

Client Report

Prepared for Clutha Agriculture Development Board

February 2006

An assessment of soil aeration and K-line irrigation technology as management strategies to prevent overland flow of land applied farm dairy effluent.

D J Houlbrooke



An assessment of soil aeration and K-line irrigation technology as management strategies to prevent overland flow of land applied farm dairy effluent

Prepared for Clutha Agriculture-Development Board

February 2006

D J Houlbrooke

DISCLAIMER: While all reasonable endeavour has been made to ensure the accuracy of the investigations and the information contained in this report, AgResearch expressly disclaims any and all liabilities contingent or otherwise that may arise from the use of the information.

COPYRIGHT: All rights are reserved worldwide. No part of this publication may be copied, photocopied, reproduced, translated, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of AgResearch Ltd.

Table of Contents

1.	Executive Summary	1
2.	Introduction	2
3.	Methodology.....	3
3.1	Research site and layout	3
3.2	Soil and water measurements	4
3.3	Statistical analysis.....	6
4.	Results	6
4.1	Soil physical properties.....	6
4.2	Farm dairy effluent irrigations	7
4.3	Nutrient losses in overland flow	10
5.	Discussion.....	11
5.1	Soil physical properties.....	11
5.2	Farm dairy effluent irrigations	11
5.3	Nutrient losses in overland flow	13
6.	Conclusions.....	13
7.	Acknowledgments.....	14
8.	References.....	14

1. Executive Summary

This report evaluates the potential of soil aeration to improve surface infiltration properties and, in combination with K-line spray irrigation systems, prevent the generation of overland flow on sloping land following the application of farm dairy effluent (FDE). K-Line technology has been identified as an irrigation system that can much reduce the risk of pollutant losses from dairy farms following the application of FDE to soils that have low infiltration rates such as the Pallic soil types found extensively in the South Otago region. Findings from field research comparing the environmental performances of K-line irrigation systems with travelling irrigators are summarised. Research findings indicate that K-line effluent irrigation systems have the potential to considerably reduce overland flow pollutant losses induced by the application of FDE to land. This improvement results from two characteristics of the K-line irrigation system: (i) it applies effluent to land more evenly than the rotating travelling irrigators currently used, resulting in lower application depths of FDE, and (ii) because it applies effluent at a much lower application rate (approx. 4 mm/hr), less overland flow of effluent is observed, resulting in greater soil attenuation of nutrients contained in the FDE.

Minimal soil physical treatment effects were picked up following soil aeration however the aeration treatment had the effect of decreasing overland flow generation as a likely result greater pore space and drainage capability.

2. Introduction

With a herd population now approaching 3.75 million cows (LIC 2003), New Zealand dairy farms currently produce between 40 - 50 million m³ of farm dairy effluent (FDE) annually. Under current guidance from local regulatory authorities, this dilute effluent, which is collected from washings of the farm milking parlour and yard, is typically returned to pastures via irrigation during non-winter months. Although land application of FDE has been promoted to maximise nutrient use efficiency and minimise faecal bacteria losses to waterways, this farm practice does present its own risk on farms that contain soils with (i) a high degree of preferential flow, or (ii) low infiltration rates. Large transfers of contaminants in FDE through mole and pipe drainage have recently been documented by Dairy Industry- and FRST-funded research conducted over the past 5 – 10 years (Houlbrooke et al. 2004a, Monaghan and Smith 2004). Critical factors identified as contributing to pollutant losses are soil moisture content and uniformity of FDE application. Applying FDE at as low a depth as can be achieved using the travelling irrigator has also been identified as a key BMP, as is the necessity to store FDE when soils are wet and apply when a suitable soil moisture deficit exists.

In some circumstances intensive dairy farm operations are located on rolling country with weakly structured soils. These soils typically belong to the Pallic Soil Order which are characterised by high density, slowly permeable subsurface horizons often over a fragipan which has a highly restricted permeability when wet (Hewitt 1998). These Pallic soil types, such as those found in the South Otago region, are prone to contaminant losses via overland flow, particularly on rolling land. As for mole and pipe drained land, applications of FDE to these rolling landscapes are difficult to manage. With their high instantaneous application rate and poor control of application depth and uniformity, rotating travelling irrigators present a high risk of ponding FDE or generating overland flow on sloping land, particularly when soil water deficits are low (Houlbrooke et al. 2004b, Monaghan and Smith 2004). K-line irrigation technology, with its low rate of application (approx. 4 mm hr⁻¹), and its high degree of flexibility in control of application depth, offers much potential for minimising the direct drainage loss of contaminants following irrigation of FDE to mole and pipe drained land.

