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Prepared for Marlborough District Council

June 2011

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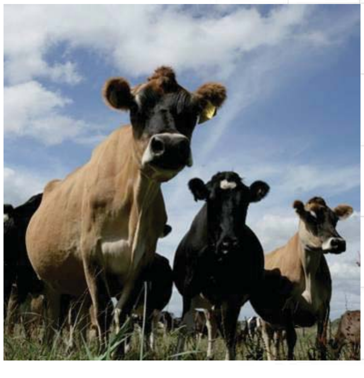

Categorising the environmental risk from land application of liquid wastes based on soil properties.

Prepared for Marlborough District Council

June 2011

D Houlbrooke[1], S Laurenson[2], S Carrick[3]

[1] AgResearch, Hamilton

[2] AgResearch, Mosgiel

[3] Landcare Research, Lincoln

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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 through increased loss of 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. Other effluents such as those from winery and domestic sources are also commonly applied to land in Marlborough. When irrigated to land, these wastes may contribute to the deterioration of surface waters or the decline in soil quality if poorly managed.

This report focuses primarily on the suitable management of FDE, however the proposed framework also provides information on the management of winery wastewater and is intended to accompany the AgResearch report '*Winery wastewater irrigation- The effect of sodium and potassium on soil structure*' prepared for Marlborough District Council. A detailed best management plan has not been developed for sites where domestic wastewater is irrigated through on-site systems as these systems are outside the expertise of the authors. Instead readers are directed to the Ministry for the Environment Report http://www.mfe.govt.nz/publications/waste/wastewater-mgmt-jun03/html/index.html Based on the nutrient and salt loading however, in particular sodium (Na^+), a brief discussion is provided along with its inclusion in the framework approach.

The risk of direct contamination of water bodies associated with effluent 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 applied to wet soils (insufficient soil water deficit to store incoming moisture) and/or when the application rate of effluent exceeds the infiltration rate for the receiving soil. 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.

By comparison the risk of direct effluent loss from soils that exhibit matrix flow is considerably lower, 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 structure and high porosity. 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 effluent to well-drained soils that indirectly leach to groundwater should be kept in context. FDE for instance 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 also 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 effluents. Management practices should therefore be targeted where they will be most effective. We have developed a decision framework to guide minimum management practice requirements that farmers should adopt in order to avoid direct losses from land-applied effluents. It is recommended to Marlborough District Council 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 FDE Pond Storage Calculator.

2. Introduction

The safe application of effluents, including farm dairy effluent (FDE), winery wastewater and domestic wastewater 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 (namely 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 effluent 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, Monaghan et al 2010, 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. In New Zealand there has been only limited research to test the hypothesis that FDE application to these soils will not result in the direct loss of FDE constituents, even when the soil water content (SWC) is at field capacity at the time of application. To date, the issue of hydrophobicity and its potential impact on rapid re-wetting of dry, well-drained soils in rolling landscapes is also unclear.

A review of New Zealand literature by Houlbrooke et al. (2004b) on land application of FDE, and its effects on water quality, showed that between 2 and 20% of N and P was 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 soil nutrient enrichment during the spring, summer and 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 (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 BMP (deferred irrigation and low rate tools) will be provided in Section 3 of this report.

AgResearch Ltd has been recently engaged to provide management advice to Regional Councils (Horizons Regional Council 2008, Environment Southland 2009, Bay of Plenty Regional Council 2010, Waikato Regional Council 2010) regarding the effectiveness of 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 has now been released and uses an adapted version of the FDE risk framework as a design standard. In addition to the regional councils described above, Environment Canterbury, Greater Wellington and Taranaki Regional Council also utilise the FDE risk framework as part of their pond storage guidance using the pond storage calculator described in section 5.4.

The aim of this report to Marlborough District Council (MDC) 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 and land application practices for a range of soil and landscape categories. We also discuss management aspects for other forms of liquid waste produced in significant quantities within the Marlborough region that have the potential to be applied to land.

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. 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.

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 to reach 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, 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).

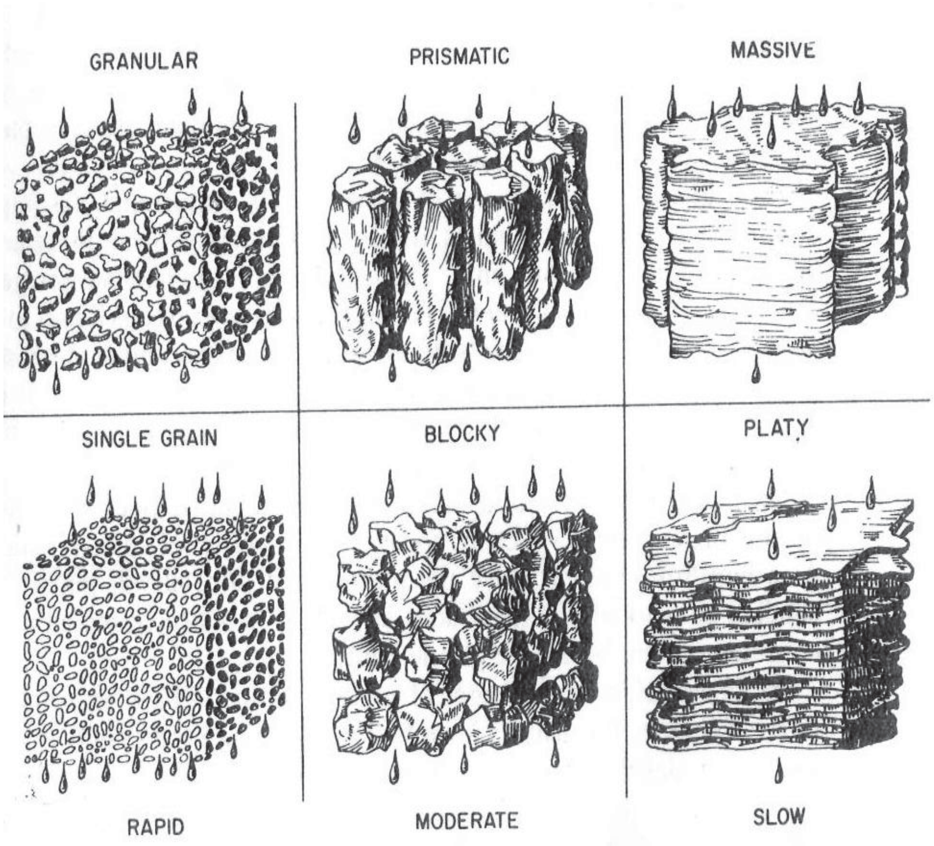


Figure 1. Diagram of the influence of soil structure on drainage (Bowler 1980).

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 35% v/v and a wilting point of 15% v/v has a total water holding capacity of 60 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 30 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.

