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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

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Abstract There is little information available on the magnitude of nutrient losses to surface water from the two-pond and daily irrigation treatment systems for farm-dairy effluent (FDE). A research site has been established on a mole-pipe drained Tokomaru silt loam at Massey University's No. 4 Dairy Farm (475 cows) to investigate some of these issues. The site consists of four plots (40 × 40 m) that have been instrumented to allow the continuous monitoring of drainage and surface runoff. The research was conducted over three lactation seasons (2000/01–2002/03). Based on data collected at the study farm it was calculated that in the past 1500 kg N yr^{-1} and 250 kg P yr^{-1} were potentially discharged from the two-pond system directly to a stream. A simulation exercise suggests that approximately 108 kg N yr^{-1} and 18 kg P yr^{-1} would be lost to surface waters if daily irrigation was practised at the farm. The problems of daily irrigation, particularly those related to surface runoff, were further quantified in an experiment in which a single 25-mm FDE irrigation was applied to a soil near field capacity. Approximately 40% of the applied effluent left the soil profile as mole and pipe drainage and 30% as surface runoff. These losses equated to 12 kg N ha^{-1} and 2 kg P ha^{-1}. To minimise nutrient losses from land application of FDE, a system called "deferred irrigation" was designed. Deferred irrigation involves storing effluent in a two-pond treatment system and then applying it strategically when there is a suitable soil water deficit, i.e., the irrigation volume does not exceed the potential soil-water storage. The evaluation of deferred irrigation over three lactation seasons showed that direct losses of nutrients to surface waters were almost eliminated and resulted in the drainage of only approximately 1% of the total effluent nutrients applied. The successful adoption of the deferred irrigation system would require only the capability to store effluent and model or measure soil moisture status within the active root zone.

Keywords farm-dairy effluent; spray irrigation; nutrient loss; soil water balance; mole drainage; pipe drainage; preferential flow

INTRODUCTION

The impact of dairy farming on the aquatic environment has come under increasing scrutiny in recent times. It is widely believed that intensive dairy farming is responsible for accelerated contamination of waterways by nutrients, suspended solids, pathogenic organisms, and faecal matter (Sharpley & Syers 1979; Monaghan et al. 2002; Houlbrooke et al. 2003). In particular, farm-dairy effluent (FDE) is implicated as a major contributor to the degradation of surface water quality (Ledgard et al. 1996; Sukias et al. 2001). Poorly managed FDE land-treatment systems may generate nutrient-rich surface runoff and drainage waters which have the potential to pollute surface and ground waters (Macgregor et al.

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1979; Di et al. 1998; Singleton et al. 2001). In addition, high effluent loads may decrease soil quality (Cameron et al. 1997).

The standard aerobic-anaerobic two-pond treatment system efficiently reduces the sediment load due to settling and the biological oxygen demand of FDE where excess oxygen produced by algae is used by bacteria to break down effluent, but discharge from ponds to surface water typically has a high concentration of nutrients (Longhurst et al. 2000; Sukias et al. 2001). Consequently, the direct discharge of effluent from the two-pond treatment system to surface water is being phased out by regulatory authorities (Cameron & Trenouth 1999). Spray irrigation of FDE to land is considered to be a major improvement on the two-pond system which discharges directly to surface water, and accordingly, land treatment is the preferred treatment option of regulatory authorities (Heatley 1996).

In most cases, regulatory authorities attach conditions to land application of FDE, including setting minimum sizes for treatment areas based on cow numbers and maximum nitrogen loading rates (usually 150–200 kg N ha^{-1} yr^{-1}). In addition, some attention is given to the hydraulic loading of the soil to restrict or prevent surface water ponding (Heatley 1996). However, the conditions imposed by regulatory authorities are too general and lacking in soil-specificity to help farmers schedule spray irrigation of FDE and minimise the risk of nutrient loss in surface runoff and drainage.

Many farmers need to spray-irrigate raw (untreated) FDE daily, irrespective of soil moisture conditions, because they have no or limited storage facilities. Under these circumstances, direct drainage of effluent is likely in spring and late autumn when the soil is close to, or at, field capacity. These problems can be further exacerbated when FDE applications are made to soils with drainage limitations where there is the risk of generating runoff. Also, when FDE is applied to soils that are artificially drained with mole and pipe systems, such as is common in many of the dairy-farmed areas of the Manawatu and other regions of New Zealand, there is the risk that FDE will move quickly through the preferential flow paths above mole channels before exiting pipes into surface waters (Scott et al. 1998).

