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On-farm dairy effluent risk assessment

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On-farm farm dairy effluent risk assessment

Report prepared for DairyNZ

August 2013

Bob Longhurst, Dave Houlbrooke, Seth Laurenson

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Table of Contents

Executive Summary 1

1. Introduction 3

2. Methodology 4

2.1 Base farms 4

2.2 Components within effluent management that contribute to nutrient loss 5

2.3 Infrastructure 7

2.3.1 Pond discharge to water 7

2.3.2 Sand/stone trap cleanings 7

2.3.3 Leaking ponds 8

2.3.4 Laneways/underpasses 11

2.3.5 Pipe breakdowns, leaks and drips 14

2.3.6 Silage stack leachate 16

2.3.7 Feed pads 18

2.3.8 Stand-off pads (uncovered) 18

2.3.9 Animal shelters 19

2.4 Land application 19

2.4.1 Travelling irrigators 21

2.5 Low rate applicators 22

2.5.1 Pond storage capacity 22

3. Results and discussion 23

3.1 Infrastructure losses 23

3.1.1 Two-pond losses to water 23

3.1.2 Sand/stone trap cleanings 23

3.1.3 Leaking ponds 24

3.1.4 Laneways and Underpasses 26

3.1.5 Pipe breakdowns, leaks and drips 28

3.1.6 Silage stack leachate 29

3.1.7 Feed pads 30

3.1.8 Stand-off pads (uncovered) ... 30

3.1.9 Animal shelters ... 31

3.2 Land application ... 31

3.2.1 Travelling irrigator failure ... 32

3.2.2 Influence of application depth and soil risk ... 33

3.2.1 Good management practices ... 34

4. Benchmarking components ... 35

5. Conclusions ... 41

6. Acknowledgements ... 42

7. References ... 42

Executive Summary

Nutrient losses and faecal contamination from dairy farms can have a deleterious effect on water quality and are becoming a major concern for regulatory authorities, milk companies and the general public of New Zealand. Farm dairy effluent (FDE) is generated in a number of locations around the dairy farm including the milking shed, off-paddock animal confinement facilities, stock laneways and silage stacks. The storage and management of this effluent, with respect to the specific attributes of the farm (e.g. soil type, proximity to water, topography and climate) has a huge bearing on the proportion of the nutrients (and other potential contaminants) that are lost. However, the relative contribution of nutrients that are lost from the various points of FDE generation, storage, distribution and land application are not widely documented.

This study assessed the risk of nutrient loss that is associated with a given management decision or defect in the design and/or maintenance of the effluent infrastructure on a typical or average Waikato farm. We have distinguished between the ‘at risk’ components, i.e., the total quantity of nutrient that could potentially be lost (worst case scenario), and, an ‘attenuated loss’, which is the quantity that is actually lost given best case soil attenuation potential. The ‘at risk’ and ‘attenuated losses’ of nutrients from a number of individual contributing factors have been reported. This approach highlights the potential non-compliance magnitude and enables farmers to prioritise management efforts toward the most influential factor contributing to overall farm losses. It is intended that an approximation of the overall farm loss can be calculated by summing overall loss from all relevant components for a given farm. This information will form the quantitative data set on which DairyNZ’s proposed Warrant of Fitness (WoF) risk assessment for dairy effluents will be based.

The risk of nutrient loss tends to be closely related to the quantity of effluent generated along with application method and timing, i.e. the ‘at risk’ component. The ‘at risk’ value represents the size of the effluent resource for a given activity that could all be lost to surface water given worst case conditions. In comparison, the ‘attenuated’ loss represents a best case scenario whereby environmental loss is restricted to leaching loss through the root zone based on the size of the nutrient input and the area that is affected. Subsequent loss from factors with low ‘at risk’ nutrient quantity are likely to be less than high ‘at risk’ components such as effluent ponds that discharge directly to stream or poor land application techniques that encourage excessive nutrient loss. For instance, discharging treatment ponds contain approximately 2.2 tonne (t) of ‘at risk’ nitrogen (N) per year compared to stone trap cleanings which contain approximately 6

kg N/year. Therefore the potential risk posed by discharging ponds is obviously considerably greater. Pond discharges, off-grazing systems and large silage stacks pose the greatest potential risk to surface water quality. However, as shown in this study, adequate management of effluent from these areas can substantially reduce the risk and the actual environmental impact. Certainly, where soil attenuation does occur, whether optimised (i.e., well managed irrigation systems) or not (e.g., a pipe from an underpass draining to a paddock as opposed to directly to water), nutrient loss is reduced considerably. We suggest the greatest gains in reducing nutrient loss from farms can be achieved by preventing pond discharges, ensuring adequate capture of effluent from off-grazing systems and employing sound irrigation practices when land applying effluent.

1. Introduction

Poor management of Farm Dairy Effluent (FDE) and suboptimal effluent-related infrastructure and management practices can lead to losses of nutrients and faecal microorganisms from farms to water. Losses may occur at various locations around the farm where effluent is generated, stored or distributed e.g. feed pads, storage ponds or during application to land. Here we have broadly categorised potential loss pathways into those associated with either infrastructure (e.g. a broken pipe) or land application components (e.g. losses from a travelling irrigator).

The objective of this assessment is to provide a data set of best and worst case whole farm nutrient losses that occur where effluent is stored, distributed or applied to land on a yearly basis. This includes risk components (e.g. animal shelter), management decisions (e.g. application depth) or incidents (e.g. stalled irrigators). Information from this report will support DairyNZ's proposed Warrant of Fitness (WoF) risk assessment for dairy effluents and will enable farmers to prioritise management efforts toward the most influential factor contributing to overall farm losses.

We have devised an assessment of risk i.e., as the relative contribution to nutrient loss from a series of contributing factors through a comparison to the total size of the effluent resource for a standardised farm described below. This task has been achieved by compiling knowledge from literature values, estimations based on experience and whole farm modelling (using the OVERSEER® model; Wheeler et al, 2006). Nutrient losses from a number of contributing factors associated with infrastructural or land-application processes are reported separately.

Finally, we have summarised these findings in an overview graph that fairly and equitably presents a comparison of the potential loss pathway across the whole farm, as well as their potential environmental impact.

2. Methodology

2.1 Base farms

Two base farms were set-up using the OVERSEER® Nutrient Budgets 2012 program (version number 6.0.3). Data obtained from DairyNZ was used to model 1) an 'average' Waikato farm (from Dairy Statistics, 2011), and 2) a DairyNZ Production System 4 farm operation (i.e., higher intensity farm). In relation to risk associated with infrastructure, soil type has limited effect on overall farm nutrient loss; therefore we have considered a single soil (Gley, flat) type across the two base farms. However, for dairy effluent application to land, soil type has a greater influence and so we considered two soil type scenarios: a low risk Allophanic and a high risk Gley soil.

Nutrient loss associated with off-paddock facilities was determined based on modelling of the System 4 farm because it was more likely to have feed pads, stand-off pads and/or animal shelters. Assumed characteristics of both base farms are clearly defined in Table 1. Background farm losses were determined by exporting (i.e. taking off-farm) all FDE generated on the base farm.

Table 1: Farm characteristics of 'average' Waikato and typical DairyNZ System 4 farms.

Farm characteristics	Units	Average [1]	System 4 [2]
Effective farm area	ha	112	132
Topography		Flat	Flat
Rainfall	mm	1,200	1,200
Total cow numbers (July 1)	cows	328	449
Stocking rate (cows wintered)	cows/ha	2.93	3.40
Cow live-weight	kg	445	412
Yearlings grazed on or off farm		off farm	off farm
Days in milk	days	268	270
Milk solids production/cow	kg MS/cow	317	389
Milk solids production/ha	kg MS/ha	929	1312
Annual milk solids production/farm	kg MS/farm	104,050	173,160
Annual pasture production (consumed)	t DM/ha	9.32	11.57
Brought in supplements	t DM/ha	1.34	3.43
Conserved pasture silage	t DM	30	110
Fertiliser nitrogen used (5 applications)	kg N/ha	150[3]	150[3]
Stock wintered off farm	%	0	0

[1] Data produced from a combination of LIC statistics and an average value obtained from DairyBase®

[2] Data supplied courtesy of Alfredo Alder, Agricultural Consultant, Waikato.

[3] Fertiliser N application rates were set at 150 kg N/ha to match Waikato Regional Council effluent loading limit for N.

A number of scenarios (listed in Section 3.2), including risk components (e.g. animal shelter), management decisions (e.g. application depth) or incidents (e.g. broken pipe), were individually incorporated into the two modelled base farms. An actual contribution to farm nutrient loss is then attributable to each individual factor. Here we have assumed that there is no compounding effect from a series of contributing factors that might occur on farm.

Nutrient losses are reported as absolute values (kg/yr) rather than as proportional losses. This enables farmers to add various components together, such as a broken pipe, unlined off paddock facilities or FDE applications via a travelling irrigator to high risk soil. The sum of these components will be the estimated nutrient loss across the whole farm. Two assessments (leaking pipes and stalled irrigators) are not actually year-round contributors and are actually assessed on an event basis. For the purposes of this study we have benchmarked this with other components on the assumption of having only one such event per year. This also means that the factor is potentially multiplied by the expected occurrence if required to determine greater frequency of these events.

2.2 Components within effluent management that contribute to nutrient loss

A list of the various components included in this risk assessment study is provided (Table 2). Various methods were used to predict the risk posed from each of the components. These included:

- Modelling via OVERSEER® Nutrient Budgets*
- Literature review
- Where no information was available, using scientific first principles.
- Combination of the above.

* Note that OVERSEER® assumes best management practice.

Table 2: Components within the effluent generation, distribution and application process that contribute to whole farm nutrient losses and the principle method used for assessing the associated risk.

Effluent risk assessment area.	OVERSEER® modelling	Literature review	First principles
Infrastructure			
Pond discharge to water	✓		
Stone trap cleanings	✓	✓	
Leaking ponds		✓	✓
Laneways/ Underpasses		✓	✓
Leaking/broken pipes			✓
Silage stack leachate	✓	✓	
Feed pad (effluent not contained)	✓	✓	
Stand-off pad (uncovered & drainage not captured)	✓	✓	
Animal shelter (unsealed carbon base)	✓		
Land Application			
Pond storage capacity	✓		
High risk soils	✓		
High risk soils – mole and tile drained	✓		
Low risk soils	✓		
Travelling irrigator	✓		
Low rate applicator	✓		

The total amount of FDE generated on the average 112 ha Waikato dairy farm (328 cows) was 2,240 kg N and 224 kg P per year. Subsequent loss of this volume of FDE will differ spatially (and to some extent temporally) across the landscape depending upon proximity (and timing) of management practices. Therefore, the actual loss will differ between and within farms depending on factors more likely to route FDE to surface waters than attenuation on land. Our approach has been to present two values which demonstrate the range of losses for a given component: an 'at risk' value versus an attenuation potential. The 'at risk' value represents the size of the effluent resource for a given activity that could all be lost to surface water given worst case conditions. In comparison, the 'attenuated' loss represents a best case scenario whereby environmental loss is restricted to leaching loss through the root zone based on the size of the nutrient input and the area that is affected.