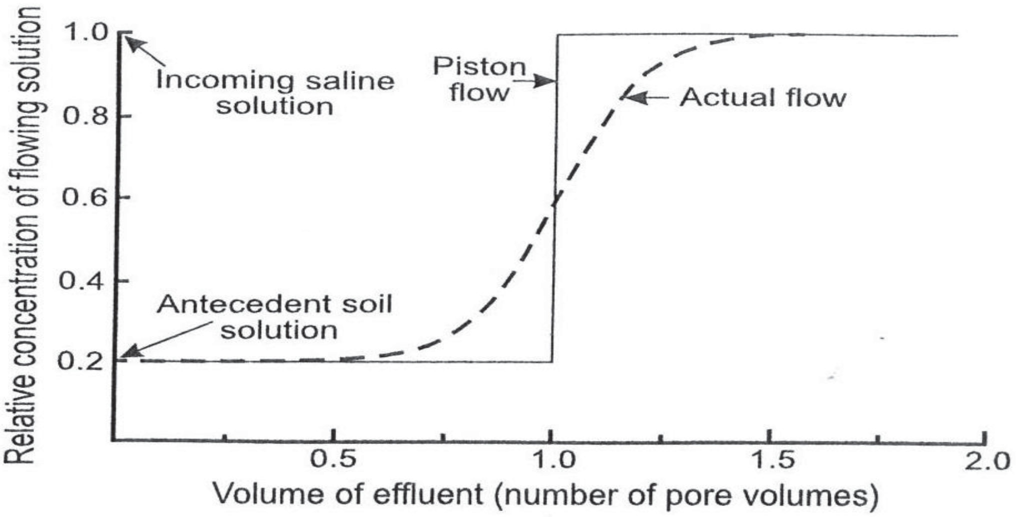


Figure 2. Graphic illustration of theoretical vs. actual piston flow drainage flux of an applied solution (Hillel 1998).

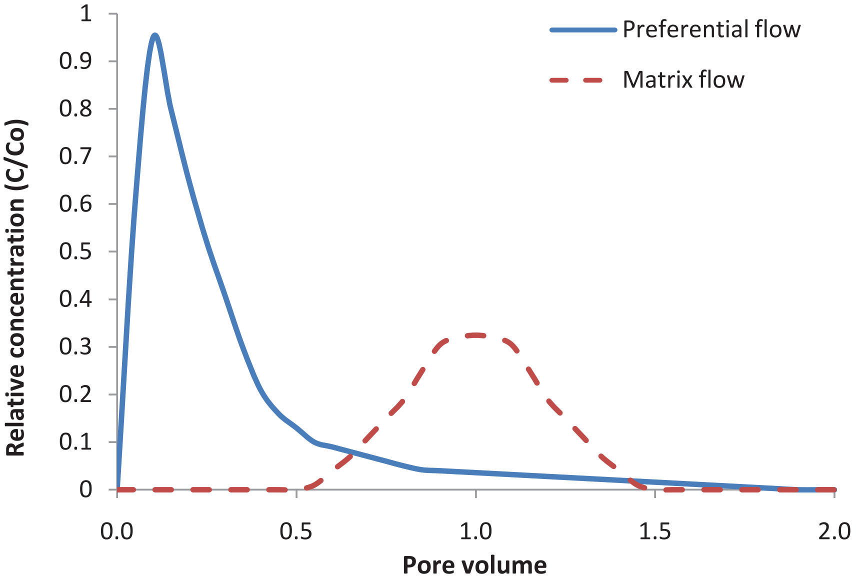


Figure 3. Illustration of concept breakthrough curves for preferential vs. matrix flow

3.2 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. Research 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.. The physicochemical nature of the soil material seems to be less important than soil structure.

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.

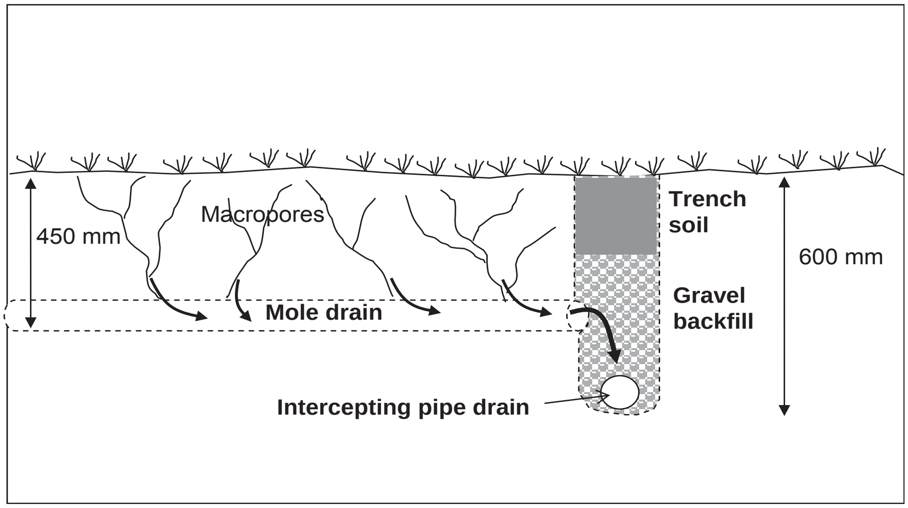


Figure 4. Diagrammatic representation of a mole-pipe drained soil.

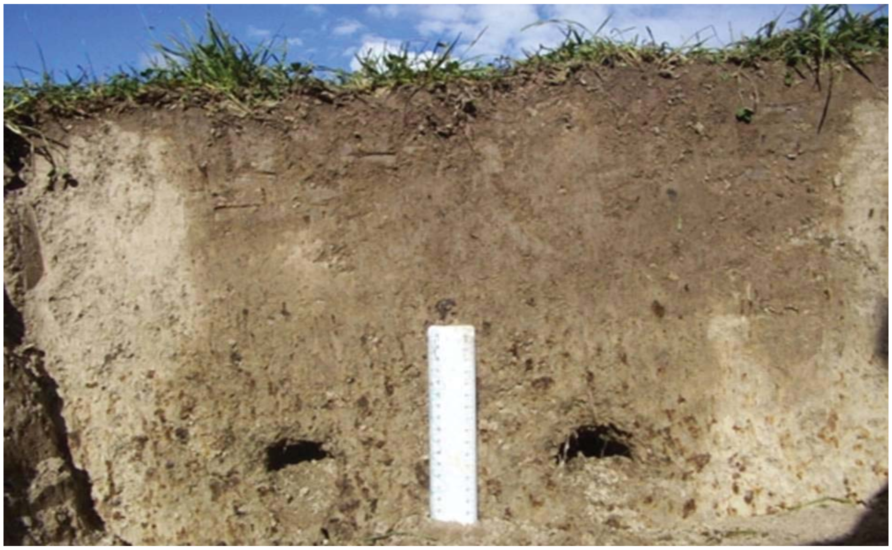


Figure 5. Field example of preferential flow through a Pallic soil containing remnants of old mole drains.

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 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 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 receive further water additions until drainage water is displaced, therefore water ponds on the soil surface encouraging overland flow conditions (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). Figure 6 provides a diagrammatic example of all three drainage mechanisms working in a farming landscape.

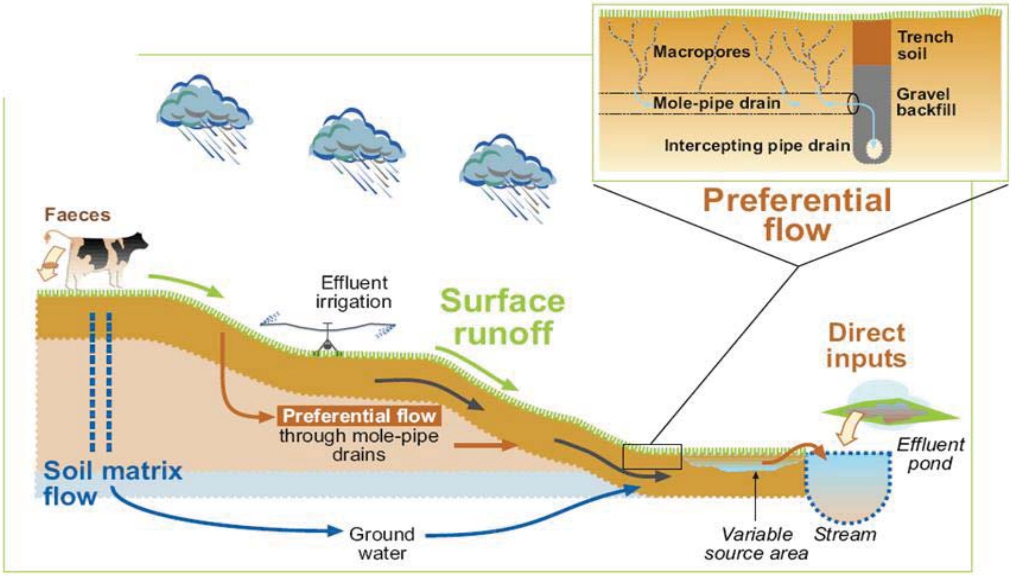


Figure 6. Conceptual diagram of water transport processes linking to surface water bodies.