To date, there has been no published research in New Zealand documenting the direct loss of spray-irrigated FDE to freshwater bodies via surface runoff. The high instantaneous application rates of many travelling irrigators means that, at larger application depths, ponding and surface runoff of effluent may occur. Also, the nutrient composition of effluent lost as surface runoff is likely to be greater than that of effluent lost as drainage because there will be fewer opportunities for chemical (sorption) and biological (plant uptake) processes to remove nutrients from effluent that runs across the soil surface. Although we refer to the “drainage and runoff of FDE” throughout this paper, we acknowledge that the drainage and runoff that results from FDE irrigation is not likely to be undiluted FDE but will be the product of a complex set of interactions—involving mixing, dilution, and displacement—between applied FDE and resident soil moisture.

Land treatment of FDE is still a relatively new technology and many farmers experience difficulties implementing effective systems. There are currently no rigorous criteria (based on soil water status) for the day-to-day management of effluent irrigation, particularly in difficult situations, such as those presented by imperfectly drained soils with established mole and pipe drainage. Therefore, it is not surprising that anecdotal evidence suggests that current land-treatment practices for FDE are causing nutrient enrichment of surface waters via runoff or rapid movement through artificial drainage systems. It is clear that when FDE irrigations are carried out frequently in the late-winter/spring period, irrespective of soil water status, there is a clear risk to the aquatic environment from nutrient loss.

As stated above, the maximum effluent irrigation rate is commonly set so that the nitrogen loading of land does not exceed 150–200 kg N ha^{-1} yr^{-1}. When the maximum amount of FDE is applied to soils, K is added at rates of 120–160 kg ha^{-1} yr^{-1}, which is far in excess of the 50–90 kg K ha^{-1} yr^{-1} required for maintenance of K reserves in the soil (Roach et al. 2001). When K is applied to dairy farm soils at rates that are far greater than maintenance requirements, the increase in K levels in spring-time pasture, and the concomitant decrease in calcium and magnesium in the cows’ diet, can induce metabolic disorders in cows, particularly milk fever (hypocalcaemia) and ryegrass staggers (hypomagnesaemia) (Roach et al. 2001; Tillman & Surapaneni 2002).

To help overcome the problems associated with the spray irrigation of FDE to artificially drained soils and soils with drainage limitations, an improved treatment system called “deferred irrigation” has been developed. Deferred irrigation is a synthesis of current scientific knowledge and best management practices into a comprehensive package that allows farmers to manage effluent irrigation in a sustainable manner. Deferred irrigation utilises existing resources while streamlining and simplifying the irrigation procedure.

Deferred irrigation involves storing effluent in the aerobic pond of a two-pond treatment system, then irrigating it strategically from the aerobic pond when there is a suitable soil water deficit. Scheduling effluent irrigation when sufficient soil water deficits exist avoids the risks of generating surface runoff or direct drainage of effluent. When applied effluent adds to the pool of plant-available water and not to the pool of drainage water, then the soil-plant system's ability to remove soluble nutrients via plant uptake and immobilisation processes in the soil is maximised. Thus, the application criteria for spray irrigation of FDE if drainage is to be avoided are:

$$E_i + \theta_i Z_R \leq \theta_{FC} Z_R \quad (1)$$

$$E_i \leq Z_R\,(\theta_{FC} - \theta_i) \quad (2)$$

Where E_i is the depth of FDE (mm) applied on day i, Z_R is the effective rooting depth (mm), θ_{FC} is the soil water content at field capacity ($m^3\,m^{-3}$), and θ_i is the soil water content on day i ($m^3\,m^{-3}$).

In many areas of New Zealand, soil water deficits greater than 10 mm usually only occur between the months of October and May, however the generation of FDE starts at the beginning of lactation in late winter (August). Consequently, having sufficient storage for FDE is essential to ensure that spray irrigation only occurs during times when the soil water deficit is adequate.

The first objective of this study was to estimate annual losses of nutrients (N and P) to surface waters from two common FDE treatment systems: a two-pond system and a daily spray irrigation system. The second objective was to quantify the nutrient composition of surface runoff and drainage resulting from a single irrigation of FDE at a rate in excess of the soil water deficit, as might be the case when FDE is applied irrespective of soil water status in a daily land application system. The final objective was to demonstrate the effectiveness of the deferred irrigation system at minimising the risk of direct losses of FDE to surface waters.

