of irrigation across all treatments varied from 145 mm (15/10) to 187 mm (15/15), or 0.58 PV and 0.75 PV respectively. Variation arose in the irrigation applied due to the differences in irrigation return interval. For example, completion of Experiment 1 coincided with the completion of irrigation cycles for the 60/60, 60/40, 30/20 and 15/15 treatments, but the 15/10 and 30/30 treatments were still mid cycle at the end of Experiment 1, and were hence an irrigation application behind the other treatments. Irrigation frequency is reflected by the variation in the degree of soil moisture content fluctuation between treatments, with FC found to be between 150-160 mm total water content for the lysimeters determined by measurements for the initial pre-experiment lysimeter wetting up (refer to section 3.3.1 Pre-wetting and establishment of antecedent moisture conditions).

The average treatment application efficiency (AE) defined as the water lost to drainage/amount of irrigation applied (mm/mm) is presented in Table 3 as a proportion (%). Average AE for all treatments ranged from 88.7% (60/60) to 99.7% (15/10). At any particular moisture deficit irrigation trigger, average AE was lowest for FC treatments compared to deficit treatments. On average, the lysimeters

in the 15/15 had five times the number of drainage events and 15 times the quantity of drainage compared to the 15/10, equating to an average AE difference of 3.5%. The 30/30 had over three times the number of drainage events and over five times the quantity of drainage compared to the 30/20 on average. In AE, the 30/20 and 30/30 varied by 7.9%. The 60/60 and 60/40 had a similar number of drainage events on average (2.7 and 2 respectively), however the 60/60 had nearly four times the quantity of drainage compared to the 60/40 and a corresponding difference in AE of 8%. Regardless if treatment was deficit or FC, increasing application volume had a positive correlation with average AE. AE for FC treatments was in the order of 15/15 (96.2%) > 30/30 (90.8%) > 60/60 (88.7%), deficit treatments in the order of 15/10 (99.7%) > 30/20 (98.7%) > 60/40 (96.7%).

Lysimeter 9 was the only lysimeter to drain in the 15/10 treatment (Figure 4; Figure 5). The drainage in the 30/20 treatment was dominated by lysimeters 12 and 24, while lysimeter 20 accounted for most of the drainage in the 60/40 treatment. All lysimeters in FC treatments generally drained, however lysimeters 17 (15/15) and 23 (30/30) demonstrated higher, or more numerous drainage events to other lysimeters within their treatments (Figure 4; Figure 5).

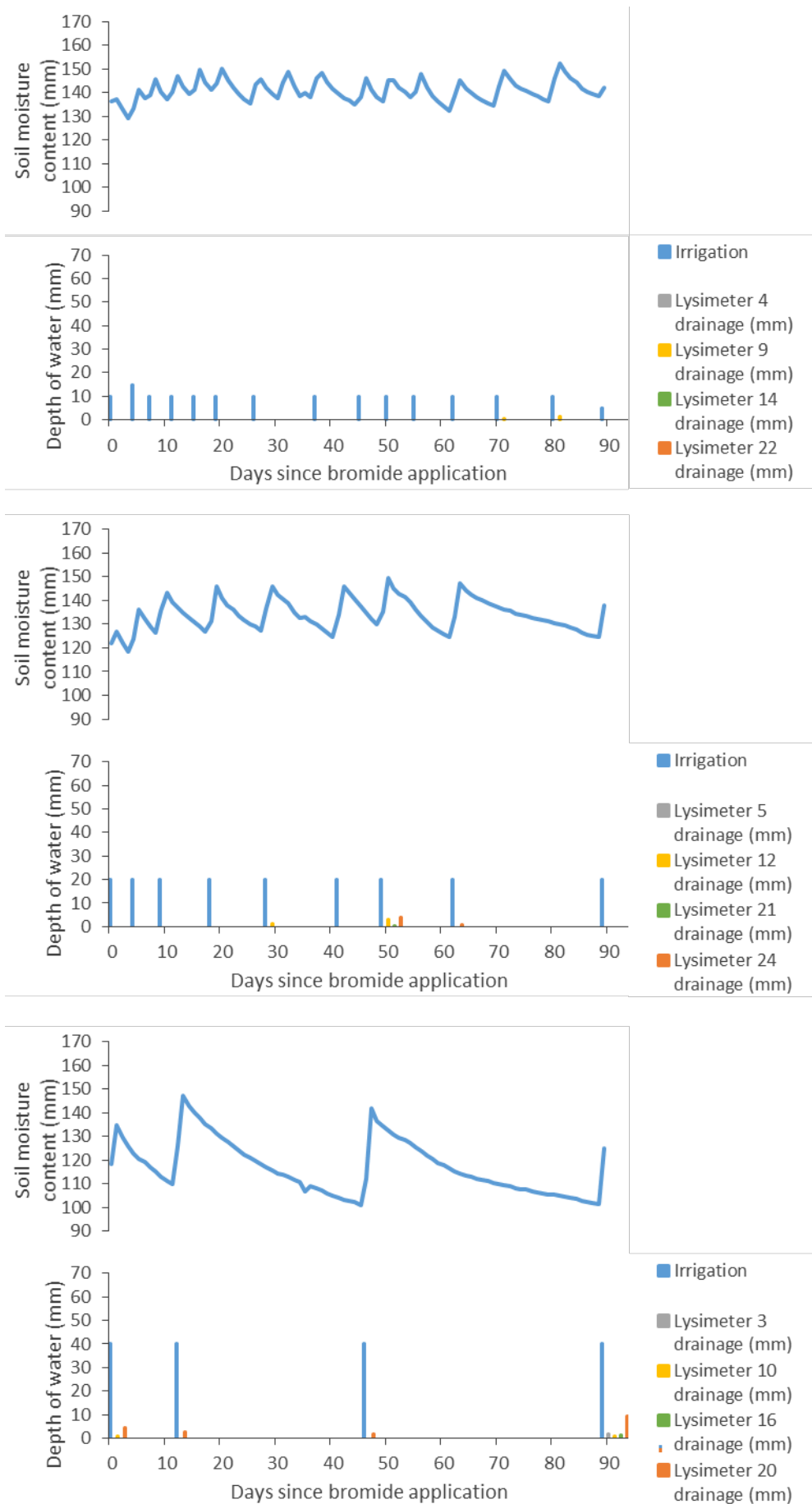
Due to the difference in total depth of irrigation applied for each treatment (Table 3), significance testing was not viable as any statistical trends may be due to a difference in applied irrigation as opposed to a treatment effect.

**Table 3 Experiment 1 irrigation applied and drainage for the different treatments. Drainage values represent the average of the lysimeter reps within a treatment, whilst values in brackets represent the treatment range, and application efficiency is the proportion of irrigation that wasn't lost as drainage (average of the lysimeter reps).**

Treatments	Number of irrigations	Depth of irrigation (mm)	Number of drainage events	Total depth of drainage (mm)	Application efficiency (%)
15/10*	14	145	0.5 (0-2)	0.4 (0-1.5)	99.7 (99-100)
15/15	12	187	4.5 (0-8)	7.1 (0-18.1)	96.2 (90.3-100)
30/20	9	180	1.3 (0-2)	2.4 (0-4.8)	98.7 (97.3-100)
30/30*	5	150	5 (1-5)	13.8 (1.1-37.6)	90.8 (74.9-99.3)
60/40	4	160	2 (1-4)	5.3 (1.2-16.7)	96.7 (89.5-99.3)
60/60* ^	3	180	2.7 (2-3)	20.3 (8.5-32.5)	88.7 (82-95.3)

\*Final irrigation not included, as was not a full irrigation.

^ This treatment only includes three lysimeters due to issues involving lysimeter 19.



**Figure 4 Experiment 1, wetting and drying cycles for deficit-irrigated treatments. Top graph: 15/10 treatment; middle graph: 30/20 treatment; bottom graph: 60/40 treatment.**

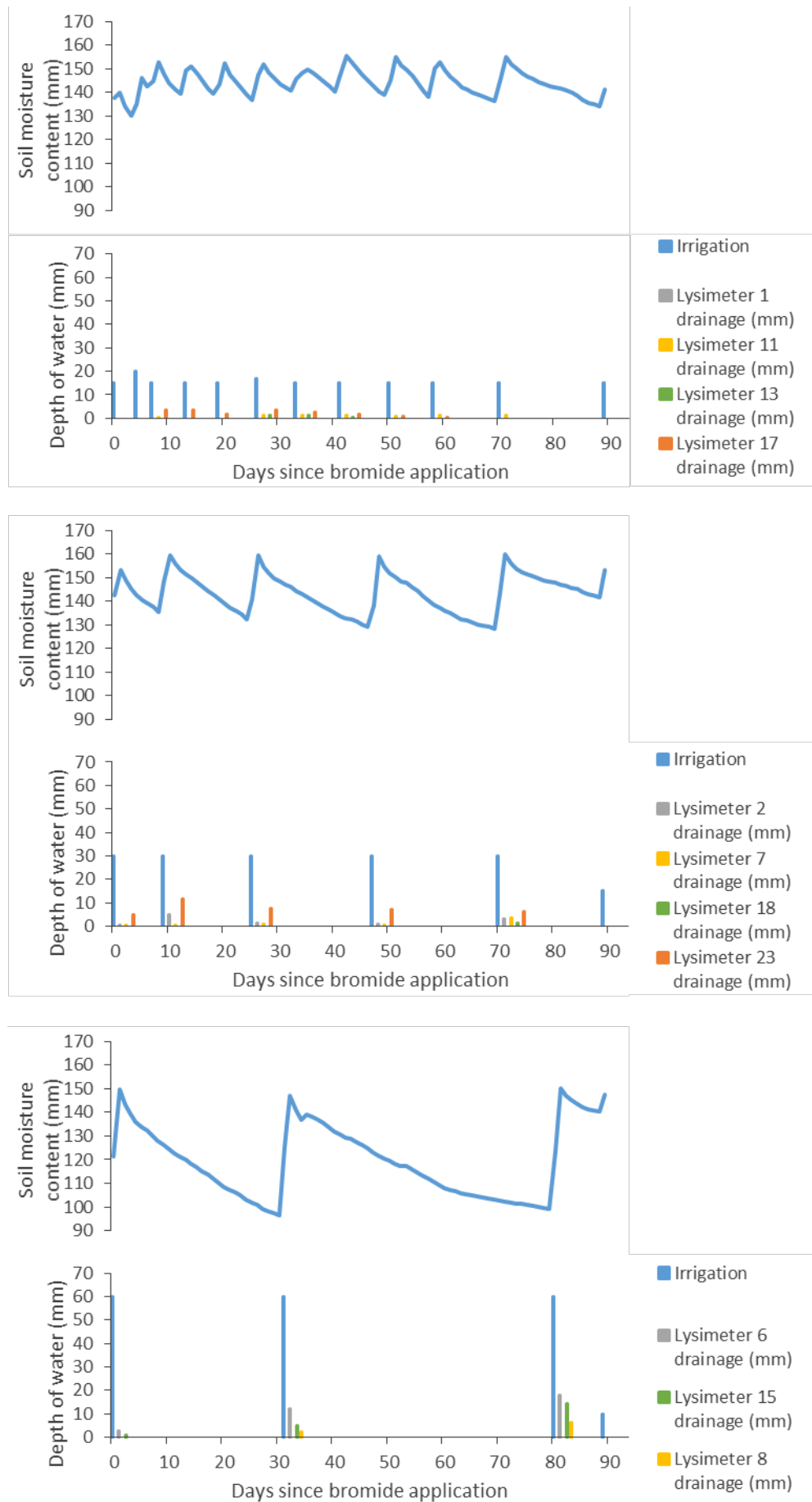
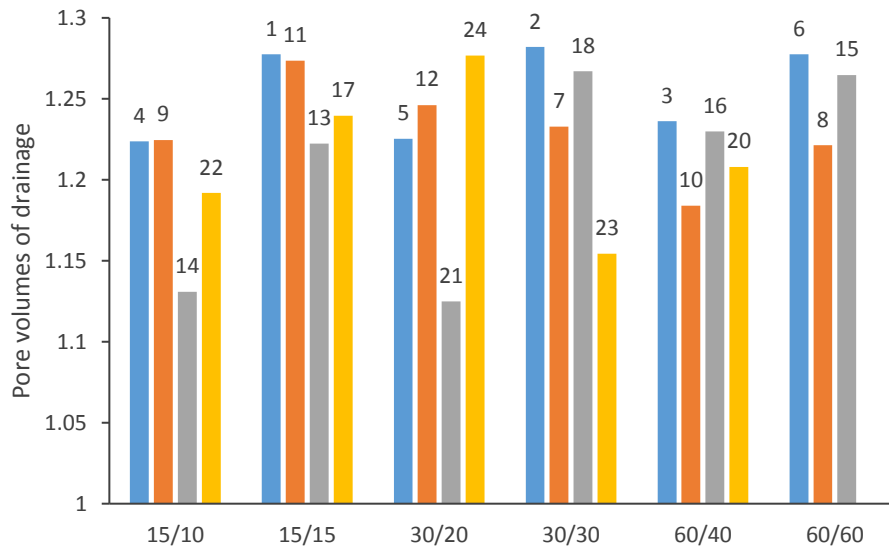


Figure 5 Experiment 1 wetting and drying cycles for the field capacity-irrigated treatments. Top graph: 15/15; middle graph: 30/30; bottom graph (60/60).

