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Matching farm dairy effluent storage requirements and management practices to soil and landscape features

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Prepared for Environment Waikato

June 2010

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Table of Contents

1. Summary

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, sediment and faecal micro-organisms. In particular, farm dairy effluent (FDE) is frequently implicated as a major contributor to the degradation of surface water quality. 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. The risk of direct contamination of water bodies associated with FDE application is dependent on the transport mechanism of water and, therefore, solutes and suspended solids in the water. Three primary mechanisms exist for the transport of water (containing solutes and suspended solids) through soil: matrix flow, preferential flow and overland flow. Soils that exhibit preferential or overland flow are capable of considerable direct loss of FDE when applications are made when soils are considered too wet (insufficient soil water deficit to store incoming moisture) and/or when the application rate of FDE is too high for the receiving soil's infiltration rate. Preferential and overland flows provide little soil contact time and thus minimal opportunity for the attenuation of the applied contaminants (N, P and faecal micro-organisms). Critical landscapes with a high degree of risk include soils with artificial drainage or coarse soil structure, soils with either an infiltration or drainage impediment, or soils on rolling or hilly country.

Soils that exhibit matrix flow show a relatively low risk of direct loss of FDE, even under moist soil conditions (i.e. field capacity). Matrix flow involves the relatively uniform migration of water through and around soil aggregates (so called 'piston' type displacement) and therefore provides a greater soil contact time and opportunity for nutrient attenuation and filtering of sediments and faecal micro-organisms. Such soils are typically well-drained with fine soil structure and contain high porosity. Research conducted in the Waikato region and throughout New Zealand suggests there is a low risk of direct contamination from FDE applied to well-drained soils provided applications are scheduled to avoid saturated or near saturated conditions. Examples of such low risk soils typically belong to the Allophanic, Pumice, Recent and to a lesser extent, Brown Soil orders that are prevalent in the Waikato region. However, well-drained soils often have an inherently higher N leaching risk associated with the deposition of animal urine patches to land. Therefore, the extent of, and impacts from, N inputs added as FDE to well-drained soils that indirectly leach to groundwater should be kept in context, as FDE typically represents only 5-10% of the daily nutrient output in cattle excreta. Therefore, effective mitigation techniques for N loss on these well drained soils should target the cumulative effects of urine patches deposited during animal grazing.

The effectiveness of current effluent best management practices (BMPs) (deferred irrigation and low application rate tools) varies between soil types depending on their inherent risk of direct contamination from land-applied FDE. Management practices should therefore be targeted where they will be most effective. AgResearch has developed a decision framework to guide minimum management practice requirements that farmers should adopt in order to avoid direct losses of land-applied FDE throughout the lactation season. It is recommended to Environment Waikato that this framework is used to determine soil and landscape risk and subsequent concept storage requirements prior to determining farm-specific storage volumes using the newly developed Pond Storage Calculator.

Introduction

The safe application of farm dairy effluent (FDE) to land has proven to be a challenge for dairy farmers and Regulatory Authorities throughout New Zealand. Recent research has identified that poorly performing FDE systems can have large deleterious effects on water quality, particularly when direct losses of FDE with high concentrations of contaminants (phosphorus, nitrogen and faecal microbes) discharge, drain or runoff directly to surface water bodies (Houlbrooke et al. 2008, Muirhead et al. 2008, Houlbrooke et al. 2004a, Monaghan and Smith 2004). In particular, land application of FDE has proven difficult when it has occurred on soils with a high degree of preferential flow, soils with artificial drainage or coarse structure, soils with infiltration or drainage impediments, or when applied to soils on rolling or hill country (McLeod et al. 2008, Houlbrooke et al. 2006, Monaghan and Smith 2004). The effect of these conditions can be exacerbated by climate, where high rainfall can further contribute to the poor environmental performance of such land application systems. In comparison, well drained soils with fine to medium soil structure tend to exhibit matrix rather than preferential drainage flow, even under soil moisture conditions close to or at field capacity (McLeod et al. 2008). These soils are therefore likely to pose a lower risk of direct loss of effluent contaminants. However, there is only limited research conducted in New Zealand on these lower risk soil types to test the hypothesis that FDE applications when soil water content (SWC) is at field capacity will not result in direct drainage losses. The issue of hydrophobicity and its potential impact on rapid re-wetting of dry, well-drained soils in rolling volcanic landscapes is still somewhat unknown.

A literature review of New Zealand data by Houlbrooke et al. (2004b) on land-applying FDE, and its effects on water quality, showed that between 2 and 20% of both the nitrogen (N) and phosphorus (P) applied in FDE is lost either in runoff or via leaching. It should be noted that this range included indirect losses of N under extremely high nutrient inputs (up to 1518 kg N/ha/yr). Losses of FDE can be measured in the direct drainage of untreated or partially-treated effluent immediately following irrigation events and/or in the indirect drainage that occurs in the following winter/spring period. Indirect losses of nutrients associated with land application of FDE are the result of nutrient enrichment of the soil during the spring-summer-autumn period followed by leaching during the subsequent winter-spring drainage period. Indirect drainage losses therefore reflect a soil's fertility level and cannot be managed using effluent application BMPs. Effluent BMPs have been developed to specifically address the risk of direct drainage losses of effluent contaminants on soils with a critical limitation, as described above. A full description of two key effluent best management practices (deferred irrigation and low rate tools) will be provided in section 3.

AgResearch Ltd has been recently engaged to provide management advice to Regional Councils (Horizons Regional Council, 2008, Environment Southland, 2009, Environment Bay of Plenty, 2010) regarding the effectiveness of effluent best management practices (BMPs) and the importance of soil and landscape risk features when applying FDE to land. During this process a risk framework/decision tool was developed to guide recommendations regarding minimum management practice and concept storage requirements, considering a soil's inherent risk for direct losses of FDE contaminants during land application. During this process, the risk framework has been peer reviewed by soil scientists from AgResearch, Landcare Research, Massey University, Lincoln University and Plant and Food Research. Furthermore, the development of an Industry Code of Practice for effluent designers and installers is nearing completion and due for final release in mid 2010. The code uses an adapted version of the FDE risk framework as a design standard in order to recommend concept storage requirements for installers to design against.

Environment Waikato (EW) allows the application of FDE to land under a permitted activity rule. However, continued non-compliance has been a problem with council data suggesting that poor management has been the primary cause of non-compliance. EW has expressed concern that much of the poor management relates to inadequate storage facilities for operations to avoid FDE application to land under conditions likely to cause adverse effects. Therefore, the aim of this report to EW is to illustrate how soil drainage mechanisms influence the likelihood of direct drainage losses of applied FDE. We present a FDE risk framework that can be used as a guide to identify minimum concept storage requirements land application practices for a range of soil and landscape categories.

2. Water and solute transport mechanisms in soil

The transport pathway of solutes and suspended solids in drainage water is dictated by soil hydrology. A soil's drainage capacity is usually determined by factors such as soil texture, pore continuity and proximity to water tables. Water movement through the soil is measured as hydraulic conductivity, usually in units of mm hr^{-1} or m s^{-1}. Hydraulic conductivity is an important component of Darcy's Law which states that a flux of water is proportional to the hydraulic gradient multiplied by the conductivity of a soil (McLaren and Cameron, 1996). In general, the finer a soil texture, the less continuity of pores. Hence a sandy soil will have a greater drainage capacity than a fine-grained silt or clay soil (Hillel, 1980). However, many exceptions occur. Soil texture is one factor governing unsaturated flow, whereas saturated flow is largely governed by soil density, macroporosity and soil structure. Three mechanisms for the movement of excess soil water are described below.

2.1 Matrix flow

In saturated soils the force of gravity creates a hydraulic gradient that drives water downward. In unsaturated soils the process of diffusion means that soil water will flow from areas of high potential to low potential in order to come to equilibrium (McLaren and Cameron 1996). Soils that are draining excess water have soil moisture contents greater than field capacity and do so under saturated flow conditions. If water drains through the soil body in a relatively even manner, wetting the whole soil profile, then it is termed matrix flow. Matrix flow moves water through micropores within and around soil aggregates, rather than rapidly around soil aggregates. Soils with a fine and spheriodal structure typically exhibit rapid drainage under a well distributed matrix flow (Figure 1).

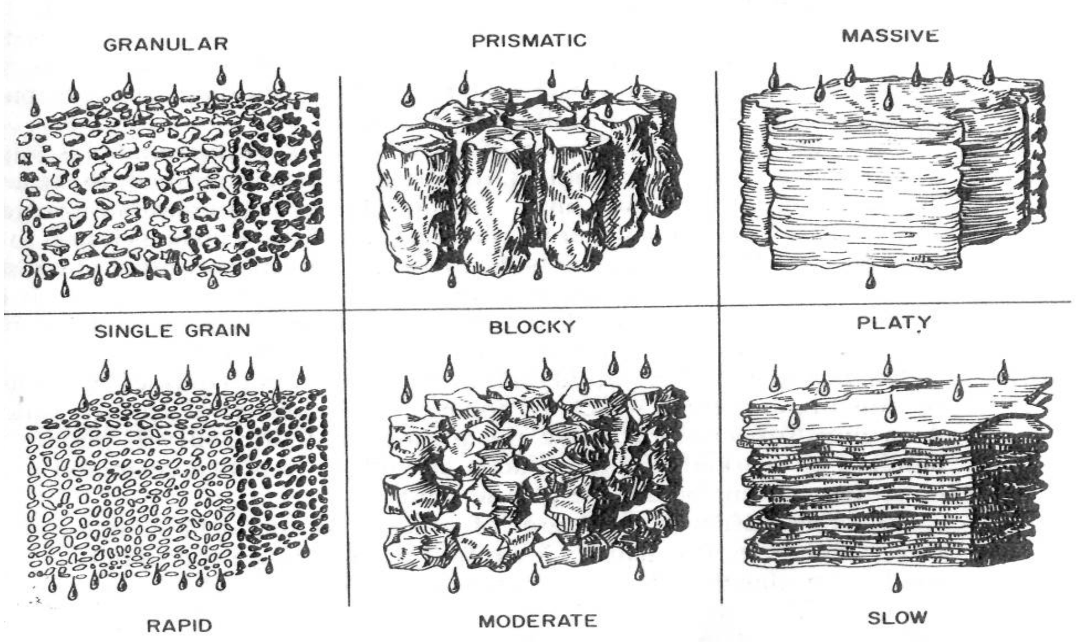


Figure 1. Diagram of the influence of soil structure on drainage (Bowler 1980).

