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The influence of soil drainage characteristics on contaminant leakage risk associated with the land application of farm dairy effluent

Prepared for Environment Southland

October 2009

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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. 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 contamination 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 or overland flow provides little soil contact time and decreased opportunity to attenuate the applied contaminants. 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/sloping country.

Soils that exhibit matrix flow show a very low risk of direct contamination loss of FDE under wet soil moisture conditions. 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 high porosity. Research conducted in New Zealand suggests there is a low risk of direct contamination from FDE applied to well-drained soils. However, well drained soils typically have an inherently higher N leaching risk associated with the direct deposition of animal urine patches to land as a result of the smaller denitrification influence and smaller water holding capacities often associated with such soils. Therefore, the extent and impact from N inputs added as FDE to free draining soils that leach to ground water indirectly should be kept in context as FDE makes up approximately 10% of the daily nutrient load from cattle excreta. Therefore, effective mitigation techniques for N loss on these free draining soils should target the cumulative effects of autumn-applied urine patches during animal grazing.

The effectiveness of current effluent best management practices (deferred irrigation and low application rate tools) varies between soil types depending on their inherent risk of direct contamination from land-applied FDE. Best practice management should therefore be targeted where it will be most effective. It is, however, acknowledged that there have

been no targeted field studies to assess the risk of FDE application to shallow well-drained land when soil moisture contents are close to or at field capacity.

2. 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 in Manawatu and Otago 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 run-off directly to surface water bodies (Houlbrooke et al. 2008b, 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/sloping 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 soil types. The issue of hydrophobicity and its potential impact on rapid re-wetting of dry well drained is soils in Southland are 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, has shown that between 2 and 20% of both the nitrogen (N) and phosphorus (P) applied in FDE is lost either in runoff or via leaching. 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 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 best management practices. Effluent best management practices 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 4.

In 2008, Horizons Regional Council engaged the services of AgResearch Ltd to report on potential best management practices (BMPs) for land application of FDE in the Manawatu-Wanganui region (Houlbrooke et al. 2008b). As part of this report, a decision tree was developed that took account of soil and landscape features when recommending best management practices and associated pond storage requirements. Following subsequent discussion with Environment Southland, the decision tree (slightly adapted for Southland conditions) was provided to Environment Southland for consideration for their region. This original version of the decision tool is presented in Figure 1.

Recommendations regarding management practice and storage requirements using the decision tree considered a soils inherent risk for direct losses of FDE contaminants during land application. For the soil and landscape features that contained an inherent risk of direct FDE loss, the proposed BMP also reflected minimum appropriate practice based on the potential for environmental effect. However, storage recommendations for the original well drained soil flow chart were made assuming a cautious approach to ensure FDE was not applied to wet soil and also to capture the benefits associated with labor rationalisation during the busy wetter spring period on a farm when calving takes place. Recommendations did not, therefore, reflect minimum requirements for an effects-based strategy managing FDE on well drained soils. Nor did they capture the appropriate storage requirement to implement a full deferred irrigation strategy. Hence, the recommendations were a compromise between an effects-based approach and perceived best practice. Subsequently, Environment Southland has expressed some concern with regard to the potential for ground water contamination if FDE was applied to well drained soils overlying shallow groundwater tables during wet conditions. Therefore, the aim of this report is to further investigate the effect of soil drainage mechanisms on the likelihood of direct drainage losses of applied FDE. The scope of this investigation included a review of international literature, although due to the contrasting nature of animal effluents and manures, few relevant studies were found.