2.3 Infrastructure

2.3.1 Pond discharge to water

The two-pond (anaerobic/aerobic) system was the main form of FDE treatment and management prior to 1990. Since then land application has been encouraged by Regional Councils as the preferred method for handling FDE. However, where farmers still hold an existing resource consent, two-pond systems may still be discharging to waterways. OVERSEER® has been used to estimate direct loss of N and P to water ways from a discharging FDE treatment pond.

2.3.2 Sand/stone trap cleanings

Sand/stone traps are designed to intercept, slow and modify effluent flow so that inert heavier materials (sand, stones and debris) drop out, thereby preventing blockages or excessive wear and tear on pumping systems. Farmers periodically remove and stockpile this accumulated material for several months before surface spreading it or using it to fill holes in paddocks.

During the spring and autumn of 2010, Waikato Regional Council (WRC) undertook a sand trap study on six farms (Harford, 2010). Mean nutrient concentrations of stone trap scrapings from the six case study farms are summarised in Table 3. These values encompass stored and fresh material from both spring and autumn samplings (n=24). Observations by the author were that sand traps varied in size and gradient (meaning some collected more solids than others), and varied in solid content depending on type of feed supplement used (Don Harford, WRC, pers. comm.).

Table 3: Mean concentrations of N, P and K (%) of sand/stone trap materials from the 2010 WRC study (% DM data courtesy of Don Harford, WRC).

DM	N	P	K
40%	0.27%	0.06%	0.11%

The WRC (2012) study also measured *Escherichia coli* (*E. coli*) in the fresh sand trap material. The mean *E. coli* concentration was 5.4×10^5 ($\underline{+}1.0 \times 10^6$) most probable number per gram (MPN/g). *E. coli* concentrations were found to be higher in spring than in autumn.

To ascertain potential runoff and leaching from sand trap cleanings it was assumed 4 t was collected annually and that nutrient concentration were similar to that detailed in

Table 3, and storage was on an unlined area of 10 m^2. Application of sand trap scrapings to land was modelled using OVERSEER® by scaling up the loading rate to a per hectare basis to obtain an estimate of N and P losses, then back-scaling the results to determine the actual loss contribution at the whole-farm scale. In choosing this method it is recognised the position of sand trap scrapings may move spatially between years, however OVERSEER® will assume it remains constant. Losses will therefore potentially be overestimated. Furthermore it is also recognised that the nutrient loading rates applied in these areas (albeit a very small area) is likely to be outside the validation dataset for the model. However this method provides a mechanistic way of determining the resulting loss from the root zone whilst taking into account other factors such soil type, drainage and land use.

2.3.3 Leaking ponds

As mentioned in Section 3.3.1 oxidation ponds were the main means of effluent treatment on NZ's 14,000 dairy farms until the late 1980s (Hickey et al, 1989). The normal configuration of the two-pond treatment system was to have a small surface area and deep (3 to 4 m depth) anaerobic pond followed by a larger surface area but shallower (1.2 to 1.5 m depth) aerobic pond. Both ponds typically had a clay-based liner material.

To prevent environmental contamination to groundwater, it is recommended that liner materials have a leakage rate less than 1×10^{-9} m/sec (IPENZ, 2011). This is in-line with many regional council requirements. The leakage through a clay liner will depend on: 1) the depth (head) of water above the pond floor; 2) thickness of the clay liner; and 3) permeability of the clay (usually measured by saturated hydraulic conductivity; IPENZ, 2011).

Water quality degradation from pond discharges to surface water bodies has meant that land application is now the preferred means of effluent treatment and management. However, many two-pond systems are still used for storage purposes on farms. In addition, many custom-built storage ponds have been constructed over the past decade in order to avoid irrigating FDE during high-risk wet periods. There are approximately 2,000 farms in the Waikato region that have either two-pond systems or storage ponds that are unlined and suspected to leak at a rate greater than IPENZ recommendations and WRC rules (Bob Franks, WRC, pers. comm.). In a study of pond seepage rates, Ray et al, (1997) found that mean seepage rates varied between 1.5×10^{-8} to 5.1×10^{-8} m/sec, a rate which reportedly equates to 0.4 to 2.7 m^3/day. In many cases, leakage was due primarily to inadequate compaction of the pond floors and/or insufficient clay content of liner material. Unfortunately no information was provided on the size of either the ponds or the herds.

Nutrient concentrations of leaking pond effluent

Data on pond nutrient values has been sourced from three publications and is summarised in Table 4. Vanderholm (1984) reported detailed effluent characteristics for both anaerobic and aerobic ponds. Hickey *et al.* (1989) reported median nutrient concentrations (based on 1 year of sampling) across six ponds in the Manawatu and five ponds in Southland, and Longhurst & Nicholson (2011) provided average values for ponds in the Waikato region.

Table 4: Published data on nutrient concentrations in pond effluents (g/m^3).

Source	Solids (% DM)	Total N (g/m^3)	Total P (g/m^3)
Vanderholm, (1984)[1]	0.23-3.50	73-159	27-34
Longhurst & Nicholson, (2011)[1]	0.20-6.00[#]	150-1890	19-191
Vanderholm, (1984)[2]	0.18-0.20	32-116	16-29
Hickey et al, (1989) [2]	0.005-0.080[‡]	7-191[§,£]	13-51[4]
Longhurst & Nicholson, (2011)[3]	0.10-1.20	50-370	14-47
Longhurst & Nicholson, (2011)[#]	0.10-8.20*	150-2060	19-212

[1]anaerobic; [2]aerobic; [3]single storage pond
[‡]suspended solids; [#]stirred effluent; [§]ammonia-N; [£]5-95% percentile

From the data presented in Table 4, our judgement has been to use the following N and P concentrations for calculating nutrient losses from potential pond leakages (Table 5).

Table 5: Nutrient concentrations (g/m^3) used in pond leakage calculations.

Pond type	Total N g/m^3	Total P g/m^3
Storage	250	40

Rate of pond leakage

Regional Councils usually require some form of lining for effluent ponds. However, no liner system, including geomembranes, is completely impermeable and all will have some seepage loss, albeit generally very small (IPENZ, 2011). Compacted clay is also used to line ponds and seepage rates are generally dictated by degree of compaction during installation. However, generally seepage rates are higher than that for geomembranes. The seepage rate from clay lined ponds is determined by the hydraulic conductivity of the clay lining material and head pressure (i.e., depth of water in pond). Seepage rates have been calculated using the following equation (IPENZ, 2013):

$$\text{Seepage rate} = \frac{[\text{hydraulic conductivity x (pond depth + liner thickness)] x area}}{\text{liner thickness}}$$

$$Q = k \times \frac{\Delta h}{\Delta l} \times A$$

Q = flow rate rate (m^3/sec or litres/day)

k = hydraulic conductivity (m/sec)

A = area (m^2)

Δ h = vertical height from pond surface to base of liner (m)

Δ l = liner thickness (m)

Seepage rates from an effluent pond area of 750 m^2 with different degrees of clay liner compaction have been calculated using the above equation. Different heads of FDE and a uniform liner thickness have been assumed (Table 6): a 3 m head of water is akin to a permanently full storage pond; a 2 m head equates to a potential annual average depth; and a 1 m head reflects a well-managed pond i.e., emptied regularly.

An 'at risk' nutrient loss value was determined assuming zero attenuation within the clay liner or subsoil below. The 'potential attenuated' was determined based on OVERSEER® modelling through a subsoil with low organic C content and low production potential (plant uptake) in order to most closely mimic the likely poor attenuation potential under a long term pond site.

Table 6: Calculated seepage rates (m^3/yr) using the equation from IPENZ (2013) and assuming a pond area of 750m^2.

Head of FDE	3m	3m	2m	1m
Depth of clay liner	0.25m	0.5m	0.5m	0.5m
Compacted to:				
1 x 10^{-9} m/s	307	166	118	71
1 x 10^{-8} m/s	3,075	1,656	1,183	710
1 x 10^{-7} m/s	30,748	16,556	11,826	7,096
1 x 10^{-6} m/s	307,476	165,564	118,260	70,956

2.3.4 Laneways/underpasses

Laneways

Runoff from laneways is a potential nutrient loss pathway. In a Waikato farmlet study, Ledgard *et al.* (1999) reported that approximately 5% of cow excreta were deposited on laneways. However, total loss will be highly dependent on the degree of trafficking (including herd size and frequency of use), the proximity of the laneway to waterways and rainfall. Little data is available on laneway losses apart from a 2-year study in Southland's Bog Burn catchment by Monaghan & Smith (2012). In this study, run-off from laneways had a mean concentration similar to that found in FDE. These authors also reported a higher concentration of pollutants in run-off that occurred from laneways closer (~100 m) to the milking shed relative to those further away (~450-720 m).

In this calculation, nutrient loss in laneway runoff has been calculated using raw data presented by Monaghan and Smith (2012). Here we include estimates of runoff concentrations for two distances, near (within 100 m) and far (beyond 100 m) from the shed. For each distance, values represent the average concentration for samplings near and far from the milking shed as reported by Monaghan and Smith (2012). Here we have assumed a lactation season is 270 days, from mid-August to mid-May, with no winter milking. Runoff concentrations (g/m^3 runoff) for the lactation and winter period are provided (Table 7).

Table 7: Estimated concentrations of nitrogen (N) and phosphorus (P) in surface runoff (g/m^3 of runoff).

Season	Location	Nutrient (g/m^3)	
		N	P
Lactation	Near	48	19
	Far	10	6
Winter	Near	15	17
	Far	3	5

Monaghan and Smith (2012) presented a relationship between the amount of rainfall landing on laneways and the volume of runoff collected. Their results indicate 40% of rainfall landing on concrete surfaces will subsequently contribute to runoff, while on sand/gravel surfaces it will be 15%. These 'curve numbers' relating to the two surfaces have been used in our estimates. We have calculated a total laneway area of 1.4% of the farm area, 90% of which is further than 100 m from the shed. All laneways further than 100 m from the shed are gravel/sand. Laneways near the shed comprise 70% gravel/sand and 30% concrete.

Average rainfall data recorded at AgResearch Ruakura (2004-2012) indicates 50 rain days per year, 44% of which occur during the lactation season and the remaining 56% during winter (Catherine Cameron, AgResearch, pers. comm.). The magnitude of rain events has been categorised as either >10 mm or >20 mm (Table 8).

Table 8: Estimated rainfall events during lactation and winter.

Season	> 10 mm	> 20 mm
Lactation	7	15
Winter	20	8

A range of potential runoff loss contributions are presented based on the proportion of runoff that is assumed to enter surface water.