Soil aeration technology has been developed to primarily alleviate soil compaction or break up plough pans. Soil aeration has been shown to result in improved soil physical condition, however the longevity of such effects has proven to be variable (Burgess et al. 2000, Drewry et al. 2000, Drewry and Paton 2000). Some evidence exists that the soil aeration process improves the passage of water through soil and may therefore be beneficial in decreasing the likelihood of overland flow generation.

This report follows up on previous a AgResearch experiment at Kelso, South Otago (Sustainable Farming fund contract 03/041) which investigated the manipulation of soil structure to improve effluent infiltration into soil. The findings of this research were that soil aeration increased surface infiltration rates for at least 6 months and that FDE could be safely applied to aerated soil so long as 2-3 grazing rotations had occurred to reseal some of the large surface cracks that resulted from the soil aeration process.

The objective of this report is to assess the suitability and environmental performance of K-Line irrigation technology to irrigate FDE to sloping land and to evaluate the benefit of soil aeration on minimising overland flow generation.

3. Methodology

3.1 Research site and layout

The research site was established at Stephen and Judith Ray's property near Clydevale in South Otago, New Zealand. The property was traditionally a sheep farm that was converted to a 465 cow dairy farming unit six years ago. The Clydevale area experiences a moderate climate with 650-750 mm of rainfall per annum and median annual air temperature of 9.6-10.0°. The farm is situated on Waikoikoi silt loam, a Mottled Fragic Pallic soil (Hewitt 1998) developed on deep loessial deposits and is underlain by an impermeable fragipan. The naturally poorly drained soil has been mole and pipe drained at the Ray property to alleviate water-logging. The paddock chosen for the research (paddock 11) was identified by the farmer as a sloping paddock that had a history of problems associated with overland flow following land applications of FDE using a rotational travelling irrigator. Field inspection, subsequently identified the paddock as having poor soil structural condition likely to impede surface infiltration of water.

.A soil aeration treatment was imposed in a randomised block design on four out of the eight experimental plots established at Clydevale (Figure 1). Soil aeration was carried out on the 15th of March 2005 using a 'James' aerator as described by Drewry *et al.* (2000). In brief, tines were pulled through the soil at 50 cm spacing loosening the soil profile to approximately 25-30 cm depth. The plot dimensions were approximately 90 m by 22 mm.

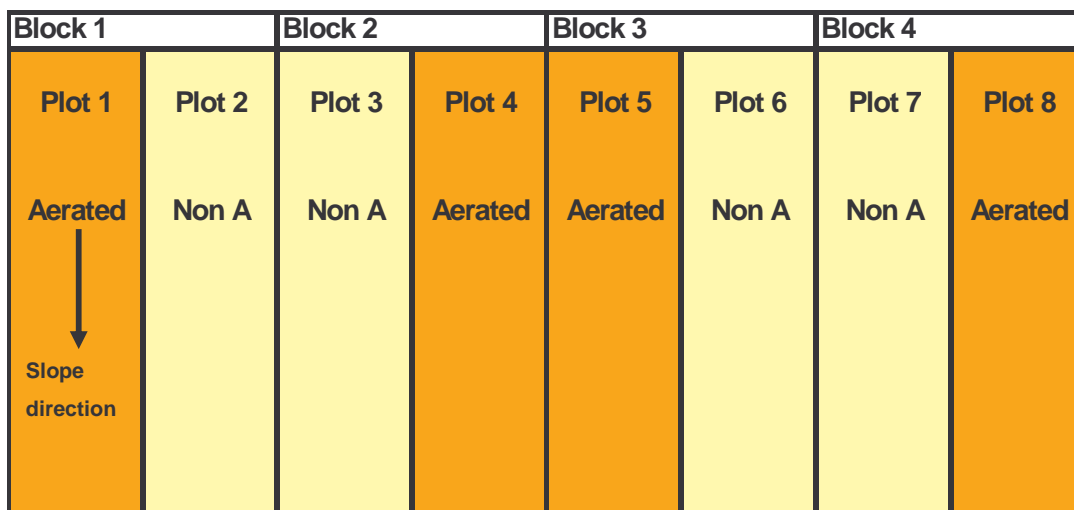


Figure 1. Layout of experimental treatments.

3.2 Soil and water measurements

A range of field, soil physical and water measurements were made at the research site from March to November 2005 and are described in brief below. The activity carried out during each field visit is summarised in Table 1.