MATERIALS AND METHODS

Site and soil

A research site was established in January 2000 on a mole-pipe drained Tokomaru silt loam soil on Massey University's No. 4 Dairy Farm near Palmerston North, New Zealand. The soil, which is classified as an Argillic-fragic Perch-gley Pallic Soil (Hewitt 1998) or a Typic Fragiaqualf (Soil Survey Staff 1998), is derived from deep deposits of loess-blown river sediments which form on a deeply dissected uplifted marine terrace (Molloy 1998). The Tokomaru silt loam soil consists of a weakly to moderately developed, brown, silt loam A-Horizon (c. 0–250 mm soil depth), a weakly developed, grey, strongly mottled, clay loam B-Horizon (c. 250–800 mm soil depth) and a highly compacted, weakly-developed, pale-grey, silt loam fragipan C-Horizon, which acts as a natural barrier to drainage (Scotter et al. 1979a). Most of the effective plant roots were found above the level of the fragipan. The site is located in a flat to easy rolling landscape (c. 3% slope) which receives an average annual rainfall of approximately 1000 mm. The site supports a mixed pasture of perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*). The Tokomaru silt loam was reported by Scotter et al. (1979a) to have a bulk density of 1.1 Mg m^{-3}, a saturated hydraulic conductivity of 32 mm day^{-1}, and a field capacity of 45% v/v at a depth of 0–100 mm. In May 2003, an Olsen P of 40 mg P ml^{-1} was measured for the 0–75 mm depth using the MAF Quick Test method (Cornforth & Sinclair 1984).

The research area consisted of four plots (each 40 × 40 m). Each plot had an individual mole-pipe drain system. Mole drains were installed at 2-m intervals at a depth of 450 mm. Drainage from the mole system was intercepted by a collecting 110-mm perforated pipe drain perpendicular to the mole drains at 60 cm depth. At the corner of each plot, a pit was excavated and a V-notch weir placed at the exit of the pipeline to monitor drainage flow rates. All pits were instrumented with data loggers to provide continuous measurements of flow rate. Any drainage water occurring as a result of the application of FDE was sampled manually from the pipe outlet for water quality analyses. For the 2003 winter drainage season, two of the plots each had an isolated subplot (50 m^2) installed for the measurement of surface runoff. Surface runoff water collected from each subplot passed through a tipping bucket instrument to measure flow rate and to provide a flow-proportioned mixed sample for water quality analyses.

Experimental procedure

Aerobic pond effluent was irrigated onto the plots, in accordance with the deferred irrigation scheduling criteria, for the three lactation seasons (c. 280 days from August to May) between 2000 and 2003. Farm-dairy effluent was applied to the plots by travelling irrigators. In the first two lactation seasons (2000/01 and 2001/02), a Briggs Model 15 rotating travelling irrigator was used and in the third season (2002/03) a Spitfire Mark I oscillating travelling irrigator was used. Adjustable speed settings on the irrigators allowed the depth of the effluent applied to be varied. Irrigations varied in timing and quantity between seasons.

The quantity of direct drainage resulting from the land application of FDE using the deferred irrigation system was monitored immediately following application, and the nutrient (N and P) concentrations in drainage waters were determined during the three lactation seasons. The nutrient concentration of the applied FDE was also measured at each irrigation. The quantity and nutrient concentration of surface runoff was also monitored, where it occurred, in the 2002/03 season. In the simulation study, the concentrations of N and P in effluent exiting the aerobic pond were the mean concentrations of N and P in effluent samples collected under the travelling irrigator during the 2001/02 lactation season.

Near the start of the 2003/04 season, an additional effluent irrigation was made to provide quantitative data on the nutrient composition of effluent lost in surface runoff and drainage in a case when deferred irrigation criteria was not followed, e.g., daily irrigation systems where FDE is applied irrespective of soil moisture conditions. In September 2003, a single irrigation (25 mm depth) of FDE was applied (at a rate of approximately 2.7 mm min^{-1}) to the plots when the soil water deficit was only 6 mm.

Another dictate of the deferred irrigation system, the annual removal of a cut of grass silage, was also practised. For the rest of the time, the plots were grazed according to the farm's normal management programme, i.e., with an average grazing density of approximately 80 cows ha^{-1} for a 12-h period.

Soil water deficits were computed using the soil water balance for Tokomaru silt loam described by Scotter et al. (1979b). The soil water balance was used to predict the likelihood of drainage of FDE when it was applied to land at 30 mm day^{-1} on a daily basis throughout the lactation season. Scotter et al.'s (1979b) model uses the Priestly and Taylor method to calculate evapotranspiration and requires the key parameters of daily rainfall, solar radiation, and air temperature in order to predict soil water deficits, drainage, and runoff.