4. 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 or attenuation of nutrients and contaminants applied. 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:

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

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

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.

4.2 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). 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).

5. Best management practices for industrial and municipal wastewaters

Industrial wastewaters, such as winery wastewater, generally have higher salt concentrations relative to river, ground or mains supply (i.e. town) water and therefore a greater amount of salts are applied with irrigation. Specific ions, in particular sodium (Na^+) and potassium (K^+), originating from cleaning products and waste products from grapes may also have confounding effect on soils beyond that imposed by salinity alone. A high concentration of either Na^+ or K^+ in irrigated waters is undesirable and when continually applied to soils as it can displace calcium (Ca^{2+}) and magnesium (Mg^{2+}) cations that would otherwise encourage the stability of soil aggregates (Bond, 1998; Pils et al. 2007). This raises the potential for a decline in soil structure. This chemically driven process of soil dispersion tends to reduce the size and distribution of meso- and macropores within the soil. A more detailed description of the soil dispersion process and management option for the application of winery wastewater to land is described in the accompanying AgResearch Report '*Winery wastewater irrigation - The effect of sodium and potassium on soil structure*' prepared for Marlborough District Council.

Structural attributes that promote soil aeration and water movement generally result in well developed crop roots and adequate water infiltration rates that allow for the amelioration of wastewater constituents (Figure 1). Greater soil bulk densities, associated with lower macroporosity, can however restrict the movement of air and water in the soil and lead to poor root growth and/or surface water run-off (McDowell et al. 2008). As previously mentioned, coarse textured soils with high porosity generally have high hydraulic conductivity and are well drained. When irrigated, water tends to move in a predominantly vertical direction rather than the horizontal and vertical movement evident in finer textured soils with higher clay content. This causes a piston-flow effect whereby irrigation input at the soil surface displaces and drains water situated deeper in the soil profile and in doing so leaches solutes including Na^+ and K^+ down the soil profile thereby mitigating the soil dispersion risk. Leaching of salts can be carried out annually prior to commencement of the proceeding irrigation season. Salts are more readily leached from coarse textured soils due to the unimpeded percolation of water. The instantaneous vertical distribution of irrigation water in finer textured soils is however less than coarse textured soils, therefore at a single location in the soil profile where winery wastewater has been applied, the concentration of constituents tends to be greater. In addition to the water distribution characteristics of finer textured soils, greater clay content also increases the likelihood of soil dispersion relative to sand-dominated coarse textured soils.

In fine textured soils that pose difficulty in salt leaching, application of Ca^{2+} in amendments/compounds such as gypsum ($CaSO_4$), lime ($CaCO_3$) and calcium nitrate ($Ca(NO_3)_2$)is recommended and will help displace exchangeable Na^+ and K^+ from the soil. In well drained soils where the accumulation of salts during the irrigation season is limited, Ca^{2+} contained in rainfall may be enough to instigate the exchange of Na^+ and K^+ i.e. directly leached. Maintaining soil hydraulic conductivity will help facilitate percolation of water required to leach salts under field conditions, thereby overcoming the build-up in salinity that may otherwise occur under regular application of winery wastewater.

6. Contaminant leakage risk from effluent land application

6.1 Soils that exhibit overland flow

Soils with low infiltration rate and on sloping land will provide the greatest risk of surface runoff generation and surface redistribution when wet (McDowell et al. 2008). The risk is most pronounced where wastewater and FDE application rates exceed surface infiltration rates, which is often the case under high application rate travelling irrigators. Low rate irrigation tools have application rates more suitable for these soil types and thus allow for infiltration and therefore greater capture and filtration of contaminants in the applied wastewater. Soil moisture content also affects the risk of overland flow generation, as applying wastewater to soils when the soil water content is beyond field capacity will induce either saturated runoff conditions or interflow within the near-surface layers of the soil.

Monaghan et al. (2010) 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 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.

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 sloping landscapes is the potential for hydrophobicity to result in overland flow generation of applied wastewaters and 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. Presumably the regular application of water prevented excessive drying conditions necessary for the development of hydrophobicity in soils..

6.2 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.

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. 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 high saturated to unsaturated (40 mm tension) conductivity ratio i.e. K_{SAT}:K_{-40}.

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

Wells (1973) discussed the suitability of different soil properties (using the old New Zealand Genetic Soil Classification System) to receive wastewaters and effluents. In 1973 there were few land treatment schemes 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, low rate applicators and in the case of wastewaters of high salt content, Ca^{2+} amendment and routine leaching, these limitations on soils types considered unsuitable by Wells (1973) can generally be minimised. Routine monitoring of fine textured soils irrigated with wastewaters with high salt content will be essential, in particular the soils hydraulic properties and the monovalent cation composition (detailed in the AgResearch Report '*Winery wastewater irrigation- The effect of sodium and potassium on soil structure*' prepared for Marlborough District Council). Such monitoring will provide forewarning to potential issues of wastewater irrigation and will necessitate a change in the application rate/volume.

A number of published New Zealand studies outline the considerable risk of direct drainage of wastewater and 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 wastewater and FDE contaminants in drainage waters (Houlbrooke et al. 2008a, 2004a, Monaghan & Smith 2004, Monaghan et al. 2010, 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 wastewater contaminants via preferential flow (McLeod et al. 2008, 2004, Aislabie et al. 2001, McLeod et al. 1998). Research recently conducted by Aislabie et al. (2011) has demonstrated that there is considerable risk associated with applying effluent to land with high water tables and therefore application should only be considered when the water table falls again.

Direct FDE N and P losses in mole and pipe drainage and overland flow under best management practice (deferred irrigation) has been 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.

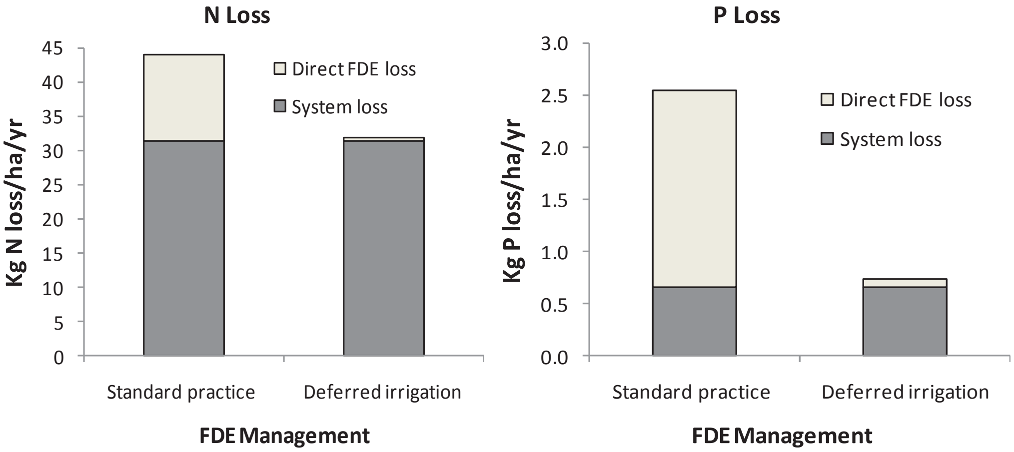


Figure 7. Direct losses of FDE under deferred irrigation and compared for a one-off poor FDE application. Direct losses of FDE are presented as additional to dairy land use loss of N and P not derived directly from FDE application (Houlbrooke *et al.* 2008, Houlbrooke *et al.* 2004).