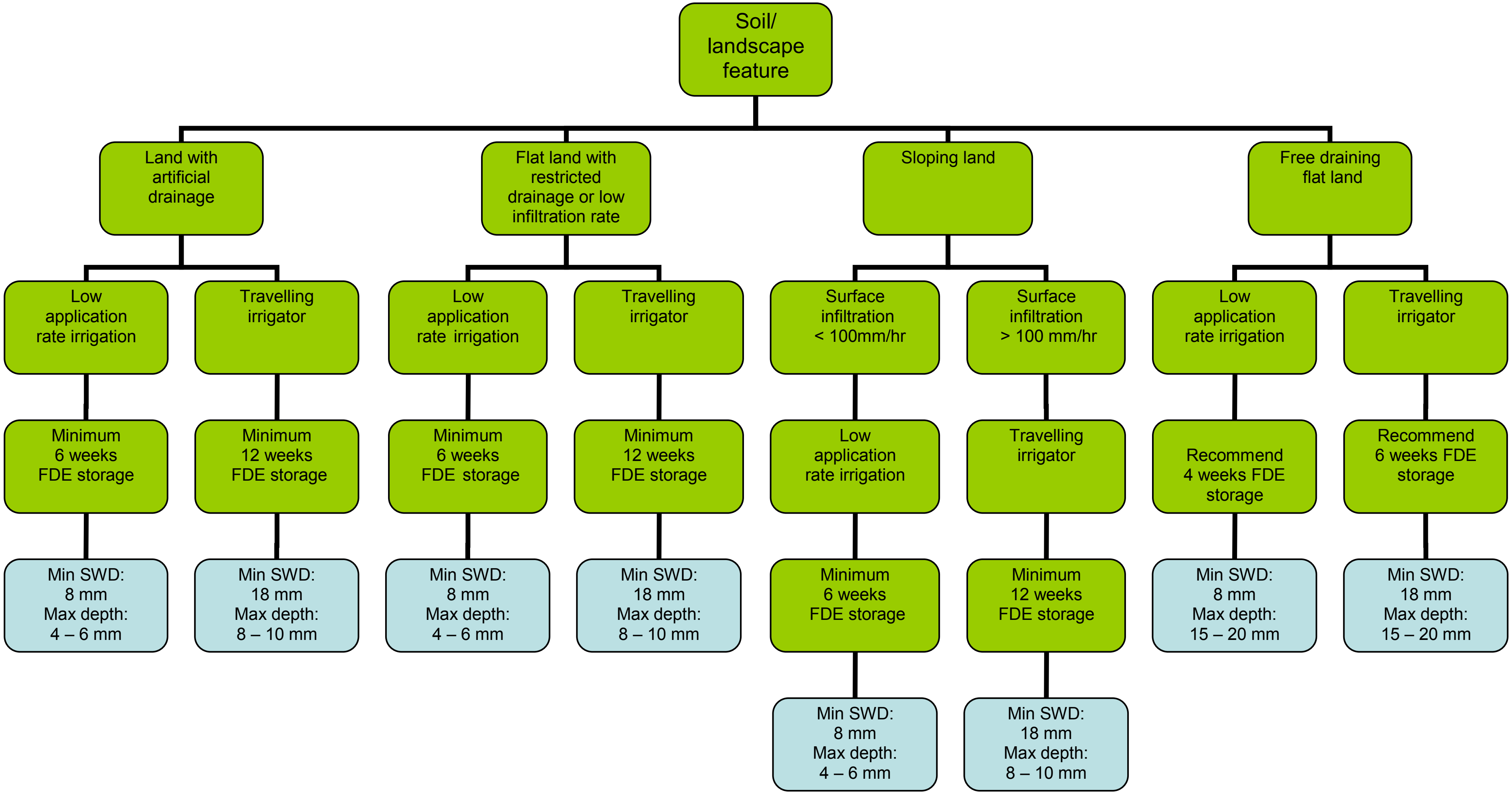

Figure 1. Original flow chart to guide proposed best management practice for land application of FDE.

3. 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 as soil texture is strong factor in governing unsaturated flow, however, saturated flow is largely governed by soil density, macroporosity and soil structure. Three mechanisms for the movement of excess soil water are described below.

3.1 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 2).

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 3 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 previous 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 35% v/v has a total water holding capacity of 105 mm depth in the top 300 mm of soil (dominant root zone). It should therefore require an application depth to a wet soil of at least 50 mm in order to result in direct drainage of FDE contaminant losses. Figure 4 presents a diagrammatic example of an idealised breakthrough curve (plot of relative 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 attenuation of the applied solute during the matrix flow.

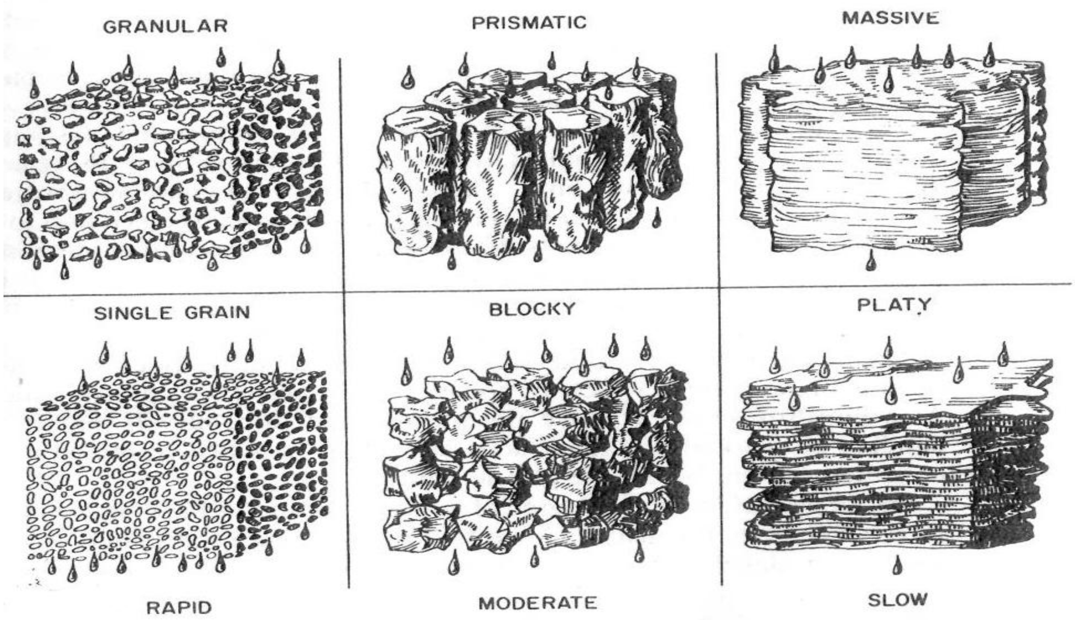

Figure 2. Diagram of the influence of soil structure on drainage (Bowler 1980).

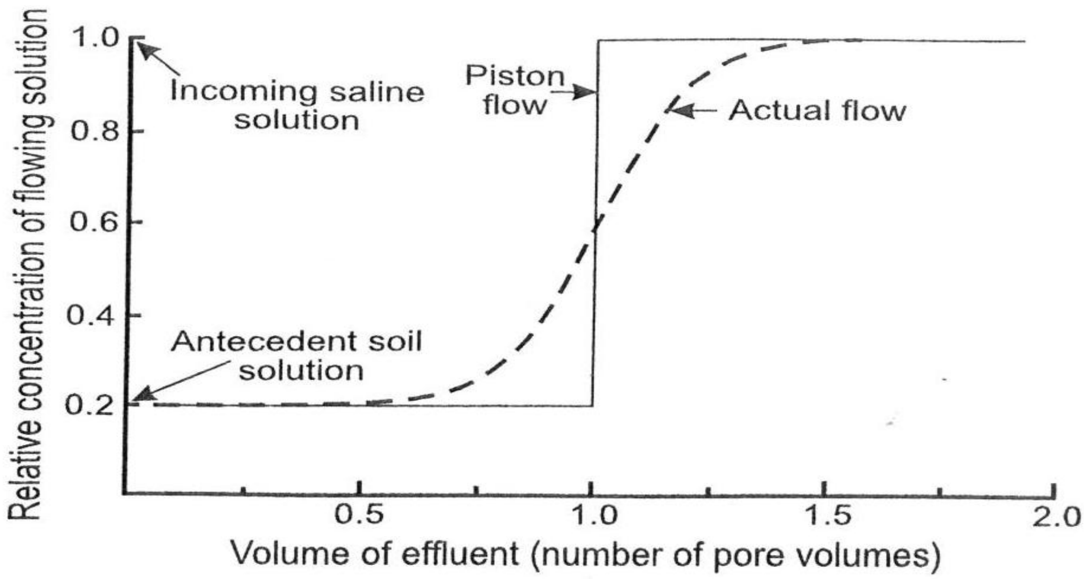

Figure 3. Graphic illustration of theoretical vs. actual piston flow drainage flux of an applied solution (Hillel 1998).