Underpasses

Underpasses allow cows to pass from one area of the farm to another without the need to cross over roads thus removing the potential for cows to excrete on roadways. Underpasses are generally constructed from concrete modules of 3.7 m width x 2 m height x 2 m depth, without a concrete base. They are normally sited at a low point of the landscape into which rainfall and effluent tend to converge. Stock access the underpass by walking down the laneway which slopes from ground level to ~2 m below ground level (i.e., base of underpass); they then walk through the underpass and up a similar slope on the opposite side. We have modelled the ‘at risk’, and ‘attenuated risk’ for the average base farm.

Assumed rainfall events are similar to those used for laneway runoff calculations (Table 9). The catchment area draining into the underpass is 300 m^2 (50 m x 6 m). Under small rainfall events (i.e., 10 mm), the area of ponding in the underpass is 30 m^2 and for large events (i.e., 20 mm) it is 50 m^2. On average there are 12.5 days of dry weather between rainfall events (this affects accumulation of dry manure).

Underpass losses have been estimated under two separate scenarios. The first assumes a drainage pipe is located at a height of 150 mm from the base of the underpass. If the pond of effluent rises above 150 mm in height (4.5 m^3 in volume) it will drain via gravity to a water course. This scenario represents a worst case design assuming the underpass is located in a higher position than a nearby waterway. Losses also occur via leaching through the laneway material, to which the hydraulic conductivity is strongly dependent. The second scenario assumes the volume of effluent in excess of 4.5 m^3 forming at the base of the underpass is periodically pumped to an adjacent paddock rather than draining to water. Pumped effluent simply expels from a pipe onto the paddock. Losses from the paddock have been modelled using OVERSEER® assuming soils are at or near field capacity at the time effluent is applied. Subsequent effluent remaining in the underpass after pumping is subject to leaching across an area of 30 m^2. On dry days, the area subject to leaching loss is 1 m^2. Hydraulic conductivity of the underpass surface is 1.2×10^{-8} m/sec and the thickness of the underpass material is 300 mm. We have assumed effluent is pumped from the underpass during the lactation season only. In winter, effluent (a combination of rainfall and dry manure) is left to accumulate at the base of the underpass and is subject to leaching losses only, i.e., it is not actively pumped.

Average stock excretion in the underpass is 0.765 L/cow/pass - calculated assuming the rate of cow defecation is twice that under paddock conditions (due to space confinement) and is equal to 35 g/N/hour (Fenton 2011). Cows spend 20 seconds in the underpass and respective concentrations of N and P in the raw effluent are 254 and 66 g/m^3 (Laurenson & Houlbrooke, 2013). During rainfall events the concentration of raw effluent is diluted by the volume of rainfall that enters the underpass (Table 9). Resulting concentrations (g/m^3) under small and large rainfall events are as follows;

Table 9: Resulting concentrations (g/m^3) of underpass effluent under small and large rainfall events that are pumped to paddocks or subject to leaching.

Season	Small event (10 mm)		Large event (20 mm)	
	N	P	N	P
Lactation	51.7	11.7	12.8	2.9
Winter	7.0	1.5	1.3	0.3

Dry manure in the underpass accumulates at a rate of 6.2 L/day (dry matter fraction of raw effluent is 10%) and has a respective N and P concentration of 480 and 120 g/m^3 (Laurenson & Houlbrooke, 2013). During rain events, a proportion of N and P in the manure will be subject to loss via leaching. Here we assume that 30 and 25% of N and P in the dry manure is subject to loss, respectively.

2.3.5 Pipe breakdowns, leaks and drips

Pipe breakdowns

There are several potential areas where broken pipes can cause a flow of effluent. One possibility could be that a buried mainline cracks due to expansion/contraction stress. It has been suggested that the probability of this happening is thought to be low (i.e. ~1%, Brian Nicholson, Hi-Tech Enviro Ltd, pers. comm.). However this is somewhat unproven and is an area that merits further investigation. Some other scenarios include:

1) There is no valve at the irrigation equipment to prevent the effluent in the hydrant line draining downhill of the pond.
2) No anti-syphon valves on the pumps. If a pump located downhill from the pond/tank stops then pond or tank continues to flow through the pump.
3) Hydrant lines when opened can spill out a lot of FDE because the farmer hasn't put in non-return or lever valves to stop effluent flowing.
4) Damage due to farm machinery and heavy loading on shallow pipes.

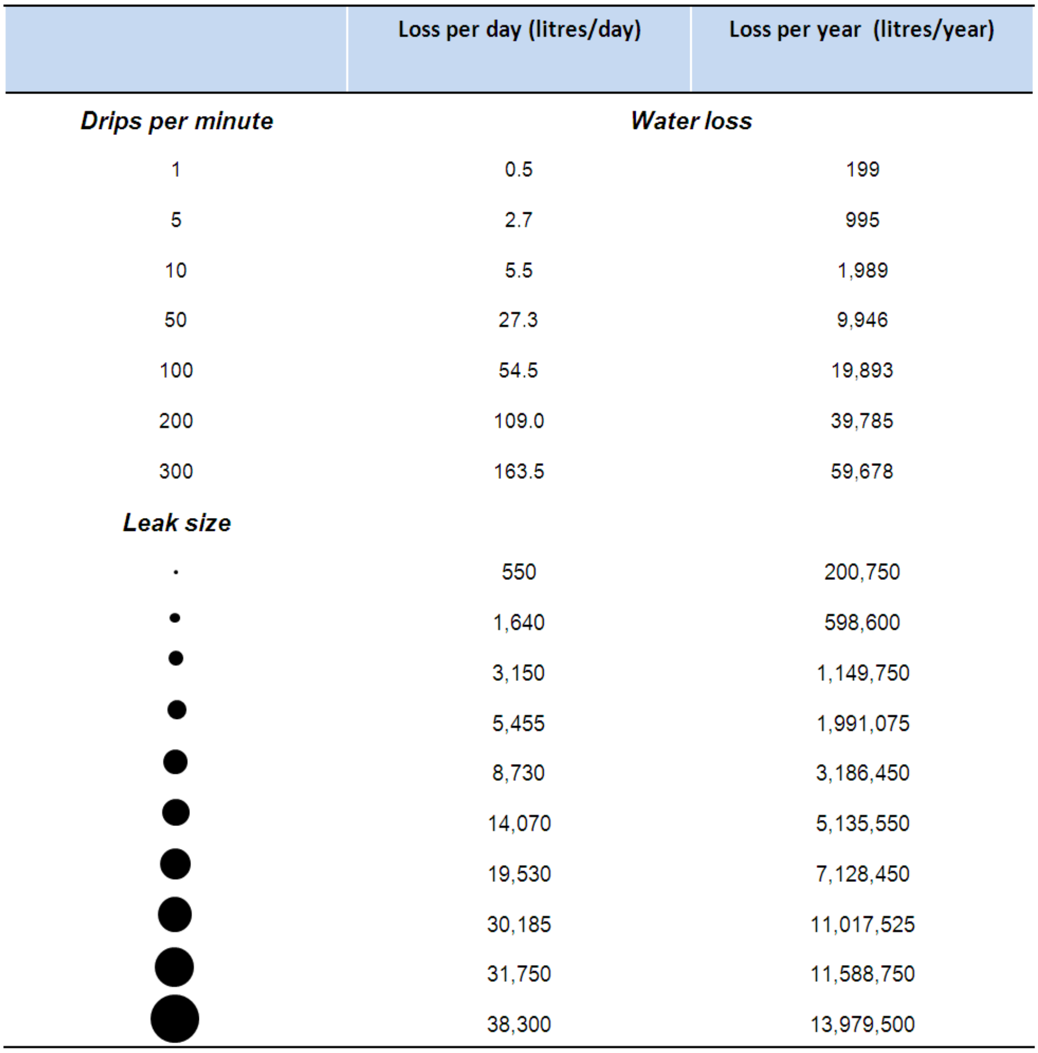
Here we assume a pipe 150 m in length and 90 mm diameter empties FDE to a small area before being discovered. Our approach is similar to that used for sand-trap cleanings. The amount of FDE contained in the 150 m length of 90 mm pipe was assumed based on judgement to have been spilt over a small area (10 m^2). Potential runoff and leaching losses from the leaking pipe were modelled using OVERSEER® by scaling up the application to a per hectare basis to obtain N and P losses, then back-scaling the results to 10 m^2 to determine the loss contribution at the whole-farm scale.

The nutrient loading in the FDE was 22.5 kg N and 3.6 kg P. In choosing this method it is recognised the position of a burst pipe will most likely move spatially between years, however OVERSEER® will assume it remains constant. Losses will therefore potentially be overestimated. Furthermore it is also recognised that the nutrient loading rates applied in these areas (albeit a very small area) is likely to be outside the validation dataset for the model.

Leaks and drips

Stewart & Rout (2007) reported that small leaks in water lines that are under pressure can lead to big losses over time (Figure 1). These losses could be hard to detect in effluent pipes if they are buried. Stewart & Rout (2007) also reported that a seemingly insignificant drip can also result in substantial losses, particularly if pipes and fittings have many such leaks. Two scenarios of effluent losses from leaking pipes and drips in a pressurised effluent system have been used to extrapolate nutrient losses using data from the Stewart & Rout (2007) report. We have assumed an effluent pumping time of 2 hours per day.

Figure 1: Predicted losses from leaks and drips (adapted from Stewart & Rout 2007).



	Loss per day (litres/day)	Loss per year (litres/year)
Drips per minute	***Water loss***	
1	0.5	199
5	2.7	995
10	5.5	1,989
50	27.3	9,946
100	54.5	19,893
200	109.0	39,785
300	163.5	59,678
Leak size		
·	550	200,750
•	1,640	598,600
●	3,150	1,149,750
●	5,455	1,991,075
●	8,730	3,186,450
●	14,070	5,135,550
●	19,530	7,128,450
●	30,185	11,017,525
●	31,750	11,588,750
●	38,300	13,979,500

2.3.6 Silage stack leachate

When silage is compressed during storage the plant cell contents are squeezed out producing leachate with high soluble sugar, protein, and nutrient contents which seeps from the stack (Tikkisetty & Kuperus, 2004). The contamination potential from silage leachate is significant due to high concentration of nutrients, particularly N and biological oxygen demand (BOD). Leachate problems are more prevalent when silage is poorly wilted (prior to being placed in the bunker) because the volume produced is greater (Table 10, ECAN, 2009). The transport of nutrients in silage leachate will be considerably greater during prolonged high rainfall events.

Table 10: Volume of silage leachate produced (from ECAN, 2009).

Preparation of grass prior to making silage	Leachate produced (litres/tonne grass)
Leafy grass, no wilting	500
Wilted to 20% dry matter	50-120
Wilted to 25% dry matter	0-30

NB: Baled silage can also leak leachate; to minimise risk it should be sited away from waterways.

Percolation occurs when: a) silage is not covered by plastic; b) runoff from the plastic flows into the silage (i.e., at the bunker wall); or c) precipitation passes through waste feed piles (Holmes, 2007). The pollutant characteristics of silage leachate have been sourced from Vanderholm (1984) and are presented in Table 11.