Matrix flow is often called a piston flow effect where soil surface inputs displace and drain water situated deeper in the soil profile. This will allow applied FDE to have a suitable residence time to attenuate potential contaminants (McLeod et al. 2008). In reality, a sharp wetting front caused by piston displacement will be somewhat distorted by the process of hydrodynamic dispersion reflecting microscopic non-uniformity of the water-conducting pore dimensions, and therefore, flow velocity (Hillel, 1998). Figure 2 demonstrates the likely nature of soil matrix flow whereby one pore volume of drained water (equivalent to the sum of total water holding capacity for a given depth) will represent a mixture of the incoming soil solution and the displaced water (Hillel, 1998). It would, therefore, be expected that an application of FDE to a soil at field capacity would have to be greater than 50% of a pore volume before any direct losses of FDE contaminants could be expected in drainage waters given matrix flow conditions. As an example, a typical fine to medium textured soil with soil moisture at field capacity of 39% v/v and a wilting point of

15% v/v has a total water holding capacity of 72 mm depth in the top 300 mm of soil (dominant root zone). Given adequate soil permeability, it should therefore theoretically require an application depth to a wet soil of at least 36 mm in order to result in direct drainage of FDE contaminant losses. Figure 3 presents a diagrammatic example of an idealised breakthrough curve (plot of relative tracer solute concentration in drainage vs. cumulative drainage in pore volumes). The matrix flow curve demonstrates the passage (piston effect) of an applied solute between 0.5 and 1.5 pore volumes of cumulative drainage. The peak in relative concentration at c. 30% demonstrates the piston effect of the applied solute during the matrix flow.

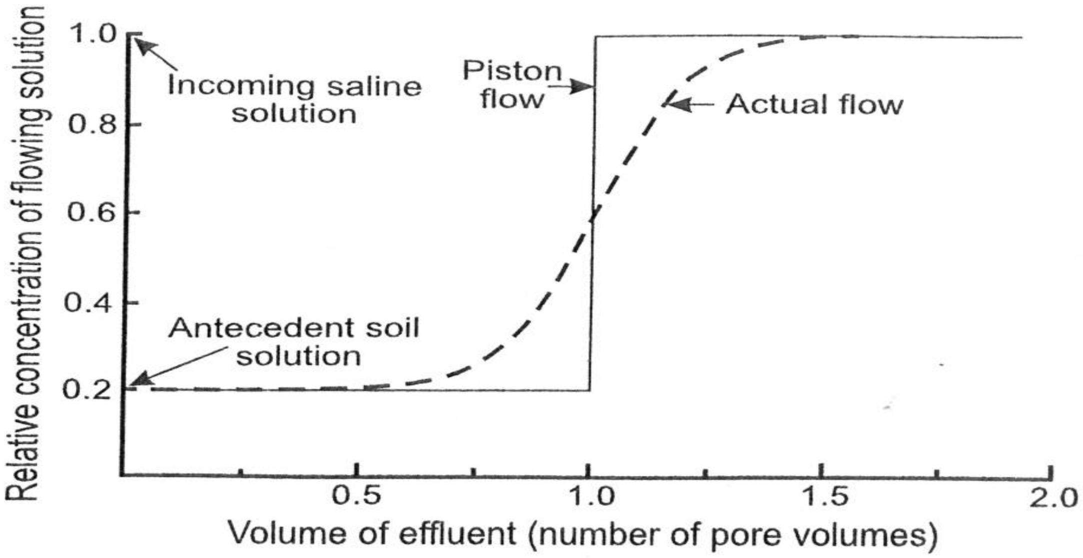


Figure 2. Graphic illustration of theoretical vs. actual piston flow drainage flux of an applied solution (Hillel 1998).

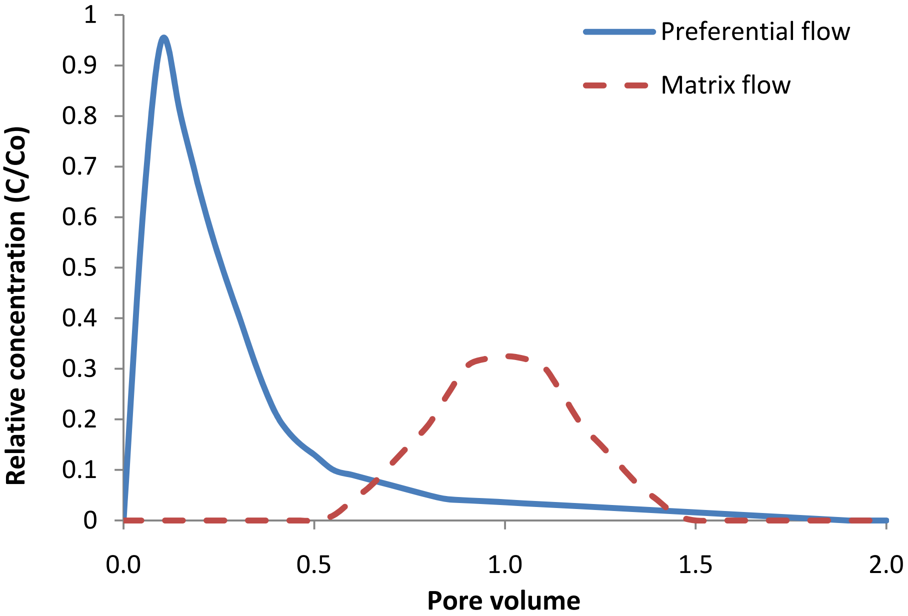


Figure 3. Illustration of concept breakthrough curves for preferential vs. matrix flow

2.2 Preferential flow

Preferential flow means that water favours movement down preferred pathways when soils are draining (Hillel 1998). This phenomenon is also commonly called bypass flow, as it results in a large proportion of the soil matrix being bypassed during the drainage process. Preferential flow typically takes place down large continuous cracks or a series of intermittent and somewhat connected soil cracks or channels with large pore space. Such cracks or channels are commonly caused by earthworms or plant roots. Soil cracks may also occur as a result of freeze-thaw processes and wetting and drying cycles, particularly in very fine textured soils with a drainage impediment (McLeod et al. 2008, Hillel 1998). Soil structure also has an influence on preferential flow processes. Our research and insights suggest that the preferential flow of microbes through soil is related to soil structure, with coarse soil structure (prisms, column or blocks) promoting preferential flow and fine soil structure (crumb, fine nut) minimizing preferential flow (Figure 1). If water and entrained contaminants flow via cracks, they largely follow a less tortuous (preferential) pathway and only minor amounts enter the fine soil pores (McLeod et al. 2008, McLeod et al. 2004, Magesan et al. 1999, Wells 1973). It is in the fine pores where there is greater interaction with the soil and consequent adsorption or filtering of contaminants. Soils with a fine soil structure (often developed in silty tephric soil material) tend to filter microbes.

The physicochemical nature of the soil material seems to be less important than soil structure. In laboratory experiments, recovery of microbes from a solution of clay soil (high preferential flow) shaken with water was low, i.e. a high % of microbes attached to the clay particles. In contrast, the recovery rates for a tephric soil (low preferential flow) were high, i.e. a low % of microbes attached to the tephra particles. The results for microbial recovery are the reverse of that expected based on the numbers of microbes leached from undisturbed soil cores irrigated with farm dairy effluent (FDE).

Preferential flow paths can also be induced by the installation of artificial drainage (Monaghan and Smith 2004). In particular, mole-pipe drainage systems can considerably change soil hydrology from a poorly drained to relatively well-drained status. This occurs by the creation of macropores and preferential flow paths linking to mole drains typically spaced at two meter intervals, and in turn, a receiving pipe line (Figure 4). Mole drains are installed into the soil by a mole plough at approximately 450 mm depth. The installation of mole-pipe drainage has agronomic and soil physical advantages associated with decreased water-logging and the subsequent time that a soil is wet and prone to animal treading damage (Bowler, 1980). However, the preferential nature of artificial soil drainage (as demonstrated in Figure 5) creates a considerable risk of direct losses of FDE contaminants (Houlbrooke et al. 2004a, Monaghan and Smith 2004). The preferential flow curve presented in Figure 3 demonstrates the potential for high concentrations of solutes to be rapidly eluted in bypass flow, compared to the piston effect observed under matrix flow.

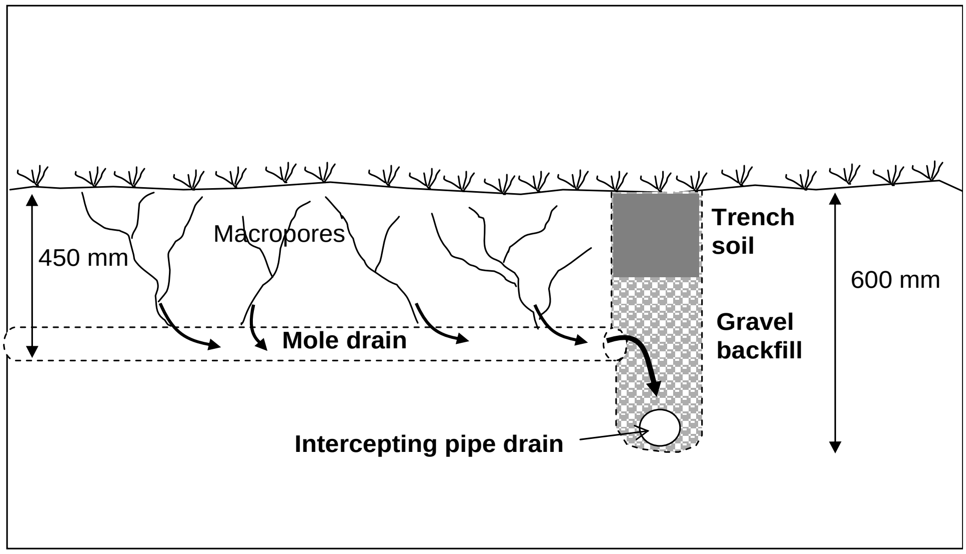


Figure 4. Diagrammatic representation of a mole-pipe drained soil.

Figure 5. Field example of preferential flow through a Pallic soil containing remnants of old mole drains.

2.3 Overland flow

Overland flow can be generated by two different processes. The first process is termed ‘infiltration excess’ flow commonly also referred to as ‘Hortonian’ overland flow (Horton, 1940). Infiltration excess conditions imply that rainfall (or irrigation) intensity exceeds the soil’s surface infiltration rate. On flat land this condition will result in surface ponding (Needelman et al., 2004). A suitable lag time is required post rainfall for all of the ponded surface water to infiltrate the soil body. However, on sloping land ponded water will move downslope, hence creating surface runoff or overland flow (Srinivasen et al., 2002; Needelman et al., 2004). Natural soil properties can influence infiltration excess conditions such as soil infiltration rate, as can animal grazing-induced soil physical damage (Greenwood and McKenzie, 2001; Kurz et al., 2006). Soils with massive or platy soil structure are prone to infiltration excess overland flow generation (Figure 1). The second process that results in overland flow generation is known as 'saturation excess' flow. This condition requires a saturated soil, often as a result of a high water table or a slowly permeable subsoil layer that restricts drainage (Needelman et al., 2004). Saturated soils are filled beyond field capacity to the point that large and typically air-filled pores are filled with water. Once all pores are storing water, the soil has no capacity to infiltrate further water unless drainage water is displaced and so overland flow conditions are created and water ponds or flows downslope (Srinivasen et al., 2002). Flow conditions will stop once the water source is removed. However, saturated soil profiles can only be alleviated by drainage or evapotranspiration (Hillel, 1980).