Table 1. Summary of field work activities

Activity	Date
Four plots sub-soiled using a James Aerator	15/03/05
Measurement of saturated soil hydraulic conductivity.	23/03/05
Irrigation of FDE using K-Line applicator (7 mm); Measurement of saturated soil hydraulic conductivity.	02/05/05
Irrigation of FDE using rotating irrigator (19.7 mm); Bulk density measurements performed.	30/05/05
Irrigation of FDE using K-Line applicator (12.4 mm); Field assessment of surface infiltration rates.	10/06/05
Irrigation of FDE using K-Line applicator (3.4 mm). Field assessment of surface infiltration rates.	17/08/05
Irrigation of FDE using K-Line applicator (11.9 mm). Field assessment of surface infiltration rates.	25/11/05

Saturated hydraulic conductivity (K_{sat}) measurements were determined 8 days following soil aeration on the 23rd of March, and again on the 2nd of May at the time of the first application of FDE in an attempt to quantify treatment differences following aeration. Initially six 5 cm depth cores were taken per plot on the 23rd of March; this number was doubled for later collection on the 2nd of May. On the aerated plots, cores were taken at

12.5 cm distance from the tine slot so as to avoid extreme values of water movement through large cracks in the soil. Cores were then returned to the lab and analysed for saturated hydraulic conductivity in the manner described by Drewry and Paton (2000).

Soil bulk density cores were collected on 30 May at the same time as the second application of FDE was made to the trial plots. Six 5 cm deep cores were collected per plot as a series of three pairs and taken back to the lab for analysis of weight per unit volume (Hillel 1980).

In-field surface infiltration measurements were made at the time of FDE applications on 10 June, 17 August and 25 November using a disk permeameter to measure a falling column of water as described by Perroux and White (1998).

FDE was applied to the research plots on five occasions between May and November 2005 to represent a range of different irrigation rates, application depths and soil moisture conditions. Application depth and uniformity was assessed at each irrigation event by the placement of a collection tray transect line across the path or expected wetted footprint for each irrigator type. Application rate for K-Line applications was calculated as a function of depth and time to apply FDE. Literature values were obtained for the rotating travelling irrigator (Houlbrooke et al. 2004b).

Antecedent and post-irrigation soil moisture contents were determined at the time of each FDE application event. Gravimetric soil water content was determined as the mass of water per mass of dry soil and converted to volumetric content by multiplying against the soil bulk density.

Overland flow volumes generated as a result of FDE irrigation were determined on a micro-plot scale by the placement and insertion of 4 m² frames that isolated surface runoff into a 20 litre collection container (Photo 1). One frame was inserted into each trial plot (4 aerated and 4 non-aerated).

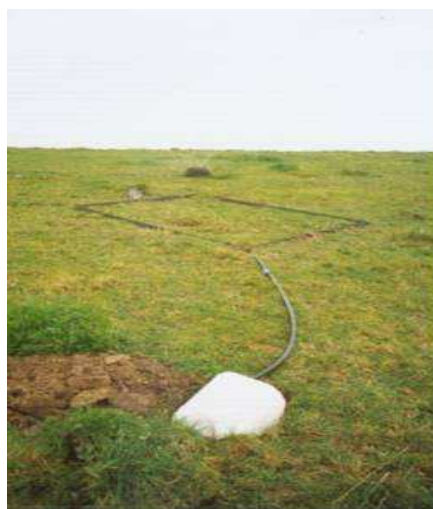


Photo 1. Collection tray for overland flow

Overland flow samples were taken back to the laboratory for analysis of nutrient concentration in particular Ammonium-N, Total N and Total P contents. Analysis took place using flow injection analysis on a Foss FIA 500 (Foss Teactor AB, 2001).

3.3 Statistical analysis

Soil physical data and overland flow volumes were analysed by Analysis of Variance with a randomised block design using the statistical package Genstat (Genstat Committee 8.0 2005). Statistical analysis of K_{sat} and surface infiltration measurements was performed on log transformed data.

4. Results

4.1 Soil physical properties

Three different soil physical properties were analysed to determine if any treatment differences existed following soil aeration to half of the experimental plots. K_{sat} cores taken at an eight day and seven week interval following soil aeration showed no significant treatment difference, with P values of 0.78 and 0.74, respectively (Table 2). Soil bulk density cores taken at 0-5 cm depth 11 weeks following the soil aeration process showed a trend of lower bulk density in the aerated treatment (1.15 vs. 1.19 $Mg\ m^{-3}$). However this was not significant at the 5% level (P value = 0.08). Following the lack of treatment difference measured using K_{sat} cores, the movement of soil water was determined by field surface infiltration measurements 12, 18 and 31 weeks following soil aeration. No significant difference ($P < 0.05$) between treatments was observed for any of the surface infiltration measures. there was however a trend of greater surface infiltration in the aerated plots (P value 0.08) on the 17th of August approximately 18 weeks following soil aeration (Table 2).