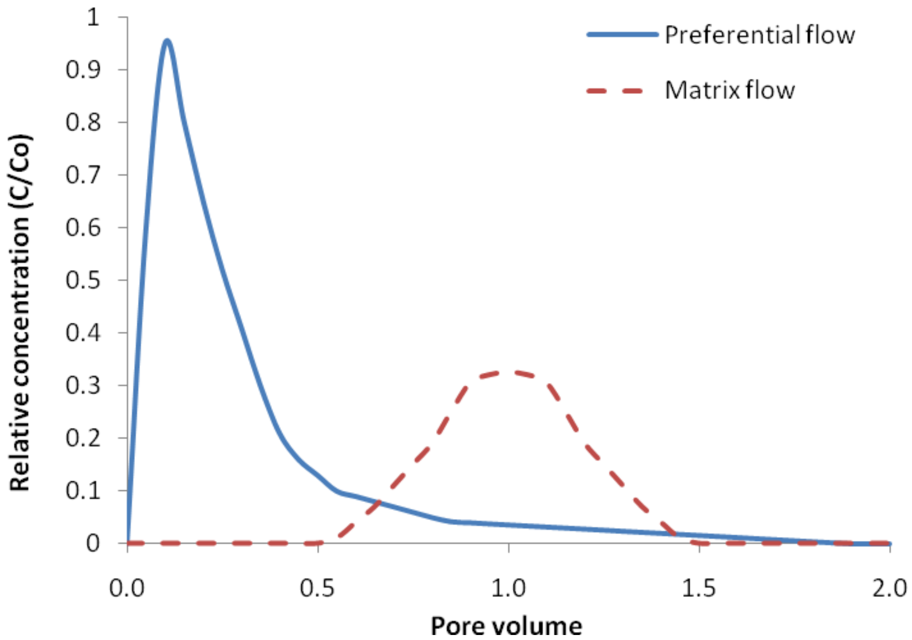

Figure 4. Illustration of breakthrough curves for preferential vs. matrix flow

3.2 Preferential flow

Preferential flow means that, water favors 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 where soils with coarser prismatic or large blocky structures (Figure 2) and firm clay coated peds can inhibit micropore flow (McLeod et al. 2008, McLeod et al. 2004, Magesan et al. 1999, Wells 1973).

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 5). 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 soil drainage (as demonstrated in Figure 6) 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 4 demonstrates the potential for high concentrations of solutes to be rapidly eluted in bypass flow, compared to the piston effect observed under matrix flow.

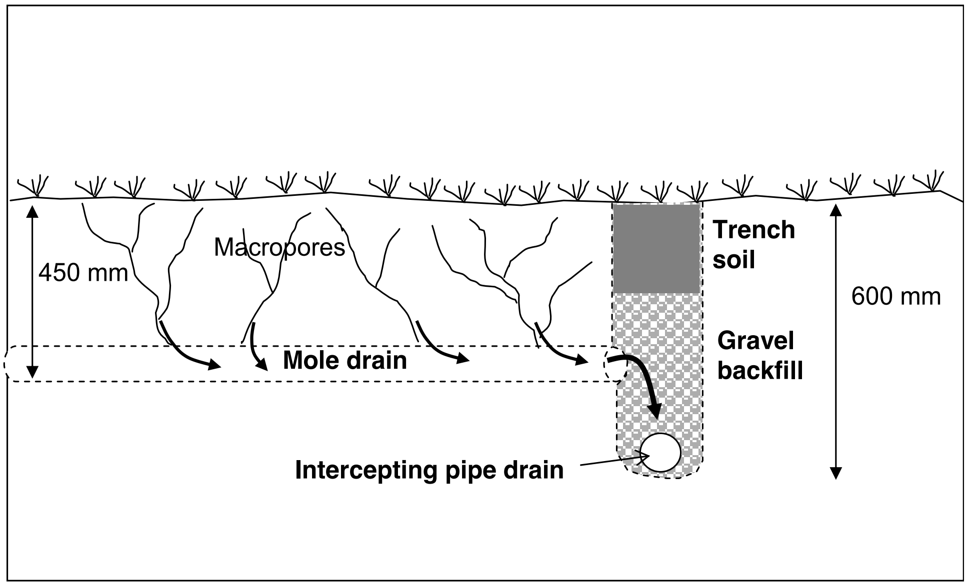

Figure 5. Diagrammatic representation of a mole-pipe drained soil.

Figure 6. Field example of preferential flow through a Pallic soil containing remnants of old mole drains.

3.3 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 soils 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 2). The second process that results in overland flow generation is known as 'saturation excess' flow. This condition requires a fully 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 all 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 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).

4. Existing 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.

4.1 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:

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

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

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 at field capacity ($m^3\ m^{-3}$), and θ_i is the soil water content on day *i* ($m^3\ m^{-3}$) (Houlbrooke et al. 2004a). Both of 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 Southland, regular soil water deficits greater than 10 mm mainly occur between the months of October and May. 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 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.