3. Best management practices for land application of farm dairy effluent

For a land treatment system to be sustainable it must be efficient in both the retention of effluent in the soil and the subsequent plant uptake of nutrients applied in the effluent. The longer the effluent resides in the soil's active root zone, the greater the opportunity for the soil to physically filter the effluent whilst attenuating potential contaminants and making the nutrients available to plants. Two effluent management technologies described below provide New Zealand dairy farmers with tools which will assist the aim of keeping applied nutrients in the root zone and, therefore, minimise potential environmental effects.

3.1 Deferred irrigation

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' was developed (Houlbrooke et al. 2004a). Deferred irrigation involves storing effluent in a pond then irrigating it strategically when there is a suitable soil water deficit, thus avoiding the risk of generating surface runoff or direct drainage of effluent. When applied effluent remains in the soil as plant available water (rather than exiting the soil as drainage water), the soil-plant system's ability to remove soluble nutrients via plant uptake and immobilisation processes is maximised (Houlbrooke et al. 2004a, Monaghan and Smith 2004).

The application criteria for spray irrigation of FDE if drainage is to be avoided are presented in the following equations:

$$E_i + \theta_i Z_R \leq \theta_{FC} Z_R \qquad \text{eq. 1}$$

$$E_i \leq Z_R\ (\theta_{FC} - \theta_i) \qquad \text{eq. 2}$$

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 (SWC) at field capacity ($m^3\ m^{-3}$), and θ_i is the SWC on day i ($m^3\ m^{-3}$) (Houlbrooke et al. 2004a). Both these equations effectively state that the existing soil moisture deficit in the root zone plus the depth of applied FDE is required to be less than maximum soil water storage (field capacity).

In New Zealand, regular soil water deficits greater than 10 mm will often not occur until October each year (large regional and temporal variations exist though). However, the generation of FDE starts at the beginning of lactation in late winter (late July/August). Consequently, having sufficient storage for FDE is essential to ensure that spray irrigation to soils with an inherent risk only occurs during times when an adequate soil water deficit exists. Whilst storage is the most important infrastructural requirement, the accurate scheduling of FDE to coincide with soil moisture deficits is also critical.

Houlbrooke et al. (2004a) reported the results of a 3-year research trial at Massey University that assessed direct losses of nutrients in mole and pipe drainage when FDE was applied to high risk land according to deferred irrigation criteria. When averaged over all three lactation seasons (2000/01 to 2002/03), FDE application to the soil generated drainage equivalent to 1.1% of the total volume of effluent applied. Over the three seasons a range of different application depths were assessed. The strategy of irrigating smaller quantities of FDE, more frequently (7 events at an average of 9 mm depth) in 2001/02, resulted in zero drainage of applied effluent through the mole and pipe drainage system, and consequently, no direct loss of nutrients. Average annual nutrient losses from direct drainage of FDE following irrigations using the deferred irrigation criteria over three lactation seasons were c. 1.1 kg N ha^{-1} and 0.2 kg P ha^{-1}. Similar environmental performance has also been reported in the Otago region by Monaghan and Smith (2004) when FDE was stored and applied at appropriate soil water deficits. This shows that an improved FDE land application system, such as a deferred irrigation strategy, 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 should be applied at the lowest depths possible (< 10 mm) during the critical times of the season to reduce the risk of FDE drainage and run-off.

3.2 Low application rate tools

Low rate sprinkler applicators are temporarily fixed in one place and deliver at rates of approximately 4-8 mm per hour on an average and instantaneous basis. Therefore, a one hour application would deliver only 4-8 mm of FDE to the soil (depending on the sprinkler system and nozzle used). Such applicators allow FDE to be applied in smaller amounts and more often during periods of low soil moisture deficit (<10 mm) In principle, any tool capable of delivering FDE at a rate less than 10 mm/hr can be considered 'low rate'

(McLeod et al. 1998). For soils that exhibit a high degree of preferential flow, a drainage limitation, or are situated on sloping land, the application rate of an irrigator has a strong influence on environmental performance. Different soils have different infiltration rates and abilities to absorb and drain water. Where there is a risk of surface water contamination, particularly as a result of overland flow, then FDE application rates should be matched to a soil type's ability to absorb or infiltrate effluent. Travelling irrigators typically have very high instantaneous application rates, usually greater than 100 mm/hr (Houlbrooke et al. 2004c) (Houlbrooke et al. 2004c). If the average depth of applied FDE is divided by the whole time for one complete pass of the irrigator (including time when trays do not receive FDE because of the donut shaped pattern) then the average application rate would be approximately 20-30 mm/hr. Low rate applicators apply FDE at rates < 10 mm/hr (and often < 5 mm/hr) and therefore reduce the risk of exceeding a soil's infiltration capacity, thus preventing ponding and surface runoff of freshly applied FDE. Furthermore, the slower application rates increase the likelihood of retaining the applied nutrients in the root zone as the low application rate decreases the likelihood of preferential flow and allows a greater volume of applied FDE to move through smaller soil pores via matrix flow, thus allowing for greater attenuation of effluent contaminants (Monaghan et al. 2010, McLeod et al. 1998).

4. Contaminant leakage risk from effluent land application

4.1 Soils that exhibit overland flow

The combination of low soil infiltration rates and wet soil conditions on sloping land will provide the greatest risk for overland flow generation (McDowell et al. 2008). When sloping land contains soils with low infiltration rates or impeded drainage at depth then the risk of surface runoff generation and surface redistribution increases. The risk is most pronounced where FDE application rates are > surface infiltration rates, such as often is the case with high application rate travelling irrigators. Low rate irrigation tools have application rates more suitable for these soil types and thus allow for infiltration and hence capture and subsequent filtration of contaminants in the applied FDE. Soil moisture content also affects the risk of overland flow generation, as applying FDE to soils at soil water contents beyond field capacity will induce either saturated runoff conditions or interflow within the near-surface layers of the soil.

Houlbrooke et al. 2006 reported on a South Otago trial established on sloping land with poor surface infiltration. Applications of FDE made at this site under moisture conditions close to field capacity resulted in 78% of the volume of FDE applied using a rotating travelling irrigator being generated as overland flow, compared to 44% when using low rate (K-Line) irrigation. The relative concentrations of ammonium N, Total N and P in overland flow generated following the application of FDE using a travelling irrigator were all greater than 90% of the concentration applied as raw FDE. In contrast, the relative concentrations of these contaminants in overland flow generated following the application of FDE using a low rate system were considerably lower (between 20 to 45%). The low application rate and associated decrease in surface ponding of FDE allowed a greater volume of applied FDE to move into the soil body, thus allowing for greater attenuation of effluent contaminants.

In the Waikato region, intensive dairy farm operations are located on rolling landscapes of a volcanic origin (c.>7°). These soils typically belong to the Pumice and Allophanic Soil orders which are characterised by rapid drainage rates that do not contain the slowly permeable subsurface horizons which restrict permeability (Hewitt 1998). However, an EW report by Taylor et al. (2009) suggested that both surface infiltration rates and macroporosity were considerably depressed under intensive pastoral land uses (3–99 mm/hr) in the upper Waikato catchment compared to soil under stands of long term exotic forest (121–1207 mm/hr).The sites assessed were dominated by well drained soils of the Pumice, Allophanic and Podzol orders. The low infiltration rates reported on some of the dairy farmed soils are likely due to the land use pressures from intensive farming and could be mitigated with improved grazing practices. Slow infiltration rates are considered anything less than 4 mm/hr with moderately slow from 5-19 mm/hr. The safe application of FDE to sloping land with low infiltration rates would require the use of low application rate technology.

Of further concern on these sloping landscapes is the potential for hydrophobicity to result in overland flow generation of applied FDE. There are still many unknowns regarding the potential development and risk of hydrophobicity. However, in a study of municipal wastewater application to a Pumice Soil in the upper Waikato catchment, Vogeler (2009) measured greater hydrophobicity under dryland conditions than areas receiving regular wastewater and thus maintaining a higher SWC. FDE receiving blocks will typically receive FDE during potentially dry summer and autumn periods on an irregular basis and thus may not necessarily overcome the potential risk of hydrophobic conditions.

4.2 Soils that exhibit preferential flow

Preferential flow has been identified as the early presence (<0.1 of a pore volume) of a large increase in solute concentration during a breakthrough curve (McLeod et al. 2008) or as the uneven and elongated depth distribution of an applied tracer (Monaghan et al. 1999, McLeod et al. 1998). McLeod et al. (2008) have provided a summary of previous research conducted by Landcare Research investigating the potential for preferential flow across a wide range of New Zealand soil types and characteristics.

Soils with a high water table (poorly drained soils) are usually drained under intensive land use. Drains rapidly remove water from the large pores in the soil resulting in preferential flow. For this reason soils with a New Zealand Soil Classification (NZSC) of “Mottled” at a subgroup level are considered to have a high potential for preferential flow of micro-organisms. Similarly, Organic Soils have a high water table and are drained so considered to have high microbial preferential flow. Furthermore, humic acids in Organic Soil water compete for the same binding sites as some microbes, presenting another reason to classify soils with elevated organic matter status as having a high risk of microbial preferential flow. Finally, on any soil, preferential flow can be induced by excessive irrigation rates at soil, particularly at high soil moisture contents close to or at saturation.

4.2.1 Categorisation of preferential flow risk

The categorization of soil classes by McLeod et al. (2008) as having low, medium or high preferential flow risk was derived from research conducted assessing breakthrough curves on a range of soils (Barton et al. 2005, McLeod et al. 2004, Aislabie et al. 2001, McLeod et al. 2001, Magesan et al. 1999). In these studies effluent (dairy or municipal) was applied to the soil surface (typically 25 mm depth at 5 mm/hr) followed by the application of a further pore volume of irrigation water at a rate of 5 mm/hr to simulate rainfall conditions. The soils analysed represented a range of NZ soils targeted to give the maximum information about soil properties pertinent to the NZSC. The NZSC was then used to regionalise the preferential flow risk.

- *Soils with high preferential flow risk*

The soil classes listed in Table 1 were identified as having a high preferential flow risk based on specific characteristics of that soil class (McLeod et al. 2008).

Table 1. Soil classes with high preferential flow risk.

Soil class	Brief reason
Organic Soils order	High water table, artificially drained under intensive land use
Ultic Soils order	Coarse soil structure
Granular Soils order	Coarse soil structure
Podzol Soils order	Some contain slowly permeable layer
Gley Soils order and perch-gley soils	High water table, artificially drained under intensive land use
mottled subsoils	High water table, artificially drained under intensive land use
peaty soils	High water table, artificially drained under intensive land use
skeletal and pedal soils	Coarse soil structure
soils with a slowly permeable layer	Slowly permeable layer, artificially drained under intensive land use
soils with coarse soil structure	Coarse soil structure

- *Soils with medium preferential flow risk*

The following soil classes (Table 2) in the New Zealand Soil Classification (Hewitt 1998) were identified as having a medium preferential flow risk (McLeod et al. 2008).

Table 2. Soil classes with medium preferential flow risk.