Table 11: Pasture silage leachate characteristics (from Vanderholm, 1984).

	Pollutant characteristics (%)				
	BOD	Total solids	Total N	Total P	Total K
Mean	6.0	6.0	2.30	0.10	0.40
Range	2.0-7.0	4.0-14.0	na	na	na

In a 2008 survey of Waikato dairy farmers, Kira et al (2008) found that 46% of respondents had a silage pit with most (89%) ensuring that seepage from the pit was excluded from entering waterways. The silage was commonly made when between 20-40% DM. Howse *et al.* (1996) reported that the average quantity of pit or stack silage was 115 t fresh wt (FW) at 31% Dry Matter (DM) or 36 t DM; crude protein averaged 15% or 2.4% N. The volume of leachate produced from an average silage stack of 115 t FW is 15 litres per tonne grass or 1,725 L per stack (assuming bulk density of silage leachate is 1:1) per year. From the 1,725 L of leachate produced and using the nutrient concentrations from Table 11, we estimate the leachate would contain: 40 kg N and 1.7 kg P per year. We assumed the 115t FW silage stack covers a 40 m x 5 m area (200 m^2). Estimated nutrient losses based on soil attenuation were modelled through OVERSEER® at an equivalent per ha rate, and values scaled back to 200 m^2 to ascertain the contribution to whole farm losses. For the two scenarios (average and System 4 farms) the data was scaled to represent conserved feed amounts of 30 and 110 t DM, respectively.

2.3.7 Feed pads

Feed pads are used for feeding supplementary food to stock. A recent survey of Waikato dairy farmers found that 24% had feed pads and 87% were constructed with concrete, 6% gravel and a further 6% were described as “other” (WRC, 2012). There are still farms around using other surfaces such as hard rock or races where there is no adequate effluent capture or treatment. The WRC (2012) survey also found that 7% of feed pads had no adequate effluent containment; this is an improved situation from an earlier AgResearch survey where 17% of feed pads had no runoff collection (Kira *et al.* 2008).

Fenton (2011) investigated the potential scale of ponding effects and seepage from feed pads (and stand-off pads) on nutrient loss. Findings from this desktop assessment showed feed pads could contribute significantly to total farm losses if runoff from the pad surface was not managed. It was reported that N losses could be 25% more when no proper effluent management (i.e., solid and liquid components) was in place.

The assumptions made in this scenario include feed pad usage of 2 hours per day for six months of the lactation season. It is also assumed that although the feed pad has its manure scraped, the liquid component is not properly contained. OVERSEER® was used to model the difference when a feed pad has been scraped and effluent exported compared to when all feed pad effluent is exported. From this data it was possible to determine the total amount of N and P in respective feed pad solids and liquid. The liquid fraction was considered to be ‘at risk’ and represents the quantity of nutrients that were then available for leaching through the soil. The amount of liquid ‘at risk’ was determined using OVERSEER®. Firstly, all feed pad nutrients were exported from the farm, and then scraped solids were exported only. ,. The ‘at risk’ amount was then ‘applied’ to soil to determine the attenuated losses.

2.3.8 Stand-off pads (uncovered)

Stand-off pads are typically constructed with a carbon-based material, such as post peelings or wood chips to provide a comfortable surface for resting cows. The minimum recommended stand-off pad area is $5m^2$/cow (Dexcel, 2005). A WRC (2012) study found that 22% of dairy farms had a pad and that these structures were more likely to be found in regions with typically wet soils. These structures are normally uncovered and therefore present a large catchment area for rain. Drainage is produced from pads when liquids (urine and rainwater) percolate throughout the media profile. Longhurst *et* *al.* (2013) reported that nutrient concentrations of pad drainage increased greatly following stock usage. Most farms capture this drainage in an effluent storage pond. However if the stand-off pad has an unlined base then this drainage will contribute to groundwater contamination. The WRC (2012) survey also found that of the farms with stand-off pads 45% were unlined pads with a further 3% not knowing if a lining was in place. The WRC (2012) report also found 67% of farms stood cows' off-paddock for 9-16 hours/day on at least some occasions. Fenton (2011) reported that when a stand-off pad is constructed with good absorbent cover (i.e., high carbon substrate such as bark or wood chips) and proper effluent drainage capture, N loss was 27 kg N/ha/yr compared to 30-34 kg N/ha/yr from stand-off pads with no proper subsurface drainage capture system.

Assumptions for stand-off pad losses are that the herd uses the pad for long-term use over the wintering period, i.e., cows spend 12 hours per day on the pad over a six week period. Losses were modelled using OVERSEER® by setting up two scenarios with a lined and unlined stand-off pad. Nutrient loss in drainage was then determined and compared between the two scenarios.

2.3.9 Animal shelters

Animal shelters are defined as temporary or partial housing structures. They are essentially covered stand-off pads, usually with an internal or external feeding lane. Many shelters are constructed with a drainage system but have an unlined base. Normally at least 30 cm of bedding material, i.e., woodchips or carbon-based product, is spread across the shelter floor. Bedding materials are periodically turned using cultivation equipment in order to soak up effluent and reduce effluent run-off. Animal shelters with under floor concrete bunkers are not included in this scenario as their liquid fraction is adequately contained. Nutrient losses were modelled through OVERSEER® using the same approach as for the stand-off pads.

2.4 Land application

The safe application of FDE to land has proven to be a challenge for dairy farmers and regulatory authorities throughout New Zealand. Research in Manawatu and Otago has identified poorly performing FDE systems can have large deleterious effects on water quality, particularly if FDE with high concentration of contaminants (P, N and faecal microbes) are discharged directly to surface water bodies (Houlbrooke *et al.* 2004a, Houlbrooke *et al.* 2008, Monaghan & Smith 2004, Muirhead *et al.* 2008). Land application is now the preferred option for treating FDE and it is normally applied via one of four methods: 1) low rate application system (e.g., K-line pods or uni-sprinklers), 2) travelling irrigators, 3) stationary rain guns or cannons, and 4) pivot irrigators. As most problems are likely when using travelling irrigators, our focus here will be on them.

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 (Monaghan *et al.* 2010). McLeod *et al.* (2008) identified the following soil orders/subgroups in the New Zealand Soil Classification (Hewitt, 1988) as having high or medium preferential flow risk: Organic, Ultic, Granular, Melanic, Podzol, Gley, Pallic, Brown, Oxidic soils; and the following soil characteristics of: mottled subsoils, peaty soils, skeletal and pedal soils, soils with a slowly permeable layer, those with coarse structure and soils with a high K_{SAT}:K_{-40} ratio. The effect of these conditions can be exacerbated by rainfall and result in 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, therefore, pose a lower risk of direct loss of effluent contaminants. Houlbrooke and Monaghan (2010) designed a soil risk framework which categorises all soil and landscape features into one of 5 different classes that can be labelled as either ‘high’ or ‘low’ risk. The key management difference is the scheduling criteria whereby high risk soils must have an application depth less than any soil water deficit available. In contrast, low risk soils can receive modest depths (< 10 mm) of applied FDE until they reach field capacity.

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. 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. Losses of FDE can therefore be considered ‘direct’ or 'indirect’ (Houlbrooke *et al.* 2008). Direct losses represent applied FDE that is lost as surface runoff or immediately drained through the root zone at the time of application. These losses are considered manageable and can be avoided by use of good management practices (Houlbrooke & Monaghan 2010). Direct losses have been shown to be considerable when inappropriate depths of FDE are applied to wet soils (Houlbrooke *et al.* 2004, Monaghan & Smith 2004, Houlbrooke *et al.* 2008, Monaghan *et al.* 2010). In comparison, ‘indirect’ losses will take place following an application event as nutrients not taken up by the plant will still be at risk of leaching in subsequent winter drainage events. Indirect losses will result from multiple nutrient sources (such as excreta returns and fertiliser) and do not simply reflect any FDE contribution. In essence when applying FDE the aim should be to achieve fertiliser equivalency so as to minimise or avoid the direct loss contribution.

A comparison of the effect on nutrient losses for the same farm on either high or low risk soils has been modelled using OVERSEER®. Two soil types, typical of the Waikato, are used as the effluent receiving area to create a typical ‘high’ vs ‘low’ risk comparison. The Horotiu silt loam is a well-drained Allophanic Soil and the Te Kowhai silt loam is an imperfectly drained Gley Soil. These soil risk comparisons are embedded into the different management comparisons below for comparison of effect. OVERSEER®. does not have the capacity to differentiate between direct and indirect losses and therefore includes both components. However it is important to note that N loss data presented excludes urine patch influence and therefore represented N inputs (in this case FDE) and mineralised N from the soil organic pool. The comparison of different management techniques can however be used to assess changes in FDE block loss contributions under different management assuming that ‘indirect’ losses are likely to change very little from management practice; this implies that variations will be a result of ‘direct’ contributions.

2.4.1 Travelling irrigators

Travelling irrigators have been the most popular method of FDE application to pastures. The application depth is governed by the irrigator’s speed, i.e., the faster the speed the less time taken to apply FDE and therefore a lower application depth compared to a slow travel speed. Three FDE application scenarios were modelled using OVERSEER® for the average base farm, for three applied depths: <12mm, 12-24mm, or >24mm. Applying depths greater than 24mm will increase the nutrient loading to pastures from a single event and increase the risk of ponding, runoff or preferential flow losses as a direct result of FDE application (Houlbrooke *et al.* 2004a).

Travelling irrigators are known to be prone to ‘mishaps’ that can result in nutrient contamination of waterways. Such incidents could include: the winch wire breaking, nozzles blowing off, or the anchor point being pulled out of the ground. A scenario of a travelling irrigator suffering a mechanical breakdown two hours into its eight hour run and remaining stationary for six hours before being discovered applying effluent in a ‘donut’ effect pattern has been calculated. The rotating boom travelling irrigator has a spreading pattern of 20 m (radius) and was scheduled to apply 120 m^3 during its run. The ‘donut’ band width of effluent applied during the breakdown is assumed to be 2 m wide. The band width of the irrigator ‘donut’ while stationary is thus:

Outer area [3.14×20^2] = 1,257m^2
Inner area [3.14×18^2] = 1,017m^2
Wetted area = 240m^2

Potential leaching losses accounting for soil attenuation from the stalled irrigator scenario was modelled using OVERSEER® by scaling up the application to a per hectare basis to obtain N and P losses, then back-scaling the results to 10 m^2 to determine the loss contribution at the whole-farm scale. In choosing this method it is recognised the position of a stalled irrigator will most likely move spatially between years, however OVERSEER® will assume it remains constant. Losses will therefore potentially be overestimated. Furthermore it is also recognised that the nutrient loading rates applied in these areas (albeit a small area) is likely to be outside the validation dataset for the model.