4.2 Low application rate tools

Low rate applicators such as K-Line and Larall are temporarily fixed in one place and deliver at rates of approximately 4 mm per hour. Therefore, a one hour application would deliver only 4 mm of FDE to the soil. 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, 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). 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 donut pattern) then the application rate would be approximately 20 mm/hr. Low rate applicators apply FDE at rates of only 4 mm/hr or less 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 (Houlbrooke et al. 2006, McLeod et al. 1998).

5. Contaminant leakage risk under contrasting soil types

5.1 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). In some circumstances, intensive dairy farm operations in the Southland Region are located on rolling country (c.>7°) with low surface infiltration. These soils typically belong to the Pallic soil order which are characterised by high density, slowly permeable subsurface horizons often over a fragipan which has a highly restricted permeability (Hewitt 1998). The low infiltration rates (< 100 mm/hr) of many of these soils in combination with sloping land poses a high risk of surface ponding and subsequent overland flow and surface redistribution when FDE is applied using 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 storage and subsequent filtration of contaminants in the applied

FDE. For a number of practical and environmental reasons, it is recommended that such systems are run in accordance with the principles of deferred irrigation.

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.

5.2 Soils that exhibit preferential flow

There are a number of published New Zealand studies outlining 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, Houlbrooke et al. 2006, Houlbrooke et al. 2004a, Monaghan and 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, McLeod et al. 2004, Aislabie et al. 2001, McLeod et al. 1998).

Preferential flow has often been identified as the early presence (<0.1 of a pore volume) of a change 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) has 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. The following soil characteristics or soil orders/subgroups in the New Zealand Soil Classification (Hewitt, 1998) were identified as having a ***high preferential flow risk***:

- Organic soils,
- Ultic soils
- Granular soils
- Melanic soils
- Podzol soils

- Gley and perch-gley soils
- mottled subsoils
- peaty soils
- skeletal and pedal soils
- soils with a slowly permeable layer
- soils with coarse soil structure
- soils with a high K_{SAT}:K_{-40} ratio.

The following soil characteristics or soil orders in the New Zealand Soil Classification were identified as having a ***medium preferential flow risk*** (McLeod et al. 2008):

- Brown soils
- Pallic soils
- Oxidic soils

The categorisation of the Brown soil order as medium risk for preferential flow may seem intriguing, considering its often well drained. However, its inclusion results from research conducted on a Typic Brown Southland soil (Waikiwi silt loam) by McLeod et al. (2003) where a peak in its breakthrough curve was reported at only 0.15 of a pore volume. The soil at the site of lysimeter collection was described as well drained but yet the remnant of a mole and pipe drainage system was reported. However the Waikiwi silt loam is a Firm Brown soil and hence has a coarse nearly massive underlying horizon that impedes drainage and hence fulfils one requirement for risk of preferential flow. Furthermore, the presence of a reported well developed structure of blocky peds (albeit only fine to medium in size) which may have contributed some preferential flow paths. The results presented by McLeod et al. (2003) also contrast with those of Monaghan et al. (1999) who reported that 95% of simulated urine applications to the Waikiwi silt loam were contained within the top 300 mm of the soil. We recommend that for the Brown soil class that each soil may have to be considered on a case by case basis to determine if it contains features that are likely to result in a risk of preferential flow drainage characteristics.

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 likely 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. We believe that with the adherence to some best management practices such as deferred irrigation and low rate tools, these limitations on such critical soil types can largely be overcome.

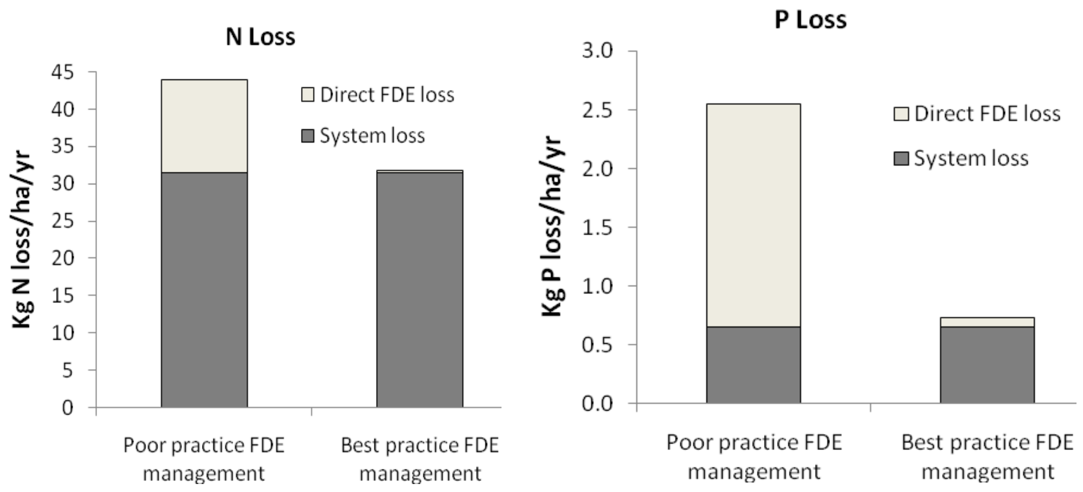

Figure 7. Direct drainage losses of FDE under deferred irrigation and compared for a one off poor FDE application. Direct losses of FDE are presented on top dairy land use loss of N and P (not derived directly from FDE application (Houlbrooke et al. 2008a, Houlbrooke et al. 2004).

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 Houlbrooke et al. (2004a & 2008a) on a Manawatu Pallic soil. 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 the adjacent area that did not receive FDE inputs respectively.