Soil class	**Brief reason**
Brown Soils order	Brown Soils from the EW region have not been analysed for microbial bypass flow but are classified as having medium microbial preferential flow risk, except for Mottled Subgroups, based on their soil morphology.

Brown Soils encompass a wide range of parent materials and morphologies. Subsurface soil horizons as well as surface characteristics can influence bypass flow. Where argillic horizons are present in non-tephric soil material, the soils tend to have greater microbial preferential flow. In contrast, upper layers of silty tephric soil material promote less microbial preferential flow. We recommend for the Brown Soil order that each soil be considered on a case-by-case basis to determine if it contains features likely to result in a risk of preferential flow drainage characteristics.

- *Soils with low preferential flow risk*

The following soil classes (Table 3) in the New Zealand Soil Classification (Hewitt 1998) were identified as having a low preferential flow risk (McLeod et al. 2008).

Table 3. Soil classes with low preferential flow.

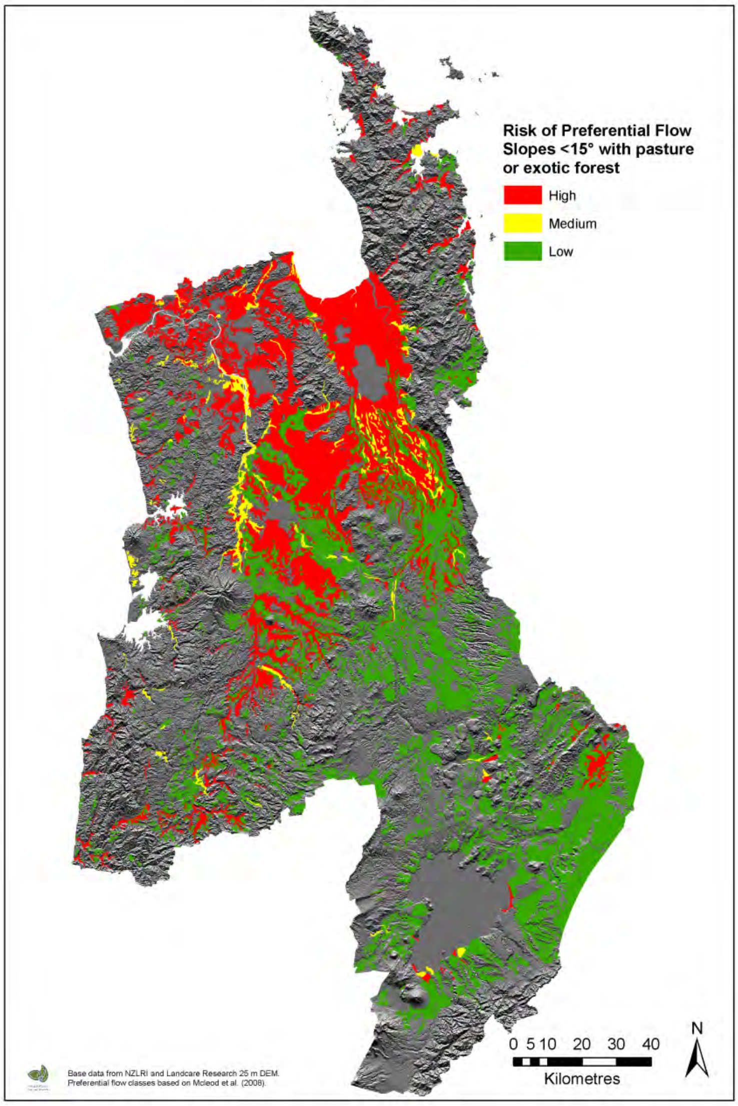
Soil class	**Brief reason**
Recent Soils order	Some Recent Soils with greater soil development likely lie within the Medium class. Excludes soils with mottled profile form.
Pumice Soils order	Excludes soils with mottled profile form.
Allophanic Soils order	Excludes soils with mottled profile form.

Experiments on the well-drained soils in Table 3 resulted in breakthrough curves with minimal or no preferential flow, indicative of a very high degree of soil matrix flow. These experiments leached only very small amounts of microbial tracer or none at all (McLeod et al. 2008). The common soil characteristics were a weakly developed soil structure comprised of fine peds and a high uniform porosity. The fine nature of these soil peds and discontinuous nature of macropores provided large opportunity to filter out faecal microbes added in FDE (McLeod et al. 2008).

4.2.2 Soils in the Waikato region that exhibit preferential flow

In this section we restrict our analysis to land likely to receive irrigated FDE. Irrigable land is considered to be land on slopes <15° and, within the New Zealand Land Resource Inventory (NZLRI), has vegetation codes for pasture or exotic forest. Exotic forest is included to capture areas of land, generally in the south of the region, which may be converted from forestry to dairying. The ratings for preferential flow are based on microbial bypass flow. However, we also note that where microbial preferential flow occurs, nutrients are also likely be entrained within the fast-travelling leachate. The spatial distribution of the different classes (high, medium, low) of preferential flow soils in the EW region is shown in figure 6.

Figure 6. Spatial distribution of preferential flow classes in the Environment Waikato region.



Base data from NZLRI and Landcare Research 25 m DEM.
Preferential flow classes based on Mcleod et al. (2008).

4.2.3 Research studies of preferential flow losses

Wells (1973) discussed the suitability of different soil properties (using the old New Zealand Genetic Soil Classification System) to receive effluents. In 1973 there was very little land treatment of FDE and much of the discussion was related to a range of effluent types including agricultural and industrial sources. The publication reported that soils with very poor, poor and imperfect drainage classes were considered unsuitable for the application of effluents, as were soils with coarse soil structures (prisms, column or blocks) or very fine textures (clay). Reported unsuitability based on drainage class, soil texture and aggregate structure was related to perceived permeability and the likelihood of regularly high soil moisture contents. With adherence to best management practices such as deferred irrigation and low rate applicators, these limitations on soils types considered unsuitable by Wells (1973) can generally be minimised. However, as yet unpublished research recently conducted by Landcare Research has demonstrated that there is considerable risk associated with applying to land with high water tables. Land application should only be considered when the water table falls again.

A number of published New Zealand studies outline the considerable risk of direct drainage of FDE contaminants on soils that exhibit preferential flow characteristics. Some of these studies have identified mole and pipe drainage systems as the cause of direct losses of FDE contaminants in drainage waters (Houlbrooke et al. 2008a, 2006, 2004a, Monaghan & Smith 2004, McLeod et al. 2003). Other studies have identified coarse soil structure (large structural cracks) or soils with a drainage impediment (containing wetting and drying cracks) as contributing to direct losses of FDE contaminants via preferential flow (McLeod et al. 2008, 2004, Aislabie et al. 2001, McLeod et al. 1998).

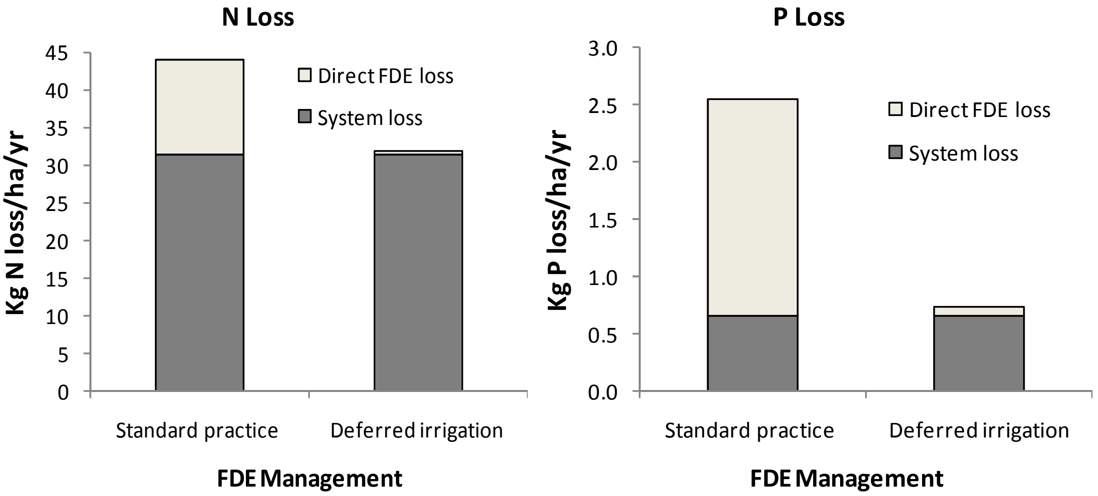


Figure 7. Direct losses of FDE under deferred irrigation and compared for a one-off poor FDE application. Direct losses of FDE are presented as additional to dairy land use loss of N and P not derived directly from FDE application (Houlbrooke *et al.* 2008, Houlbrooke *et al.* 2004).

A comparison of direct FDE N and P losses in mole and pipe drainage and overland flow from best practice (deferred irrigation) is compared with losses from a one-off poorly timed application on a Manawatu Pallic soil (Houlbrooke et al. 2004a & 2008). Losses reported in Figure 7 from poor practice represent direct contaminant loss from one 25 mm application of FDE when the soil moisture content was close to field capacity. These losses of N and P were approx 30 times greater than direct losses reported under deferred irrigation practice for a one year period (80 mm over four irrigation events). The losses of N and P were the equivalent of 40% and 290% of reported whole-farm losses from the adjacent area that did not receive FDE inputs, respectively.

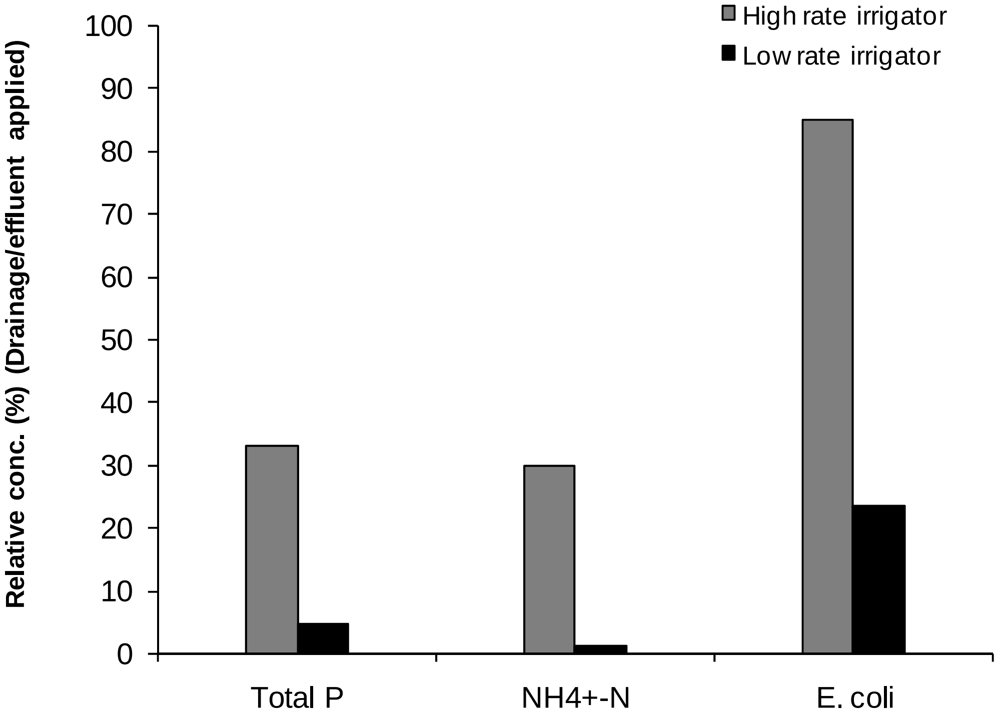


Figure 8. Relative concentrations of total P, ammonium N and *E. coli* in drainage waters collected following the irrigation of FDE to a mole-pipe drained soil using a travelling irrigator or low rate irrigation system (Houlbrooke et al. 2006).