2.5 Low rate applicators

Low rate application systems for FDE irrigation have increased in popularity since being introduced about a decade ago. The instantaneous and average application rate achieved is typically 4 to 5 mm/hr which provides greater control of depth and uniformity of application. Considerable decreases in both the volumes of mole and pipe drainage (and overland flow), and the relative concentration of effluent contaminants in the flows was measured when low rate applicators were used to apply FDE in Otago (Monaghan *et al.* 2010). These authors also found that another advantage of using low rate systems was the ability to use an intermittent pumping regime to further decrease the application rate. Low rate application systems are ideal for applying FDE on farms with high-risk soils or sloping land (> 7^o).

FDE low rate application scenarios were modelled in OVERSEER® to compare against the travelling irrigators on both low and high risk soils, as described in the previous section.

2.5.1 Pond storage capacity

Pond storage is considered an essential requirement in order to prevent ‘direct’ losses of effluent at the time of land application to wet soils (Houlbrooke *et al.* 2004a, Houlbrooke *et al.* 2008, Monaghan & Smith 2004). OVERSEER® has been used to demonstrate the effect of not having effluent storage facilities by comparing an average farm spraying directly from the sump versus spraying from a storage pond (i.e. deferred irrigation) on both low and high-risk soils.

3. Results and discussion

3.1 Infrastructure losses

3.1.1 Two-pond losses to water

The N and P losses from a two-pond system using the average Waikato scenario farm were predicted by modelling through OVERSEER® (Table 12). Results from Table 12 shows that 784 kg N and 67 kg P is lost directly to water, representing approximately one third of the total FDE resource. This loss represents both the 'at risk' (worst case) and attenuation potential (best case) loss as direct discharge to surface water offers little or no opportunity for soil attenuation. These losses are the largest of any of the FDE management or infrastructure components tested and clearly represent an area to target for reducing environmental losses from farms. The remaining nutrient is either lost to the atmosphere or potentially recaptured in the accumulated pond sludge. Table 25 in Section 5 below also presents the 'at-risk' and loss following attenuation potential for this component and all other components benchmarked.

Table 12: Pond losses of N and P from an average Waikato farm as modelled through OVERSEER®.

	Nutrient loss, kg/yr	
	N	P
Total FDE nutrient ('at risk')	2,240	224
Direct pond discharge	784	67
% of total FDE	35	30

3.1.2 Sand/stone trap cleanings

Nutrients contained in sand trap cleanings, as reported by WRC (2012), are provided for fresh and stored cleanings (Table 13). Total nutrient losses calculated from the WRC study (2012), based on an annual volume of 4 t of stored sand trap cleanings, amounted to 6.4 kg N/yr and 1.2kg P/yr and represent the 'at risk' potential of this component. This extent of loss would only likely be realised if sand trap piles were sited so that leachate was connected to adjacent waterways.

Table 13: Range of Autumn and Spring Nitrogen 'at risk' of loss (kg/t of sand trap material).

Nutrient Season	Fresh kg/t	Stored kg/t	Average loss kg/t	Total kg lost in 4t
Nitrogen				
Autumn	2.7 - 6.8	1.5 - 3.7	1.9	
Spring	1.0 - 5.3	1.1 - 2.2	1.3	
Average			1.6	6.4
Phosphorus				
Autumn	0.4 – 0.7	0.3 – 0.8	(0.1)	
Spring	0.5 – 2.1	0.3 – 0.5	0.5	
Average			0.3	1.2

While Table 13 reports annual nutrient losses from stored sand trap cleanings it does not mean that these amounts actually reach waterways. To estimate the quantities lost through the soil root zone, assuming no direct runoff to surface water, we assumed that 4 t of annual cleanings was stored over a 10 m^2 area and modelled N and P losses through OVERSEER® to determine the attenuation potential (best case) loss. The estimated whole farm contribution from this source was only 0.2 kg N and <0.1 kg P, demonstrating that without surface water connectivity these losses would be negligible.

3.1.3 Leaking ponds

Pond seepage rate was calculated using the equation in IPENZ (2013) to estimate nutrient losses from effluent ponds with different design scenarios. Basic assumptions for pond calculations were: 2:1 batter, 0.5m freeboard and 0.5m un-pumpable sludge. The nutrient losses were calculated at two rates of seepage through two clay liner thicknesses (0.25m and 0.5m) for storage ponds compacted to 10^{-9} and 10^{-8} m/sec (Table 14) For the purposes of this assessment we have assumed that the 'at risk' proportion of nutrient loss from a leaking pond will have a leakage rate of 10^{-8} m/sec and nil soil attenuation below the pond.

Table 14: Predicted pond N and P losses (kg/year) for effluent storage ponds with different head and liner thicknesses using the IPENZ (2013) equation and nutrient concentrations from Table 5.

	Pond Storage			
Head	3m	3m	2m	1m
Liner thickness	0.25 m	0.50 m	0.50 m	0.50 m
	N loss (kg)			
Leakage rate				
1 x 10^{-9} m/s	77	41	30	18
1 x 10^{-8} m/s	769	414	296	177
	P loss (kg)			
Leakage rate				
1 x 10^{-9} m/s	12.3	6.6	4.7	2.8
1 x 10^{-8} m/s	123.0	66.2	47.3	28.0

This demonstrates the potential for large nutrient losses as the thickness of the clay liner decreases. Even more significant is the ten-fold increase in nutrient loss due to the degree of compaction (as measured by hydraulic conductivity) being less than the industry standard of 1 x 10^{-9} m/s.

However these losses do not account for soil attenuation in the subsoil below the pond and therefore OVERSEER® was used to determine a best case potential loss below the immediate pond sub-soil. However there is a clear knowledge gap regarding attenuation potential of subsoil below a leaking pond. It is feasible that the low organic matter subsoil will become N and P saturated overtime and thus limit the long term attenuation potential. Table 15 estimates the seepage losses of N and P below the pond for two different liner thicknesses. A head of 2 m has been used to represent an average pond depth throughout the year. Findings indicate that 125 kg N and 0.6 kg P per year would be lost to water when clay liner hydraulic conductivity is 1x10^{-8} m/s. This is in contrast to only 5 kg N and 0.1 kg P lost from a clay liner of 1x10^{-9} m/s conductivity. This latter value represents the best case attenuation scenario. This difference in attenuation rate largely reflects the large difference in long term annual nutrient loading rate under the two different seepages presented.

Table 15: Predicted annual pond losses for N and P after accounting for soil attenuation as modelled through OVERSEER®. Assuming a pond depth of 2 m and clay liner thickness of 0.5 m.

Compacted to	Attenuated loss (kg/pond)
N loss (kg/yr)	
1 x 10^{-9} m/s	5
1 x 10^{-8} m/s	125
P loss (kg/yr)	
1 x 10^{-9} m/s	0.1
1 x 10^{-8} m/s	0.6

3.1.4 Laneways and Underpasses

Laneways

The proportion of the total laneway contributing to nutrient loss will vary between farms due to laneway drainage characteristics and contouring that affects surface water runoff. Therefore nutrient loss under five scenarios has been modelled whereby the proportion of total laneway area contributing to runoff increases from 5 to 100% (Table 16).

Table 16: Estimated nitrogen (N) and phosphorus (P) loss from laneways where the proportion of total laneway area contributing to surface runoff increases from 5 to 100%.

Laneway area contributing to surface water runoff	Nutrient loss (kg/farm)	
	N	P
5%	1	1
20%	4	3
60%	11	8
100%	18	13

The potential 'at risk' loss has been estimated by assuming the total volume of surplus rainfall is lost as runoff to surface waters. As detailed in the methodology section, surplus rainfall represents 15 and 40% of total rainfall that lands on concrete and gravel surfaces respectively. The 'at risk' nutrients equate to 18 kg N and 13 kg P per farm per year (i.e. 100% of laneway area contributing to runoff to surface water). In comparison, depending upon the topography and proximity to surface water, a large proportion of laneway runoff may infiltrate into the soil located immediately beside the laneway area. Here we have assumed that the best case scenario is that all of the laneway runoff is infiltrated into the soil area up to 0.5 m from the laneway edge and down the full length of the laneway (1.8km). Based on this assumption using OVERSEER® it is estimated to attenuate for 98% and 97% of N and P, respectively, leaving actual losses of only 0.4 kg N and 0.4 kg of P.

Underpasses

Throughout the year, the volume of effluent accumulating in the underpass is highly influenced by rainfall. During the lactation and winter seasons, the estimated volume of effluent collected in the underpass is 1,400 m^3 and 2,400 m^3, respectively. However, the nutrient concentration of effluent is considerably greater in summer relative to winter due to frequency of use. Estimated effluent concentration was also strongly affected by magnitude of the rainfall event, whereby the concentrations of N and P decreased by approximately 75% during large events due to rainwater dilution.

Our two potential scenarios for underpass effluent were: 1) effluent drains under gravity from the underpass to a water course, and 2) effluent is pumped from the underpass to an adjacent paddock during summer, yet left to drain during winter. In the first scenario, the amounts of effluent nutrients draining to water and leaching through the base of the laneway were 14.7 kg N and 3.6 kg P. This represents the potential ‘at risk’ loss (Table 17). Pumping to an adjacent paddock during summer increases soil attenuation and therefore represents a comparatively lower risk (Table 22). However, as detailed in the Methodology section, sound irrigation practices are not employed (at least for this assessment anyway) and therefore some risk remains. It is assumed that if best management irrigation practices are followed, losses will be negligible. Attenuation of nutrients in the soil following pumping to land (including leaching losses) represents 6.1 kg N and 1.7 kg P, representing 60% and 53% of N and P respectively.

Table 17: Estimated nitrogen (N) and phosphorus (P) losses from underpasses where laneway effluent is leached through an underpass during winter and lost via surface runoff and leaching following pumping to a nearby paddock during the lactation period.

	Underpass losses (kg)		Paddock losses (kg)		Total lost to water (kg)	
	N	P	N	P	N	P
Drains to water	0.03	0.01	N/A	N/A	**29.9**	**3.6**
Pumped to paddock (summer only)	0.03	0.01	6.02	1.67	**6.1**	**1.7**

3.1.5 Pipe breakdowns, leaks and drips

Pipe breakdown

The leakage application scenario described in the methodology had an equivalent nutrient loading rate of 425 and 57 kg/ha of N and P, respectively. However, the actual loading into the 10 m^2 area was only 0.4 kg N and 0.1 kg P. These latter values represent the potential 'at risk' loss should the location of the scenario leak being located spatially on a farm so that direct runoff to surface water resulted. For comparison, we have estimated that applying these nutrient loads to a 10 m^2 area (disconnected to surface water) and allowing for soil attenuation would result in root zone losses that were effectively zero (< 0.1 kg N and P).

Leaks and drips

Figure 1 showed that a small leak of approximately 1 mm can lose 1,640 L/day and 5 drips/minute, and if undetected can accumulate to a considerable 995 m^3 over the period of a year. The following table presents some scenarios using typical N and P concentrations of 250 and 40 g/m^3, respectively (Table 18). It has been assumed that the pump has been running a pressurised FDE system for 2 hours/day.

Table 18: Calculated N and P nutrient losses from leaks and drips (based on data from Stewart & Rout, 2007).