Nutrient analyses

The following analyses was conducted on samples of the FDE applied at each irrigation, and on any resulting drainage samples (and runoff on one occasion) captured from each of the experimental plots. The analyses included: suspended solids, total phosphorus (P) and total dissolved P (TDP), dissolved inorganic P (DIP), total nitrogen (TN), total dissolved nitrogen (TDN), nitrate-N (NO_3^--N), and ammonium-N (NH_4^+-N). Total N and TDN were calculated by adding NO_3^--N values to those of Kjeldahl-N and dissolved Kjeldahl-N. Analyses were carried out calorimetrically on a Technicon Auto Analyser II using the following methods: Kamphake et al. (1967) using a hydrazine reduction for NO_3^--N; Searle (1975) for NH_4^+-N; McKenzie & Wallace (1954) for Kjeldahl-N and dissolved Kjeldahl-N following a Kjeldahl acid digest; and Murphy & Riley (1962) for analyses of DIP. Total P and TDP were determined by the Vanadomolybdate method (AOAC 1975) following a Kjeldahl acid digest as described by McKenzie & Wallace (1954). All measures of dissolved nutrients were determined on samples passed through a 1.2 µm glass filter paper. The variability in measured data was quantified using the standard error of means (SEM) from four replicates.

RESULTS AND DISCUSSION

Theoretical analysis of two effluent treatment systems

Two methods of treating FDE, the two-pond system with direct discharge to surface water and daily irrigation, vary in their ability to prevent effluent-derived nutrients from contaminating surface waters. Provided below are estimates of losses of nutrients from these types of treatment systems on an annual basis.

Two-pond treatment of FDE and discharge to surface water

The two-pond treatment system at Massey University's No. 4 Dairy Farm receives approximately 10 000 m^3 yr^{-1} of wastewater. This wastewater consists of the farm dairy cleaning and wash-down water containing the dung and urine associated with the milking of 490 cows (assumed to be 50 litres cow^{-1} day^{-1}; Vanderholm 1984), plus rainfall landing on the farm dairy, yards, and a large feed pad. The average N and P concentrations of the effluent in the aerobic pond (second pond) were 150 mg N litre^{-1} and 25 mg P litre^{-1}. In the past this effluent was discharged directly to a stream, adding approximately 1500 kg N yr^{-1} and 250 kg P yr^{-1} to the aquatic environment.

Daily spray irrigation of FDE

Due to limited, or lack of, storage facilities for FDE on many dairy farms, FDE may need to be applied on a daily basis irrespective of climate and soil moisture conditions. Consequently, immediate losses of nutrient-rich FDE to surface waters, in either direct drainage or surface runoff, could be expected.

To identify the potential for daily FDE applications to generate direct drainage or runoff, the soil water balance for No. 4 Dairy Farm was simulated using past climate data for the 10-year period from 1991 to 2001 (Scotter et al. 1979b). A typical lactation period for No. 4 Dairy Farm, 280 days, was assumed. In this simulation, a standard rotating travelling irrigator was assumed to apply a mean depth of 30 mm of effluent at each application. This is a common application depth used by farmers. The poor application uniformity under the rotating irrigator (Houlbrooke et al. 2004) is accounted for in the simulation using the procedure described by Houlbrooke et al. (2004).

Results from the simulation suggest that under daily FDE irrigation, on average, 16% of the total annual volume of FDE reaches surface water as either direct drainage or surface runoff. Losses of FDE under daily irrigation would have been less if a lower application depth than 30 mm had been used in the simulation (Houlbrooke et al. 2004). Typically, the majority of these losses under daily irrigation occur in the late-winter/spring period when soil water deficits tend to be less than 10 mm or non-existent. If nutrient concentrations in the FDE were undiluted during its passage across the soil surface or through macropore drainage channels, then an annual loss of 16% of FDE to surface waters would add approximately 240 kg N yr^{-1} and 40 kg P yr^{-1} to the aquatic environment. However, it is unlikely that the FDE lost in direct drainage or surface runoff will have nutrient concentrations identical to the applied FDE because some dilution or treatment can occur as it passes through or across the soil profile.

The extent of treatment, mixing, and dilution undergone by effluent as it moves through and across the soil is described below. In an experiment conducted at the site, the average concentrations of TN and TP of the effluent volume that directly drained were 45% of the original effluent applied. In comparison, the nutrient concentration in surface runoff was c. 80% of concentration of TN and TP originally applied as FDE. As the model (Scotter et al. 1979b) does not differentiate between drainage and runoff volumes, for the purpose of calculating nutrient losses here it is assumed that all the excess effluent drains through the soil. For this best case scenario of zero surface runoff, the annual losses of TN and TP from the simulated daily application of FDE would be 45% of the applied effluent concentrations, which equates to 108 kg N yr^{-1} and 18 kg P yr^{-1}. If these total losses were spread over an area of 16 ha (the area irrigated with FDE at No. 4 Dairy Farm), they would equate to about 7 kg N ha^{-1} yr^{-1} and 1 kg P ha^{-1} yr^{-1}. If it had been possible to simulate the surface runoff that accompanied daily irrigation, these nutrient losses would have been considerably greater.