Table 2. Summary of soil physical properties measured

Property	Treatment	Measurement date during 2005					
		23 Mar	02 May	30 May	10 Jun	17 Aug	25 Nov
Ksat (mm/hr)	Aerated	124	260	-	-	-	-
	Non-Aerated	164	293	-	-	-	-
	P value	0.78	0.74	-	-	-	-
Bulk density (Mg/m^{-3})	Aerated	-	-	1.15	-	-	-
	Non-Aerated	-	-	1.19	-	-	-
	P value	-	-	0.08	-	-	-
Surface infiltration (mm/hr)	Aerated	-	-	-	60	167	132
	Non-Aerated	-	-	-	24	71	138
	P value	-	-	-	0.16	0.08	0.57

4.2 Farm dairy effluent irrigations

A K-line effluent application of 7 mm running for two hours continuously was made on 2nd May (Photo 2). This resulted in only one non-aerated plot generating less than 0.5 mm of overland flow (Table 3). Application distribution using two lines of K-Line pods at 15 m distance is presented in Figure 2.

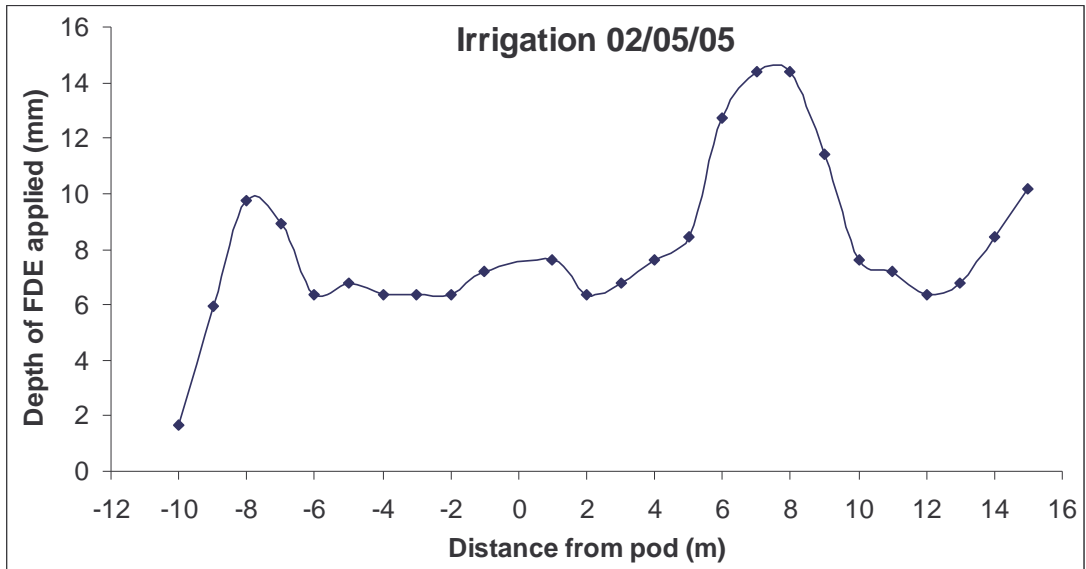


Figure 2. Application uniformity from a K-Line pod. Depths to the left of the centre of the pod represent the distribution pattern from one pod whilst depths to the right of the centre of the pod include inputs from an up -slope line of pods.



Photo 2. K-Line pods irrigating FDE at the Clydevale trial site.

Table 3. The generation of overland flow, as a percentage of FDE applied, on five different occasions under different irrigator types, application depths and soil moisture conditions.

	Irrigator	Soil moisture v/v, %	Depth (mm)	Rate (mm/hr)	% overland flow		
					Non- Aerated	Aerated	LSD
2-May	K-Line	37	7	3.5	1	0	-
30-May	Travelling	58	20	132	81	22	31
10-Jun	K-Line [#]	55	12	3.1	49	1	31
17-Aug	K-Line*	55	3	0.7	0	0	-
25-Nov	K-Line [#]	35	12	3.0	0	0	-

* Intermittent pumping to deliver FDE during six cycling intervals of 20 minutes on: 30 minutes off.

Nearly continuous pumping (50 min on, 10 min off).