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 (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 using low rate technology. Concentrations of total P, ammonium N and *E. coli* measured in drainage induced by the application of the FDE using K-line 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

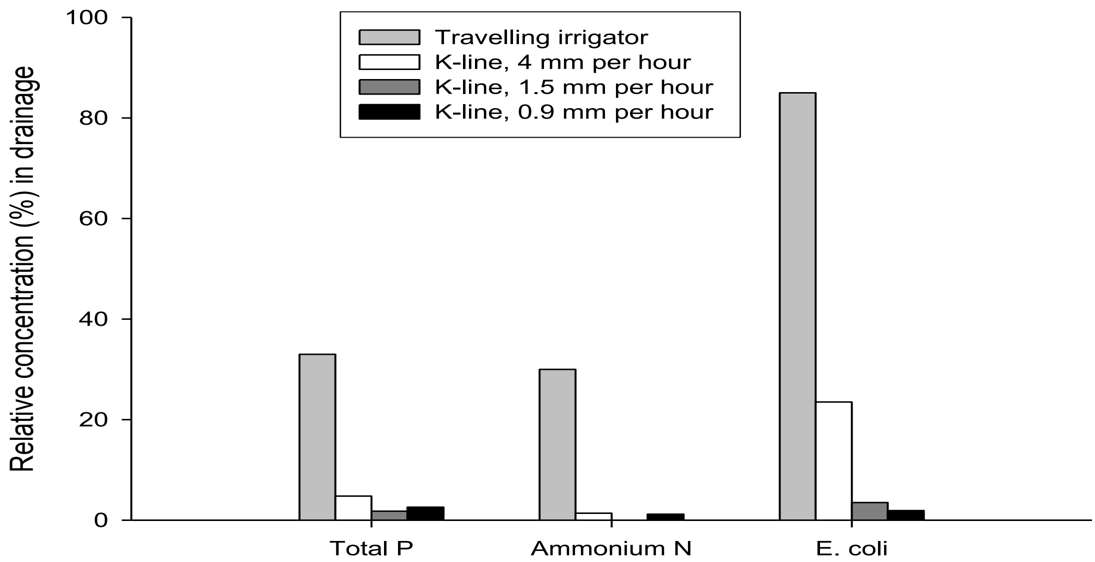

Figure 8. Relative concentrations of total P, ammonium N and *E. coli* in drainage waters collected following the irrigation of FDE to a mole-pipe drained soil using a travelling irrigator or K-line irrigation system (Houlbrooke et al. 2006).

An investigation of the effect of irrigation application rate on the incidence of preferential flow in a well drained Allophanic soil and poorly drained Gley soil 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 5-20 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 greater in the poorly drained Gley soil than the well drained Allophanic soil which was limited to some conduits caused by earth worm burrowing. For both soil types, application rates ≤10 mm/hr resulted in all of the applied 25 mm depth 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 as sustained low rate application at keeping FDE in the topsoil. 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. Therefore, preferential flow pathways will not be continuous out of the dominant root zone (c. 300 cm).

5.3 Soils that exhibit matrix flow

There has been no research undertaken in New Zealand to determine the direct loss of contaminants associated with FDE application to wet but well drained land. However, there have been numerous studies that have investigated either transport pathways of land-applied FDE in well drained soil, or the fate of multiple N inputs (including FDE). In a review of the potential for preferential flow across a wide range of New Zealand soil types and characteristics, McLeod et al. (2008) reported that the following soil orders in the New Zealand Soil Classification were identified as having a ***low preferential flow risk***:

- Recent soils,
- Pumice soils
- Allophanic soils
- Semi-arid soils

The categorization of the above soil orders as having low preferential flow risk was derived from research conducted assessing breakthrough curves on a range of well drained 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 50 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. All of these assessments for well-drained soil 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 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). Well drained soils often deliver greater amounts of drainage water than poorly drained soils, providing more opportunity to leach mobile nitrate-N in soil solution. Furthermore, poorly drained soils suffer higher denitrification (gaseous) loss 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).

With little or no likely direct drainage contribution, the extent and impact from N inputs added as FDE to free draining soils that leach to ground water indirectly should be kept in context. 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 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 a only component of the total N inputs that are mineralised into nitrate-N and subsequently leached from the root-zone (Houlbrooke et al 2008a). Therefore, effective mitigation techniques for controlling N losses on these free draining soils should target the cumulative effect of autumn-applied urine patches 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.

The report on suitable soil properties to receive land applications of effluent by Wells (1973) suggested that well drained soils with a silt loam texture were the most suitable for disposal of effluents. However, Wells also stated 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. The excessively drained class related to soils mapped as lithosols (shallow soils with no or poor horizon definition on steep slopes). Such soils will not currently be receiving applications of FDE in New Zealand. There is no longer a 'somewhat excessively drained' drainage class as these have been incorporated into the 'well drained' category (Lynn et al. 2009). These soils would likely have been well-drained flat land with a shallow soil profile and very low clay content. We believe that 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. In this manner, Barton et al. (2005) reported considerable N drainage losses (173 kg/ha over 2 years) from a well drained Recent soil which received 772 kg N/ha over a two year period from municipal effluent. This drainage loss was predominantly organic N (87%); this was not, however, derived from N contained in the applied effluent but, rather from increased leaching of the native soil organic N as a result of the high N loading rate. 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 considering these soils have a low water holding capacity and the potential for water repellency when very dry, it is recommended that application depths should be kept as low as possible on these soils (< 10 mm per application).

A large amount of research has been conducted at Lincoln University investigating the effect of a range of different N inputs (including urine patches, fertiliser and FDE) on subsequent nitrogen (in particular nitrate-N) leaching losses. These studies were undertaken using lysimeters with well-or moderately well-drained Canterbury soils. 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). The overwhelming theme of this line of research was that urine patches deposited directly on the paddock surface were responsible for the majority of subsequent N leached from the deep lysimeters (Di and Cameron 2002, Silva et al. 1999). Furthermore Di et al. 1998 measured greater losses associated with ammonium- N fertiliser applications than for FDE containing approximately 66-75% organic-N. The Lismore stony silt loam (Orthic Brown soil) is very similar in nature to the well drained Gore stony silt loam. High N leaching losses under the border dyke irrigated Lismore soil (between 112 to 162 kg N/ha/yr depending on amount and form of N) were attributed to its low water holding capacity and shallow profile (20-30 cm) underlain by coarse gravels (Di and Cameron 2002). Recommended mitigation for this high N loss was to target the effect of urine patch inputs by the use of a nitrification inhibitor to decrease the conversion of ammonium-N to nitrate-N, thus decreasing farm N drainage losses (Di et al. 2007 & 2004).