The losses estimated here for daily irrigation are significantly smaller than nutrient losses to surface waters from the traditional two-pond system. However, daily irrigation still poses an unacceptable risk of contamination to the aquatic environment, which potentially, could be reduced by scheduling FDE land application to coincide with soil water deficits.

Spray irrigation of FDE to wet soils

To demonstrate the potential effect of applying FDE to wet soils, the impact of applying 25 mm of FDE to soil with a soil water deficit of 6 mm was measured. As a consequence of a single irrigation of 25 mm of FDE, there was 10 mm of drainage and 8 mm of surface runoff (Table 1). Approximately 70% of the applied FDE left the experimental plots (about 30% as surface runoff and 40% as direct drainage). With the exception of NO_3^--N, concentrations of different forms of both N and P in drainage were less than half (40–45%) of the corresponding concentrations in applied FDE (Table 1). The concentrations of N and P in drainage were still 550 and 50 times greater, respectively, than the ecologically significant levels (0.1 mg N $litre^{-1}$ and 0.1 mg P $litre^{-1}$) deemed likely to promote aquatic weed growth (Ministry for the Environment 1992). The greater concentration of NO_3^--N measured in drainage water than was applied in FDE may be a result of leaching of NO_3^--N resident in the soil mineral pool at the time of application (Table 1). NO_3^--N leaching has been measured at the experimental site in winter-spring drainage induced by natural rainfall (Houlbrooke et al. 2003).

Concentrations of different forms of both N and P in surface runoff were approximately 80% of the corresponding concentrations in the applied FDE (Table 1). This suggests that where effluent runoff enters surface waters, it does so in a more-or-less unchanged state.

In this single irrigation, 30 kg N ha^{-1} and 4 kg P ha^{-1} was applied to the soil. From this application, over 12 kg of N ha^{-1} (5.1 kg N ha^{-1} in drainage and 7.5 kg N ha^{-1} in surface runoff) and nearly 2 kg of P ha^{-1} (0.8 kg P ha^{-1} in drainage and 1.1 kg P ha^{-1} in surface runoff) was lost to surface water (Table 2). These nutrient losses from a single, badly-managed irrigation are significant, particularly when compared with annual losses from mole and pipe drainage of around 27 kg N ha^{-1} and less than 0.4 kg P ha^{-1} reported by Monaghan et al. (2002) and Houlbrooke et al. (2003) from pastures grazed by dairy cattle without effluent irrigation. In other words, N losses from a single FDE irrigation event to wet soil equate to about 45% of the expected annual loss from grazed dairy pasture, while P losses were at least six times greater than the expected annual loss from grazed dairy pasture.

Principles of deferred irrigation

Soil water and nutrient balance models were used to define the key design parameters of deferred irrigation. The key elements of the deferred irrigation system are:

(a) Effluent is stored in the two-pond system during winter and early lactation when the soil is at or near field capacity.
(b) Daily weather records and computer simulation models are used to track storage pond volumes and soil moisture deficits (Scotter et al. 1979b) to identify opportunities for irrigation.
(c) Effluent irrigation events are strategically scheduled on occasions when soil water deficits are sufficient to prevent drainage of applied FDE (October–May).
(d) Four to six irrigation events per year ranging from 10 to 25 mm depth per event are applied at the appropriate soil water deficit. Early season events are likely to be smaller than late summer events, as soil water deficits are usually small (<10 mm) in the late winter-spring period.
(e) Soil and pasture quality is maintained by removing excess nutrients (particularly K) from the soil-plant system in conserved pasture (hay or silage).

One of the most important requirements for the successful implementation of deferred irrigation is the capacity to store effluent produced in the early-winter/spring period when soil moisture deficits are small (<10 mm) or non-existent. Soil water balances for the Tokomaru soil were computed for the period 1991–2001. In most years, a soil water deficit suitable for the application of FDE (for example, 25 mm) would not develop until at least October. For the period from commencement of lactation to the middle of October, approximately 4000 cubic metres of aerobic pond storage would be required at Massey University's No. 4 Dairy Farm to accommodate the wash-down water (475 cows requiring approximately 50 litres of water cow^{-1} day^{-1}) plus the rainfall onto yards, feed pad, and ponds minus evaporation from the ponds. This assumes that the ponds are empty at the end of the previous lactation season.