### 4.3 Uniformity of drainage events

#### 4.3.1 Experiment 2

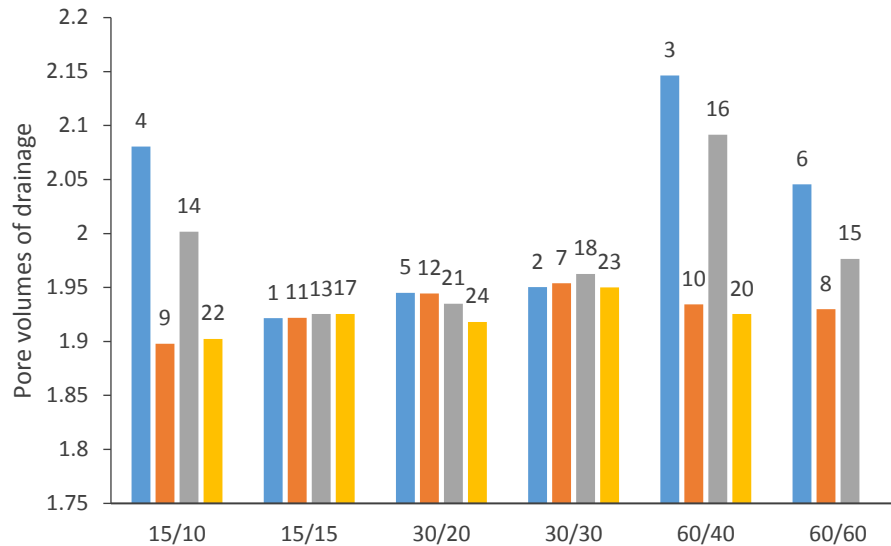
Neither the moisture deficit irrigation trigger ( $P>0.9$ ) nor the moisture status after irrigation ( $P>0.05$ ) had significant effects on the cumulative drainage in Experiment 2, showing there was no residual effect of the irrigation treatments in Experiment 1 on the quantity of drainage water in Experiment 2. The relatively low P-value for the effect of moisture status after irrigation (i.e. irrigation to FC or deficit) is caused by three variable results from lysimeters 14 (15/10), 21 (30/20) and 23 (30/30). Variable lysimeters had approximately 0.06 PV less drainage (c. 15 mm) compared to other lysimeters in their treatments (Figure 6). Causation is mostly due to lysimeter variation in soil water properties and the initial soil water content, with smaller and more variable drainage volume in the first drainage sample due to lysimeters wetting up to steady state conditions, and variation in the final drainage following cessation of the irrigation. Any errors in irrigation calibration appear to have only had a minor effect.



**Figure 6 Experiment 2 cumulative drainage. Number labels refer to the lysimeter where drainage results were collected from.**

#### 4.3.2 Experiment 3

Lysimeters 4 and 14 had about 0.16 PV (c. 40 mm) more drainage compared to other lysimeters in their treatment (15/10) (Figure 7). Lysimeters 3 and 16 also had about 0.16 PV (c. 40 mm) more drainage to other lysimeters in their treatment (60/40) (Figure 7). These higher drainages may be due to lysimeter variation, but is likely as a result of calibration errors for irrigation or a change in solenoid response over time. This arises as the low 2 mm/hr rate was the limit of precision that could be achieved with the irrigation system, especially over such a prolonged drainage event where minor drips can cause substantial differences in drainage.



**Figure 7 Experiment 3 cumulative drainage. Number labels refer to the lysimeter where drainage results were collected from.**

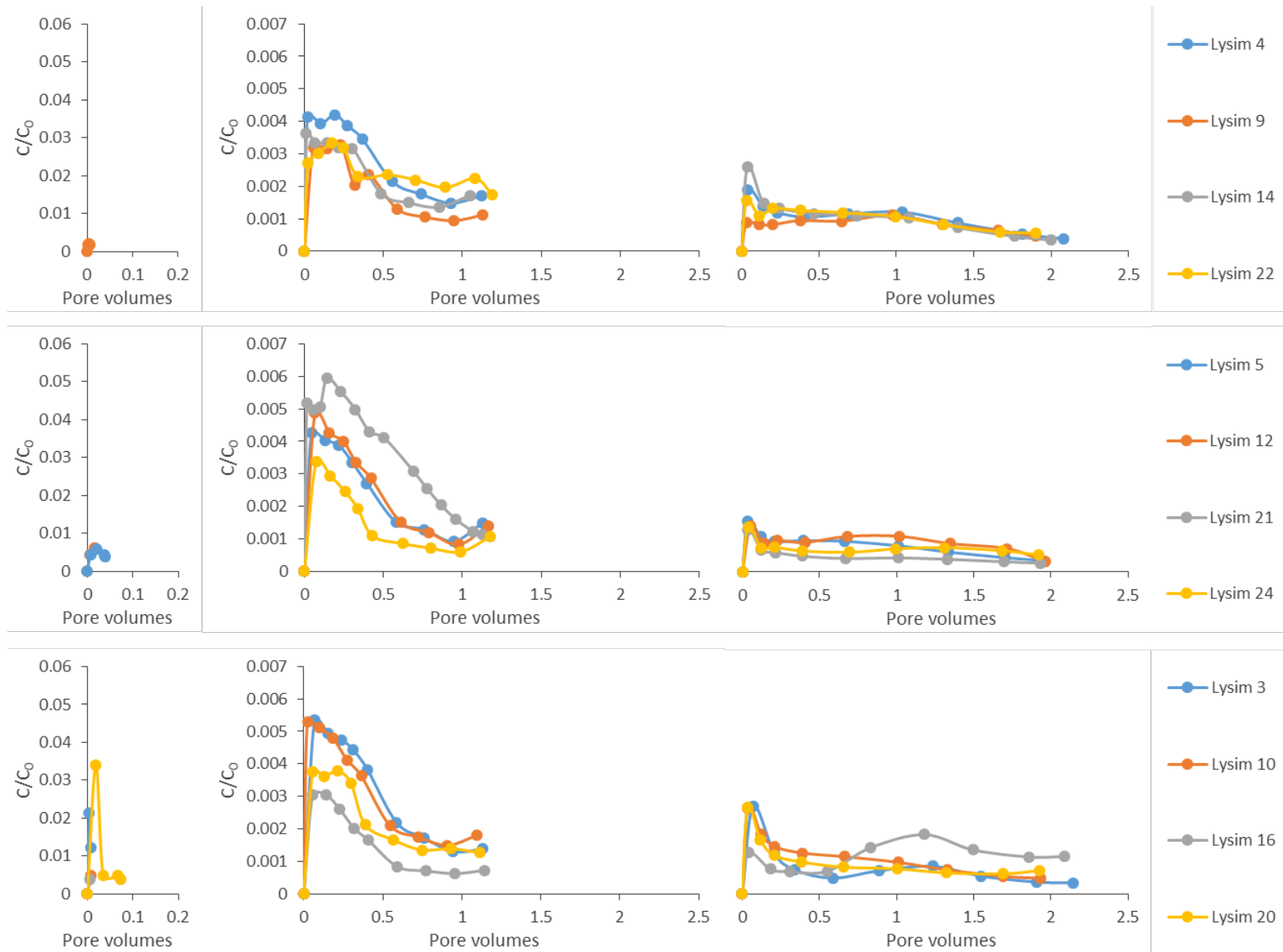
## 4.4 Bromide concentration

### 4.4.1 Experiment 1-3 overview

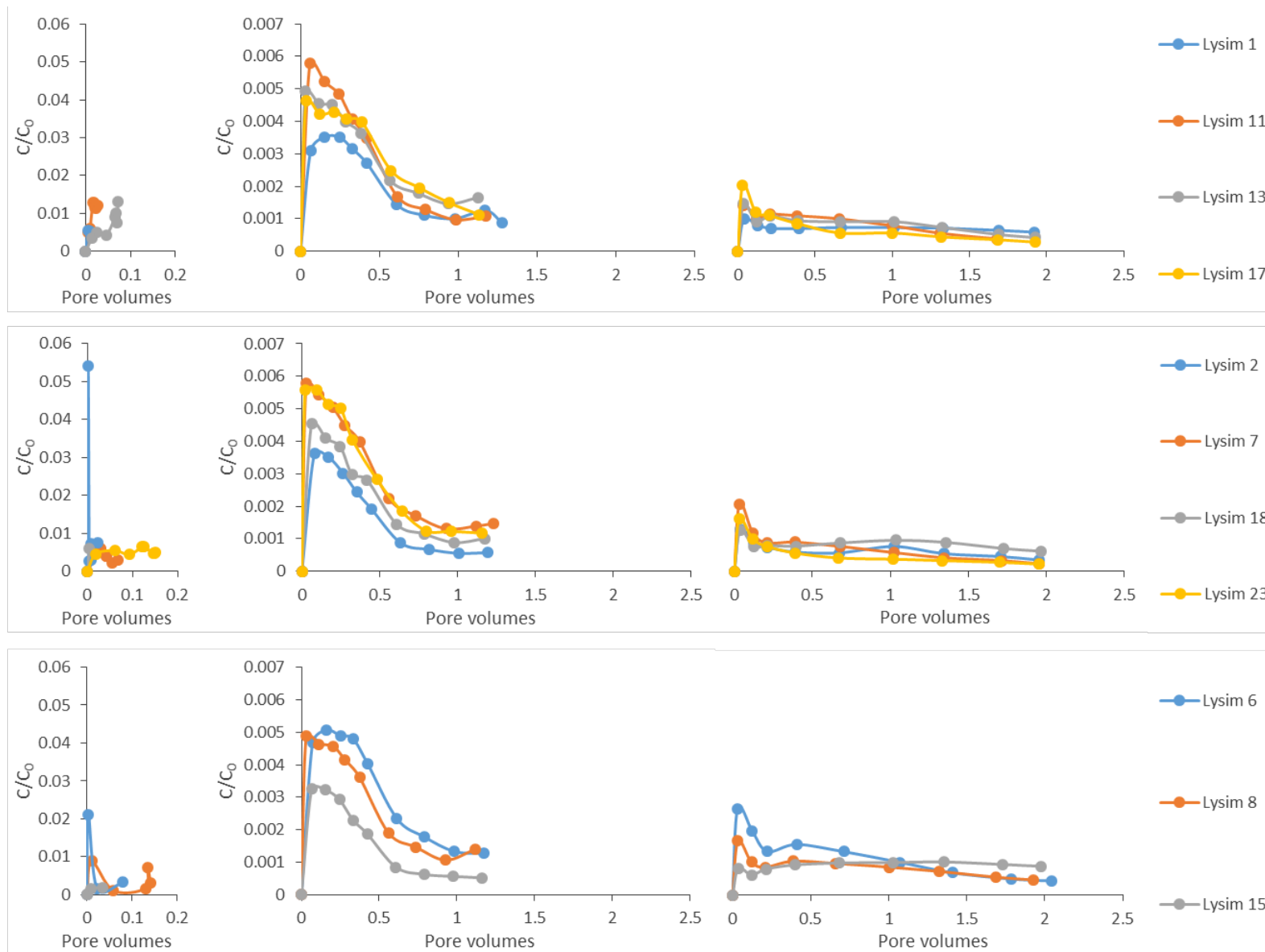
The bromide breakthrough concentrations for the three experiments are displayed in Figure 8 and Figure 9. Common convention in preferential flow studies is to present leaching breakthrough curves in terms of PV of drainage and the quantity leached at a drainage increment as  $C/C_0$  (ratio of measured solute concentration to the concentration of bromide solution initially applied to soil). By following this convention, it is possible to compare with other experiments that used different soil types or tracer concentrations.