Because well-drained soils have typically high infiltration rates without drainage impediments, combined with 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. In reality, well-drained soils that do not have drainage or infiltration limitations will struggle to reach a true state of saturation. However, the combination of prolonged heavy rainfall and application of FDE (particularly large depths) may be enough to induce temporary saturation conditions. It is, therefore, recommended that a small amount of storage (approx. 3-6 days) combined with a strategy of low application depth (irrigator set at fastest travel speed) would be sufficient to avoid any direct losses of FDE during conditions of low soil water deficit (close to field capacity). In order to prevent macropore flow through large pores (> 300 μm) typically at low suctions (-1 KPa or less) then it is recommended that soils should be withheld from FDE application for a drainage period of at least 24 hours post the attainment of soil saturation.

Some operators may still wish to include a 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 and such a practice should still be considered best practice. In summary, when drainage and runoff pathways to surface water bodies are limited, then the current practice using a high application rate travelling irrigator with minimal storage is likely to be suitable with regards to minimising potential environmental effects.

Considering Environment Southland's concern regarding the application of FDE to shallow well-drained soil when wet (close to or at field capacity), it is important to discuss the potential implications of wetting front instability. Figure 9 demonstrates the variable rate but uniform nature of drainage when water is applied to dry soil with either a uniform coarse or fine texture or soils with a distinct texture contrast of coarse over fine material. However, where fine textured soil overlies coarse textured material there is a likelihood of preferential finger flow developing once drainage water enters the coarse textured layer if the coarse layer was previously dry (Brady and Weil 2007, Hillel 1998). The mechanism for such wetting front instability is associated with a low matrix potential in the fine textured overlaying layer until large pore spaces fill up and the soil becomes saturated (Hillel 1998, McLaren and Cameron 1996). Essentially, this mechanism provides a check valve for drainage waters and ensures matrix flow of draining solutes (McLaren and Cameron 1996). Therefore, it will be important to run travelling irrigators at their fastest speed (lowest depth) on such shallow soils overlaying a coarse-textured layer, such as, gravels in order to ensure that the applied depth is less than the water holding capacity of the fine textured horizon(s) and, therefore prevent the preferential flow of FDE through the coarse gravel layer.

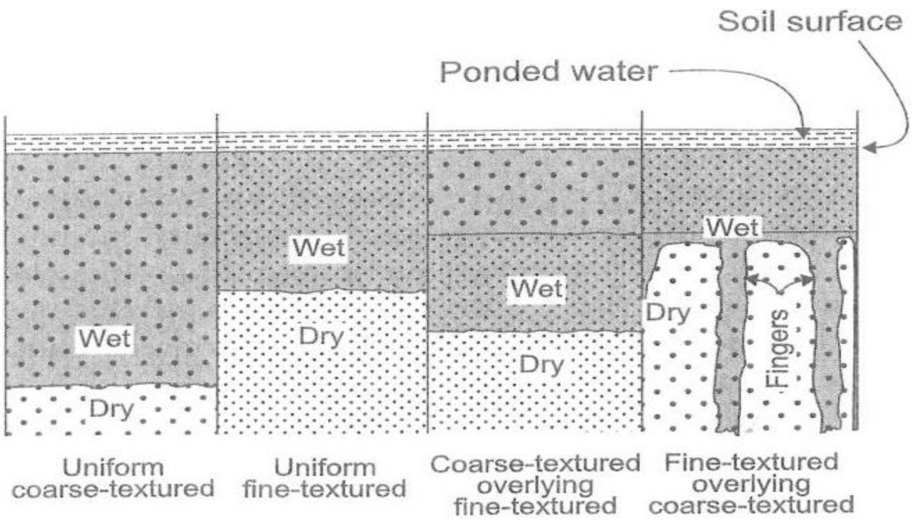

Figure 9. The influence of soil texture on expected wetting fronts during drainage (Hillel 1998).

5.4 Modelling assessment of the influence of soil type on P loss from land applied farm dairy effluent

An assessment of the environmental performance of a range of FDE management practices has been made using the Overseer nutrient budgets® model for two different soil types. Overseer® captures the effect of effluent management practices on P loss as drainage and/or surface runoff. Losses of N are not able to be assessed in a similar manner as the Overseer model does not currently determine direct (non nitrate) N losses in drainage/runoff. The assessments were established with the following conditions:

- Fixed rate of N and P inputs as either FDE or fertiliser (145 kg N/ha and 48 kg P/ha)
- Olsen P of 42 on FDE block and rest of milking platform
- Poorly drained soil = Pukemutu silt loam (Fragic Pallic soil, NZSC)
- Well drained soil = Gore stony silt loam (Orthic Brown soil , NZSC)
- Milking platform = 150 ha, FDE block = 40 ha
- Stocking rate = 2.8 cows/ha.
- Milk solids = 1220 kg/ha/yr

The poorly-drained Pukemutu silt loam is a mole and pipe drained soil found extensively in the Southland region. It is typical of undulating loess-covered terrace soils. The Gore stony silt loam is a shallow well-drained soil overlying sandy gravelly sub-soils. The Gore soil is situated in low alluvial river terraces in Southland and is typical of many Southland well-drained alluvial river terrace soils. Five different effluent management scenarios have been evaluated over the two different soil types in order to test the influence and inherent risk of soil and landscape features on the effectiveness of FDE best management practices:

- Sump slow = Daily application using a travelling irrigator set with high depth per application (> 24 mm).
- Sump fast = Daily application using a travelling irrigator set with lowest depth per application (< 12 mm).
- Sump low rate = Daily application using a low application rate irrigator
- Deff irr fast = Pond storage and deferred irrigation using a travelling irrigator set with lowest depth per application (< 12 mm).
- Deff irr low rate = Pond storage and deferred irrigation using a low application rate irrigator.