The application of nearly 20 mm of FDE in late May 2005 using a rotating twin gun travelling irrigator (Photo 2) resulted in the considerable generation of overland flow (Photo 3) and a significant treatment difference ($P < 0.05$) between aerated (17% of applied FDE) and non-aerated (78% of applied FDE) plots (Table 3). The application distribution using a rotating travelling irrigator is presented in Figure 3. A nearly continuous application of 12 mm of FDE (50 min on, 10 min off) using a K-line system on the 10th June 2005 resulted in a further significant difference ($P < 0.05$) between treatments, with 44% of applied FDE generated as overland flow on the non-aerated plots compared to 5% from the aerated plots (Table 3). A comparison of irrigator hardware demonstrates a significant difference ($P < 0.05$) between the 10 June application using K-Line and the 30 May application using a travelling irrigator.



Photo 2. Effluent application to the field site using a rotating travelling irrigator. An overland flow collection frame can be seen at bottom of photo.



Photo 3. Part of a collection frame with overland flow visible.

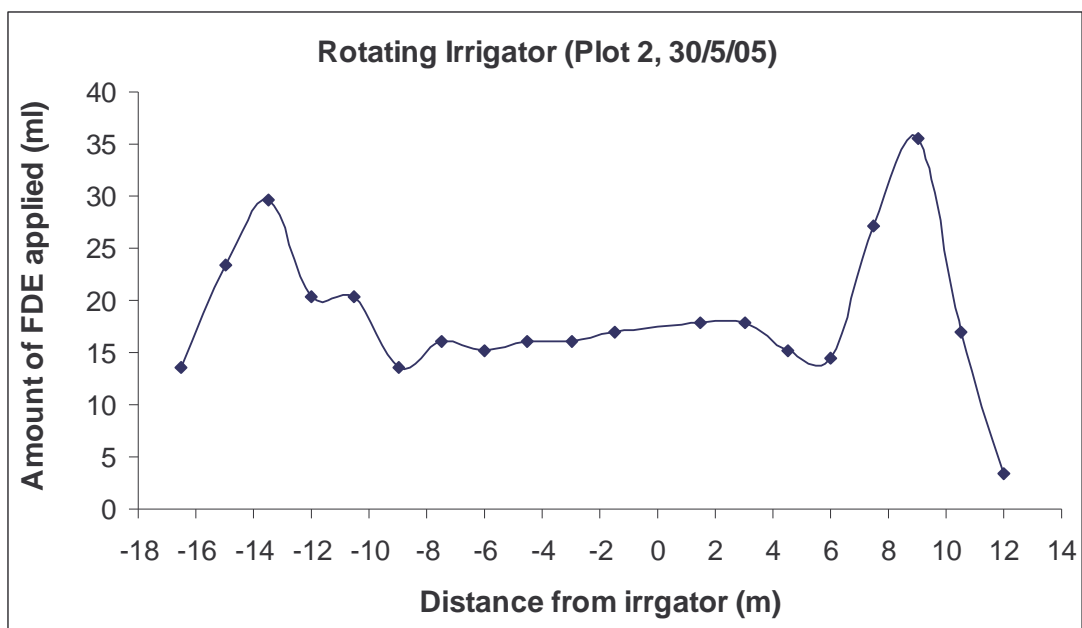


Figure 3. Application uniformity from a rotating travelling irrigator.

A further application of FDE was made using the K-line system in mid August 2005 when the soil was close to field capacity/saturation (Table 3). An intermittent pumping cycle of 20 minutes on followed by 30 minutes off over six cycles was employed. This total of two hours of running time resulted in an application depth of 3 mm, spread out over four hours duration. This depth was lower than expected due to the windy conditions experienced. It appeared that approx. half of the applied FDE drifted outside the tray collection areas, which were located within a 10 m radius of the irrigation pods.

A final application of 12 mm of FDE was made on the 25th of November using K-Line in a nearly continuous fashion (50 min on, 10 min off). With only moderate soil moisture status (35% v/v) this larger application depth resulted in no overland flow from either treatment (Table 3).

4.3 Nutrient losses in overland flow

The concentrations of ammonium N, Total N and P in overland flow generated on the 30th May were close to those measured in the FDE applied via a travelling irrigator (Figure 4). In contrast, the relative concentrations of ammonium N, Total N and P in overland flow generated following the application of FDE using a K-line system on 10 June were considerably lower and ranged from approximately 20 to 45% of the concentrations measured in the applied FDE.