Leakage type	Leakage (L/2hrs)	Time (weeks)	FDE vol. (L)	Nutrient	Applied (kg)	Lost to water (kg)
Small	45.8	4	1,283	N	0.32	0.25
				P	0.05	0.001
Larger	227.3	1	1,838	N	0.46	0.37
				P	0.07	0.001
Drips (5/min)	0.225	52	82	N	0.02	0.01
				P	0.003	0
Drips (10/min)	0.46	4	13	N	0.003	0
				P	0.001	0

The potential 'at risk' quantity from a larger leak over one week of 0.46 kg N and 0.07 kg of P assumes that all of the FDE lost from a leaking pipe was spatially located so that it was connected to surface water. For comparison, these leakage and drip losses were also modelled through OVERSEER® assuming that the losses covered a very small area of 1m^2. Estimated losses of 0.37 kg N and <0.1 kg of P represent the best case root zone losses based on potential soil attenuation.

3.1.6 Silage stack leachate

The volume of leachate produced from silage stacks on an average Waikato farm and a System 4 farm as modelled through OVERSEER® are presented in Table 19. For the average Waikato farm it has been assumed that 1,438 L leaches from a 30 t DM stack which covers a 200m^2 area. For the System 4 farm, 5,270 L leaches from a 110 t DM stack and spreads over 500m^2. These leachate volumes create a potential 'at risk' loss of 32 kg N and 1.4 kg P for an average Waikato farm (Table 19). This loss would only be realised if the location of a silage pit was such that any leachate was easily transported to surface water. In comparison, if all the leachate infiltrated into the soil in the area immediately under the stack, then estimated root zone losses using OVERSEER® (following attenuation) amount to 7 kg N and no loss of P (an 80% reduction). Table 19 demonstrates that both the 'at risk' and potential attenuation losses are considerably greater for a System 4 farm, which will have approximately 4 times the amount of silage stored on-farm.

Table 19: Predicted N and P nutrient loadings and losses from silage stacks per year.

	‘At risk’ loading (kg)	Losses, accounting for attenuation potential (kg)
Average farm		
N	32	7
P	1.4	0
System 4 farm		
N	299	50
P	13.0	<0.1

3.1.7 Feed pads

The amounts of N and P generated from feed pads without proper effluent containment were determined by modelling the System 4 farm through OVERSEER®. This indicated that the liquid fraction represents 57% of total captured N and 22% of the captured P (Table 20). Predicted ‘at risk’ losses of 1,277 kg N and 110 kg P would require direct connectivity to surface water from a feed pad that was used for 2 hours/day over six months. OVERSEER® was then used to estimate the potential losses from underneath an unconfined feed pad based on the ‘at risk’ loading. The resulting estimated loss accounting for attenuation within the subsoil below the pad amounted to 60 kg N and <0.1 kg P.

Table 20: Predicted amounts of N and P generated on a feed pad*. The liquid component represents the worst case ‘at risk’ loss

Source (kg/yr)	Liquid	Solids	Total
Nitrogen	1,227	924	2,151
Phosphorus	110	396	506

*Usage 2hours/day, 6 months/year x 449 cows

3.1.8 Stand-off pads (uncovered)

The quantity and losses of N and P generated from animal standoff pads without effluent containment were modelled for the System 4 farm through OVERSEER®. Results showed a potential ‘at risk’ quantity of 883 kg N and 201 kg P, which represents the volume of liquid post seepage through the pad surface that would otherwise be captured and land applied. In comparison, OVERSEER® estimates that not capturing and utilising the liquid fraction from a standoff pad used for 12 hours per days during a 6 week winter period would result in the loss of 165 kg N and 1 kg P following any soil attenuation (Table 21).

Table 21: Predicted nutrient losses (kg/yr) from an undrained stand-off pad on the System 4 farm.

Loss (kg/yr)	N	P
At risk loss	883	201
Attenuation loss	165	1

3.1.9 Animal shelters

As for the animal standoff pads, the quantities and losses of N and P generated from covered animal shelters but without liquid effluent containment were modelled through OVERSEER® for the System 4 farm. Results showed a potential 'at risk' quantity of 883 kg N and 201 kg P which represents the volume of liquid following seepage through the shelter surface that would otherwise be captured and land applied. In comparison, OVERSEER® estimates that not capturing and utilising the liquid fraction from an animal shelter used for 12 hours per day during a 6 week winter period would result in the loss of 10 kg N and 0 kg P following any soil attenuation (Table 22). The 'at risk' value is the same as that for the standoff pad, as the usage assumptions are identical. However the greatly decreased losses following soil attenuation are reflective of the decreased transport factor without added rainfall.

Table 22: Predicted nutrient losses (kg/yr) from a roofed but undrained animal shelter.

Loss (kg/yr)	N	P
At risk loss	883	201
Attenuation loss	10	0

3.2 Land application

By far the largest 'at risk' proportion of effluent on a farm is that which will be land applied. This 'at risk' proportion is effectively the quantity of N and P derived from FDE generation for the 'Waikato Average' farm (2,240 kg N and 224 kg P) minus any loss from pond seepage and sand trap drainage plus any extraordinary loss. In this case we have decided to allow for one pipe breakage, one pipe leak and one travelling irrigator fault (causing it to stall while still operating) to occur over the course of the year and have accordingly subtracted these extraordinary losses from the annual total of FDE produced. Using the data presented and described as ‘at risk’ for these components, we have determined that the actual volume of FDE being land-applied to our Waikato average farm would amount to 1,895 kg N and 224 kg P. However, OVERSEER® assumes best practice (zero loss) with regards to these potential extraordinary losses and pond seepage and therefore all of the 2,240 kg N and 224 kg P is applied to land This in effect represents the ‘at risk’ quantity for the practice of land application and demonstrates the importance of managing the nutrients well. In essence we have therefore considered those extraordinary sources of ‘at risk’ nutrient loss as additional to the quantity that was land applied (rather than subtracting these values).

The following data (with the exception of the travelling irrigator failure) represent the whole farm effluent block contribution (per ha loss scaled up by the block size) across a range of different management options (irrigator rate, application depth, high vs. low risk soil, pond storage). As emphasised in the methodology, the losses represented in OVERSEER® demonstrate the large attenuation potential of land applying FDE when comparing nutrient loading inputs with estimated losses. Despite the fact that the lolsses presented exclude urine patch influence, the losses presented cannot all be attributed to the effluent loading rate of 150 kg N/ha as it will include any mineralised N inputs from the soil organic pool. The aim for successful effluent application is to try and achieve fertiliser equivalency so that a kg of nutrient input from FDE will have no greater impact on losses to water than a kg of fertiliser nutrient. Unfortunately OVERSEER® cannot attribute the estimated losses in an FDE block to either direct effluent (time of application) or indirect losses (collective nutrients applied but not lost immediately because of poor practice) and so reported values represent both the direct and indirect impacts of nutrient inputs to the FDE block.

3.2.1 Travelling irrigator failure

The size of the ‘at risk’ loss for a stalled travelling irrigator (given the assumptions described in the methodology) equates to 40.7 kg N and 6.4 kg P. If such a mishap occurred with direct connectivity, then this ‘at risk’ portion would represent a worst case scenario. On the other hand, if the ‘donut’ was located in the middle of the paddock in an area with sufficient permeability to allow all FDE to be drained through the root zone, then the losses following attenuation would be 4 kg N and < 0.1 kg P (Table 23).

Table 23: Predicted nutrient losses from a travelling irrigator 'donut'; 90m^3 FDE applied to 240 m^2.

Farm Block		
	N	P
At risk loss (kg/donut)	40.7	6.4
Attenuated loss (kg/donut)	4	<0.1

3.2.2 Influence of application depth and soil risk

Increasing application depth without adjusting for soil moisture conditions will result in a greater number of events exceeding field capacity and creating direct drainage as a result of FDE application. Soil risk will influence the loss of nutrients associated with creating direct drainage from FDE, as high risk soils will transport more solutes via preferential flow paths or by surface runoff. Table 24 compares the effect of different application depth strategies for both high and low risk soils. Poor natural drainage of some soils prompts the need for artificial mole and pipe drainage networks in order to manage wet periods so as to avoid adverse effects during grazing of pasture. However, these drainage systems provide an effective conduit for solutes and pathogens from effluent to enter waterways with decreased assimilation of nutrients (Houlbrooke et al, 2004 & 2008) and FDE applications therefore need to be carefully managed.

Table 24 demonstrates that the typical attenuation of nutrients in soil increases with decreasing application depth of FDE, resulting in decreased losses at a per ha and whole block level. As a proportional loss reduction, the greatest potential reduction from improving FDE management (decreasing application depth) is observed for P, rather than N. For example, a 25% decrease in whole block P loss is achieved on high risk soils by managing the depth of FDE application, compared to only 5% for N.

Table 24 also clearly demonstrates that, irrespective of FDE management, high risk soils (i.e. Gley) have a greater P loss risk but lower N loss risk compared to low risk soils (i.e. Allophanic). As previously described, the definition of high risk soils for FDE management relate to the inherent risk of contributing direct losses of applied FDE through the root zone or via runoff to surface water at the time of application. This transport mechanism lends greater risk to P and faecal microbial losses than the more typically leached N. The higher loss of N on freely drained soils is unrelated to liquid FDE application, and is instead associated with the greater proportion of surplus N in the soil from all sources (dominated by urine patch returns) being subjected to leaching loss rather than denitrification processes, which are greater under poorly drained conditions (Schofield *et al.*1993).

Table 24: Predicted effluent block N land P losses (kg/year) from different management scenarios on high and low-risk soils. N losses presented represent non-urine patch loss.

Storage	Depth (mm)	Other feature	High risk soil		Low risk soil*	
			N (kg)	P (kg)	N (kg)	P (kg)
Sump	>24		55	15	71	5.0
Sump	12-24		61	13	70	4.3
Sump	<12		57	11	69	3.8
Sump	12-24	M&P	56	28	n/a	n/a
Pond	< 12	DI	44	8	73	1.0
Pond	< 12	DI, LR	39	6	58	1.0
Pond	<12	M&P, DI, LR	56	9	n/a	n/a

M&P = mole and pipe drainage, DI = deferred irrigation, LR = low rate application (mm/hr)

* NB: Whole farm N losses on the average farm presented are c. 1,400 kg N/yr and 110 kg P/yr for high-risk soils; and 3,000 kg N/yr and 50 kg P/yr for low risk (well drained) soils.

The scientific literature can be consulted to provide a distinction between direct and indirect losses from applied FDE and to assess the effect of inherent soil risk and management practices such as application depth. Some trials such as those presented by Houlbrooke *et al.,* (2008) or Monaghan and Smith (2004) have measured all aspects of drainage and runoff losses and can identify losses caused by FDE at the time of application. Direct losses from high risk soils under adverse soil moisture conditions can be very high. For example, Houlbrooke *et al., (*2004a) measured a loss of 1.9 kg/ha from an application of 4.4 kg/ha of FDE P made to a high risk Tokomaru silt loam when soil moisture content was close to field capacity. Another method for determining the risk of direct losses of FDE is to measure a breakthrough curve for solute applied to a soil surface followed by forced drainage of at least one pore volume. McLeod *et al.,* (2008) has summarised a wide range of New Zealand soil type responses to surface-applied FDE which has been used to define their preferential flow risk.