Effluent management practice had a considerable influence on whole farm P losses (Figure 10a). The practice of daily application using a travelling irrigator at slow speed on a mole and pipe drained soil contributed approx. 60% of whole farm P losses or 5 kg P/ha/yr from the FDE block (Figure 9b). Increasing the speed of the irrigator (decreasing depth applied) decreased this loss to 40% of whole farm losses or 2 kg P/ha/yr from the FDE block. Implementing a deferred irrigation strategy was predicted to decrease the direct loss of P to 3% of whole farm losses at a rate of only 0.1 kg P/ha/yr from the FDE block. The combination of deferred irrigation with low application rate irrigators predicts a zero direct loss of P from FDE on a soil that has a high inherent risk of preferential flow and direct losses. In summary, incremental improvements in the management practice resulted in decreased whole farm P losses on the Pukemutu silt loam.

It is important to note that the following results are therefore simulations based on the assumptions on the mechanisms for water balance and P loss imbedded in the Overseer model. Estimated losses for daily application of FDE using a travelling irrigator at slow and fast speed on a well-drained Gore soil was predicted to make up 30% and 20% respectively of whole farm P losses (Figure 10a). However, as whole farm P losses are very small in magnitude on well drained soils (0.1 kg P/ha/yr compared with 0.6 kg P/ha/yr from the poorly drained Pukemutu silt loam), these losses corresponded to a direct FDE P loss of only 0.2 and 0.1 kg P/ha/yr from the FDE block. The inclusion of either deferred irrigation and/or low rate tools was predicted to eliminate all direct P loss from FDE.

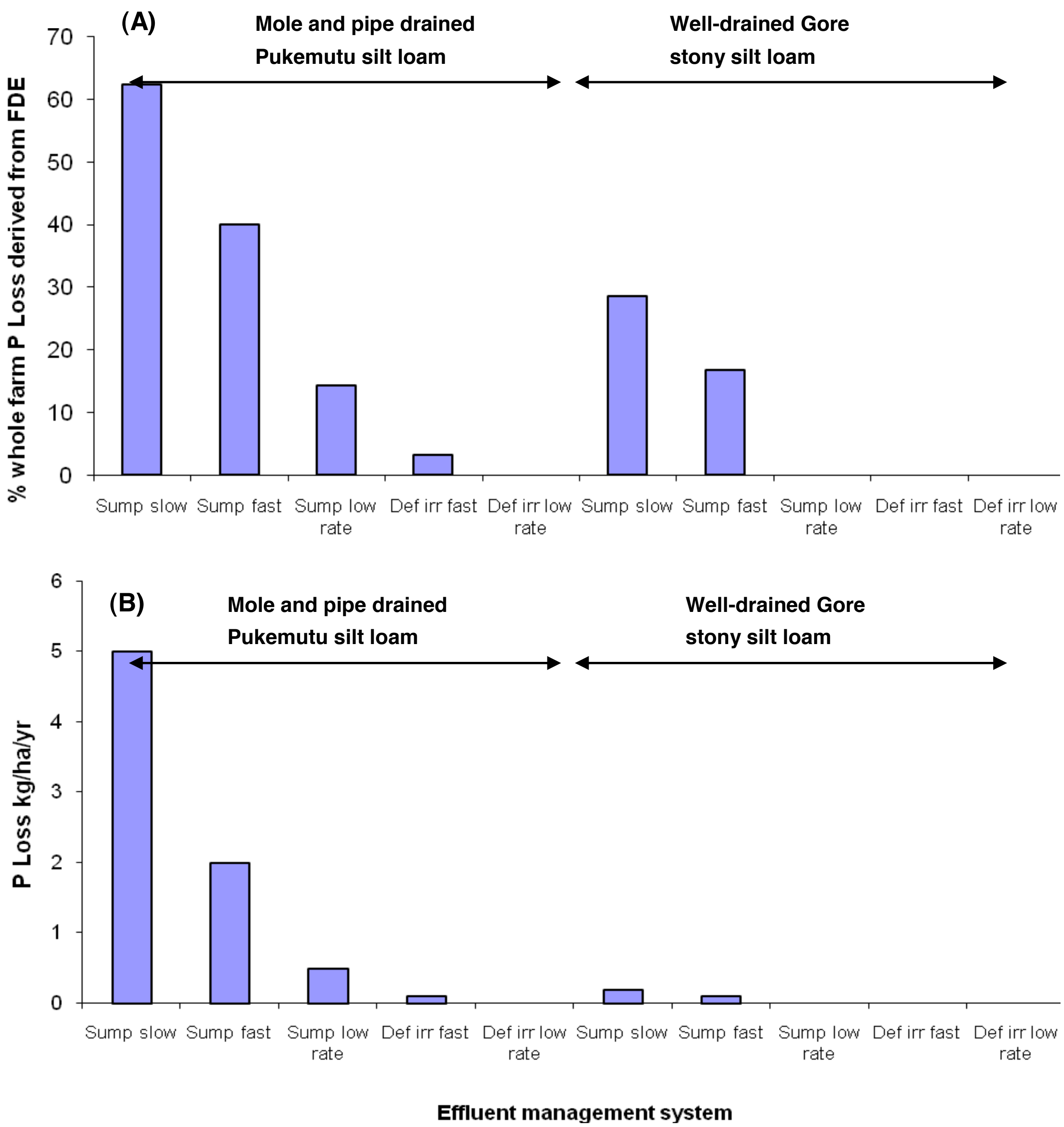

Figure 10. The influence of different effluent management practices on estimated whole farm P losses (A) % derived whole farm loss from direct loss of FDE (B) loads from direct loss of FDE in the effluent application area in units of kg P/ha/yr

6. Recommendations to Environment Southland

6.1 Minimum criteria for effluent management systems

Considering the risk/effects-based assessment of different soil and landscape features, minimum management criteria can be defined to avoid direct losses of land-applied FDE (Table 1). It should be noted that these criteria may differ from those recommended under BMP and are considered the minimum conditions that should be adhered to. An example of the difference between minimum criteria and BMP 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 application depths).