Low rate effluent irrigation technology in the form of 'K-Line' has been evaluated as a tool for applying FDE to land and its environmental performance compared with that of a traditional rotating travelling irrigator (Monaghan et al. 2010; Houlbrooke et al. 2006). Drainage monitoring of a mole and pipe drained Pallic soil in West Otago showed that concentrations of contaminants in artificial drainage were much reduced when comparing the low rate applicator with a rotating travelling irrigator. Specifically, much of the P, ammonium-N and *E. coli* bacteria contained in the FDE was filtered by the soil when FDE was applied using low rate technology. Concentrations of total P, ammonium N and *E. coli* measured in drainage induced by the application of the FDE using low rate sprinklers at 4 mm/hr were, on average, only 5, 2 and 25% of that found in the applied FDE, respectively (Figure 8). This was in contrast to that observed when FDE was applied using a travelling irrigator (mean application depth of 9 mm), where concentrations of total P, ammonium N and *E. coli* measured in drainage induced by the application of the FDE were 33, 30 and

85% of that found in the applied effluent (Monaghan & Smith, 2004). The greater attenuation under low rate irrigation is attributed to the greater filtration of nutrients in the FDE, compared to that achieved under the high instantaneous rate of application observed under a rotating travelling irrigator

A study on a poorly drained Gley soil (Te Kowhai silt loam) in the Waikato region by Singleton et al. (2000) measured N leaching losses from deep lysimeters (120 cm depth and 59 cm diameter) over a two year period. FDE was applied at loading rates of 511 kg N/ha/yr (year one; pasture cut and 50% returned) and 1518 kg N/ha/yr (year two; pasture cut and carried) to lysimeters with different levels of controlled drainage: high water table (25 mm from surface), medium water table (50 mm from surface) and low water table (75 mm from surface). This study further demonstrated that N leaching losses are proportional to N input with only 33.3 kg N/ha lost in year one compared with 131.4 kg/ha in year two. The depth to water table (and therefore degree of drainage impediment) had an important influence on the form of N leached, with a greater proportion of organic N losses occurring within low water table treatments. It was suggested that this was in part a result of denitrification of the nitrate-N component. However, it was also suggested that direct loss of FDE was occurring as preferential flow through this highly structured soil.

An investigation of the effect of irrigation application rate on the incidence of preferential flow in the Waikato region on a well-drained Allophanic Soil (Horotiu silt loam) and poorly drained Gley Soil (Te Kowhai silt loam) was conducted by McLeod et al. (1998). Water irrigations of 25 mm depth containing a tracer dye were applied using a range of application rates from 5 to 20 mm/hr. Some preferential flow was observed for both soil types when application rates were >10 mm/hr, although the magnitude of preferential flow was considerably greater in the poorly drained Gley Soil than the well-drained Allophanic Soil (which was limited to some conduits caused by earthworm burrowing). For both soil types, application rates ≤10 mm/hr resulted in all the applied tracer remaining in the top 200 mm of soil. Pulsing applications (on–off) at the higher application rate of 40 mm/hr also created preferential flow and was not as effective at keeping FDE in the topsoil as sustained low rate application. The potential for preferential flow in the topsoil of well-drained soils caused by earthworm activity is worth noting; however, its activity is usually restricted to the A horizon and the mixed A and B horizons. Preferential flow pathways will therefore not be continuous out of the dominant root zone (c. 300 mm).

4.3 Soils that exhibit matrix flow

Soils that exhibit matrix flow have been described as having a low preferential flow risk in section 4.2.1 (Table 3). The common characteristics of these soils are a weakly developed spherical soil structure comprised of fine peds and a high uniform porosity. The fine nature of these soil peds and discontinuous nature of macropores provided large opportunity to block and filter out faecal microbes added in FDE (McLeod et al. 2008).

While well drained, porous soils that exhibit matrix flow appear to have a low direct contaminant risk from applied FDE, they are typically leaky in nature with regards to the leaching loss of nitrogen (in particular nitrate-N) due to their free-draining nature Furthermore, poorly drained soils usually have higher denitrification (gaseous) losses than well drained soil and so the concentration of nitrate-N in drainage water is often lower than for well drained soils (McLaren and Cameron 1996, Scholefield et al. 1993).

Much of the total annual N loss associated with land receiving FDE will be a result of N cycling inefficiency within the soil-plant system and would be considered an indirect loss (Ledgard et al. 1999). As FDE makes up approximately 5-10% of the daily nutrient load from cattle excreta, nutrient loading from animal excreta deposited in the field is usually the main contributor to N leaching losses (Monaghan et al. 2007). Well-drained soils with high total inputs of N are often characterised by high nitrate-N losses (Ledgard et al. 1999). However, FDE contributes only a component of the total N inputs that are mineralised into nitrate-N and subsequently leached from the root-zone (Houlbrooke et al. 2008). Therefore, effective mitigation techniques for controlling N losses on these free draining soils should target the cumulative effect of urine patches deposited during animal grazing (Monaghan et al. 2007). Furthermore, the nutrient loads into groundwater will differ from that which left the root zone and will reflect the potential time for further attenuation (depth to water table) and any denitrification that may take place throughout the vadose zone. Stenger et al. (2009a) noted that in the Toenepi catchment of the Waikato region, it was currently not possible to reliably quantify catchment scale N loss due to denitrification along the flowpaths from the bottom of the root zone to the stream, but available data suggest it could be in the order of 50% of the leaching losses. At a research site within the Lake Taupo catchment, Stenger et al. (2009b) also suggested denitrification at depth in a Pumice Soil was common where residual organic debris from the vegetation destroyed by the Taupo eruption 186 AD occurred below the water table. The spatial extent of this denitrification mechanism is currently unknown.

Wells (1973) suggested that soils classified as ‘somewhat excessively drained’ were only suitable to receive effluent with a low nutrient concentration and that soils classified as ‘excessively drained’ were unsuitable to receive effluents. We note the paper by Wells (1973) does not present experimental results but observations largely agree with those of McLeod et al. (2008). In the EW region the excessively drained class pertains predominantly to the coarse end of Pumice Soils. We have unpublished data to suggest these soils are still effective at filtering microbes. There is no longer a ‘somewhat excessively drained’ drainage class as this has been incorporated into the ‘well drained’ category (Milne et al. 1995). In the EW region well-drained soils are predominantly Allophanic and Pumice Soils, which are excellent at filtering microbes. We believe the recommendation for only low nutrient concentration effluents relates more to the inherent N ‘leakiness’ of these soils under high inputs of N, rather than a perceived risk of direct losses given the likely matrix flow.

McLeod et al. (2001) irrigated FDE onto barrel lysimeters containing undisturbed Pumice, Allophanic or Gley Soil material collected from the EW region. The application rate of FDE was 5 mm/h, with a 25-mm depth of FDE being irrigated, followed immediately by simulated rainfall at 5 mm/h. The leachate was analysed for a Salmonella bacteriophage tracer. The bacteriophage tracer was not detected in the Allophanic Soil leachate (to 1.8 pore volumes) and was detected only at very low concentrations in the Pumice Soil leachate. In leachate from the Gley Soil, the tracer was detected at about 80% of the application concentration. The visual difference in leachate quality of the first litre of leachate collected by McLeod et al. (2001) from Gley (clayey) and Pumice Soils is shown in (Figure 9).

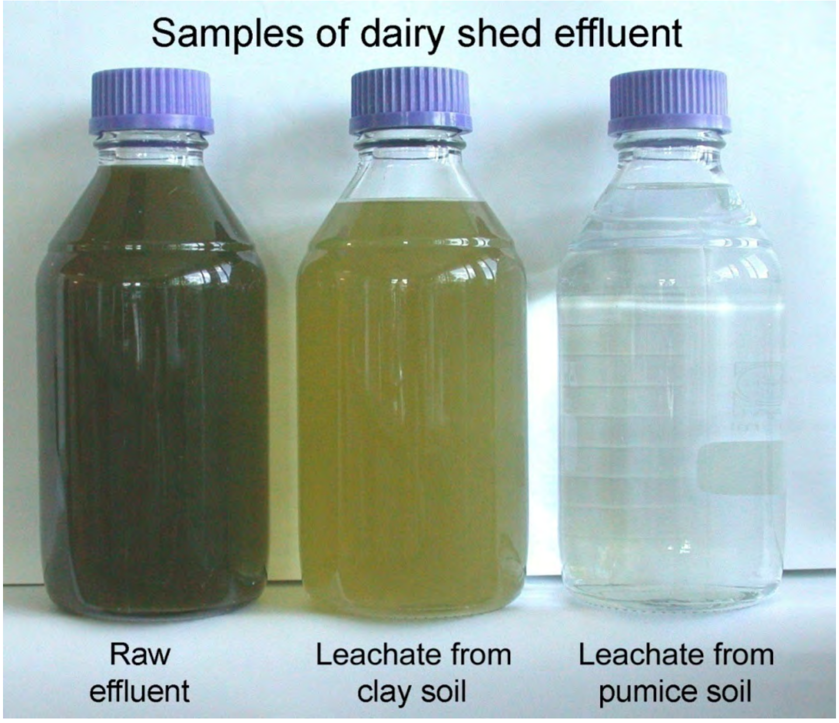


Figure 9. The first litre of leachate collected from Gley and Pumice Soil lysimeters irrigated with farm dairy effluent (FDE).

Over two years, Barton et al. (2005) applied secondary treated municipal effluent to some common Waikato soils in large undisturbed and ungrazed soil cores 700 mm high and measured the N content of the leachate. The results are shown in Table 4. Such high loading rates of effluent N are not reflective of dairy farm operations, which are usually capped at N loading rates of either 150 or 200 kg N/ha/yr (Houlbrooke et al. 2004b).

However, the results do indicate that N leaching under irrigation on Gley Soils can be significantly greater than on Allophanic or Pumice Soils. Barton et al. (2005) attributed the greater N leaching loss from the Gley Soil to preferential flow that reduced contact between the effluent and the soil matrix.

Table 4. N content of leachate from soil cores irrigated with municipal effluent.