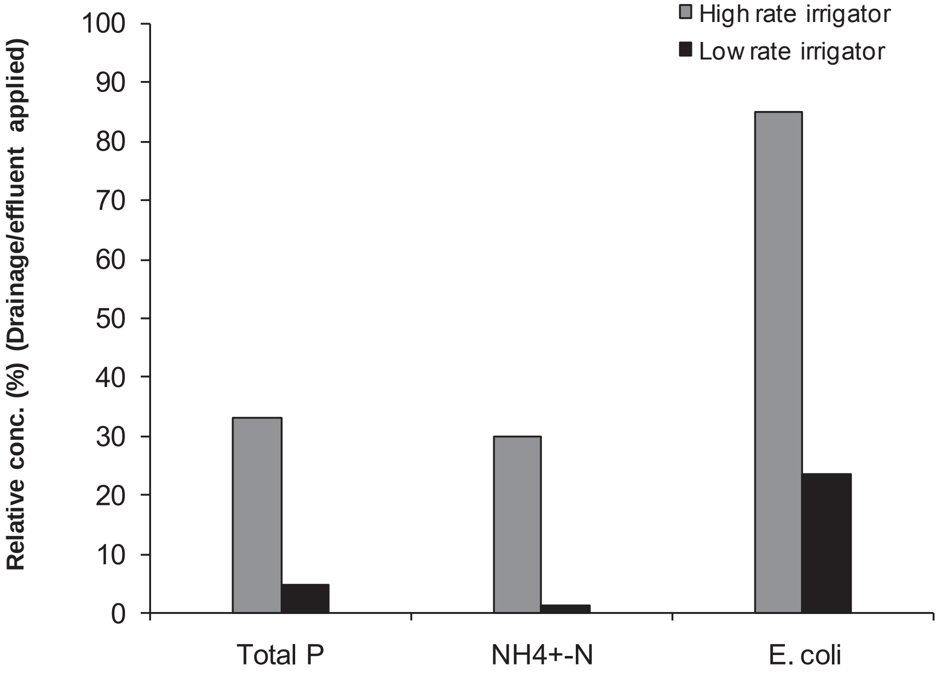


Figure 8. Relative concentrations of total P, ammonium N and *E. coli* in drainage waters collected following the irrigation of FDE to a mole-pipe drained soil using a travelling irrigator or low rate irrigation system (Houlbrooke et al. 2006).

Low rate effluent irrigation technology in the form of 'K-Line' has been evaluated as a tool for applying wastewaters, including 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 FDE was filtered by the soil when 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 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) 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. Similar findings are reported by Barton et al. (2005) following the application of municipal wastewater to a Gley soil, again the majority of N leached was in organic form and was attributed to preferential flow and was proportional to the input N content.

An investigation of the effect of irrigation application rate on the incidence of preferential flow 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 the entire 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).

6.3 Soils that exhibit matrix flow

Soils that exhibit matrix flow have been described as having a low preferential flow risk by McLeod et al. (2008). 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.

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 N (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 wastewater and 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.

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 however observations largely agree with those of McLeod et al. (2008). There is no longer a ‘somewhat excessively drained’ drainage class as this has been incorporated into the ‘well drained’ category (Milne et al. 1995). 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.

Over two years, Barton et al. (2005) applied secondary treated municipal effluent to 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 1. 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 1. 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

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). In a recent study in Canterbury, Carrick et al. (2010) 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. Many of the soils present in Marlborough region are similar to the soil types that have been well researched in the Canterbury region.

Because well-drained soils have typically high infiltration rates without drainage impediments, and because they exhibit predominantly matrix flow, direct losses of wastewater and FDE constituents 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 wastewater or 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. This may be the case where domestic wastewater passively drains from septic tanks through a series of leaching lines.

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 well drained 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.

7. Recommendations to Marlborough District Council

7.1 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 management framework has been constructed to guide appropriate effluent management practice considering the effects-based assessment of different effluent land management units (Table 2) and to include the various wastewater characteristics (Table 2 and Table 3). It should be noted that these criteria are considered the minimum conditions that should be adhered to, to avoid direct losses of land-applied liquid wastes. 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 application depths).

Table 2. 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 land with hump & hollow drainage	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 & < 50% of PAW#
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
Risk	High	High	High	Low	Low

* 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

Table 3. Additional requirements for wastewaters with high salt content such as domestic and winery wastewater.

Category	**A**	**B**	**C**	**D**	**E**
Likelihood that Ca^{2+} amendment required	high	high	medium	Low	Low

7.1.1 Artificial drainage or coarse soil structure (Category A)

The application of wastewater and 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 effluent. Soils that exhibit a high degree of preferential flow pose a high risk of direct effluent loss particularly in early spring 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 effluent to be scheduled according to a deferred irrigation strategy, thus minimising or preventing the likelihood of raw or partially-treated wastewater 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 wastewaters and FDE to this landscape class. As a minimum, effluent 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 Marlborough region but can be found in poorly drained soil types such as those found in the Gley and Pallic 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 which are not found in the Marlborough Region.

For wastewaters high in salt concentration these soils are likely to require annual application of a Ca^{2+} amendment such as gypsum to displace exchangeable K^+ or Na^+ that may have accumulated on the soil exchange complex. An example calculation that enables the quantity of gypsum to be applied is provided in Appendix A of the accompanying report (Laurenson and Houlbrooke 2011). It is advisable that application of Ca^{2+} products coincide with annual winter rainfall.

7.1.2 Impeded drainage or low infiltration rate (Category B)

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 effluents. 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. This is exacerbated by their low P retention status.

The adherence to a deferred irrigation management strategy is also essential for this risk category in order to minimise or prevent direct losses of land-applied constituents. As a minimum, wastewater and 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 soils with impeded drainage often fall in the Pallic, Gley or Organic Soil Orders, but can occur in many of the NZSC Orders such as Brown and Recent. Some Marlborough examples are the imperfectly drained Brancott silt loam (Mottled Fragic Pallic) or the poorly drained Grovetown silt loam

(Typic Orthic Gley), Waimairi loamy peat (Peaty Orthic Gley Soils) and Burleigh Peat (Mellow Humic Organic).

7.1.3 Sloping land (>7°) or land with hump and hollow drainage (Category C)

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 Soil Conservation Service (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 (LUC) 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 effluent 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 irrigation 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 and restriction in soil infiltration should also be considered in very dry soils. The use of low application rate tools will help minimise 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 wastewater management and risks. 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 land application of effluent. 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 effluent at an instantaneous rate lower than the soil infiltration rate.

7.1.4 Well drained land (Category D)

Well-drained soils with little or no connection to surface water pose the lowest risk for direct losses of applied effluents. 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 application with low application rate tools. 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 effluent 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 effluent storage in order to remove all risk associated with applying effluent 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 or at field capacity. Applying effluents at soil moistures greater than field capacity would increase the risk of inducing preferential flow through large pore spaces. Effluent 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. 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). Examples of soils that fit into the well drained category in the Marlborough region include the Kaituna silt loam (Typic Orthic Brown) and the Tahunanui sandy loam (Typic Sandy Recent).