Table 1. Minimum criteria for a land applied effluent management system to achieve.

Soil and landscape feature	Artificial drainage or coarse soil structure	Impeded drainage or low infiltration rate	Sloping land (>7°)	Well drained flat land (<7°)	Other well drained but very stony[X] flat land (<7°)
Application depth (mm)	< SWD*	< SWD	< SWD	< 50% of WHC[#]	≤ 10 mm
Application rate (mm/hr)	N/A**	N/A**	< soil infiltration rate	N/A	N/A
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,

[#] WHC = water holding capacity 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

6.2 Implementation of policy taking into account soil and landscape features

It is recommended that soil and landscape features are taken into account when determining appropriate FDE management practice. The original best management practice decision tree presented in Figure 1 has been modified and presented below as Table 2, in order to better represent the minimum appropriate management criteria for farm dairy effluent land application whilst still taking into account soil and landscape features below. This decision tool varies in four places from the original charts:

i) The inclusion of a clause for coarse soil structure has been added to the artificial drainage category to reflect the high degree of preferential flow of applied FDE in soils with coarse structure, as reported by McLeod (2008). In essence, the installation of artificial drainage modifies the drainage properties of a soil to behave similarly to those with a well developed coarse soil structure. By definition, 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. 08). Coarse soil structure favours pore size exclusion when transporting microbes. For the purpose of this report any soils with 80% or more peds captured on a 10 mm sieve within the topsoil (A Horizon) is considered to have coarse soil structure

ii) The recommended threshold for sloping land has been increased from 5° to 7°. This was changed in order to be consistent with the Land Use Capability Survey Handbook (Lynn et al. 2009).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.

iii) The earlier best practice storage requirements listed for well-drained land have been changed to reflect minimum appropriate management criteria considering the low potential environmental risk of this category. The caveat for the low or minimal storage recommendation is that travelling irrigators should be run at their fastest speed when soil moisture is close to, at, or beyond field capacity.

iv) The inclusion of a fifth soil/landscape class has been added to clearly identify that very stony, well drained land should receive FDE applications of no more than 10mm depth no matter what the antecedent soil water content is. This restriction at very dry soil water contents will also help mitigate any potential adverse effects of water repellency.

In addition to the criteria stated in table 1, and the implementation guidance provided in table 2, we recommend that a minimum withholding period of 4 days between grazing and application should be adhered to when using a high application rate irrigation system (>10 mm/hr). 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. It is recommended 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 in order to allow substantial recovery of soil physical condition. Furthermore, it is recommended that the maximum application depth to be applied at any one time should in accordance with industry best practice described for soils of different texture in the DEC Manual (2006). Single applications of greater than 30 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 preferential flow paths (Houlbrooke et al. 2004a).

Table 2. Revised decision tool for matching FDE management practice (suggested minimum criteria) with soil and landscape features in the Southland region.

Soil and landscape feature	Artificial drainage or coarse soil structure		Impeded drainage or low infiltration rate		Sloping land (>7°)			Well drained flat land (<7°)		Other well drained but very stony^{X} flat land (<7°)	
Infiltration rate (mm/hr)	N/A		N/A		<100	> 100		N/A		N/A	
Irrigator hardware	LR^{XX}	HR$^{\#}$	LR	HR	LR	LR	HR	LR	HR	LR	HR
Minimum SWD* (mm)	8	15	8	15	8	8	15	0	0	0	0
Storage guide (weeks)	8	12	8	12	8	8	12	3 days	6 days	3 days	6 days

$^{\#}$ HR = High rate irrigator, ^{XX}LR = low rate irrigator, * SWD = soil water deficit, ^{X}Very stony= soils with > 35% stone content in the top 200 mm of soil. Low rate irrigation ≤ 10 mm/hr instantaneous application rate

6.3 Further research

The review of literature conducted for this report has identified some potential research gaps with regards to FDE management in New Zealand and its impact on the receiving environment. In particular, there is a shortage of targeted field scale research studies that investigate potential direct contaminant losses (P, ammonium-N, organic-N and faecal micro-organisms) of surface and ground waters following land application of FDE to well-drained soils at moisture contents close to or at field capacity. Furthermore, there is a need to determine the potential effectiveness of existing BMPs to mitigate possible losses such as the use of low rate tools. This research is needed to more robustly evaluate the framework presented in table 1. Some further questions remain concerning wetting front instability associated with fine textured soils overlaying coarse textured layers and the potential impact of water repellency, particularly on dry well-drained soils with a high sand content.

7. 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 under unfavorable soil moisture conditions. Critical landscapes include soils with artificial drainage or coarse soil structure, soils with either an infiltration or drainage impediment, or soils on rolling/sloping country.
- Soils that exhibit matrix flow show a very low risk of FDE losses under unfavorable soil moisture conditions. 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
- Research conducted in New Zealand suggests that there is a low risk of direct water contamination from FDE applied to well-drained soils. However, well-drained soils tend to have an inherently higher N leaching risk associated with the deposition of animal urine patches to land, particularly those deposited shortly prior to winter rainfall.
- There is a research gap regarding targeted field studies to assess the risk of FDE application to shallow well-drained soils when soil moisture contents are at or beyond field capacity.

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