A further key to the successful adoption of a deferred irrigation system is the accurate monitoring

Table 1 Average flow-weighted nutrient concentrations of the applied farm-dairy effluent (FDE), drainage, and surface runoff associated with an irrigation of FDE when the soil was close to field capacity in September 2003. Values in brackets indicate SEM from four replicates. TDP, total dissolved P; DIP, dissolved inorganic P; TN, total nitrogen; TDN, total dissolved nitrogen; NO_3^--N, nitrate-N; NH_4^+-N, ammonium-N.

	Average concentration (mg litre^{-1})		
Nutrient form	Applied FDE	Mole and pipe drainage	Surface runoff
TN	122.4 (3.5)	55.8 (3.5)	95.3 (1.9)
TDN	84.7 (3.2)	43.2 (6.1)	69.4 (1.9)
NH_4^+-N	71.7 (2.1)	27.1 (3.6)	55.9 (1.3)
NO_3^--N	0.08 (0.04)	0.67 (0.27)	0.06 (0.02)
TP	17.9 (0.5)	8.5 (0.6)	15.7 (1.3)
TDP	12.0 (0.6)	5.0 (0.7)	9.4 (1.2)
DIP	8.8 (1.4)	3.0 (0.4)	6.8 (0.5)
Volume	25 mm	10 mm	8 mm

of soil moisture status or the soil's ability to store effluent. The alternative to modelling the soil water deficit is the direct measurement of soil moisture contents. There are a number of instruments available—for example, probes using time domain reflectometry measure the soil moisture content *in situ* and can assist farmers in scheduling irrigation of FDE.

Bond (1998) argues that there is likely to be a gap between the design of an effluent irrigation scheme and its implementation. He suggests that effluent irrigation is unlikely to be implemented as prescribed because of imprecision in scheduling techniques, rain interruptions, problems associated with irrigation hardware performance and maintenance, and spatial variability of infiltration rates. Deferred irrigation is a simple tool that seeks to address some of these problems. It is based on the soil water status, and allows for flexibility in the scheduling of irrigation events.

Measuring drainage and nutrient losses under the deferred irrigation system

For three lactation seasons (2000/01–2002/03), deferred irrigation was implemented at the trial site on Massey University's No. 4 Dairy Farm for the purposes of both research and paddock-scale demonstration. In the 2000/01 season, 130 mm of FDE was irrigated over six events with an average application depth of 22 mm per application (Table 3). This resulted in nutrient applications of approximately 236 kg N $ha^{-1} yr^{-1}$ and 32 kg P $ha^{-1} yr^{-1}$. Whilst some irrigation events generated nutrient-enriched drainage from the mole and pipe drainage network, drainage volumes and nutrient losses were greatly reduced by the use of deferred irrigation. Except for two occasions, irrigation of FDE normally generated drainage volumes less than 1% of the total effluent applied (Table 3). The average volume of drainage leaving the mole and pipe network as a result of FDE applications was 2.6% of the total effluent applied and resulted in the nutrient loss of approximately 3 kg N $ha^{-1} yr^{-1}$ and 0.5 kg P $ha^{-1} yr^{-1}$.

Where drainage occurred following irrigation of FDE, concentrations of TN and TP in the drainage were high. For example, mean concentrations were 44 mg N $litre^{-1}$ and 6 mg P $litre^{-1}$ on 6 December 2000. However, as the practice of deferred irrigation reduced drainage volume, it also minimised the quantity of nutrients that were leached to surface waters. For example, an application of 31 mm of FDE on 6 December 2000 resulted in an average loss per plot of 0.61 kg N ha^{-1} and 0.08 kg P ha^{-1} from an input of 56.5 kg N ha^{-1} and 7.7 kg P ha^{-1}.

In the 2001/02 season, higher than average spring and summer rainfall meant that soil moisture deficits were smaller than what would be considered typical during the summer-autumn period (i.e., deficit < 100 mm) and, therefore, the potential to apply large quantities of effluent in a single irrigation event was very limited (Fig. 1). In the 2001/02 season, 63 mm of effluent was irrigated over seven events at an average of 9 mm depth. This resulted in nutrient applications of 95 kg N ha^{-1} and 16 kg P ha^{-1}. The strategy of irrigating smaller quantities of FDE more frequently resulted in zero drainage of applied effluent through the mole and pipe drainage system, and therefore, no direct loss of nutrients.

In the 2002/03 season, soil moisture deficits were greater than 200 mm due to a prolonged drought.