7.1.5 Other well drained but very stony flat land (<7°)(Category E)

The inclusion of this soil/landscape class has been added to identify very stony, well drained land that should receive effluent 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, matrix flow in these soils means that they can otherwise be considered to have similar management requirements to the well-drained category. Effluent 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 commonly found on alluvial outwash plains where soils of the Recent or Brown Orders overlie coarse gravels close to the soil surface. Examples of this soil category in the Marlborough region include the Renwick stony silt loam (Immature Orthic Brown) and the Waimakariri stony silt loam (Weathered Fluvial Recent).

7.2 Further management considerations

In addition to the criteria stated in Table 2 and 3, we recommend that, if grazed, 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 effluent irrigation for a period of approximately 6 months to allow recovery of soil physical condition.

Table 4. 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).

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 land with hump & hollow drainage	Well drained flat land (<7°)	Other well drained but very stony[x] 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.

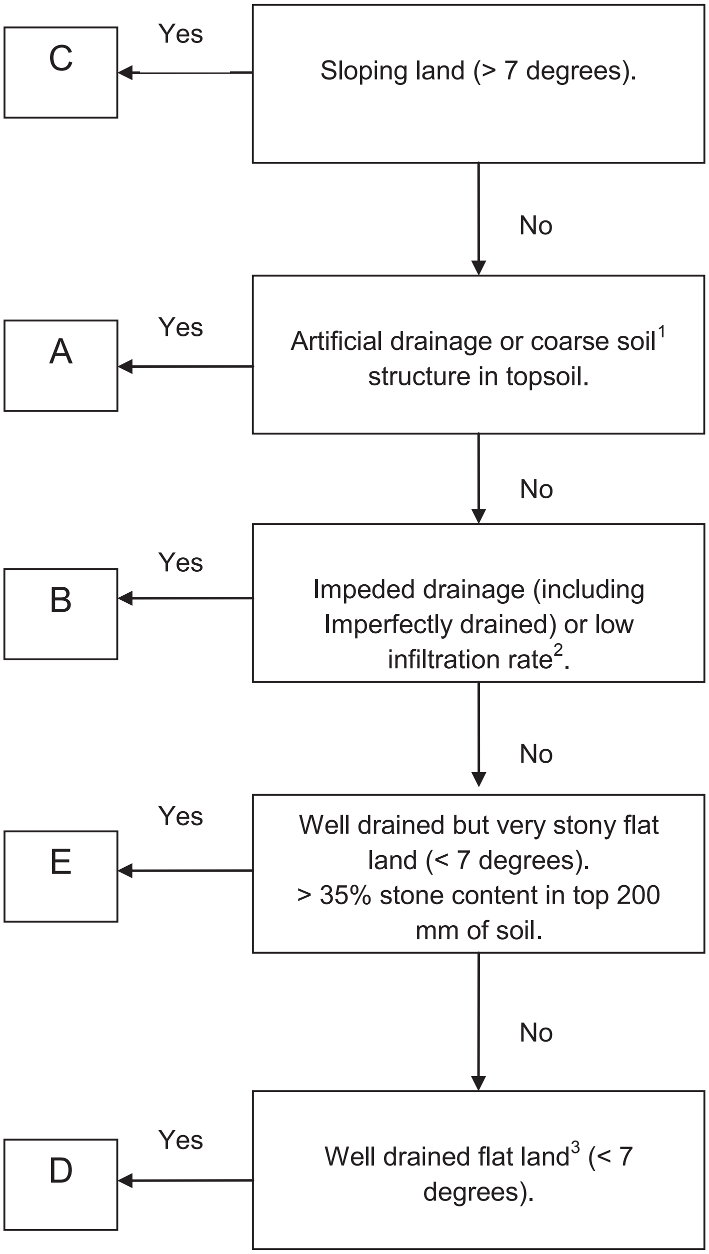
Given that all criteria are met in Table 2, it is recommended that the maximum application depth applied at any one time should be in accordance with recommendations described in Table 4. Single applications of greater than 25 mm depth are not recommended, even if large soil water deficits exist and total N loading would remain below 150 kg N/ha, due to the increased risk of inducing preferential flow losses. 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. 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 with progression into summer months. In New Zealand, the dairy cattle lactation season generally 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 the intention of returning effluent to land during the warmer spring period given suitable soil moisture conditions are met.

7.3 Determining effluent land management units in Marlborough

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 and E. Other regional councils looking to adopt the FDE risk framework within their policy framework have created a database of all dairy-farmed soil types within the region with a default risk categorisation. A workshop was held in Blenheim between the authors and Colin Gray (Marlborough District Council) in April 2011 to determine a default categorisation list of soil type risk for the land application of FDE. Figure 9 represents a decision flow chart designed to summarise and guide the categorisation process. The default categorisation considered 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. The relevant information required to categorise each soil type into the FDE risk framework on the Wairau Plain was obtained from the Landcare Research SMap Resource, as mapped by Lynn (2004). Further information was also derived from Land Resource Inventory and the National Soils Database (both databases maintained by Landcare Research Ltd) and mapped by Newsome et al. (2000) as part of the Fundamental Soils Layer (FSL).

We recommend that soils mapped in complexes or associations (due to scale of regional mapping) should be categorised as high risk to account for the greater level of management required to adequately apply FDE. More detailed soil mapping at a farm scale (1:5000) would be able to further differentiate high and low risk soil combinations should this prove more beneficial than accepting a default soil complex categorisation. In particular we recommend that the areas covered by the FSL survey (Figure 11) should have more detailed soil mapping at a farm scale. The observation density in the FSL survey is sparser than the area mapped by Lynn (2004) and therfore has greater uncertainty in the soil types mapped.



- [1] Soils with 80% or more peds captured on a 10 mm sieve within the topsoil (A horizon) are considered to have coarse soil structure (Houlbrooke and Monaghan 2010) or a layer within 300 mm of the soil surface. The Soil Description Handbook (Milne et al. 1995) describes aggregate size of 10-20 mm as medium and > 20 mm as coarse, therefore in terms of decision making criteria, medium is incorporated within the coarse category.

- [2] Low soil infiltration rate is defined as 10 mm/hr or less.

- [3] Well drained flat land includes both the well and moderately well drained soil drainage classes.

- Drainage classes (Well, Moderately well, Imperfect, Poorly) are defined by the Soil Description Handbook (Milne et al. 1995).

Figure 9. Soil categorisation decision tree

7.3.1 Default catagorisation

The lists below represent default categorisations of soils in the Marlborough region using the soil and landscape risk framework for FDE management. We suggest these lists act as default categorisations. However, it is recommended that land users should also consider undertaking a site specific investigation of their soil and its properties by a suitably trained soil pedology expert in order to make sure their soil is appropriately categorised. Maps are presented in figures 10 and 11 showing the default categories for both the Wairau Plain and regional scale FSL respectively.

- *Category A soils: Artificial drainage or coarse soil structure*

No soils in the Marlborough region were deemed to have met the coarse soil structure category as described in the FDE risk framework (Table 2). Some soils may be artificially drained via mole and pipe systems. However, this is often site specific; therefore, these soils have been initially classified as 'Impeded drainage category B'.