Bromide concentrations exceeded soil background concentrations (*c.* 0.3 mg/L) in the first drainage event for all treatments and lysimeters, regardless if initial drainage occurred in Experiment 1 or Experiment 2. This is indicative of strong preferential flow behaviour (Carrick, 2009). Peak concentrations are generally highest in Experiment 1 for lysimeters that had drainage, except for lysimeter 9 (15/10). In Experiment 2, bromide concentrations generally peaked with the first drainage sample (*c.* 0.1 PV), before rapidly declining to half the peak concentration after 0.5 PV (*c.* 125 mm). The 15/10 and 60/60 varied to other treatments, demonstrating wider concentration peaks in Experiment 2, with maximum concentrations sustained for three drainage samples. Experiment 3 generally has peak bromide concentrations within the first leachate samples (*c.* 0.1 PV), but maximum concentrations are less than half that observed in Experiment 2. Following an initial peak in Experiment 3, concentrations generally revert to a similar concentration to the last measurements in Experiment 2.

Variability was large within the treatments. For example, lysimeter 21 (30/20), had concentrations 25% greater than other lysimeters in its treatment in Experiment 2, but the lowest concentrations in Experiment 3. In Experiment 2, lysimeter 15 (60/60) had a 40% lower peak concentration compared to the other lysimeters in its treatment. In Experiment 3, lysimeter 15 and 9 (15/10) had flatter initial peaks, which was a contrast to the more pronounced peaks observed in all other lysimeters. Finally, lysimeter 16 had a low peak concentration in Experiment 2, while in Experiment 3, the maximum concentration occurred at a second peak after 1 PV (c. 249 mm) of drainage.



**Figure 8 Bromide concentration breakthrough for deficit-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). C is the concentration of bromide in the soil leachate.  $C_0$  is the concentration of the bromide solution that was initially applied to soil. Treatments shown are 15/10 (Top graphs); 30/20 (middle graphs); 60/40 (bottom graphs).**



**Figure 9 Bromide concentration breakthrough for field capacity-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph).  $C$  is the concentration of bromide in the soil leachate.  $C_0$  is the concentration of the bromide solution that was initially applied to soil. Treatments shown are 15/15 (Top graphs); 30/30 (middle graphs); 60/60 (bottom graphs).**

#### **4.4.2 Experiment 1 peak concentrations**

Peak concentrations were highly variable between all lysimeters regardless of the treatment, as despite the objective of avoiding drainage in Experiment 1, 24 drainage events were recorded. Of the lysimeters with drainage, lysimeter 9 (15/10) had the lowest max reading, peaking at 0.18% of the initial bromide applied concentration ( $7.5 \text{ mg Br}^- \text{ L}^{-1}$ ). Four lysimeters had significantly higher peak concentrations, including Lysimeter 7 (30/30), 20 (60/40), 10 (60/40) and 8 (60/60), which peaked at 5.4% ( $212.5 \text{ mg Br}^- \text{ L}^{-1}$ ), 3.4% ( $133.8 \text{ mg Br}^- \text{ L}^{-1}$ ), 2.1% ( $84.26 \text{ mg Br}^- \text{ L}^{-1}$ ) and 2.1% ( $83.15 \text{ mg Br}^- \text{ L}^{-1}$ ) of the initial applied bromide concentration respectively. These peaks occurred after the first irrigation, immediately following the application of bromide. Outside of the initial peak, the 15/15 treatment had the highest concentrations over the duration of Experiment 1.

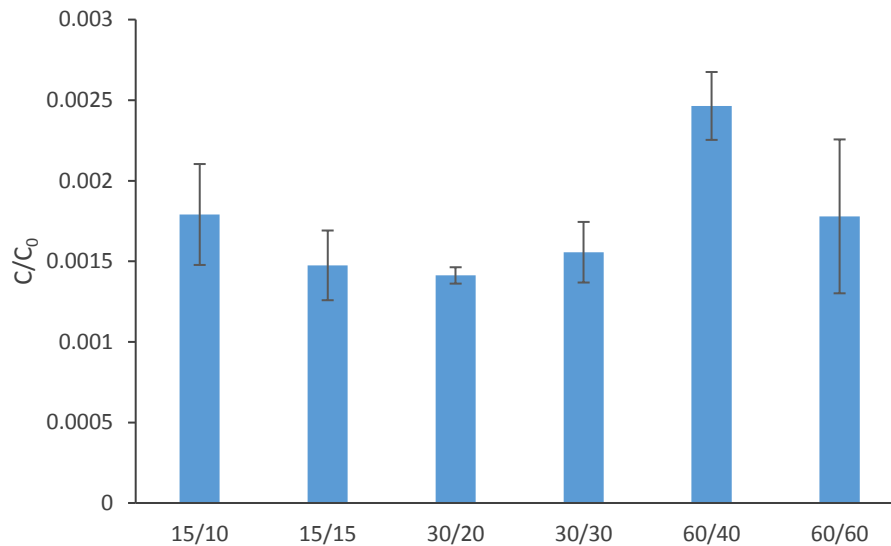
Due to the difference in total depth of irrigation applied for each treatment (Table 3), significance testing was not viable, as any statistical trends may be due to a difference in applied irrigation as opposed to a treatment effect.

#### **4.4.3 Experiment 2 peak concentrations**

Treatment average peak concentrations ranged from 0.36% of the initial bromide concentration applied (15/10) to 0.49% (30/30), which were  $14.19 \text{ mg Br}^- \text{ L}^{-1}$  and  $19.17 \text{ mg Br}^- \text{ L}^{-1}$  respectively. No significant treatment effects were identified, with the moisture deficit irrigation trigger ( $P>0.4$ ) and moisture status after irrigation ( $P>0.3$ ) accounting for little of the variation seen in treatment concentrations.

#### **4.4.4 Experiment 3 peak concentrations**

Treatment average peak concentrations are presented in Figure 10. Peak concentrations across all treatments ranged from 0.14% (30/20) of the initial bromide applied concentration to 0.16% (60/40), which were  $5.54 \text{ mg Br}^- \text{ L}^{-1}$  and  $9.67 \text{ mg Br}^- \text{ L}^{-1}$  respectively. The effect of moisture deficit irrigation trigger had a P-value close to 0.05 ( $P=0.053$ ). Mean values indicated higher peak concentrations in the 60 mm deficit treatments (especially the 60/40) compared to the 15 and 30 mm deficit treatments. Lysimeter 16 (60/40) had an unusually low concentration to other lysimeters in its treatment (c. 25% less), which makes the significance of the effect uncertain. When lysimeter 16 readings were removed from analysis, the moisture deficit irrigation trigger was highly significant ( $P<0.001$ ). The moisture status following irrigation has no apparent effect on peak concentrations ( $P>0.2$ ).



**Figure 10 Treatment average peak concentrations for Experiment 3. C is the concentration of bromide in the soil leachate.  $C_0$  is the concentration of the bromide solution that was initially applied to soil. Vertical bars represent standard error of the mean.**