3.2.1 Good management practices

Research has demonstrated that the use of Good Management Practices (GMPs) such as deferred irrigation (pond storage during periods of high soil moisture) and low application rate/intensity technology has been effective in decreasing or avoiding the direct losses of FDE from land application. Houlbrooke *et al., (*2004) and Monaghan and Smith (2004) demonstrated that the judicial use of deferred irrigation criteria (deficit irrigation) eliminated direct losses of applied FDE, particularly when combined with low application depths (< 10 mm). Furthermore, Monaghan *et al.,* (2010) measured attenuation rates of applied FDE under wet soil conditions resulting in drainage. This assessment demonstrated a greater potential attenuation rate resulting from low application rate methods compared to the more traditional high application rate travelling irrigators.

Table 24 demonstrates the effectiveness of these GMPs on contrasting high and low risk soils using modelled data from OVERSEER®. They are particularly effective at decreasing P losses; with the resulting high and low risk soil P losses reported being equivalent to estimated P losses from areas not receiving FDE. This demonstrates a zero direct loss contribution from applied FDE or fertiliser equivalency from FDE nutrients. For example, the high risk soil has an estimated background P loss of c. 6 kg for a land area the same as the FDE block, the same loss as estimated for a deferred irrigation and low rate combination. Even applying FDE to difficult-to-manage mole and tile drained soils demonstrated large reductions in P loss using the GMPs described (c. 70%). In comparison, the reduction in N loss using GMPs is smaller (c 25%) for high risk soils, and not demonstrated on low risk soils. As described above, this reflects the transport mechanisms for water in high risk soils and demonstrates that good management of FDE will usually deliver greater benefits for P than for N.

4. Benchmarking components

The results presented in Section 4 demonstrate the magnitude of both worst case losses (at risk portion given poor management and/or a high level of spatial risk) and best case scenario losses based on maximising the soil's potential attenuation of nutrients (i.e. good management practice and/or lowest spatial risk). This section presents these components collectively so that their relative magnitude of potential risk and attenuation losses for N and P can be compared against each other. This assessment can help set the prioritisation of mitigation efforts for farmers as guided by the proposed warrant of fitness assessment.

Table 25 summarises our findings for each of the contributing factors with the 'at risk' and attenuated loss values for N and P. These losses should also be considered against the context of whole farm losses which equate to c. 1,400 kg N/yr and 110 kg P/yr for high-risk soils; and 3,000 kg N/yr and 50 kg P/yr for low risk (well drained) soils.

Table 25: Summary of the ‘at risk’ and ‘attenuated’ losses of N and P for each of the contributing factors.

Contributing factor		**At Risk**		**Attenuated loss**		***Reference***
		N	P	N	P	*(report section)*
Pond discharge		2,240	224	784	78	*4.1.1*
Land application		2,240	224	39	6	*4.2*
Stone trap clearings		6.4	1.2	0.5	0	*4.1.2*
Leakage		296	47	9	0.2	*4.1.3*
Laneway		21	15	0.4	0.4	*4.1.4*
Underpasses		30	4	6	2	*4.1.4*
Leaks/drips		0.5	0.1	0.4	0	*4.1.5*
Silage	(Average farm)	32	1.4	7	0	*4.1.6*
	(System 4 farm)	299	13	50	0.1	*4.1.6*
Feed pad		1,227	110	60	0.1	*4.1.7*
Stand-off pad		883	201	165	1	*4.1.8*
Animal shelter		883	201	10	0	*4.1.9*

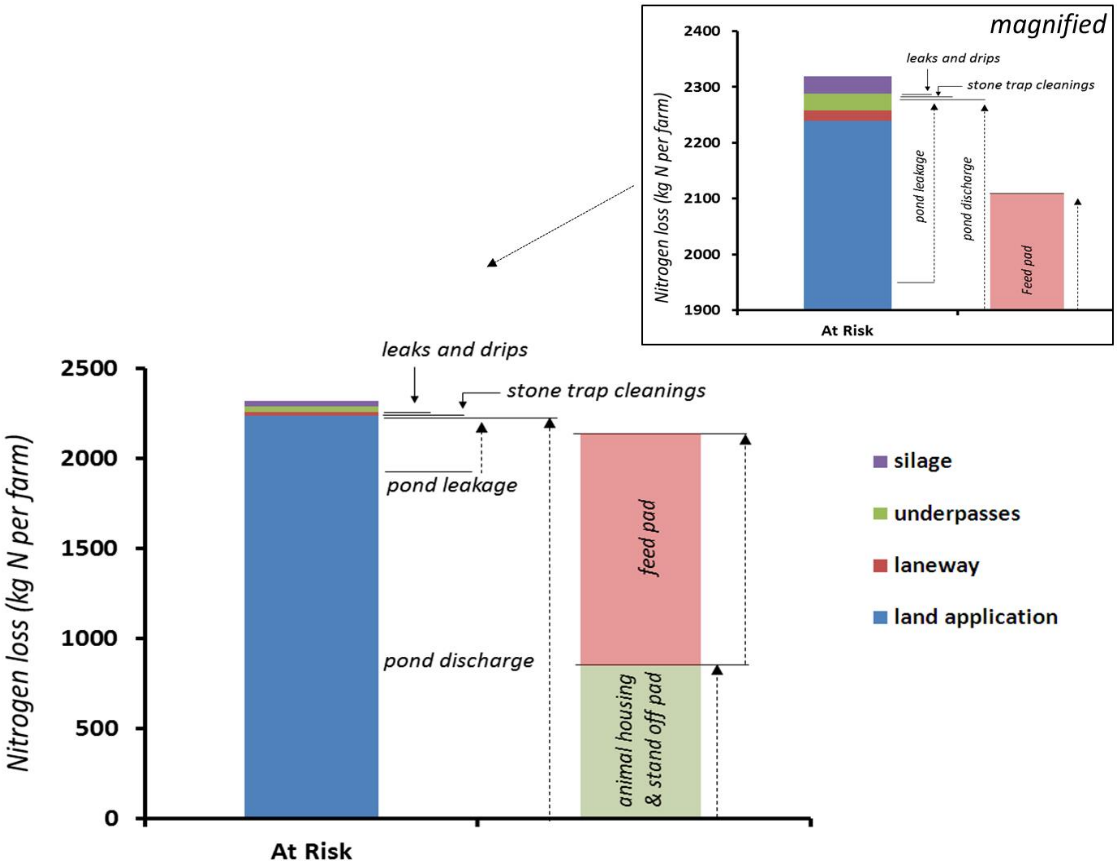


Figure 2: Estimate of the ‘at risk’ loss of N (kg/yr) derived from the multiple components for the modelled Waikato Average farm and System 4 components (stand-off pad in combination with a feed-pad). The cumulative total represents the size of the effluent resource requiring management on the farm.

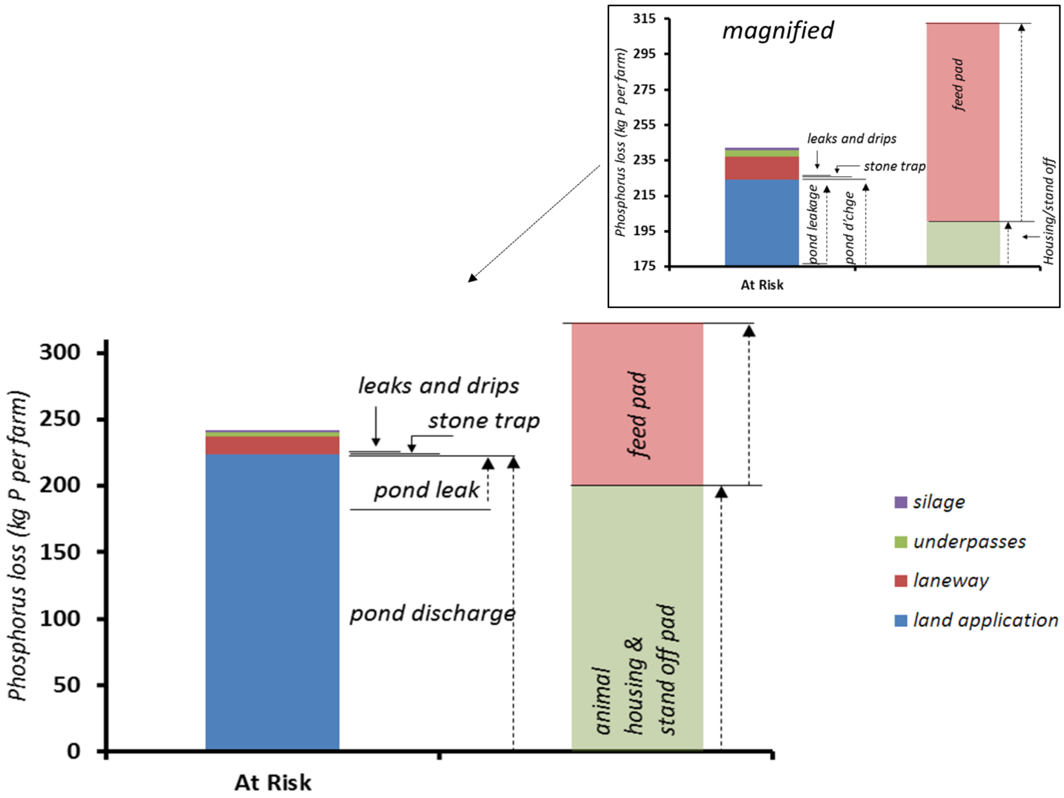


Figure 3: Estimate of the 'at risk' loss of P (kg/yr) derived from the multiple components for the modelled Waikato Average farm and System 4 components (stand-off pad in combination with a feed-pad). The cumulative total represents the size of the effluent resource requiring management on the farm.