Soil	Treatment	Effluent or fertilizer kg N ha^{-1}	Leaching kg N ha^{-1}
Allophanic	Irrigated	772	17
	Non-irrigated	200	2.5
Gley	Irrigated	746	184
	Non-irrigated	200	13
Pumice	Irrigated	815	31
	Non-irrigated	200	14

In a study of a low water holding capacity (WHC) Pumice Soil (Whenuaroa gravelly sand) near Reporoa in the South Waikato, Burgess (2003) demonstrated a complex relationship between N leached from different land-use treatments using shallow (350-mm-deep) undisturbed grazed barrel lysimeters. The study encompassed four years of data collection (1998-2002) on a rotationally grazed pasture system comparing four treatments: control, + irrigation, + FDE, + irrigation & FDE. During this time N inputs progressively increased, with stocking rate rising from 4.4 to 5.5 cows/ha on all treatments, fertiliser N inputs rising from approx. 190 to 415 kg/ha/yr on all treatments and FDE N input rising from approx. 80-150 kg/ha/yr on FDE receiving treatments. Under these experimental conditions, large losses of mineral N were measured from all treatments, especially as N inputs increased overtime. However, there were no significant ($P < 0.05$) differences between treatments despite the fact that plots receiving FDE received between 54 to 85 kg of extra N/ha/yr compared with no FDE plots. This observation is potentially further compounded by the fact that in three out of the four experimental years that N loading from FDE was only estimated based on limited FDE concentration data and a standard assumption for application depth. It is important to note that considerable additional organic N was measured in leachate from FDE receiving plots (range between 9 – 44% of total N loss). Unfortunately, organic N losses were not measured from the non FDE plots, making comparison of total N loss between treatments difficult. The studies reported by Barton et al. 2005 and Houlbrooke et al. 2003 & 2008 suggest that organic N leaching is an important component of total N loss from soils under normal farm practice (not part of the FDE block). Despite some limitations, the results and implications of this trial could be considered contrary to the previous observations of Barton et al. (2005) and McLeod et al. (2001) on similar Pumice Soil types and may warrant further investigation.

An interesting observation from the Burgess (2003) study was that increasing drainage flux did not necessarily result in increased flushing of stored mineral N, as the + irrigation & FDE treatment demonstrated increased pasture uptake through otherwise dry summer/autumn periods. We hypothesise that the very high leaching losses of N recorded from this study (up to 190 kg N/ha/yr) would be adequately mitigated using best management practices such as capping total N inputs (fertiliser and FDE) to < 150 kg N/ha/yr and, considering the very low WHC of this soil, limiting FDE applications to less than 10 mm per application. Nevertheless, this research demonstrates the potential effects of poor practice on coarse textured pumice soils low water holding capacities.

A large amount of research has been conducted using lysimeters on well drained soils in the Canterbury region investigating the effect of a range of different N inputs (including urine patches, fertiliser and FDE) on subsequent nitrogen leaching losses. Breakthrough curves presented for these studies clearly suggest a matrix flow drainage mechanism, with no evidence of preferential flow resulting from the different N sources applied (Di and Cameron 2007, Di and Cameron 2004, Di and Cameron 2002, Silva et al. 1999, Di et al 1998, Fraser et al. 1994). Preliminary results from a recent study in Canterbury has demonstrated zero direct loss of faecal microbes following the application of 10 mm of FDE to lysimeters containing a shallow, well-drained Typic Firm Brown Soil when SWC > field capacity under both simulated low (c. 10 mm/hr) and high (c. 100 mm/hr) rates of application (Sam Carrick, Landcare Research, pers. comm.).

Because well-drained soils have typically high infiltration rates without drainage impediments, and because they exhibit predominantly matrix flow, direct losses of FDE are unlikely, even during periods of low soil water deficit. Direct drainage losses are therefore only likely at close to soil saturation (-1 KPa) when all soils exhibit a greater degree of preferential flow through large water-conducting pores (> 300 µm) (Jarvis et al. 2007; Silva et al. 2000) or if application depth exceeds the soil's water holding capacity. The combination of prolonged heavy rainfall and/or application of FDE (particularly large depths) may be enough to induce saturation conditions in well drained soils. It is therefore recommended that an appropriate storage volume (see section 5.4) is required in order to avoid land application during prolonged wet periods when soil water content is greater than field capacity. Combined with a strategy of low application depth (irrigator set at fastest travel speed if using travelling irrigator) this should be sufficient to avoid any direct losses of FDE from these soils during conditions of low soil water deficit (close to or at field capacity). However applications wetter than field capacity are not encouraged even on well drained soil unless using very low depth with a low instantaneous application rate. In order to prevent macropore flow through large pores (> 300 µm) typically at low suctions (-1 KPa or less) it is recommended that FDE application should be withheld from these soils for a drainage period of at least 24 hours following the attainment of soil saturation. Some operators may still wish to include greater FDE storage in order to remove all risk associated with applying FDE to wet soil and in order to rationalise staffing during the traditionally busy and wet calving period. Such a practice should still be considered best practice.

5. Recommendations to Environment Waikato

5.1 Minimum criteria for effluent management systems to achieve

Considering the importance of different soil water transport mechanisms, we recommend that FDE management practices are matched with soil and landscape features in order to prevent direct losses of effluent contaminants. A decision tool has been constructed to guide appropriate effluent management practice considering the effects-based assessment of different soil and landscape features (Table 5). It should be noted that these criteria are considered the minimum conditions that should be adhered to, to avoid direct losses of land-applied FDE. An example of the difference between minimum criteria and best practice would be the recommendation for use of low application rate tools on soils with artificial drainage/coarse soil structure or soils with impeded drainage/low infiltration rate. The adoption of this BMP would decrease the management risk associated with these soil and landscape features. However, it is possible for these risks to be adequately managed given a judicious approach to the stated minimum criteria (e.g. through the use of adequate storage with appropriate low application depths i.e. running travelling irrigators at their fastest speed).

Table 5. Minimum criteria for a land-applied effluent management system to achieve.

Category	**A**	**B**	**C**	**D**	**E**
Soil and landscape feature	Artificial drainage or coarse soil structure	Impeded drainage or low infiltration rate	Sloping land (>7°) or hump & hollow drained land	Well drained flat land (<7°)	Other well drained but very stony[X] flat land (<7°)
Application depth (mm)	< SWD*	< SWD	< SWD	< 50% of PAW#	≤ 10 mm
Instantaneous application rate (mm/hr)	N/A**	N/A**	< soil infiltration rate	N/A	N/A
Average application rate (mm/hr)	< soil infiltration rate	< soil infiltration rate	< soil infiltration rate	< soil infiltration rate	< soil infiltration rate
Storage requirement	Apply only when SWD exists	Apply only when SWD exists	Apply only when SWD exists	24 hours drainage post saturation	24 hours drainage post saturation
Maximum N load	150 kg N/ha/yr	150 kg N/ha/yr	150 kg N/ha/yr	150 kg N/ha/yr	150 kg N/ha/yr

* SWD = soil water deficit, [#] PAW = Plant available water in the top 300 mm of soil,

[X] Very stony= soils with > 35% stone content in the top 200 mm of soil

** N/A = Not an essential criteria, however level of risk and management is lowered if using low application rates

5.1.1 Artificial drainage or coarse soil structure

The application of FDE to artificially drained land (particularly mole-pipe drained land) or land with coarse soil structure has proven difficult to manage because of the preferential drainage pathways for the potential rapid movement of irrigated FDE. Soils that exhibit a high degree of preferential flow pose a large risk of direct losses of effluent contaminants associated with the land application of FDE. The risk of direct loss of FDE contaminants is particularly high in the early spring period when soil is often close to, or at, field capacity. The provision of suitable effluent storage for periods when soils are wet, and a method for accurately determining soil moisture contents, would allow for FDE to be scheduled according to a deferred irrigation strategy, thus minimising or preventing the likelihood of raw or partially-treated FDE entering waterways via the pipe drain network or into ground water preferential flow pathways provided by coarse soil structure. The adoption of low application rate technology would further decrease the risk and management control required to safely apply FDE to this landscape class. As a minimum, FDE should be applied to this category at an average application rate that is less than the soil infiltration rate in order to prevent excess ponding.

Mole and pipe drainage systems are not common in the Waikato region but can sometimes be found in poorly drained soil types such as those found in the Gley Soil order. Coarse soil structure is well developed with large pore spaces, strong pedality (peds >10 mm) and often contains clay, silt and translocated organic matter coatings (McLeod et al. 2008). For the purpose of this framework tool, any soils with 80% or more peds captured on a 10 mm sieve within the upper subsoil are considered to have coarse soil structure. Coarse soil structure is often found with the Granular and Ultic Soil orders and a common Waikato example is the strongly pedal Hamilton clay loam, a Mottled Orthic Granular Soil.

5.1.2 Impeded drainage or low infiltration rate

Impeded drainage at depth (usually a result of a dense soil horizon or regular shallow water table during the winter- spring period) is a key soil feature identified as increasing the likelihood of overland flow and preferential flow through large continuous soil pores. Examples of such pathways include cracks created by wetting and drying cycles, and historical worm and root channels. Intensive dairy farming on some of these soils can also result in a greater susceptibility to soil compaction and therefore pose an increased risk of contamination of surface drainage waters resulting from poorly timed applications of FDE. Because of the regularly high water table that impedes drainage, peat soils also belong to this category despite their potentially high surface infiltration rates. The risk with peat soils is the potential for rapid movement of P and faecal microbes into the ground water when soils are wet and the water table is high.

The adherence to a deferred irrigation FDE management strategy is also essential for this risk category in order to minimise or prevent direct losses of land-applied FDE. As a minimum, FDE should be applied to this landscape category at an average application rate that is less than the soil infiltration rate in order to prevent excess ponding caused by infiltration excess conditions. Examples of poorly drained soils often fall in the Gley or Organic Soil Orders, but can occur in many of the NZSC Orders such as Brown and Recent. Some Waikato examples are the poorly drained Te Kowhai and Puniu silt loams (Typic Orthic Gley) or the Rukuhia peat (Acidic Fibric Organic) and Te Rapa peaty loam (Humose Groundwater-gley Podzol)

5.1.3 Sloping land (>7°) or land with hump and hollow drainage

The risk of surface runoff varies according to slope steepness, slope length, soil infiltration rate, soil moisture content, soil vegetation and land use activity and can be determined on a site specific basis using SCS runoff curve numbers (McCuen 1998). Critical parameters for influencing overland flow are antecedent soil water content and slope steepness. The recommended threshold for sloping land has been defined as 7°. This provides consistency with the Land Use Capability Survey Handbook (Lynn et al. 2009) to distinguish the boundary between undulating and rolling country. However, this does not imply that LUC mapping should be used to determine slope criteria, as slopes will vary considerably within existing mapped LUC classes. To mitigate this risk of generating overland flow when applying FDE to this landscape it is essential that small application depths (≤ 10mm) are appropriately timed using deferred irrigation criteria. Furthermore, it is essential that the instantaneous application rate (mm/min) of the irrigation method used is less than the soil's infiltration rate in order to prevent any surface ponding. For many soils this will necessitate the use of a low application rate irrigation system. Where appropriate, the risk of hydrophobicity severely restricting soil infiltration rates under very dry conditions should also be considered. The use of low application rate tools will help minimise the risks associated with this condition. Sloping landscapes greater than 7 degrees are associated with many of the NZSC Orders on a site-dependent basis.