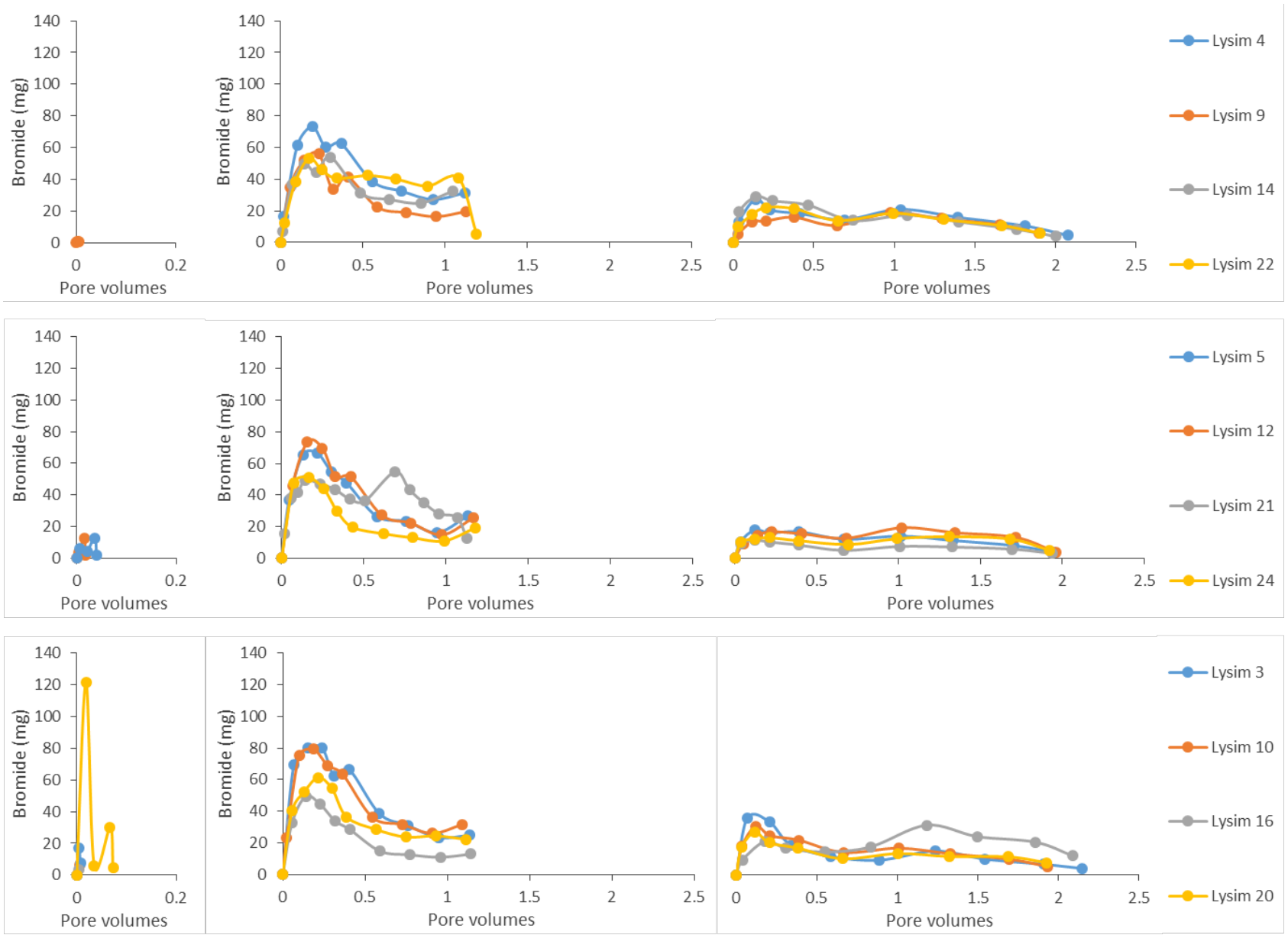
## 4.5 Bromide mass flux

### 4.5.1 Experiment 1-3 overview

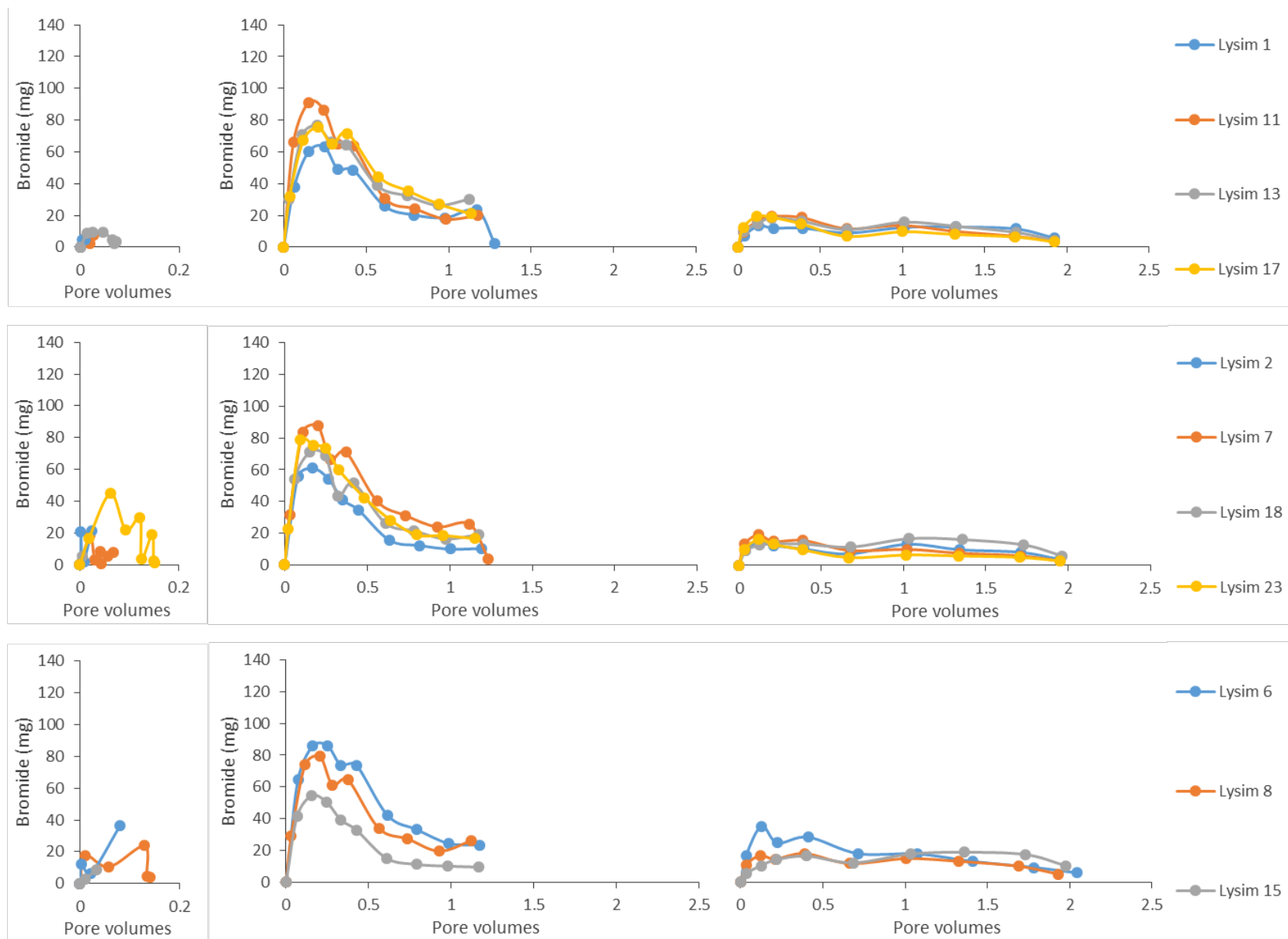
The cumulative mass of bromide leached from lysimeters over the three experiments is presented in Figure 11 and Figure 12. Unlike the concentration breakthrough, Experiment 2 had the greatest peak reading for the three experiments, reflecting the high concentration and greater quantity of drainage under the constant rate drainage conditions. The exception was lysimeter 20 (60/40), which had an uncharacteristically high mass peak in Experiment 1. Looking at mass peak under steady-state drainage provides an insight into when the main bromide pulse reached the base of the lysimeter, and whether the distribution of this pulse in the soil has been affected by the irrigation treatment. Mass peaks were generally broader compared to concentration peaks, and occurred in constant rate drainage after two or three drainage samples (c. 0.2 PV), as opposed to the sharp peaks after only one drainage sample for concentration (c. 0.006 PV). This reflects the smaller and variable drainage volume in the first drainage sample due to the lysimeter wetting up from different antecedent moisture conditions. Drainage rate between lysimeters had stabilised to a constant rate by the second drainage sample. Approximately half the amount of bromide that leached in Experiment 2 occurred within the first 0.32 PV (c. 80 mm) of drainage. Experiment 3 had a slight bimodal breakthrough in bromide mass, with an initial peak in the second drainage sample (c. 0.15 PV), when constant rate drainage had occurred after the initial wetting up, then followed by a generally lower mass peak after 1 PV (249 mm). Half the bromide collected in Experiment 3 was leached by 0.8 PV (200 mm) of drainage. Experiment 1 results were much more variable compared to Experiments 2 and 3, as the volume of each drainage event

was not uniform. For most treatments, mass flux appeared as a peak, which occurred over a larger drainage period in FC-irrigated treatments compared to deficit-irrigated treatments.

Lysimeters 9 (15/10), 21 (30/20), 16 (60/40) and 15 (60/60) had variable results, which was initially identified in the concentration breakthrough section (refer to section 4.4.1 Experiment 1-3 overview). The more apparent difference in mass flux for lysimeter 21 (30/20) is because after 0.5 PV of drainage, a longer sampling frequency was used as lysimeter 21 had half the infiltration rate of all the other lysimeters. As samples had a greater volume of drainage/leachate, bromide mass readings increased after 0.5 PV. Additional variation was seen in lysimeters 22 (15/10), 1 (15/15) and 7 (30/30), which demonstrated significant reduction in bromide readings for their final drainage sample. Low bromide measurement was because the final sample for these lysimeters was for a small drainage quantity (c. 3 mm), as these lysimeters drained for slightly longer than the other lysimeters and hence required an additional small drainage sample.



**Figure 11 Bromide mass breakthrough for deficit-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). Treatments shown are 15/10 (Top graphs); 30/20 (middle graphs); 60/40 (bottom graphs)**



**Figure 12 Bromide mass breakthrough for field capacity-irrigated treatments during Experiment 1 (left graph), Experiment 2 (centre graph) and Experiment 3 (right graph). Treatments shown are 15/15 (Top graphs); 30/30 (middle graphs); 60/60 (bottom graphs).**

### 4.5.2 Experiment 1

Mass readings were highest in larger application treatments. Lysimeter 20 (60/40) peaked at 121 mg Br<sup>-</sup> in its first drainage event, which was over 2.5 times greater than any other peak mass reading. The next highest mass readings were lysimeter 23 (30/30) and lysimeter 8 (60/60), which peaked at 45 mg Br<sup>-</sup> and 36 mg Br<sup>-1</sup> respectively.

As an average of the lysimeters within a treatment, cumulative mass bromide leached was highest in the 30/30 treatment (63 mg Br<sup>-</sup>) and lowest in the 15/10 (<1 mg Br<sup>-</sup>). Bromide leaching was generally higher in treatments irrigated to FC compared to deficit-irrigated treatments, although the 60/60 (43 mg Br<sup>-</sup>) and 60/40 (58 mg Br<sup>-</sup>) treatments had varying results due to the substantial leaching in lysimeter 20 (60/40). Greater mass leached with irrigation application depth was also apparent for deficit irrigated treatments, with 60/40 > 30/20 > 15/10. The FC treatments did not have a similar trend, as the 30/30 had greater leaching compared to the 60/60.

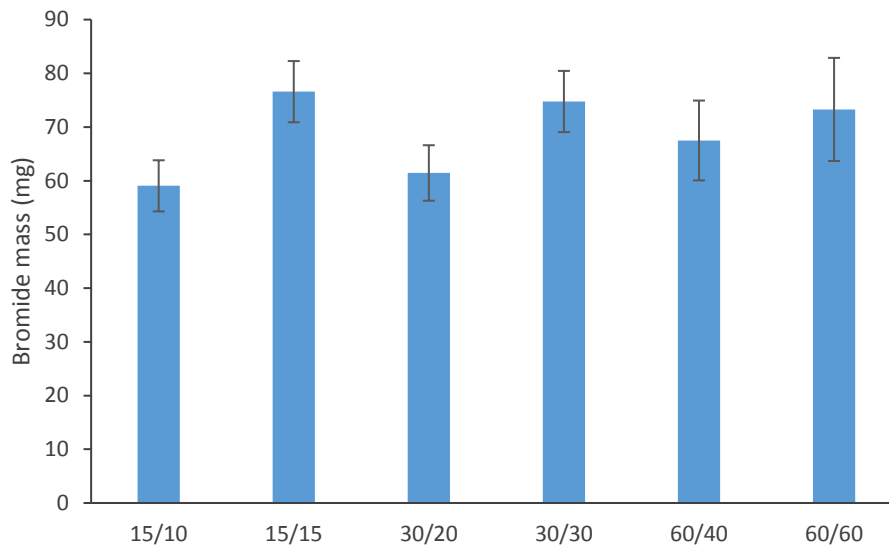
Statistical analysis was not viable in this experiment as treatments received varying quantities of irrigation.

### 4.5.3 Experiment 2

Cumulative bromide leached across all treatments ranged from 495 mg Br<sup>-</sup> (15/10) to 571 mg Br<sup>-</sup> (15/15). No significant treatment effects could be identified for either the moisture deficit irrigation trigger ( $P > 0.9$ ) or the moisture status following irrigation ( $P > 0.675$ ).

As said previously (Section 4.3.1 Experiment 2), some variation in total drainage occurred between lysimeters that may have masked treatment effects. By standardising cumulative bromide to the lysimeter with the lowest drainage (280 mm in lysimeter 21), uncertainty could be removed. Statistical analysis found the moisture deficit irrigation trigger ( $P > 0.9$ ) and the moisture status following irrigation ( $P > 0.7$ ) still had no significant effect.

The max mass bromide was significantly affected by the moisture status following irrigation ( $P < 0.03$ ;  $LSD_{(P < 0.05)} = 9.6 \text{ mg Br}^-$ ), with treatments irrigated to FC having higher max bromide mass compared to treatments irrigated to a deficit (Figure 13). Variation in mean peak mass values was most significant for the 15 mm deficit treatments (varied by 17.6 mg Br<sup>-</sup>) followed by the 30 mm deficit treatments (varied by 13.3 mg Br<sup>-</sup>). Based on the LSD of 9.6 mg Br<sup>-</sup>, the 60 mm treatments were not significantly affected by the moisture status following irrigation. The moisture deficit irrigation trigger had no significant effect on peak mass ( $P > 0.9$ ).