Table 2 Nutrient inputs, drainage, and surface runoff losses resulting from a single irrigation of farm-dairy effluent (FDE) in September 2003 when the soil was close to field capacity. TDP, total dissolved P; DIP, dissolved inorganic P; TN, total nitrogen; TDN, total dissolved nitrogen; NO_3^--N, nitrate-N; NH_4^+-N, ammonium-N.

	Nutrient quantity (kg ha^{-1})			
Nutrient form	Effluent input	Total loss to freshwater body	Total mole and pipe drainage loss	Total surface runoff loss
TN	30.1	12.6	5.1	7.5
TDN	20.8	8.6	3.2	5.4
NH_4^+-N	17.6	6.4	2.0	4.4
NO_3^--N	0.02	0.1	0.1	0.0
TP	4.4	1.9	0.8	1.1
TDP	3.0	1.0	0.3	0.7
DIP	2.2	0.72	0.22	0.5

New irrigation technology was being tested and so it was decided to experiment with higher application rates again (Houlbrooke et al. 2004). A total of 80 mm of FDE was applied in four separate FDE irrigations at an average application depth of 20 mm per application. FDE irrigation in 2002/03 resulted in nutrient applications of 154 kg N ha^{-1} and 31 kg P ha^{-1}. On one occasion, a drainage volume equivalent to 1.7% of the effluent applied left the mole and pipe network from one of the plots, and on two further occasions a small amount (<1%) of the total effluent applied drained from two of the plots (Table 3). This small amount of drainage is attributable to preferential flow, most likely through cracks immediately above the collecting pipe. The average volume of drainage exiting the mole and pipe network as a result of FDE applications was 0.1% of the total effluent applied for the 2002/03 season. This resulted in a total loss of 0.4 kg N ha^{-1} and 0.08 kg P ha^{-1}, which was < 1% of the TN and TP applied in effluent.

During the 3-year research trial, small amounts of drainage occurred on occasions when the soil moisture deficit at the commencement of the irrigation event was considerably larger than the depth of applied effluent. This drainage can be explained by reference to the variation in application depths under the rotating travelling irrigator and, to a lesser extent, preferential flow under effluent that ponds due to the mismatch between the instantaneous application rate of the irrigator and the soil infiltration rates (Houlbrooke et al. 2004).

When averaged over all three lactation seasons (2000/01–2002/03), FDE application to the soil using the deferred irrigation criteria generated drainage equivalent to 1.1% of the total effluent applied. The average nutrient loss as a result of the direct drainage of FDE following irrigations using the deferred irrigation criteria over three lactation seasons was c. 1.1 kg N ha^{-1} and 0.2 kg P ha^{-1}. This shows that an improved FDE land application system, such as deferred irrigation, can minimise the environmental risk associated with a daily application system. However, if insufficient storage is available to fully implement deferred irrigation practice, then FDE irrigations should be applied at the lowest rates possible during the critical times of the season to reduce the risk to the aquatic environment.

Table 3 The mean depth of farm-dairy effluent (FDE) applied by the irrigator at each of the irrigations, the soil moisture deficit at the commencement of irrigation, the average drainage from all plots over three lactation seasons (2000/01–2002/03), and the maximum drainage from any single plot as a proportion of the applied FDE (i.e., representing the "worst case" scenario). –, no data.

Irrigation date	Effluent applied (mm)	Estimated soil moisture deficit at irrigation (mm)	Average drainage (mm)	Maximum drainage from a single plot as proportion of irrigation (%)
23 Nov 00[a]	27	66	–	–
6 Dec 00[a]	31	63	1.4	14
10 Apr 01[a]	8	195	0	0
10 Apr 01[a]	12	187	0	0
11 Apr 01[a]	25	175	0.1	1
16 May 01[a]	26	117	1.2	6
20 Aug 01[b]	9	30	0	0
24 Jan 02[b]	7	40	0	0
20 Feb 02[b]	9	34	0	0
1 Mar 02[b]	6	53	0	0
11 Mar 02[b]	10	63	0	0
28 Mar 02[b]	13	48	0	0
22 Apr 02[b]	9	47	0	0
19 Nov 02[c]	9	29	0	0
20 Feb 03[c]	24	193	0.2	1.7
13 Mar 03[c]	29	220	<0.1	<1
3 Apr 03[c]	18	230	<0.1	<1

[a] 2000/01 lactation season; [b] 2001/02 lactation season; [c] 2002/03 lactation season.