- *Category B soils: Impeded drainage or low infiltration rate*

Wairau units
Brancott silt loam
Broadbridge silt loam
Burleigh peat
Gibsons, mottled phase
Grovetown silt loam
Hawkesbury silt loam
Jordan silt loam
Motukarara complex
Paynter clay loam
Paynter peaty phase
Spring Creek clay
Sedgemere deep silt loam
Temuka heavy silt loam and peaty silt loam
Taitapu heavy silt loam
Waimari loamy peat
Wairau mottled phase

FSL units
Brancott silt loam
Broadbridge silt loam
Hawkesbury silt loam
Jordan silt loam
Jordan silt loam and shallow silt loam
Kaiapoi silt loam
Kikiwa silt loam
Motukarara complex
Paynter clay loam
Pinedale silt loam

Seddon silt loam
Taitapu heavy silt loam
Temuka heavy silt loam and peaty silt loam

Waimairi loamy peat

- *Category C soils: Sloping land (>7°)*

Wairau units
Wither hill soils

FSL units
Altimarlock shallow silt loam easy rolling
Altimarlock stony silt loam easy rolling
Blairch silt loam
Cass soils
Craigieburn stony silt loam
Flaxbourne hill soils
Glenbrae heavy silt loam
Kahutara hill soils
Ketu steepland soils
Onamalutu hill complex
Opouri hill complex
Patriarch loams
Pelorus hill soils
Seaview silt loam easy rolling
Sedgemere silt loam easy rolling
Tekoa hill soils
Tuamarina hill soils
Wither hill soils
Wither silt loam rolling

- *Category D soils: Well drained flat land (<7°)*

Wairau units

Gibsons loam
Kaiapoi silt loam
Kaituna soils
Koromiko silt loam
Murrays silt loam
Renwick silt loam
Tahunanui silt loam
Waimakariri silt loam
Woodbourne silt loam
Wairau silt loam

FSL units
Altimarlock shallow silt loam
Altimarlock stony silt loam
Castlebrae silt loam
Dashwood gravelly silt loam
Dashwood silt loam
Dungree silt loam
Hororata loam
Hundalee hill soils
Kaituna soils
Koromiko soils
Manaroa soils
Medway hill soils
Omaka shallow silt loam

Rai soil
Renwick stony silt loam
Ronga soils
Starborough silt loam
Tahunanui sand
Tasman sandy loam
Templeton silt loam
Ugbrooke silt loam
Waimakariri silt loam
Wairau silt loam
Warwick gravelly silt loam

- *Category E soils: Other well drained but very stony flat land (<7°)*

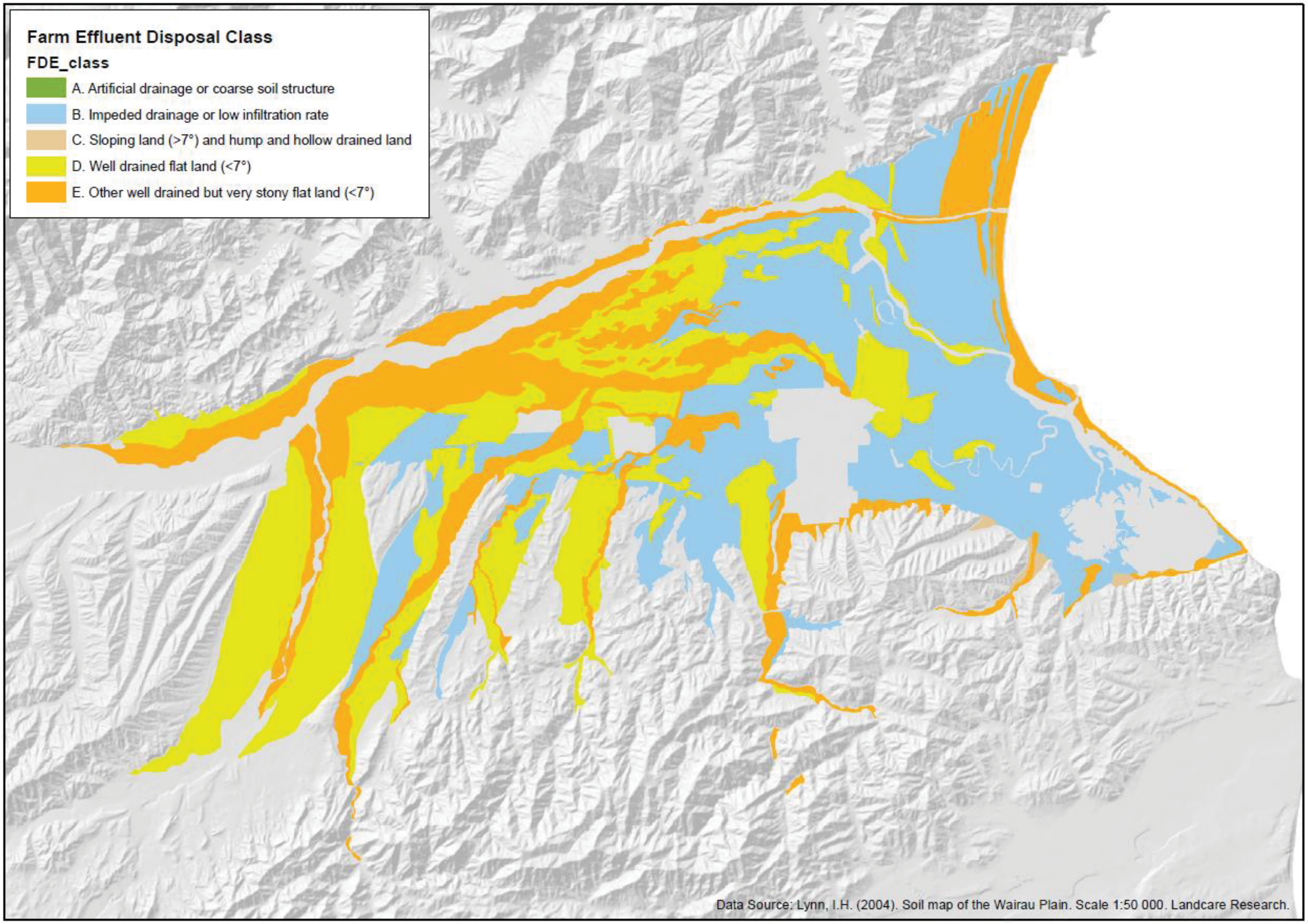
Wairau units

Awatere gravelly sand
Eyre-Paparua shallow silt loam
Rapaura silty sand
Taumutu stony gravels
Waimakariri gravelly sand

FSL units
Awatere gravelly sand
Eyre shallow silt loam
Galtymore silt loam
Renwick stony loam
Taumutu stony gravels
Waimakariri gravelly sand