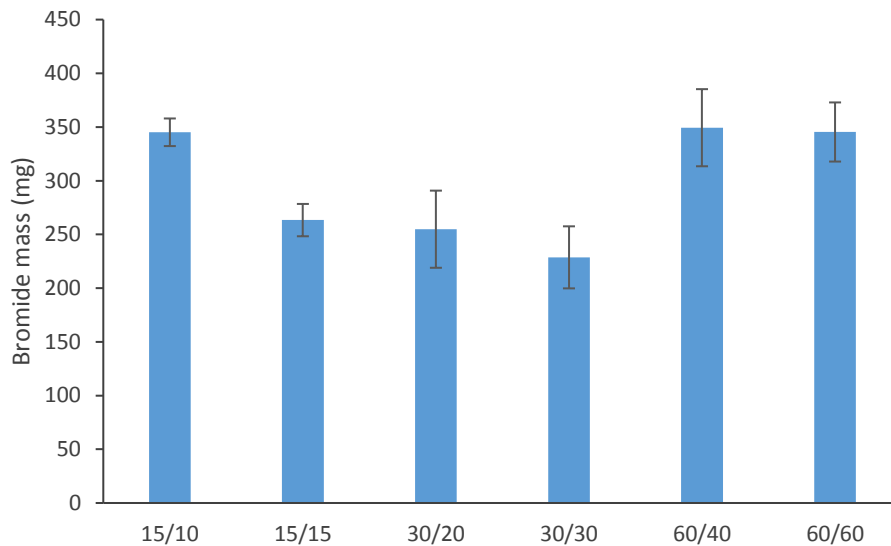


**Figure 13 Treatment average peak mass readings for Experiment 2. Vertical bars represent standard error of the mean.**

#### 4.5.4 Experiment 3

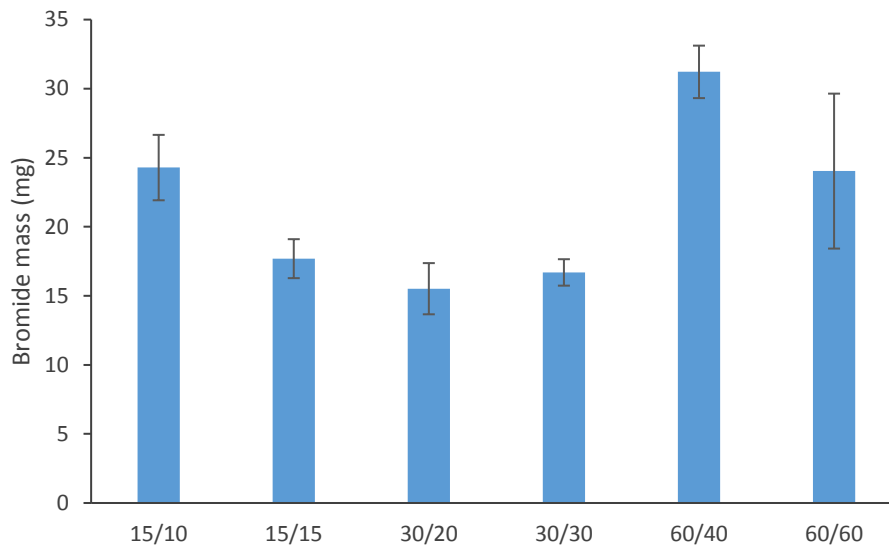
Cumulative bromide leached across all treatments ranged from 233 mg Br<sup>-</sup> (30/30) to 366 mg Br<sup>-</sup> (60/40). The moisture deficit after irrigation had no significant effect on results ( $P > 0.4$ ). The moisture deficit irrigation trigger did not affect results significantly ( $P > 0.1$ ), however, the 60 mm deficit treatments showed some deviation from the 15/15 and 30 mm deficit treatments. This potentially indicates that there is a greater quantity of bromide in the matrix for the 60 mm deficit treatments. The lack of significant difference between the 15/10 and both the 60/40 and 60/60 treatments means there is no identifiable treatment effect that can be justified by differences in hydrological conditions.

The variation in total drainage that occurred between lysimeters may have masked treatment effects, so an additional analysis (Figure 14) was done to standardise cumulative bromide to the lysimeter with the lowest drainage (472 mm in lysimeter 9). Statistical analysis found the moisture following irrigation still had an insignificant effect ( $P > 0.1$ ), while the moisture deficit irrigation trigger became significant ( $P < 0.02$ ). Like above, a lack of significant difference between the 15/10 and both the 60/40 and 60/60 treatments makes justification by differences in hydrological conditions difficult (Figure 14).



**Figure 14 Treatment average cumulative mass bromide for standardised drainage in Experiment 3. Vertical bars represent standard error of the mean.**

The mean peak mass bromide readings were significantly affected by the moisture deficit irrigation trigger ( $P < 0.001$ ) and showed some influence with differences in the moisture status after irrigation ( $P < 0.05$ ). Results indicate that the 60/60 and 60/40 treatments may have significantly higher peak concentrations compared to the 15/15 and 30 mm deficit treatments (Figure 15). The 15/10 and 60/40 treatments also had 20% higher average mass peaks compared to the corresponding FC irrigated treatments (15/15 and 60/60 respectively). However, as the 30/20 and 30/30 had no significant difference to each other and had the lowest mean values, interpretation of results is difficult due to the lack of a discernible soil hydrological trend. The 60/60 treatment has highly variable results as well, which reduces the significance of the observed variation between the 60/60 and 60/40 treatments (Figure 15).

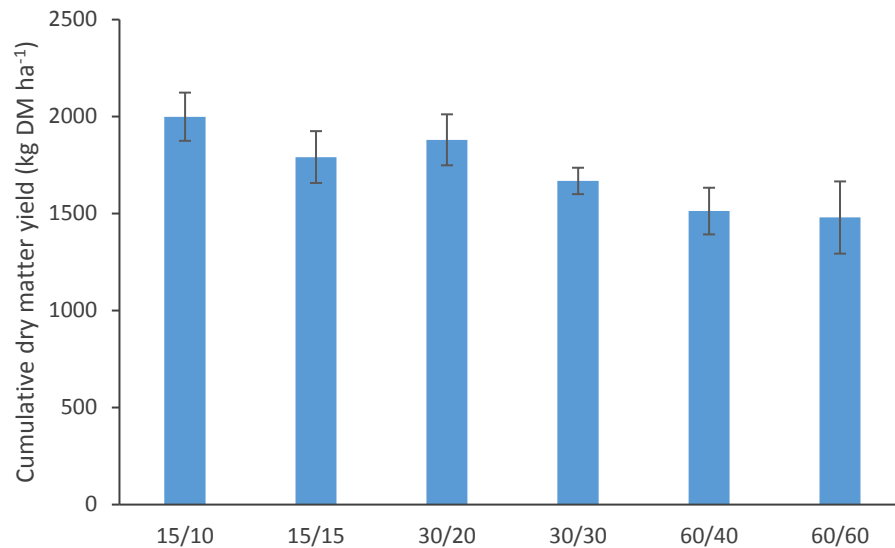


**Figure 15 Treatment average peak mass readings for Experiment 3. Vertical bars represent standard error of the mean.**

## 4.6 Pasture analysis

### 4.6.1 Cumulative pasture yield

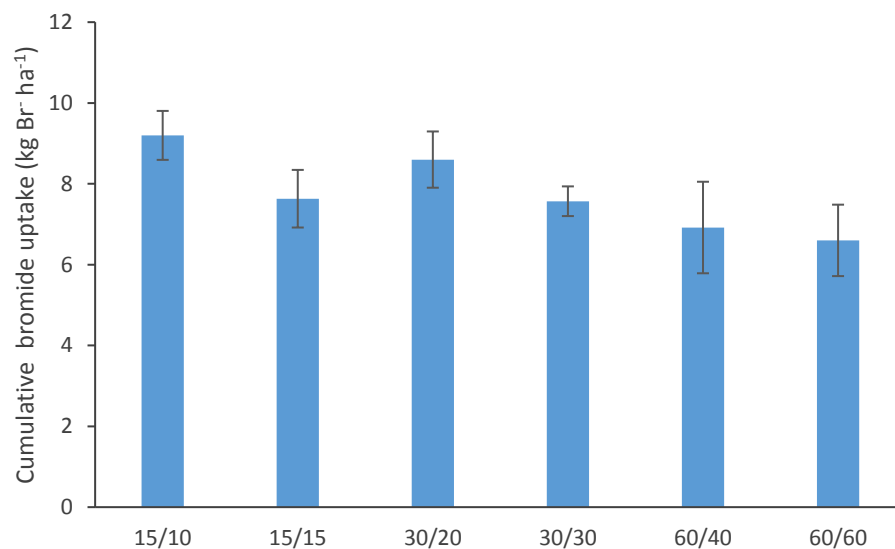
The cumulative pasture dry matter (DM) yields for the three pasture cuts (20/4/16; 15/6/16 and 12/7/16) as an average of the lysimeters within a treatment are presented in Figure 16. Average DM yield across all the treatments ranged from 1503 kg DM ha<sup>-1</sup> (60/60) to 1999 kg DM ha<sup>-1</sup> (15/10). The effect of moisture status following irrigation has no apparent significance to the cumulative DM yield (P>0.1). The moisture deficit irrigation trigger had an apparent effect (P<0.03) with regards to the 60 mm deficit treatments (40/60; 60/60) which had significantly lower yield compared to the 15 mm deficit treatments and to a smaller degree, the 30 mm deficit treatments. However, substantial variation in results was apparent, with overlap in yield readings occurring across all treatments.



**Figure 16 Treatment average, cumulative dry matter yield for three pasture cuts (20/4/16; 15/6/16 and 12/7/16). Vertical bars represent standard error of the mean.**

#### 4.6.2 Cumulative pasture mass bromide

Average bromide mass uptake by pasture for the three pasture cuts is presented in Figure 17. Average bromide uptake across all the treatments varied from 6.6 kg Br<sup>-</sup> ha<sup>-1</sup> (60/60) to 9.2 kg Br<sup>-</sup> ha<sup>-1</sup> (15/10). No significant difference in bromide uptake was observed for treatments, regardless of the moisture deficit irrigation trigger ( $P > 0.1$ ) or the moisture status after irrigation ( $P > 0.1$ ). Variation in results may have masked treatment effects, but mean values demonstrate a potentially lower uptake in the 60/40 and 60/60 treatments.



**Figure 17 Treatment average, cumulative bromide uptake for three pasture cuts (20/4/16; 15/6/16 and 12/7/16). Vertical bars represent standard error of the mean.**

## 4.7 Bromide mass balance

The dominant source of bromide recovery for all treatments was from Experiment 2, which equated to half of the total bromide recovered in the trial (Table 4). Considering Experiment 2 had only half the amount of drainage as occurred in Experiment 3, results show there is a higher quantity of bromide present in the pores that are active under 50 mm/hr compared to those pores active under 2 mm/hr irrigation. Experiment 1 represented the lowest fraction of bromide recovery.

For cumulative leaching, the 60/60 and 60/40 treatments had the greatest bromide recovery as a function of their relatively high leaching in Experiment 3. The lowest recovery from leaching was seen for the 30 mm deficit treatments, which leached 7% less bromide than the 60 mm deficit treatments. Although variation existed, no significant treatment effects could be identified for either the deficit irrigation trigger ( $P>0.2$ ) or the moisture status following irrigation ( $P>0.8$ ).

Including plant uptake, total bromide recovery only equated to around 50% of that applied. Considering over 3.5 PV (870 mm) of irrigation was used in this trial, a significant quantity of bromide has apparently translocated into the finer pores of the soil matrix where it is relatively protected from draining water.

**Table 4 Treatment average bromide recovery.**

Treatment	Leached bromide				Plant bromide uptake	Total Br recovery
	Experiment 1	Experiment 2	Experiment 3	Cumulative leached		
15/10	0%	24%	18%	42%	9%	51%
15/15	2%	28%	13%	43%	8%	50%
30/20	1%	25%	13%	39%	9%	48%
30/30	3%	25%	12%	40%	8%	48%
60/40	3%	25%	18%	46%	7%	52%
60/60	2%	25%	18%	45%	7%	52%

## Chapter 5

### Discussion

#### 5.1 Drainage

##### 5.1.1 Effect of moisture status following irrigation

Although significance testing was not viable for Experiment 1 results, apparent variation in drainage characteristics was seen with differing treatments. The most significant difference was seen between treatments with different soil moisture status after irrigation. Treatments irrigated to field capacity (FC) had more drainage than treatments irrigated to a soil moisture deficit. This result is expected, and is the rationale for many developments in irrigation efficiency in terms of precision agriculture (Hedley & Yule, 2009). Multiple studies have demonstrated that significant soil heterogeneity can exist within small areas of land (Hbirkou, 2011; Hillel, 1998). For instance, Reza et al. (2016) found water content at FC varied by 25% on an alluvial floodplain, while Gumiere et al. (2014) found saturated conductivity could range from 10-40 cm/hr in a 2 ha cranberry field. Hence, although lysimeters were of the same soil type and collected from the same area, variation in properties such as depth of soil horizons, quantity of stones or presence of macropores is likely (Haws et al., 2004; Lilburne & Webb, 2002; Mallants et al., 1997; Schneider et al., 2016). Variability in plant growth, which was demonstrated in the pasture yield and bromide uptake data, may have had an effect as well, causing variability in water uptake and hence the antecedent soil moisture content of lysimeters when irrigation was initiated. Ledgard et al. (1996) observed a similar effect, with greater pasture growth being associated with higher evapotranspiration and hence a dryer soil profile. As irrigation timing was based on treatment soil moisture averages, variation in soil properties and initial water saturations would likely cause some FC-irrigated lysimeters to drain earlier than other lysimeters causing a lower application efficiency (AE). This was demonstrated in the results, with the drainage in FC treatments generally dominated by one or two lysimeters. As deficit treatments had a moisture content buffer in regards to FC, lysimeters with lower water holding capacity to others in its treatment would still not exceed FC and hence shouldn't drain.