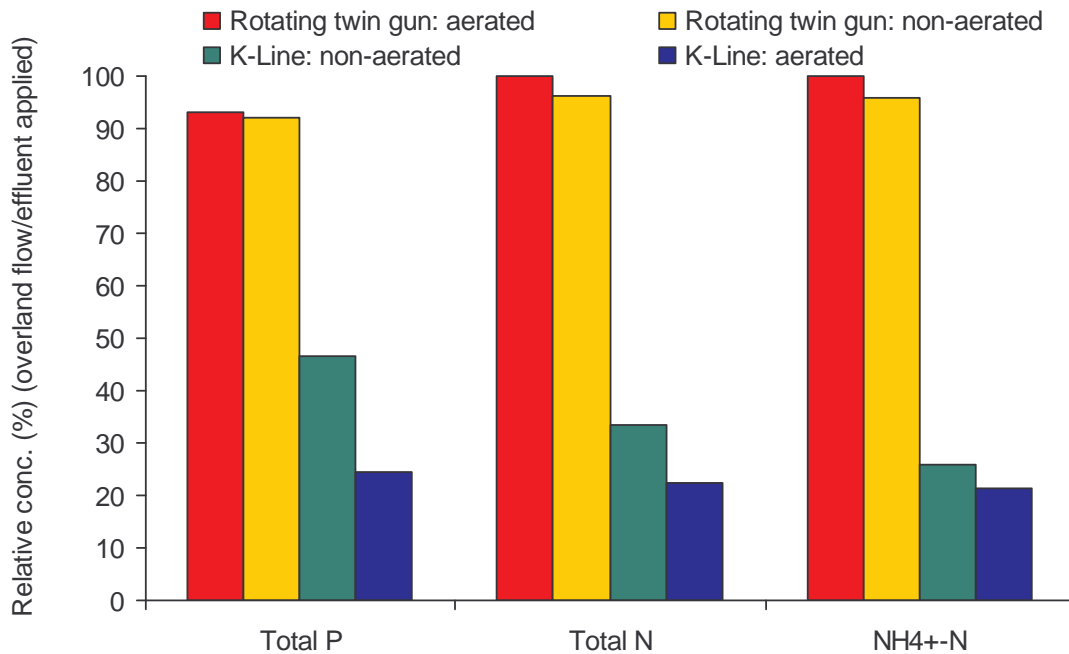


Figure 4. The relative concentration of nutrients in overland flow generated from FDE application using a standard twin gun travelling irrigator compared to a K-line system.

Similar treatment and irrigator type effects were evident when nutrient loss data expressed as a percentage of nutrient loading applied as FDE. A significant increase ($P < 0.05$) in nutrient loss was evident from overland flow generated following FDE application with the rotating travelling irrigator compared to the K-Line irrigator. A further significant increase ($P < 0.05$) in nutrient loss was evident between the aerated and non-aerated soil treatments when FDE was applied using the rotating travelling irrigator. This effect was however only present for Total P when applied using the K-Line irrigator.

Table 4. Percentage of nutrients lost in overland flow following the application of FDE using a standard twin gun travelling irrigator or a K-line system.

	Total P	Total N	NH ₄ ⁺ -N
Rotating twin gun: aerated	21	24	23
Rotating twin gun: non-aerated	75	76	77
K-Line: aerated	<1	<1	<1
K-Line: non-aerated	20	15	11
LSD(P<0.05)	19	18	24

5. Discussion

5.1 Soil physical properties

Some previous studies have measured soil physical property treatment differences following soil aeration using a James aerator (Burgess et al. 2000, Drewry et al 2000, Drewry and Paton 2000). In contrast to these studies the measurement of K_{sat} , surface infiltration and bulk density at the Clydevale research site indicated that there was no significant difference in soil physical properties between the aerated and non-aerated plots. This finding is however similar to that of Houlbrooke (1996) who also measured no treatment difference between aerated soil (using a James Aerator) and non aerated soil. This was attributed this to the drier than optimum soil condition at the time of aeration causing irregular soil disturbance and plant damage. Similarly the soil moisture content at the time of aeration for this study (approximately 20-25% v/v) may have been lower than optimum, therefore limiting the potential effectiveness of aeration on the physical condition of the soil. Another likely cause for the initial lack of treatment effect may have been that both K_{sat} and bulk density cores were taken at the soil surface (0-5 cm) when the greatest zone of soil disturbance is commonly between 10-20 cm depth (Burgess et al. 2000, Drewry et al. 2000). Over time it is expected that the benefits of soil aeration will decrease. Burgess et al. (2000) predicted that soil will have repacked to its original state within 40 weeks of mechanical soil aeration.