Hump and hollow drainage systems have not been well researched with respect to FDE management and risks. Such drainage systems are often found in the Hauraki Plains area on soils such as the Netherton clay over loam (Acidic Orthic Gley). By default this soil type would lie in category B (Impeded drainage). The regular slopes used to alleviate water logging from the raised hump area are not likely to exceed our proposed criterion of a 7 degree slope. However, we believe that the consistent way that slope is used to move drainage water to low lying poorly drained soils connected to surface bodies over a large spatial area implies considerable risk associated with the land application of FDE. To avoid direct losses on such landscapes it will be essential to apply FDE at a time when a suitable soil moisture deficit exists to absorb all effluent applied (deferred irrigation).

Furthermore, in order to prevent infiltration excess overland flow on these typically low infiltration rate soils, it will be necessary to apply FDE at an instantaneous rate lower than the soil infiltration rate.

5.1.4 Well drained land

Well-drained soils with little or no connection to surface water pose the lowest risk for direct losses of applied FDE. Well-drained soils are typically characterised by high surface infiltration rates, high drainage fluxes and a large degree of matrix flow and are therefore likely to benefit least from applying FDE with low application rate tools. Travelling irrigators should prove adequate for land-applying FDE under these circumstances. Applications can be made at field capacity on these soil types and adherence to full deficit deferred irrigation criteria is not necessary. However, some storage should be available to avoid application at saturation or near-saturated conditions. In order to prevent macropore flow through large pores (> 300 µm), it is recommended that soils should not receive FDE applications for a drainage period of at least 24 hours post soil saturation in order to return soil water content back to field capacity. Some operators may still wish to include greater FDE storage in order to remove all risk associated with applying FDE to wet soil and in order to rationalise staffing during the traditionally busy and wet calving period; such a practice should still be considered best practice. The caveat for the low or minimal storage recommendation is that travelling irrigators should be run at their fastest speed (≤ 10 mm) when soil moisture contents are close to, at, or beyond field capacity. Furthermore, highly damaged soils that otherwise fall in this category should be spelled from land application or treated as per the low infiltration rate category (B). FDE should be applied to this category at an average application rate that is less than the soil infiltration rate in order to prevent excessive ponding.

The Waikato region has large areas of soils that would fall into the well drained flat land category, particularly those derived from volcanic parent material such as the Allophanic and Pumice Soil Orders. Such low risk soils can also be found in other Orders such as Recent and Brown. Local examples include the Otorohanga silt loam and the Horotiu fine sandy or silt loam (Typic Orthic Allophanic) or the Atiamuri sand (Welded Impeded Pumice).

5.1.5 Other well drained but very stony flat land (<7°)

The inclusion of this soil/landscape class has been added to identify that very stony, well drained land should receive FDE application depths no greater than 10 mm, irrespective of the antecedent soil water content. The depth restriction relates to the low soil water holding capacity and skeletal characteristics of these soils. However, the matrix flow nature of these soils means that they can otherwise be considered to have similar management requirements to the well-drained category. FDE should be applied to this category at an average application rate that is less than the soil infiltration rate in order to prevent excessive ponding. Soils from this category are not commonly found (if at all) in the Waikato region. However, it is possible they could be found on alluvial outwash plains where soils of the Recent or Brown Soil Orders overlie coarse gravels close to the soil surface.

5.2 Further management considerations

In addition to the criteria stated in Table 5, we recommend that a minimum withholding period of 4 days (where practical, based on grazing rotation length) between grazing and application should be adhered to when using a high application rate irrigation system (>10 mm/hr on an instantaneous basis). Such a withholding period will allow for some initial recovery from soil treading damage (such as surface sealing) and increase surface infiltration rates that may have been depressed during animal grazing. We also recommend that paddocks that have been considerably pugged and damaged during wet grazing events should be spelled from FDE irrigation for a period of approximately 6 months to allow recovery of soil physical condition.

Table 6. Recommended maximum application depths for different soil and landscape features using either a high or low application rate irrigation system (assumes suitable soil moisture contents and water holding capacity). Depths listed relate to the mean delivery depth across an irrigator's wetted footprint.

Category	**A**	**B**	**C**	**D**	**E**
Maximum average depth#	Artificial drainage or coarse soil structure	Impeded drainage or low infiltration rate	Sloping land (>7°) or hump & hollow drained land	Well drained flat land (<7°)	Other well drained but very stony flat land (<7°)
Max depth: High rate tool	**10 mm**	**10 mm**	**10 mm***	**25 mm# (10 mm at field capacity)**	**10 mm**
Max depth: Low rate tool	**25 mm**	**25 mm**	**10 mm**	**25 mm**	**10 mm**

* *This method only applicable where instantaneous application rate < infiltration rate*

\# *25 mm is the suggested maximum application depth when a suitable SWD exists (≥ 15 mm). Field capacity should not be exceeded by more than 10 mm using a high rate irrigator.*

It is recommended that the maximum application depth applied at any one time should be in accordance with industry best practice as described for soils of different texture in the DEC Manual (2006). Single applications of greater than 25 mm depth are not recommended, even if large soil water deficits exist and total N loading would remain below 150 kg N/ha, as research has shown an increased risk of small volume but high concentration direct losses often associated with soil cracking along preferential flow paths (Houlbrooke et al. 2004a). Furthermore, when using a high rate travelling irrigator on high risk soil types (categories A, B & C), irrigators should be set to their fastest travel speed to restrict application depth to less than 10 mm to further decrease the risk of preferential flow (Table 6). However, the use of low application rates (<10 mm per hour on an instantaneous basis) should allow the application of up to 25 mm per application because of the much reduced risk of generating preferential flow or surface runoff.

Best management practice for the addition of fertiliser to land recommends that nutrients are only added during periods of active plant growth. The New Zealand Code of Practice for Nutrient Management (with emphasis on fertiliser use) recommends that nutrients are not applied to ryegrass pasture when soil temperatures are below 6° C and falling, as ryegrass growth stops at temperatures < 4° C. Nutrient applications can then be recommenced once soil temperatures are greater than 4° C in spring and rising. In practice, the adherence to nutrient management best practice with regards to FDE application will be easily followed by Waikato dairy farmers, as the dairy cattle lactation season coincides with the period of active pasture growth from late winter/early spring through until late autumn/early winter. However, winter milking operations that are generating FDE during periods of low soil temperature should consider storage irrespective of soil and landscape risk factors, with effluent returned to land during the warmer spring period given suitable soil moisture conditions.

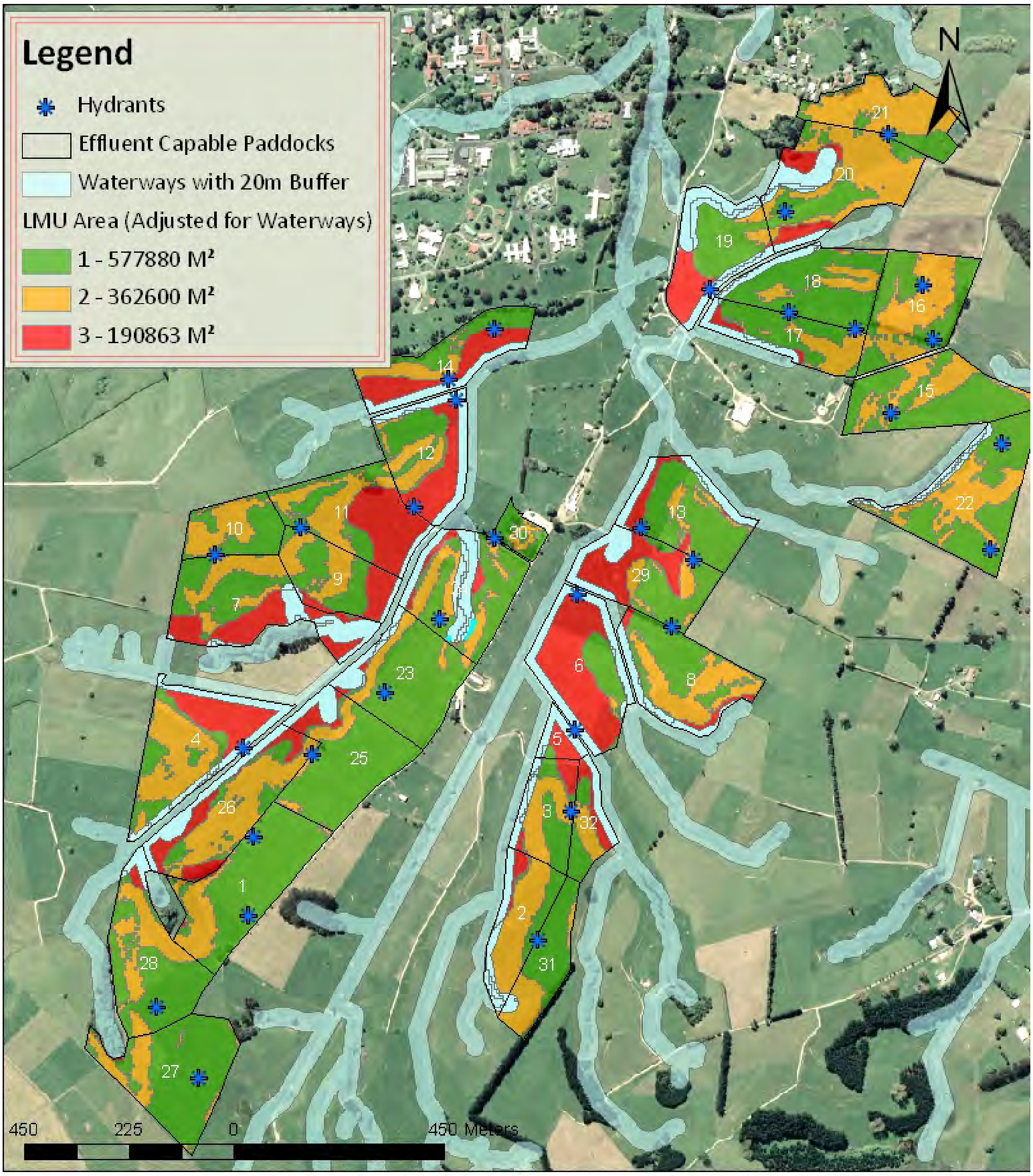
5.3 Determining effluent land management units

The Waikato region has a range of different Soil Orders as follows, most of which contain dairy farm land use (data supplied by Bala Tikkisetty):

- Allophonic - 22.2%
- Brown - 15.7%
- Pumice - 21.7%
- Gley - 5.4%
- Granular - 5.1%
- Organic - 3.6%
- Podzol - 11.1%
- Recent - 7.0%
- Ultic - 3.1%

On an NZSC Order basis, soils do not necessarily fit neatly into our proposed FDE management risk framework. For example soils in the Brown Order could easily fit into categories B, C and D. The process that other regional councils looking to adopt the FDE risk framework within their policy framework have followed has been to create a database of all dairy-farmed soil types within the region with a default risk categorisation. The default categorisation has resulted from the input of soil experts familiar with the soil types of the region and all relevant data including: drainage status, stoniness, depth to stones, depth to a slowly permeable layer, permeability of the slowest horizon, water holding capacity, structural vulnerability, soil structure and water logging vulnerability. Much of the relevant information required to categories each soil type into the FDE risk framework is available using the Landcare Research SMap resource.