##### 5.1.2 Effect of application volume

AE in Experiment 1 noticeably decreased with increasing application volume for both deficit and FC irrigated treatments. Considering lysimeters that were irrigated to a deficit were affected as well, irrigation over FC may not have been the cause of increasing drainage. Wang et al. (2009) found similar results, attributing increasing drainage to variation in water distribution. At higher application volumes, infiltration depth of water was found to increase as preferential flow became more

pronounced (Wang et al., 2009). It is thought that the 50 mm/hr rate of irrigation induces preferential flow. With higher application volumes, preferential flow is sustained for longer, causing greater breakthrough of drainage. Similar results were found by Powers (2012) who observed more preferential flow and drainage occurring in 15 mm irrigation applications to 5 mm applications. However, treatments irrigated to a deficit were generally dominated by only one or two draining lysimeters, therefore, the effect of application volume to increased drainage and leaching is uncertain. It is likely that the effect of application volume was enhanced by soil heterogeneity, which may have included variation in the antecedent soil moisture content in the lysimeters of a treatment or variation in macropore networks.

### **5.1.3 Effect on real world applications**

Overall, AE from treatments was high, even the 60/60 with the worst AE exceeding irrigation industry and regulatory authority target efficiencies of 80% (McIndoe, 2002). However, real world application would have to deal with much larger variability in water application and soil heterogeneity. Under the highly regulated conditions of the trial, potential irrigation losses due to wind, soil variability, irrigation accuracy/uniformity and error in irrigation timing would be significantly less compared to 'real' farm conditions. As such, trends that were seen to decrease AE in this study are likely to be highly significant in real irrigation practice. The apparent difference between lysimeters irrigated to FC or to a determined deficit indicates the advantages of deficit irrigation, soil moisture measurement and precision irrigation. For instance, Hedley and Yule (2009) found the adoption of variable rate irrigation could decrease annual water use by over 20% on a pastoral farm, with the quantity of drainage likely to decrease as well. The increase in drainage with higher application volume was apparent in the FC treatments but its significance to deficit treatments is uncertain. The fact that some lysimeters did drain in the deficit treatments may indicate that application depth does not need to exceed the soil moisture deficit for drainage to occur. This could have significant impacts to the perceived efficiency of irrigation practice, with conventional knowledge implying that risk of drainage only exists when application depth exceeds FC (Powers, 2012). Considering the rate of irrigation (50 mm/hr) is common for centre pivots exceeding 500 m in length (Cichota et al., 2016), excess drainage from large irrigation volumes could be significant in the Canterbury region, where pivot irrigators exceeding 500 m in length are not uncommon (Powers, 2012). Alternatively, drainage in the deficit treatments could be due to soil moisture exceeding FC as a result of variability in antecedent soil moisture content between lysimeters of a treatment. This would indicate large losses when irrigating at the paddock scale, as it would be expected that even greater variability would occur when irrigating without the precise irrigation system and careful monitoring used in this study. It is implied by the results that the most efficient irrigation practice would be frequent low irrigation applications to a determined moisture deficit to overcome soil heterogeneity.

## 5.2 Trends in leached bromide

### 5.2.1 Experiment 1 and 2, preferential flow

The immediate breakthrough of bromide in the very first drainage samples that either occurred in Experiment 1 or 2, is a strong indicator of preferential flow. The fact that bromide breakthrough occurred in Experiment 1 is interesting, considering even drainage from the frequent low application irrigation treatments (15/10; 15/15) demonstrated immediate bromide breakthrough. This implies that this stony soil is prone to preferential flow, with rapid solute breakthrough occurring at 50 mm/hr regardless of the application volume or moisture status the soil is irrigated to. Many papers have implied the susceptibility of stony soils to preferential flow (Carrick et al., 2014; Toor et al., 2004; Webb et al., 2010), however the actual range of studied conditions is limited. What studies could be found focused on nitrogen/phosphorus flux, or bromide movement under constant flow conditions.

Constant flow experiments on stony Lismore soils demonstrated significant preferential flow at concentrations equal to or greater than what was observed in this study. For instance, immediate breakthrough concentrations of 10% and 5% of the initial bromide applied was found by Pang et al. (2008) and Cichota et al. (2016) respectively. In a lysimeter study with transient soil moisture conditions simulating a frequent rainfall period, Cameron et al. (1995) found nitrate also preferentially moved through stony Lismore soils within 0.17 pore volumes (PV) of drainage (c. 20 mm). Carrick et al. (2014) on a Selwyn stony sandy soil, observed preferential nitrate breakthrough within 15-30 mm drainage, even under best management irrigation practices (12-18 mm depth at 35-40 mm/hr applied every 3-4 days). While Gray et al. (2016), whose transient moisture study used the same lysimeters as used in this study, found preferential flow was still present at rates as low as 12 mm/hr, and showed only a marginal rate effect on phosphorus leaching between 12 and 50 mm/hr irrigation. This suggests that preferential flow may have a significant impact on the dynamics of solute through these stony New Zealand soils.

As the depth at which preferential flow was first initiated could not be determined with the measurements available, the mechanism of preferential flow can only be speculated. Considering deficit treatments were used, the development of hydrophobicity and surface cracking could have initiated preferential flow. Ritsema et al. (1998) detailed the ability of hydrophobic conditions to form unstable wetting fronts, however, water repellence required quite dry soils. Though this may have occurred in the 60 mm deficit treatments, it would be unlikely to occur in the 15/10 and 15/15 treatments. As all treatments displayed similar preferential flow, hydrophobicity or surface cracking is unlikely to have influenced the observed results. Another common mechanism of preferential flow is unstable flow or funnel flow caused by significant textural changes or lenses in the profile (Dobrovolskaya et al., 2014; Kung, 1990b). Considering irrigation of only 10 and 15 mm caused

preferential flow, the initiation of rapid water movement is likely to be at the top of the profile. Based on a field analysis of lysimeter soil textures (Appendix B) no apparent textural variation can be identified that would cause the preferential flow observed in the results. This makes macropore flow the likely mechanism of preferential flow. Macropore flow occurs when the rate of water application exceeds the infiltration rate of the smaller pore fraction of the soil, causing water to move into larger pores as the water entry potential of macropores is exceeded (Hendrickx & Flury, 2001). Considering the uniform nature of preferential flow across the treatments, it is likely that the stony soil has an overriding macropore network that was initiated under the irrigation rate of 50 mm/hr. Ghodrati and Jury (1992) had similar results with widespread preferential flow occurring in a Tujunga loamy sand as a result of irrigation rates of only 5 mm/hr. Carrick et al. (2014) showed preferential flow in all stony soil cores under 40 mm/hr irrigation. While multiple field studies under rainfall have demonstrated widespread and uniform macropore flow occurring when rainfall had exceeded certain intensities (Graham & Lin, 2011; Lennartz & Kamra, 1998).

The prevalence of preferential solute movement has negative connotations towards the use of irrigation and land intensification in Canterbury, with estimates indicating stony soils cover more than 200,000 ha in the region (Carrick et al., 2013). Therefore, potentially significant leaching losses may be occurring in Canterbury, even when best management practices in irrigation are used. When drainage occurred immediately following the application of bromide, lysimeters generally leached at high concentrations, with lysimeters 7, 8, 10 and 20 leaching at concentrations of over 80 mg/L in the first drainage event. Edwards et al. (1993) had similar results when applying atrazine to a no-till corn crop, with 5% of the applied herbicide leached the day after application. This was attributed to transport of the chemicals being concentrated through soil macropores, bypassing the bulk soil water with lower solute concentration that sits within the soil matrix, causing highly concentrated solute breakthrough (Edwards et al., 1993). This could have significant connotations to fertiliser, effluent or herbicide application, with even small volumes of irrigation following application causing potentially significant leaching.

Future research may require the use of reactive tracers such as  $^{15}\text{N}$  in a similar irrigation trial. The fact that bromide is a conservative tracer means the significance of preferential flow to solute leaching may be enhanced in the current study. Though preferential flow is apparently occurring for all treatments, the fact that bromide will not significantly interact with the soil matrix or undergo microbial transformation may make results misleading. For instance, three of the four lysimeters in the 15/10 treatment did not drain in Experiment 1. If a less conservative chemical had been used, a significant amount of the chemical may have become immobilised, causing less leaching to occur and potentially make treatment effects more significant.

## 5.2.2 Bromide distribution in the soil matrix

It was found that the dominant source of leached bromide was in Experiment 2, which accounted for around half of the total bromide recovered for all treatments. Considering Experiment 2 had nearly half the drainage compared to Experiment 3, mobile bromide is apparently found at substantially higher quantities in the pore fraction that is active under 50 mm/hr compared to those pores active at 2 mm/hr. In a separate project to this study, soil water content and conductivity relationships for the soil used in this study were measured and modelled for the 0-40 cm depth (Appendix D). Using this information, an estimate of the active pore fraction for the top 40 cm of soil profile in Experiment 2 and 3 was derived (Table 5). It was estimated that 90% of the drainage for Experiment 2 moved through pores greater than 0.3 mm in diameter. Though arbitrary in definition, this pore fraction would equate to the macropores of the soil (Germann & Beven, 1981; McLaren & Cameron, 1996), which represented only 2% of the PV (Table 5). Carrick (2009) found similar results in saturated flow experiments, with soil water in pores below 1.5 kPa suction accounting for only 2.4% of the drainage that was seen. While Langner et al. (1999) found as little as 2% of the PV draining in a similar saturated flow experiment. In contrast, Experiment 3 drained through approximately 10% of the PV, which was a distinctly different suite of pores to the PV fraction that drained in Experiment 2 (Table 5). This is to be expected, with a number of studies identifying an increase in hydraulic conductivity and activation of macropores at suctions below 1 kPa (Jarvis, 2007; Langner et al., 1999; Poulsen et al., 2002).

**Table 5 Characteristics of pores estimated to be responsible for 90% of drainage.**

Depth (cm)	50 mm hr experiment				2mm hr experiment			
	Suction range (kPa)	Active pore diamet er range (mm)	Soil water content range (%)	Volume of soil dominating 90% of drainage (%)	Suction range (kPa)	Active pore size range (mm)	Soil water content range (%)	Volume of soil dominating 90% of drainage (%)
0 - 7.5	0.09 to 0.7	3.3-0.4	59 - 56	3	0.7 to 9	0.4-0.03	56 - 41	14
7.5 - 15	0.0001 to 0.9	>0.3*	51 - 49	2	1 to 8	0.3-0.03	48 - 39	9
15 - 30	0.0001 to 0.9	>0.3*	49 - 47	2	1 to 6	0.3-0.5	47 - 37	10
30 - 40	0.0001 to 0.9	>0.3*	49 - 47	2	1 to 6	0.3-0.6	47 - 37	10

\* Hydraulic conductivity results indicate that under this experiment, flow was effectively saturated and hence pores above 0.3 mm would have been active.

It could be speculated that due to the prevalence of preferential flow that was seen in these stony soils, irrigation immediately following bromide application transported a large proportion of bromide into the macropore system. As a result, Experiment 2 would leach out the significant amounts of bromide surrounding the macropores, while Experiment 3 would leach the apparently lower

concentration of bromide in the finer pore fraction that may have diffused from higher concentrated areas surrounding the macropores during the irrigation season (Experiment 1). Bundt et al. (2001a) found similar results, with concentrations of soil organic carbon and total nitrogen found to be 15 to 75% higher in preferential flow paths compared to the soil matrix. Bundt et al. (2001b) also found an enrichment of nutrients, which caused microbial biomass to be 9 to 92% higher in macropores compared to the finer pore fraction. This has implications towards biogeochemical cycling, as macropores have been found to have greater biodegradation (Pivetz & Steenhuis, 1995) and microbial activity (Pankhurst et al., 2002) compared to other regions of the soil. This accentuates the need for a replication of this study using more reactive tracers (such as  $^{15}\text{N}$ ) due to reasons stated at the end of the previous section (5.2.1 Experiment 1 and 2, preferential flow).