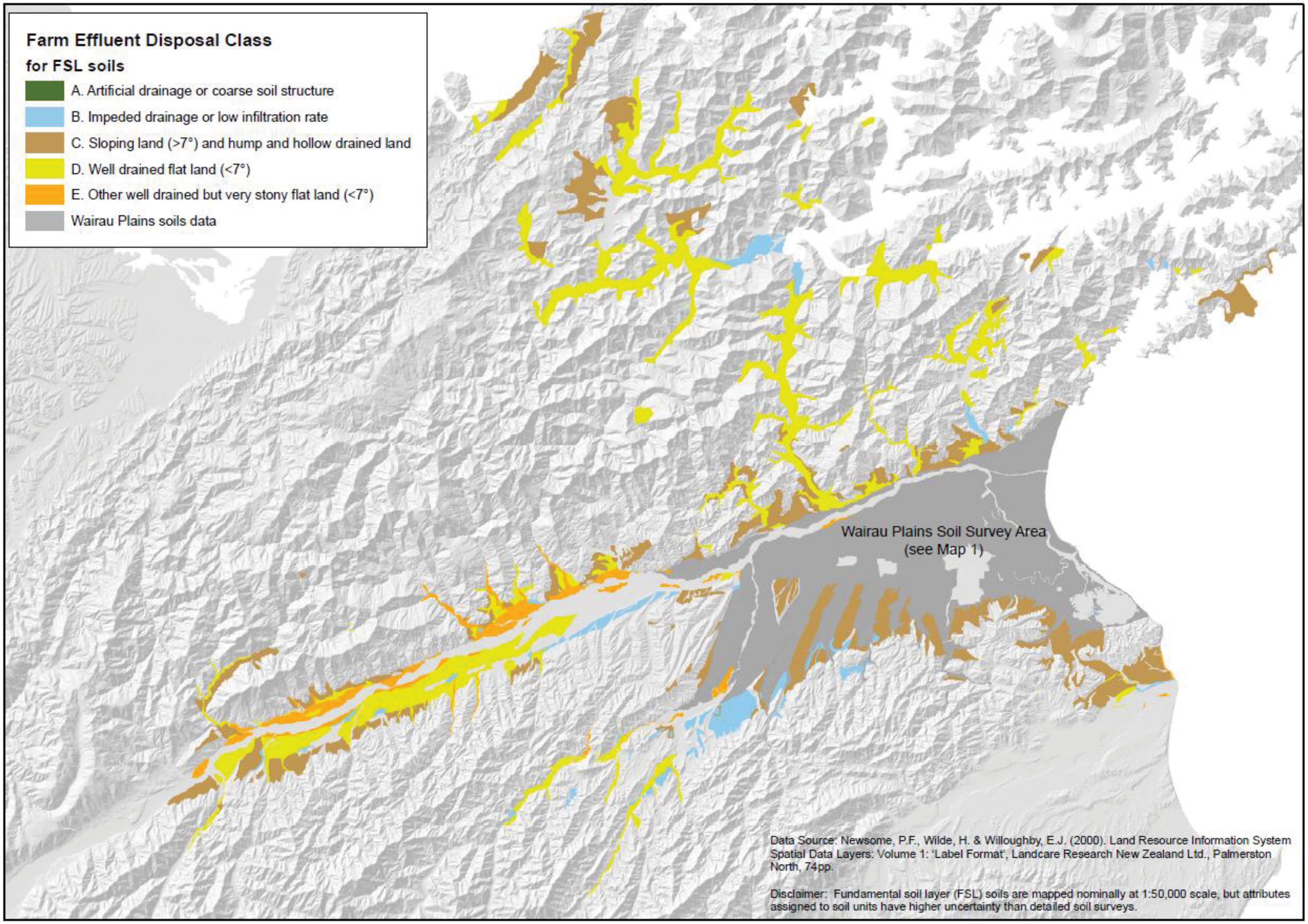
7.3.2 Farm scale soil mapping

In some cases there would be considerable benefit in generating 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 12 for the recent AgResearch dairy conversion at Tokanui near Te Awamutu. 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.



Data Source: Lynn, I.H. (2004). Soil map of the Wairau Plain. Scale 1:50 000. Landcare Research.

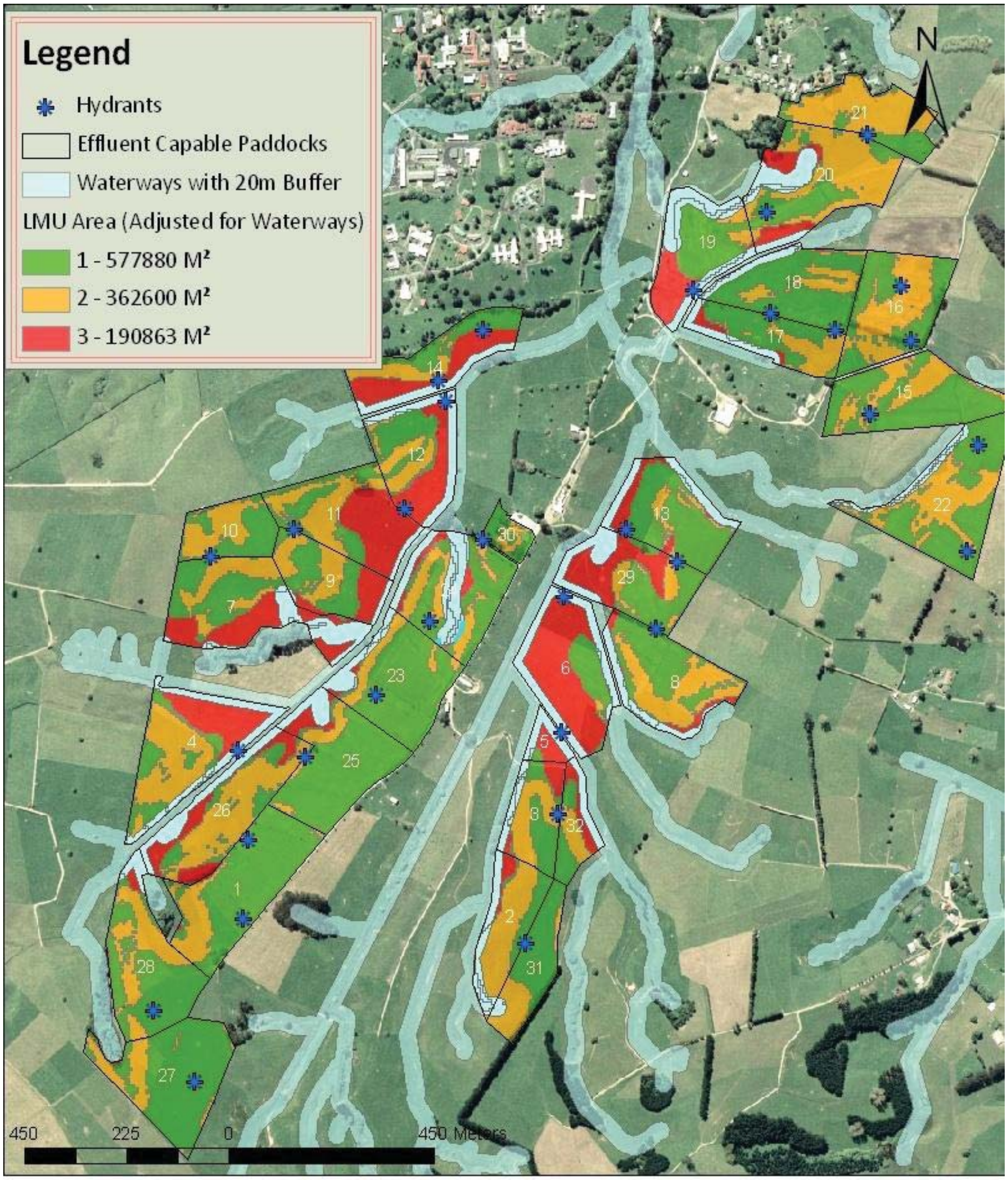
Figure 10. Wairau valley catagorisation of effluent management classes



Data Source: Newsome, P.F., Wilde, H. & Willoughby, E.J. (2000). Land Resource Information System Spatial Data Layers: Volume 1: 'Label Format', Landcare Research New Zealand Ltd., Palmerston North, 74pp.

Disclaimer: Fundamental soil layer (FSL) soils are mapped nominally at 1:50,000 scale, but attributes assigned to soil units have higher uncertainty than detailed soil surveys.

Figure 11. Marlborough region catagorisation of effluent management classes



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.