It is currently proposed that Regional Councils operating with FDE application as a consented activity would then use this default database to determine landscape risk based on regional scale soil maps and then place appropriate consent conditions against the activity. However, it has become apparent that in many cases there would be considerable benefit to generate a farm scale soil map to optimize the use of low risk soil and landscape features. This would have the greatest advantage where multiple soil types (high and low risk soils) were found in close proximity on regional scale maps. The alternative would require the more cautious approach of matching management practice to the soil with the highest risk and thus having a considerably greater effluent storage requirement. An example of whole farm soil mapping has been presented in Figure 10 for the recent AgResearch dairy conversion at Tokanui. At a regional scale this farm would have identified large areas of sloping land and land with impeded drainage. However, at a farm scale it is apparent that there is approximately 60 ha of well drained flat to undulating Allophanic soils. EW has a permitted activity rule for the land application of FDE. Using this approach we believe that farmers would either have to be encouraged to use the FDE risk framework to guide their management practices and storage requirements, or that the permitted activity rules would have to be updated to account for soil and landscape risk factors.



AgResearch Tokanui Dairy Farm Land Management Units

LMU1 - Low Risk Category - Flat and undulating, well drained soil - Use any irrigation tool.
Apply irrigation anytime except during rainfall.

LMU2 - High Risk Category - Sloping, well drained soil - Only use low application rate sprinklers.
Only apply using Deferred Irrigation*.

LMU3 - High Risk - Poorly draining soils - Requires Deferred Irrigation*. Able to use any irrigation tool
but travelling irrigator requires application depth to be less than SWD before safely applied.

Effluent must not be discharged within 20m of waterways.

*Deferred Irrigation requires the application depth being smaller than the soil water deficit (SWD)

agresearch

Figure 10. AgResearch Tokanui effluent management units using the FDE risk framework

5.4 Determining farm-specific effluent storage requirements

The FDE risk framework outlined in section 5.1 above describes the concept storage requirements for each soil and landscape risk category. In essence, two different storage and land application strategies are prescribed. The first strategy requires full deferred irrigation principles where application depth must be less than soil water deficit. Essentially field capacity becomes the critical SWC benchmark against which FDE scheduling can be determined. For low-risk landscapes FDE application must not result in saturated or near-saturated soil conditions likely to induce flow through the largest macropores (>300 µm, equivalent to a tension of -1 kPa). The application criteria should not therefore allow applications at soil water contents > field capacity.

Massey University and Horizons Regional Council have recently developed a FDE storage calculator (Horne et al. 2010). This calculator measures farm specific-storage requirements using 30 years of local met data on a daily time step. Critical input variables include rainfall catchment area, shed water use, number of cows, irrigation hardware and irrigation management (daily pumping volume). The calculator was initially established to calculate deferred irrigation requirements. However, a recent update has allowed the scheduling on low risk soils where avoiding saturation by withholding FDE applications at soil water contents > field capacity is the key application criteria. The use of the FDE risk framework and the pond storage calculator are very complementary. The risk framework is required as step one to determine landscape risk and therefore area of the effluent land management unit(s). Step two uses this information as a landscape risk input into the pond calculator. A stepwise process has been created to describe the integration of these two tools and is summarised in Figure 11 below.

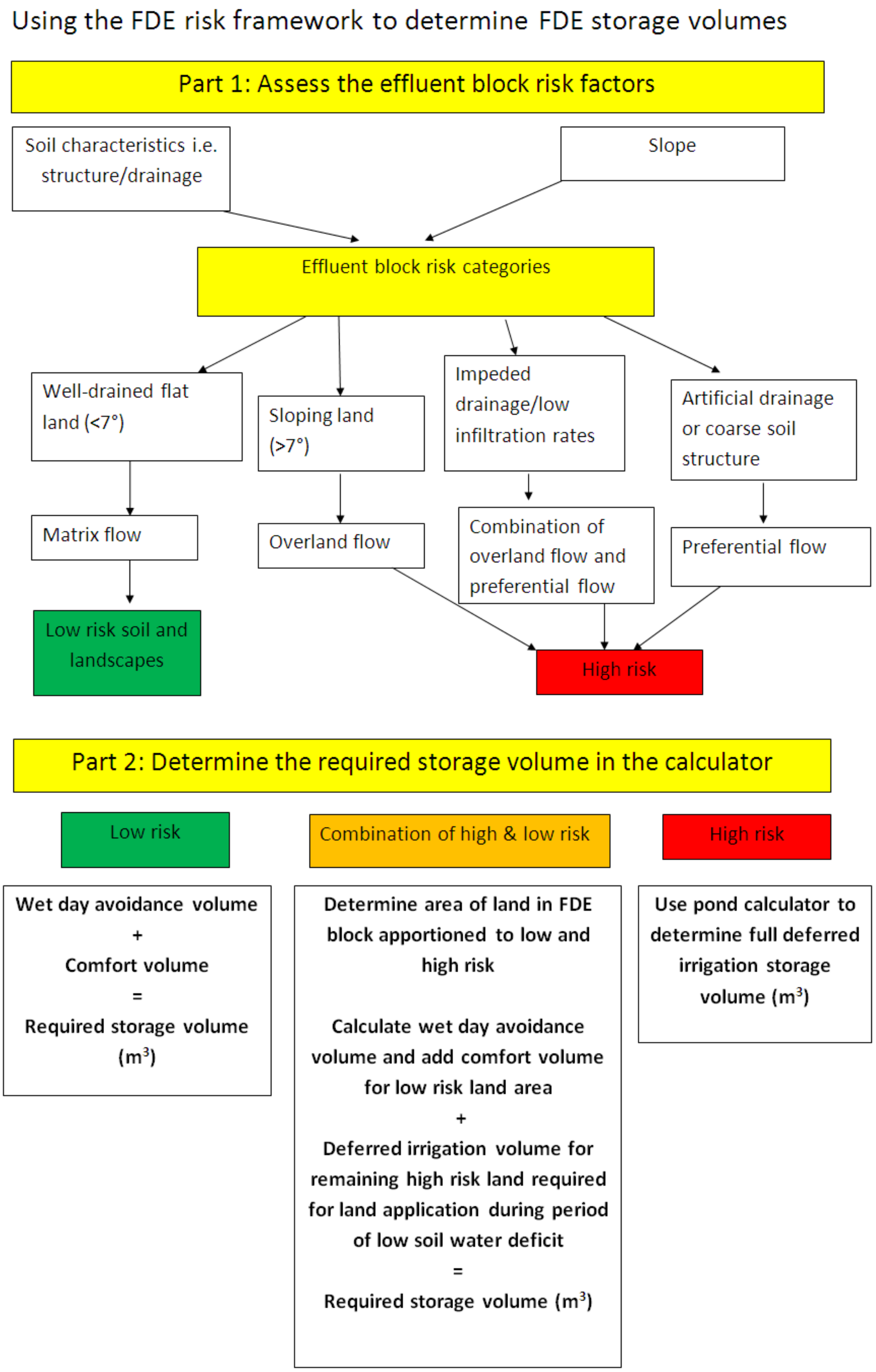


Figure 11. Summary of stepwise process for using the FDE risk framework with the pond storage calculator

5.5 Improving on-farm management practice

The adoption of the FDE risk framework to determine appropriate management practice, combined with farm specific storage requirements using the pond storage calculator, will provide farmers with the appropriate application strategy and irrigation and storage infrastructure to achieve compliance throughout the year, irrespective of climatic and soil conditions. However, following discussions with EW staff and having reviewed the past 18 months of non-compliance data, it is evident that much of the reported non-compliance is also due to poor operational management, such as excessive and heavy applications, storage leakage and overflow and equipment failure. Poor management is inevitable at certain times of the year when critical infrastructure is missing; for these situations, FDE has to be applied when soil and climatic conditions are inappropriate. However, poor management will still occur despite having adequate storage and irrigation equipment if pond levels are not actively managed and application depths and rates not adequately controlled. Specialised effluent management tools are now available commercially to provide smart guidance with relation to SWC, application depth and pond management (Hanly et al. 2010).

5.6 Further research

Some further questions remain regarding the application of FDE to land. To date few studies have investigated direct contaminant losses (P, ammonium-N, organic-N and faecal micro-organisms) to surface and ground waters following land application of FDE to well-drained soils at moisture contents close to or at field capacity. However, considerable research has been conducted on these low risk soil types using both FDE application and chemical and microbial tracers to measure solute breakthrough curves. Despite some methodological limitations, the contradictory data presented by Burgess (2003) suggests that some further research may be required on shallow Pumice Soils overlying coarse textured gravels. This report also highlights the lack of research conducted on both peat soils and land with hump and hollow drainage systems. More information on these landscapes will provide greater guidance on the minimum management practices required to practice safe land application of FDE.

Of particular relevance to the Waikato region is the lack of research available on the likelihood, risk and potential impact of hydrophobicity. With regards to FDE application to soils prone to hydrophobicity, we need more information on the generation of overland flow on sloping land and the incidence of preferential flow on otherwise well-drained flat land. Further information would help with the prescription of appropriate mitigation practices. Precautionary principles would suggest a low depth and low rate strategy on high risk landscapes i.e. sloping land during periods of very low SWC. Of greater concern is that we still need more research to be able to accurately identify key soil characteristics that define a hydrophobicity risk (Deurer and Muller 2010). Just managing soil water contents will be difficult as irrigating pasture with water may have unintended consequences around land use intensification, whilst deferring FDE to storage during excessively dry periods will further shorten the opportunity for land application (and would probably encourage the production of methane within the storage ponds).

6. Conclusions

- Three primary mechanisms exist for the transport of water (containing solutes and suspended solids) through soil: matrix flow, preferential flow and overland flow. The potential risk of direct contamination from land-applied FDE varies with water transport mechanisms and therefore varies between soil and landscape features.
- Soils that exhibit preferential or overland flow can lose considerable amounts of FDE when unfavourable soil moisture conditions exist. Critical landscapes include soils with artificial drainage or coarse soil structure, soils with either an infiltration or drainage impediment, or soils on rolling or hill country. Soils that exhibit matrix flow show a very low risk of FDE losses under most soil moisture conditions (saturation avoidance required). Such soils are typically well drained with fine soil structure and high porosity.
- The environmental effectiveness of current best management practices (deferred irrigation and low application rate tools) will vary between soil types depending on their inherent risk of direct contamination from land applied FDE
- A soil and landscape risk framework has been developed to guide minimum FDE management practices and concept storage requirements in order to avoid direct losses of contaminants from land applied FDE.
- Categorised soil types can be entered into the newly developed pond storage calculator to determine farm-specific effluent storage requirements

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