Bromide mass flux in Experiment 3 displayed an interesting dual peak, one at the beginning of drainage and one after 1 PV. Lennartz and Kamra (1998) observed a similar trend, with solute movement separated into two regions of mobility, one preferential and one matrix flow. Similar results were also found by Destouni (1993). Though the rate of irrigation application in this study was low (2 mm/hr), multiple studies have demonstrated preferential flow movement occurring under similar large application, low rate drainage events (Gish et al., 2004; Jaynes et al., 2001; Kohne & Gerke, 2005; Kung et al., 2006; Richter & Jury, 1986). Kung et al. (2006) found that as a soil profile became wetter, a range of larger pores becomes hydraulically active, even under low rate irrigation. Thus, the initial peak in Experiment 3 is possibly the result of preferential leaching from the larger pores active under 2 mm/hr rate (Table 5). These larger pores would dominate the drainage in Experiment 3 but would have only been a minor contributor in Experiment 2 where much larger macropores dominated the quantity of drainage. The height of the peak mass may then reflect the greater resident bromide within these larger pores, which were only partially active and thus partially leached in Experiment 2. However, it is more likely that the height of the peak reflects the 12-hour intermission between Experiment 2 and 3, with interruptions in drainage events known to 'recharge' larger pores by solute diffusion from the finer pore fraction (Cote et al., 2000; Lewan et al., 2009; Meyer-Windel et al., 1999). The second peak is characteristic of matrix flow, considering the breakthrough of bromide occurred after 1 PV of drainage (Hillel, 1998). Due to the lower rate, bromide that was protected from water flow at 50 mm/hr in smaller pores was now prone to leaching through matrix flow.

### **5.2.3 Treatment effect on bromide flux**

Treatment effects in Experiment 1 were closely related to the trends identified in Section 5.1 Drainage. As a consequence of greater drainage, bromide flux was generally greater in the FC and larger irrigation volume treatments compared to the deficit or lower volume irrigated treatments. These trends were uniform over all treatments except the 30/30, which leached more bromide than the 60/60 even

though the treatment had 16% less drainage. This may be due to variation in leaching efficiencies. The average number of treatment drainage events in the 60/60 treatment was 2.7 compared to 5 in the 30/30. Although having a larger drainage volume, the 60/60 treatment was confined to only 3 leaching events and is hence prone to solute dilution. As the 30/30 has more leaching events, there are more opportunities for bromide to diffuse into macropores, hence when leaching occurs it is of a higher concentration compared to drainage in the 60/60 treatment. Similar results were found by Cote et al. (1999) who found smaller drainage events increased leaching efficiency by 10-20% when compared to a continuous flow experiment due to solute diffusion from the matrix.

The cumulative mass ( $P < 0.02$ ) and peak mass ( $P < 0.001$ ) in Experiment 3 were both significantly influenced by the moisture deficit irrigation trigger, which generally showed the 60/60 and 60/40 treatments as having significantly higher readings than other treatments. Sambale et al. (2000) in a bromide transport study, found that the process of drying by transpiration causes the transport of bromide from large to small pores. As the 60 mm treatments had the greatest deficit, more solute would have diffused into the smaller pore fraction, and hence resulted in greater mass readings in Experiment 3. This may also have been caused by the boundary conditions when bromide was first applied. Kung et al. (2006) found tracer applied at dryer surface conditions had lower macropore leaching. It was speculated that this might have arose from the many small pores near the soil surface with negative matric potentials under dry conditions (Kung et al., 2006). This would have caused bromide to infiltrate into the smaller pore fraction (Edwards et al., 1993; Shipitalo et al., 1990), some of which would become mobilised in Experiment 3, potentially causing mass readings to be higher for the 60 mm treatments. This may also be the cause of the variable results seen in lysimeter 16 (60/40), which leached less in Experiment 2 compared to other lysimeters but leached relatively more bromide compared to other lysimeters in Experiment 3. The uncharacteristically high mass readings in the 15/10 treatment, which did not significantly differ from the 60 mm deficit treatments, makes the above theories uncertain. It could be speculated that the low application volume for the 15/10 treatment would cause less preferential flow and thus bromide to be concentrated in a smaller depth of soil to other treatments. Due to a greater concentration gradient, more bromide may have diffused into the smaller pore fraction in the 15/10 treatment, causing leaching in Experiment 3 to be similar to the 60 mm deficit treatments.

The peak mass readings In Experiment 2 ( $P < 0.03$ ) and 3 ( $P < 0.05$ ) were influenced by whether the treatment was irrigated to FC or a deficit. In Experiment 2, the 15/10 and 30/20 had lower peak mass measurements to their corresponding FC irrigated treatments (15/15; 30/30). This may have been caused by variation in how deep preferential flow penetrated down the lysimeters between different treatments. FC irrigated treatments exhibited the most extensive preferential flow, as demonstrated by their greater drainage (section 5.1.1 Effect of moisture status). As a result, macropores in FC

treatments would likely have bromide distributed right through the whole profile. Deficit treatments however, had a number of lysimeters that did not drain, thus preferential flow (and hence bromide) may have only moved through part of the profile. Consequently, macropores in FC treatments may have had a greater quantity of immediately leachable bromide, causing a higher peak mass. The fact that no significant difference was apparent between the 60/40 and 60/60 treatments may have been because at such relatively high applications, both treatments demonstrated similar preferential flow and diffusive processes. As a result, the macropores in both treatments may have had bromide distributed through the length of the profile, thus no significant difference in the immediately leachable bromide or peak mass readings. Due to the limitations of the with-in soil measurements of this study, this can only be hypothesised, while the lack of research into solute movement with-in pore fractions means comparable studies could not be found either. Experiment 3 had an opposing trend to Experiment 2; with significantly lower peak mass readings in the FC treatments compared to the deficit treatments ( $P < 0.02$ ). Deficit treatments may have had bromide concentrated in a smaller fraction of the soil due to less extensive preferential flow. Due to a greater concentration gradient, more bromide may have diffused into the smaller pore fraction, causing a greater peak mass reading for deficit treatments in Experiment 3. This trend is less distinct compared to Experiment 2, considering the 30/30 and 30/20 treatments did not vary, while the 60/40 and 60/60 treatments did (which is a contrast to what was seen in Experiment 2 peak mass). It is likely that the treatment effects in Experiment 3 are not a dominating influence and are thus prone to variability by other influencing factors such as soil heterogeneity or variation in plant uptake. This is demonstrated in the 60/60 treatment which had substantial variability between lysimeters and may have caused the unexpected deviation from the 60/40 treatment.

#### **5.2.4 Soil heterogeneity**

Soil variability was identified within the study, demonstrating the conventional lysimeters (50 cm width by 70 cm depth) might not be large enough to be a REV (representative elementary volume) of the studied stony soil. Powers (2012) had similar results for Lismore stony soil lysimeters, with the readily available soil water content in the upper 30 cm of soil ranging from 18 to 27 mm. In this study, Lysimeter 21 (30/20), demonstrated significant variability in infiltration characteristics in Experiment 2 compared to all other lysimeters used in the study. Unlike the other lysimeters, lysimeter 21 had significant ponding and drained at half the rate to other lysimeters. In Experiment 1, the high initial breakthrough concentrations for lysimeters 7 (30/30), 8 (60/60), 10 (60/40) and 20 (60/40) were also an indication of variable results. Lastly lysimeters 9 and 15 demonstrated stunted initial peaks in Experiment 3. Though some variation was identified, a majority of lysimeters demonstrated very similar breakthrough patterns, which shows that much of the pore network variability within the studied soil was represented. As such, the lysimeters used within the study were close to the REV, and

were a good representation of the solute dynamics that occurs in these soils under irrigation. The variability that was identified could have been caused by multiple factors including variation in water holding capacity, bromide and water uptake by plants or in the macropore networks in terms of density, continuity and tortuosity (Jarvis, 2007; Ledgard et al., 1996; Powers, 2012; Simmonds & Nortcliff, 1998). However, in light of this variability, the observed trends in bromide distribution and preferential flow demonstrate that they are significant trends, as they occurred regardless of the soil heterogeneity seen in the study.

### **5.3 Plant yield and uptake**

Pasture yield was significantly lower in the 60 mm deficit treatments compared to the 15 mm and 30 mm deficit treatments. The reduction in yield with increasing soil deficit indicates that in these treatments the plants were under water stress. This is a well-documented phenomenon and can be responsible for significant decreases in plant yield (Baars & Coulter, 1974; Martin, 1990). As soils become dryer, water is retained at progressively higher suction by the soil, decreasing the rate of water uptake by plants, plant growth and yield (Denmead & Shaw, 1962). Yield reduction occurs in relation to a stress point or critical moisture deficit that is known to range from 35-104 mm (Barker, 1983; McAnaney & Judd, 1983; Mills et al., 2006) depending on the plant and soil type. By rule of thumb, the critical moisture deficit is about 50% of the total available water held in the root zone (Allen et al., 1998). The critical moisture deficit for the studied lysimeters was estimated at 41 mm (considering an available water capacity of 82 mm; Table 2), indicating that the pasture in 60 mm deficit treatments would have become water stressed, causing the decrease in yield.

Bromide uptake by pasture leaves equated to less than 10% of the bromide that was applied for all treatments. This is relatively low compared to other studies, with pasture found to assimilate 32% of applied bromide (Owens et al., 1985; Schnabel et al., 1995). Owens et al. (1985) indicated that bromide uptake was proportional to the growth of pasture, with vigorous plant growth corresponding with considerable amounts of bromide being taken up by the plant. As the focus of this study was on leaching, pasture growth was likely to be limited in this study by nitrogen deficiencies. Considering both Owens et al. (1985) and Schnabel et al. (1995) maintained pasture growth with regular fertiliser application, the pasture yield and hence uptake of bromide in their studies was likely to be substantially higher than observed in this study, however studies did not measure yield and hence this can only be speculated. Multiple other factors would likely have influenced results as well, including differences in soil type (Hayman & McBride, 1979), pasture species (Hamilton, 2001) and season (Roberts & Thomson, 1984) which significantly affect plant growth and hence solute uptake. The lack of significant treatment effects in this study are likely due to the high variability that occurs in bromide assimilation. This was highlighted by Schnabel et al. (1995), whose study observed bromide uptake

varying from 8-86% of the applied bromide. The slight decrease in the mean bromide uptake for the 60 mm moisture deficit irrigation trigger treatments is likely due to a reduction of water uptake, similar to the reduction in yield. This arises as bromide is passively assimilated when water is absorbed into a plant (Magarian et al., 1998). At lower moisture deficit, less water is taken up by the plant thus bromide uptake is likely to reduce as well.

#### **5.4 Bromide recovery**

Total bromide recovery only equated to 50% of the bromide that was initially applied. This is similar to other transient condition studies, which generally measure bromide recovery around 40% (Jiang et al., 2008; Schotanus et al., 2013). Considering bromide recovery in constant drainage studies can be >80% (Cichota et al., 2016; Jiang et al., 2005; McLeod et al., 2014; Schoen et al., 1999), it would seem the intermittent wetting and drying that occurred under transient conditions caused significant immobilisation of bromide. This likely occurred due to the diffusion of solutes into pores that are either not active or had a minimal contribution to the drainage under 2 or 50 mm/hr irrigation, and therefore were not susceptible to leaching (Meyer-Windel et al., 1999). Bromide would also be prone to immobilisation in the soil organic matter and root biomass, which has been speculated as a cause for reduced bromide leaching (Katou & Kozai, 2010; Kung, 1990a; Leri & Ravel, 2015). Constant rate experiments often take place over a much shorter time interval of a few days, compared to the 13 weeks of transient soil moisture irrigation treatments in this experiment. This longer time interval would allow much greater diffusion driven redistribution of the bromide within the soil. McLay et al. (1991) found similar results after only 24 hours, with a significant leaching difference between lysimeters irrigated immediately after tracer application to lysimeters irrigated after a 24-hour delay.