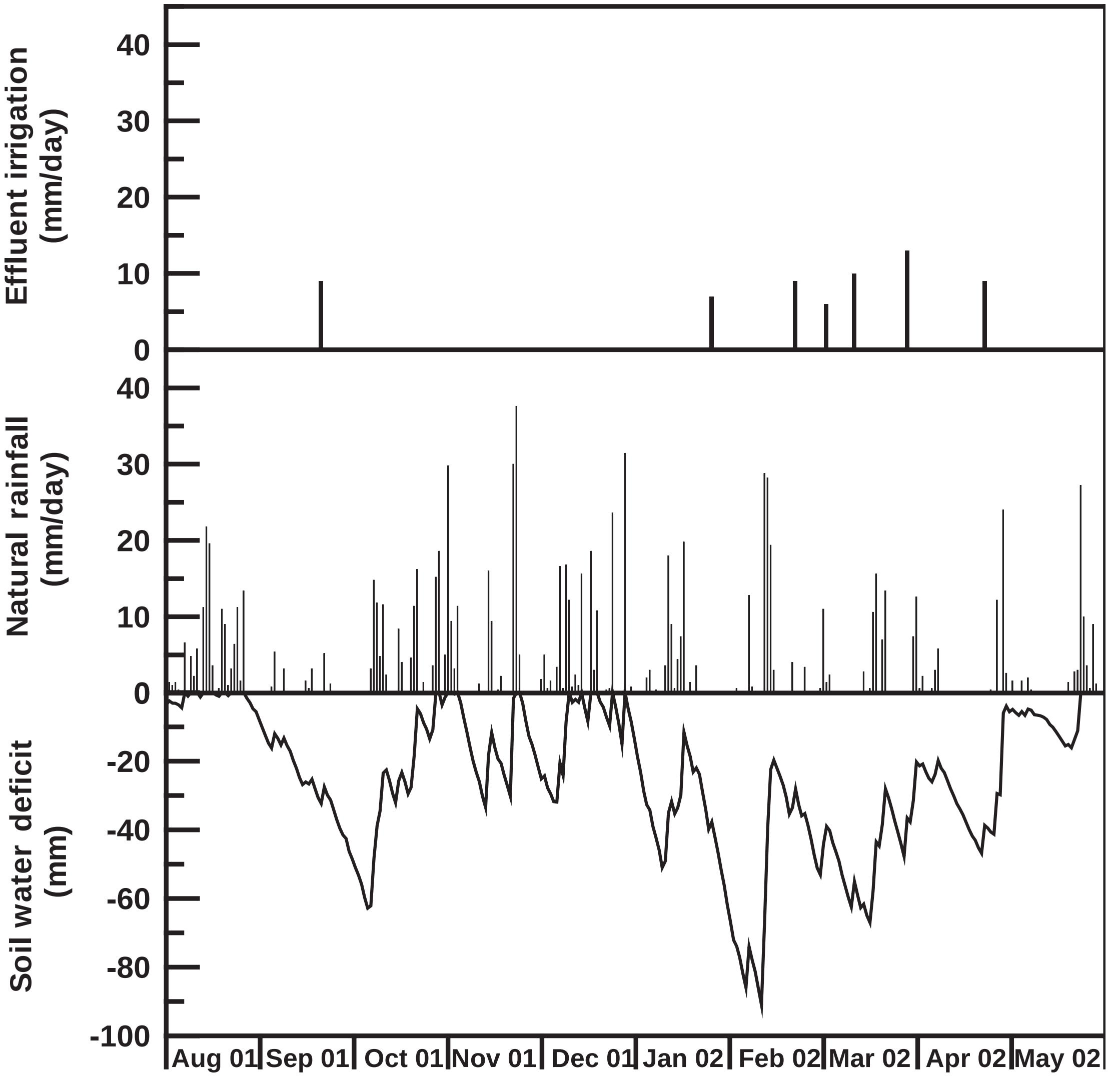

Fig. 1 The timing of irrigations during the 2001/02 season when regular spring and summer rainfall meant that soil moisture deficits remained small throughout the summer.

CONCLUSIONS

Daily spray irrigation of FDE can considerably decrease nutrient loss to surface waters compared with a direct discharge of FDE from the two-pond system to a stream. However, daily application of FDE still represents an unacceptable level of nutrient loss to surface waters. Storage of FDE and spray application only when adequate soil water deficits exist (deferred irrigation) has the potential to prevent direct contamination of drainage and surface runoff with FDE. During the three lactation seasons that deferred irrigation was evaluated, direct losses of nutrients to surface waters were almost eliminated, being on average 0.7% of the total N and 0.3% of the P applied as effluent nutrients. The successful adoption of the deferred irrigation system would require only the capability to store effluent and the ability to model or measure soil moisture status.

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