5.2 Farm dairy effluent irrigations

The application uniformity from the K-Line irrigator was considerably better than the travelling irrigator when no overlap to the wetted pattern was encountered by a nearby pod. It is therefore recommended that when using K-Line technology to irrigate FDE that the industry standard of 15 m pod spacing is increased to 20 m so that the 10 m diameter wetted footprint does not overlap with other pods thus creating unavoidably high application peaks.

FDE applications were made at a range of different application depths, rates (intermittent pumping regimes and irrigator types) and soil moisture contents. By analysing antecedent and post irrigation moisture depths in relation to estimated Field Capacity it is possible to make logical conclusions regarding the mechanism and cause of overland flow generation (Figure 5).

On 2 May, only a very small amount of overland flow was generated (approx. 1% of FDE applied) from the non-aerated plots. This is not surprising considering the soil moisture content at the time of application was only 37% v/v and ended up at approx. 40% v/v, still 16% lower than estimated field capacity.

The application on 30 May using a rotating travelling irrigator applied FDE at a high rate and depth and resulted in considerable overland flow generation. The mean moisture content at the time of application (50%) was close to Field Capacity (approx. 56%) and hence little deficit was available for water storage. The post-irrigation moisture content was greater than estimated Field Capacity suggesting that a likely mechanism for overland flow generation was saturation-excess runoff (Figure 5). Furthermore, the significant difference observed between treatments is likely due to the mechanical loosening aerated plots were subjected to at the time of 'aeration', which would have created more pore space and drainage capability. The K-Line application brought soil moisture conditions very close to Field Capacity, with a relatively high application depth on 10 June resulting in the generation of considerable volumes of overland flow. Observations and field measurements revealed that a high proportion of overland flow was generated during the second half of the irrigation event, presumably once saturation-excess conditions prevailed.

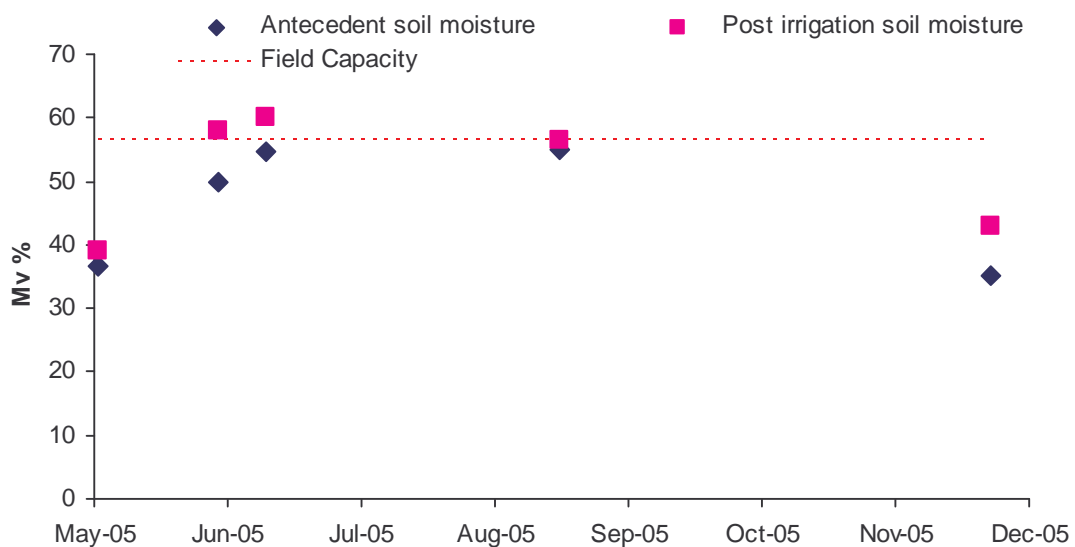


Figure 5. Antecedent and post irrigation soil moisture contents for each application FDE (% by soil volume).

A further application of FDE was made using K-Line on the 17th of August when the soil was already close to Field Capacity. The lack of any overland flow generation from either soil treatment can be attributed to the low application rate (0.7 mm/hr under intermittent pumping) and depth (3.4 mm/hr), demonstrating the importance of both the control of application depth and rate that a K-line system delivers. A final larger application depth (12mm) in November using K-Line, when there was lower soil moisture content, also resulted in nil overland flow. This demonstrates that applying FDE using a low rate K-Line system to soils with a suitable soil moisture deficit should result in little overland flow losses, either as infiltration-excess or saturation-excess flow on soils with poor infiltration.