## Chapter 6

### Conclusions

In this transient soil moisture irrigation trial, preferential flow dominated solute leaching through the studied stony soil under 50 mm/hr irrigation, occurring irrespective of the application volume and frequency of irrigation. This strongly affected the distribution of bromide within the soil, causing leached tracer to move predominately through the macropore network, which is estimated as occupying a small fraction (*c.* 2%) of the soil volume. Considering only 50% of the bromide was recovered, transient conditions over an extended period of time can cause significant redistribution of bromide into the main volume of pores in the soil matrix that are not active contributors to drainage under 2 or 50 mm/hr irrigation.

For Experiment 1, results partially confirmed the hypothesis that the rate of drainage and solute leaching increased for soils irrigated to field capacity (FC) compared to a determined soil deficit. This arose due to associated issues of irrigating to FC whilst dealing with heterogeneity in soil properties or plant growth i.e. all lysimeters in a treatment are irrigated uniformly, however heterogeneity means some lysimeters will drain earlier than others. Considering that soil water content was carefully monitored and a precise irrigation system was used in these experiments, irrigating to FC at the paddock scale is likely to involve increased drainage and leaching on these soils compared to using deficit irrigation.

In Experiment 1, the hypothesis that drainage and solute leaching would increase with the volume of irrigation was partially confirmed. This was apparent for FC treatments, with more lysimeters draining at higher quantities with increasing amounts of irrigation. However, due to a higher leaching efficiency, the 30/30 leached more bromide compared to the 60/60, even though the 60/60 had the highest drainage. As only one or two lysimeters drained in the deficit irrigated treatments, the increase in the drainage and leaching as a result of irrigation volume is less certain, and may have been enhanced by soil heterogeneity such as variation in the antecedent soil moisture content in the lysimeters of a treatment.

Generally, no significant treatment effects on the cumulative mass of bromide leached could be identified across the three experiments for either the deficit irrigation trigger or the moisture status following irrigation, indicating a lack of support for the hypotheses above. However, there was evidence that bromide distribution in the profile at the end of the irrigation season was affected by the treatments, with moisture status after irrigation primarily affecting the results in Experiment 2, while the moisture deficit irrigation trigger influenced the results in Experiment 3.

There is an indication that bromide peak mass was influenced by whether a soil was irrigated to a determined soil deficit or FC in Experiment 2 ( $P < 0.03$ ) and 3 ( $P < 0.05$ ). However, effects were not highly significant, and so were prone to variability from other factors such as heterogeneity in soil properties or plant growth. This implies that the susceptibility of a stony soil to macropore leaching is the same, with the quantity of bromide in the macropores not varying significantly regardless of the irrigation treatment used.

In Experiment 3, the 60 mm treatments (60/40 and 60/60) had significantly higher bromide peak mass ( $P < 0.001$ ) and cumulative mass ( $P < 0.02$ ), which is suggested as reflecting increased movement of bromide into the finer pore fraction as a result of the drier conditions between irrigation events. However, the fact that the 15/10 treatment had similarly high mass readings to the 60 mm deficit treatments, and the insignificant difference between the 30 mm deficit treatments (30/20 and 30/30), makes the above reasoning uncertain and demonstrates that solute distribution in Experiment 3 is affected by multiple processes, which make interpretation of treatment effects difficult.

The implication of these results is that irrigation practices on the Eyre shallow silt loam at rates of 50 mm/hr need to be adjusted to account for preferential flow. The fact that some lysimeters leached very high concentrations of bromide immediately after the application of bromide highlights the requirement to not irrigate following the application of fertiliser, pesticide or other applied chemical. The results imply that the 15/10 treatment would have the least leaching risk of the measured treatments. Although still prone to preferential flow, the low application volume in this treatment means solute remains within the soil profile, and is hence not lost from the system and has a greater opportunity to be immobilised.

## **6.1 Limitations and suggestions for further research**

- The use of more reactive tracers such as  $^{15}\text{N}$  may result in different or more significant treatment effects, as bromide is a conservative tracer making it less likely to be bound or immobilised in the soil.
- Measurement of other soil types in the same conditions to determine whether results such as susceptibility to preferential flow are characteristic of the studied soil or the irrigation practices used.
- A large amount of redistribution was speculated in the experiment and would require destructive analysis to quantify bromide movement. It could be possible to destructively

sample lysimeters at the end of an experiment, however this would be both costly and not guaranteed to be accurate enough for the pore scale measurement required.

- A limiting factor of the current study was the fact that lysimeters would not account for lateral flow and surface redistribution of solute. This may have caused the observed vertical drainage trends to be enhanced, lacking the lateral movement that may have decreased preferential flow or downward movement of solute. More study on this may look at the frequency by which surface redistribution and lateral water movement occurs on shallow and stony soils, and therefore the potential relevance of lysimeter based studies to reflect real world conditions.
- As a result of the use of undisturbed monolith lysimeters, substantial variability was seen in the experiment. Future research may require an increase in the number of replicates to overcome variability.

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## Appendix A

### Eyre shallow silt loam soil profile



## Appendix B

### Treatment blocking structure

Lysimeter	Current treatment	Lysimeter	Current treatment
1	15/15	13	15/15
2	30/30	14	15/10
3	60/40	15	60/60
4	15/10	16	60/40
5	30/20	17	15/15
6	60/60	18	30/30
7	30/30	19	60/60
8	60/60	20	60/40
9	15/10	21	30/20
10	60/40	22	15/10
11	15/15	23	30/30
12	30/20	24	30/20

#### Blocks


- Lysimeters that received no urine in previous experiment
- Lysimeters that received urine in previous experiment

## Appendix C

Field estimates of Eyre shallow silt loam profile. Sampled 13/6/13.

Described by Sam Carrick.

Horizon	Bottom (cm)	Clay (%)	Sand (%)
Ap	16	20	25
Ap/Bw	25	20	25
Bw	36-39	20	25
2Bw	50-55	15	50
2BC	65-75	80	5
2C	120+	90	5

## Appendix D

### Modelled water content and conductivity relationships at different soil depths.

In a separate project to this study, Landcare Research has been testing different models to predict the soil water content and conductivity relationships for a range of New Zealand soils (Joseph Pollaco and Sam Carrick 2016, pers comm). This work included the soil used in this study, using the data presented in Table 2, as well as measurements at high suctions of unsaturated hydraulic conductivity and soil water content using the Hyprop device (UMS, 2016, <http://www.ums-muc.de/en/products/soillab/hyprop/>). There are a number of closed-form unimodal expressions in the literature that compute the soil moisture release curve  $q(h)$  and the unsaturated hydraulic conductivity  $K(h)$  curves such as the commonly used van Genuchten and Brooks and Corey curves. Figure D.1, presents the results of fitting the physically based Kosugi closed-form unimodal log-normal function expression of  $\theta(h)$  and  $K(h)$  (Kosugi, 1996), selected because its parameters provide a close link to the soil pore-size distribution. Figure D.1 shows the fit of the unimodal Kosugi model, and as it is not uncommon for New Zealand soils to exhibit preferential flow behaviour, the Kosugi bimodal  $\theta(h)$  (Liu et al., 2013b) and  $K(h)$  (Liu et al., 2013a) models were also applied. As shown in Figure D.1, the bimodal Kosugi model provides a better fit to measured  $\theta(h)$  and  $K(h)$  data, and thus was used in Table 5 to estimate the actively conducting porosity that dominated drainage during Experiments 2 and 3. This was done by using the  $K(h)$  data to determine the minimum soil water suction at hydraulic conductivities of 50 mm/hr (Experiment 2) and 2 mm/hr (Experiment 3). Likewise, the same data was used to determine the soil water suction at hydraulic conductivities that were  $1/10^{\text{th}}$  of these rates was also determined. Using the equation (McLaren & Cameron, 1996),

$$d \text{ (mm)} = \frac{0.3}{h \text{ (mm)}} \quad (3)$$

the diameter of the largest pores ( $d$ ), based on soil water suction ( $h$ ), could be estimated for the pores active at the experiment irrigation rate and those active at  $1/10^{\text{th}}$  of the experiment irrigation rate. The pore fraction between these two diameters would be responsible for 90% of the water transport during the constant rate conditions of the experiment. The  $\theta(h)$  data was used to estimate the volume of soil that the actively conducting pore fraction occupied.

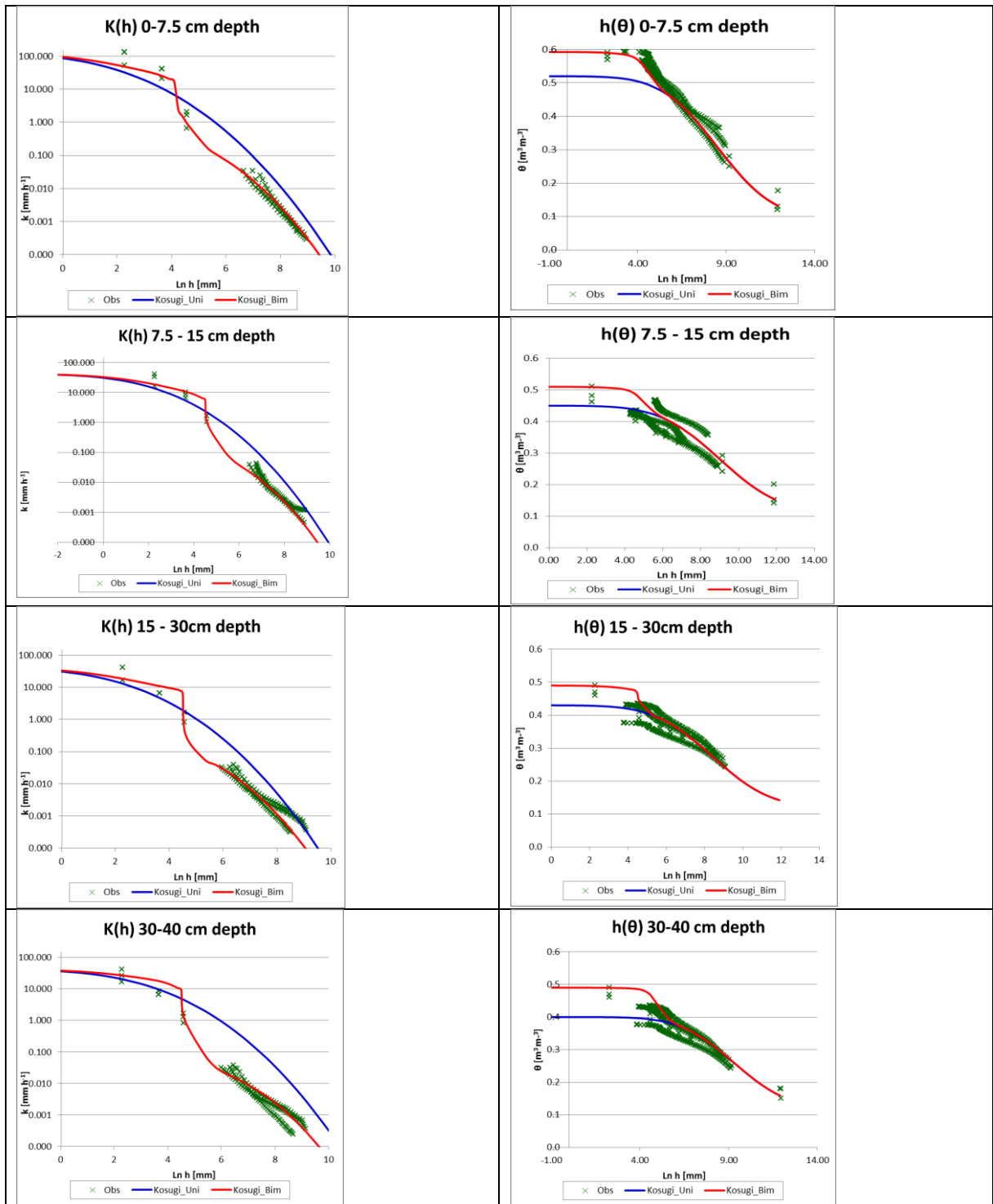


Figure D.1 Results of applying the Kosugi unimodal and bimodal models to estimate the soil water content and conductivity relationships for the 0 – 40 cm depth of the soil used in this study.