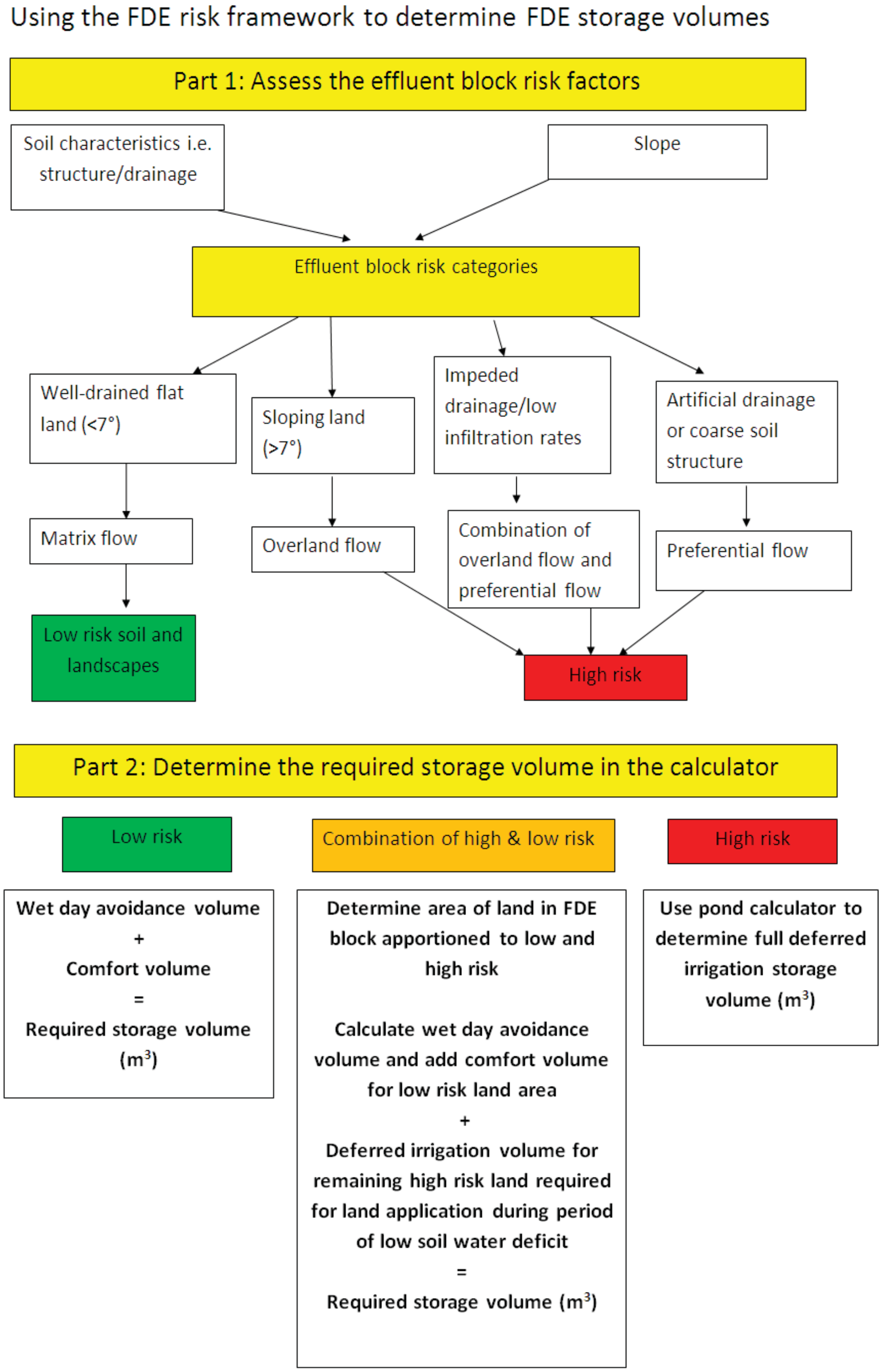
*Deferred Irrigation requires the application depth being smaller than the soil water deficit (SWD)

Figure 12. AgResearch Tokanui effluent management units using the FDE risk framework

7.4 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 effluent application at soil water contents greater than field capacity.

Massey University and Horizons Regional Council have recently developed a FDE pond storage calculator (Horne et al. 2011). 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, it has been updated to allow 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 13 below.



Wet day avoidance volume
+
Comfort volume
=
Required storage volume (m^3)

Determine area of land in FDE block apportioned to low and high risk

Calculate wet day avoidance volume and add comfort volume for low risk land area
+
Deferred irrigation volume for remaining high risk land required for land application during period of low soil water deficit
=
Required storage volume (m^3)

Use pond calculator to determine full deferred irrigation storage volume (m^3)

Figure 13. Summary of stepwise process for using the FDE risk framework with the pond storage calculator. Comfort volume additional storage to allow irrigation holidays even if conditions allow application

7.5 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, 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).

7.6 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. 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.

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. 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).

The risk of soil dispersion has been predicted based on research from outside the Marlborough region. It would be of value to MDC to validate these measurements using the key soil types found in Marlborough. Experiments that investigate changes in hydraulic conductivity in response to winery wastewaters of varying cation composition would provide suitable information to better integrate Marlborough soils into the effluent management framework.

8. 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
- Where industrial and municipal wastewaters are irrigated, it is advisable to routinely monitor exchangeable Na^+ and K^+ concentrations, particularly in fine textured soils. In coarse textured soils, Na^+ and K^+ are readily leached during annual winter rainfall and therefore pose limited risk of accumulation or soil dispersion. In fine textured soils application of Ca^{2+} amendments is likely.

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11. Appendix 1. Glossary of terms

Application depth – The depth of applied farm dairy effluent from irrigation (mm).

Application rate – The rate at which a given depth of effluent is applied per unit of time (mm/hr).

Deferred irrigation – Pond storage of effluent during wet periods and its subsequent application when suitable soil moisture storage exists so as to avoid breaching field capacity.

Drainage – The movement of excess water (including effluent water) through the soil body.

Effluent irrigation – The application of farm dairy effluent to land through an irrigator.

Effluent storage pond – A suitably sealed storage pond for farm dairy effluent.

Excreta – The defecation products from cattle i.e. urine and dung.

Farm dairy effluent (FDE) – The combination of cow and wash down water collected from the milking parlor and holding yard.

Field capacity – The water content of a soil once drainage has ceased.

Infiltration-excess ponding – when the FDE application rate exceeds a soil’s drainage capacity or surface infiltration rate.

Land Treatment – The use of the soil matrix as a medium for removing contaminants either dissolved or suspended, in effluent water or slurries.

Leaching – The drainage of nutrients through the soil beyond the active root zone

Low application rate sprinkler – A sprinkler suitable for irrigating FDE at low application rates (<10 mm/hr). Need to be moveable.

Mole and pipe drainage – An artificial drainage system suitable for poorly drained soils with a dense subsoil and appropriate clay content. The installation of such drainage creates a large degree of preferential flow paths for both water drainage and direct FDE loss.

Nutrient loss – The mass of nutrients lost per unit area in drainage or overland flow (kg nutrient/ ha)

Nutrient load - The mass addition of nutrients per unit area (kg nutrient/ha) as fertiliser or FDE irrigation.

Nutrient Concentration – A measure of the mass of contaminant enrichment per unit volume of water (mg/L).

Overland flow – The movement of water or FDE across the soil surface. Also know as surface runoff.

Plant available water – The difference between field capacity and wilting point. Represents the total volume (expressed as a depth mm) that is available for plant uptake

Rotating traveling irrigator - A traveling irrigator with twin booms that fully rotate. Currently the most common form of irrigator used applying FDE to land in New Zealand.

Root zone – The zone of soil closest to the soil surface where most of the plant roots are contained. Typically 300 mm for ryegrass-dominated pasture.

Saturation-excess ponding - When all typically air filled pores are storing water the soil has no capacity to infiltrate further water and so conditions are created and water ponds or flows down slope. This condition is pronounced when the drainage capacity is smaller than the input of water (or effluent).

Soil water deficit (SWD) – the potential of a soil to store water up to the point of field capacity. As active drainage ceases at field capacity, it is predominantly evapotranspiration that creates soil water deficits.