5.3 Nutrient losses in overland flow

The low relative concentration of Total P, Total N and NH_4^+ -N measured in overland flow indicates that the lower application rate under a K-line system allows further opportunity for filtration of nutrients in the FDE, compared to that achieved under the high instantaneous rate of application observed under a rotating travelling irrigator. Similarly, the percentage loss of Total P, Total N and NH_4^+ -N measured in overland flow was significantly lower than that measured from the traditional travelling irrigator. This is a function of the greater filtration occurring under K-Line application and the decreased volume of overland flow generated. A further significant difference exists between aerated and non-aerated treatments when FDE was applied using a traditional rotating irrigator. This decrease in percentage nutrient loss from the aerated treatment is related to the significantly lower volume of overland flow generated compared to non-aerated soil. This further confirms that soils on sloping land with poor soil structure are at greater risk of generating overland flow following land application of FDE.

6. Conclusions

In summary, when FDE is applied to saturated soils with little vertical drainage, overland flow will be generated irrespective of application rate or irrigator type. However, under these circumstances control of application depth is important. K-line irrigation allows FDE to be applied at a rate of only 4 mm hr⁻¹ or less under intermittent pumping and as such the duration and hence total depth of application can be easily controlled relative to that which can be achieved using a standard travelling irrigator. Low-rate K-line application of FDE to saturated soil resulted in lower concentrations of nutrients in overland flow than observed under the high instantaneous application rates delivered by a rotating travelling irrigator. Soil aeration proved successful in decreasing the volume of

overland flow generation, most likely due to the improved surface infiltration and soil structure resulting from this treatment.

7. Acknowledgments

Thank you to Stephen and Judith Ray for the use of their property and for help with the application of effluent. Thank you to Charlotte Nicholson for considerable field assistance plus laboratory and data analysis. Thanks also to Sietse Schouwenars and Stijn van Dongen for field assistance. Thank you to the Clutha Agriculture Development Board 'Dairy Advisory Group' for advice and to Bruce Monaghan (ORC) for soil moisture data. This study was funded by the Sustainable Farming Fund. Finally thanks to Ross Monaghan (AgResearch) for advice throughout the trial and for reviewing this report.

8. References

- Burgess, C.P., Chapman, R., Singleton, P.L., Thom, E.R. 2000. Shallow mechanical loosening of a soil under dairy grazing: Effects on soil and pasture. *New Zealand Journal of Agricultural Research* 43: 279-290.
- Drewry, J.J., Paton, R.J. 2000. Effect of subsoiling on soil physical properties and pasture production on a Brown soil in Southland, New Zealand. *New Zealand Journal of Agricultural Research* 43: 259-268.
- Drewry, J.J., Lowe J.A.H, Paton, R.J. 2000. Effect of subsoiling on soil physical properties and pasture production on a Pallic soil in Southland, New Zealand. *New Zealand Journal of Agricultural Research* 43: 269-277.
- Foss Tecator AB (2001) online: *Determination of nitrate, nitrite and total nitrogen in water using Fiastar 5000*
[.http://www.foss.dk/files/productfamilyfiles/Brief5233_ftec.pdf](http://www.foss.dk/files/productfamilyfiles/Brief5233_ftec.pdf). (downloaded 18 October 2005).
- GenStat (2005) GenStat for Windows. Eighth Edition. VSN International Ltd., Oxford
- Hewitt, A.E. 1998. New Zealand soil classification 2nd ed. Lincoln, New Zealand. Manaaki Whenua - Landcare Research New Zealand Ltd Press.
- Hillel, D. 1980: Fundamentals of soil physics. London, Academic press. 413 p.
- Houlbrooke, D.J. 1996. Subsoiling and soil compaction effects on soil physical properties and pasture response. Unpublished MSc. thesis. The University of Waikato, Hamilton. New Zealand
- Houlbrooke, D.J., Horne, D.J., Hedley, M.J., Hanly, J.A., Scotter, D.R., Snow, V.O. 2004a. Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research* 47: 405-415.
- Houlbrooke, D. J., Horne, D. J., Hedley, M. J., Hanly, J. A. 2004b. Irrigator performance: assessment, modification and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research* 47: 587-596.

- LIC. 2003. Dairy Statistics. Livestock Improvement Corporation, Hamilton, New Zealand.
- Monaghan, R.M. and Smith, L.C. 2004. Minimising surface water pollution resulting from farm-dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research* 47: 417-428.
- Perroux, K., White, I. 1998. Designs for disk permeameters. *Soil Science Society of America Journal* 52: 1205 -1215.