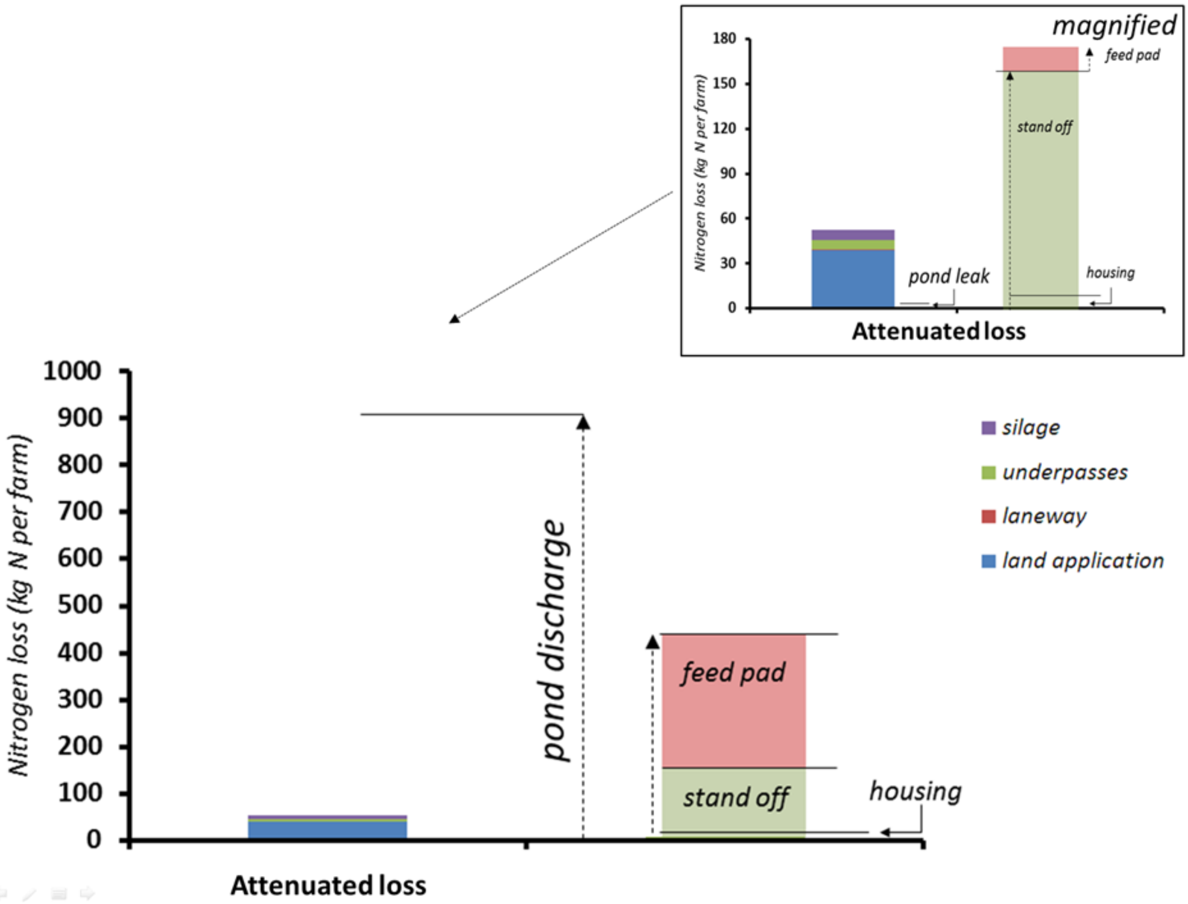


Figure 4: Attenuated loss of N (kg/yr) derived from the multiple components for the modelled Waikato Average farm and additional System 4 components (stand-off pad in combination with a feed-pad). The cumulative total represents the magnitude of the estimated best case environmental risk of N loss through the root zone.

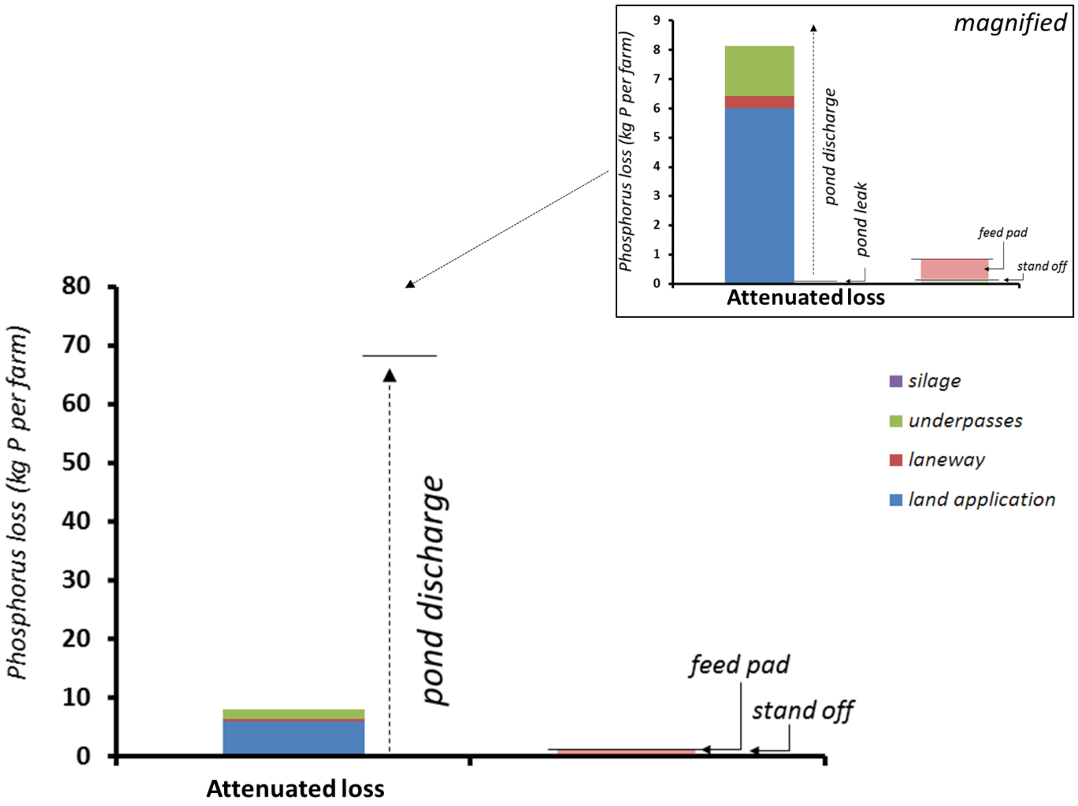


Figure 5: Attenuated loss of P (kg/yr) derived from the multiple components for the modelled Waikato Average farm and additional System 4 components (stand-off pad in combination with a feed-pad). The cumulative total represents the magnitude of the estimated best case environmental risk of P loss through the root zone.

5. Conclusions

- Hotspots for potential nutrient loss (i.e., high ‘at risk’ value) appear to be where large amounts of effluent are generated or stored, such as feed pads and ponds. Similarly, attenuation benefits for these same locations are large and present themselves as priorities for whole farm effluent management
- Discharges from treatment ponds pose the greatest risk to surface waters. Attenuated losses indicate a marked improvement in overall farm nutrient losses yet remain considerably higher than other loss pathways across the farm and somewhat unacceptable considering the pathway is direct to surface water bodies.
- In the case of land-applied effluent, there is a similar risk (i.e., similar ‘at risk’ value) yet the potential attenuation benefit is large and demonstrates that good practice should also be prioritised.
- Poor management (lack of collection) of feed pad effluent will result in large nutrient losses (i.e. high ‘at risk’ value). The attenuation benefit gained from managing this effluent source is large.
- Laneway runoff presents a high potential for P loss. Attenuation in this case is achieved by locating laneways away from waterways. This essentially lowers the risk to almost zero. By preventing underpass effluent from draining to water, losses are further reduced.
- On System 4 farms, nutrient losses, in particularly N, from silage stacks is considerably greater than on the System 2 farm (due to the difference in quantity of silage that is stored). In both cases, however, losses can be reduced considerably with adequate soil attenuation, or removed altogether with leachate collection and re-use. In the case of the average farm the estimated attenuated loss is insignificant.
- All areas included in this study contribute to nutrient loss and promoting good practice should be paramount. However, we have presented the relative effect of each factor in order to isolate those which are most influential on overall farm nutrient loss.
- Losses from FDE should also be compared against whole farm losses to provide context on the magnitude of the problem to manage. Such a comparison confirms that good land management practice and sealed or roofed off-pasture systems provide the greatest risk management advantage.

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7. References

Dairy Statistics, 2011: New Zealand Dairy Statistics 2010-11. Livestock Improvement Corporation, Hamilton.

DairyNZ. 2010: DairyNZ, Facts & Figures for NZ Dairy Farmers. DairyNZ, Hamilton,

http://www.dairynz.co.nz/page/pageid/2145866931/Facts_and_Figures

Dexcel. 2005: Minimising muck, maximising money: Stand-off and feed pads – design and management guidelines. Dexcel Ltd, Hamilton. http://www.dairynz.co.nz/page/pageid/2145855802/Stand-off_and_feed_pads

ECAN. 2009: Silage effluent and silage wrap disposal. Info Sheet 5. Environment Canterbury. http://ecan.govt.nz/publications/General/Infosheet5SilageMarch09.pdf

Fenton, T. 2011: Assessing environmental compliance of ponding and seepage from dairy feed pads and stand-off pads. Waikato Regional Council Technical Report 2012/03. www.waikatoregion.govt.nz/tr201203

Harford, D. 2010: Sand trap trial 2010. Waikato Regional Council (unpublished data).

Hewitt, A.E. 1998. New Zealand soil classification 2nd ed. Lincoln, New Zealand. Manaaki Whenua - Landcare Research New Zealand Ltd Press.

Hickey, CW., Quinn, JM., Davies-Colley, RJ. 1989: Effluent characteristics of dairy shed oxidation ponds and their potential impacts on rivers. *New Zealand Journal of Marine and Freshwater Research 23 (4):* 569-584.

Holmes, BJ. 2007: Managing silage leachate and runoff. Dairy Updates, Environment No. 93. Babcock Institute, University of Wisconsin, Madison,WI.

http://babcock.wisc.edu

Houlbrooke, D.J., Horne, D.J., Hedley, M.J., Hanly, J.A., Scotter, D.R., Snow, V.O. 2004a: Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. I. An evaluation of the deferred irrigation system for sustainable land treatment in the Manawatu. *New Zealand Journal of Agricultural Research 47*: *405-415.*

Houlbrooke D.J., Horne D.J., Hedley M.J. and Hanly J.A. 2004b: The performance of travelling effluent irrigators: assessment, modification, and implications for nutrient loss in drainage water. *New Zealand Journal of Agricultural Research* 47: 587-596.

Houlbrooke, D., Monaghan, R., Smith, C., Nicholson, C. 2006: Reducing contaminant losses following application of farm dairy effluent to land using a K-line irrigation system. In *Implementing sustainable nutrient management strategies in agriculture*. (Eds. LD Currie and JA Hanly). Occasional Report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp 290-300.

Houlbrooke, D.J., Horne, D.J., Hedley, M.J., Snow, V.O., Hanly, J.A. 2008: Land application of farm dairy effluent to a mole and pipe drained soil: implications for nutrient enrichment of winter-spring drainage. *Australian Journal of Soil Research 46*: 45-52.

Houlbrooke, D.J. and Monaghan, R.M. 2010: Land application for farm dairy effluent: development of a decision framework for matching management practice to soil and landscape risk. In *Farming's future: minimising footprints and maximising margins* (Ed L.D. Currie). Occasional report No. 23. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. pp 35-45.

Houlbrooke, D., Longhurst, B., Orchiston, T., Muirhead, R. 2011: Characterising dairy manures and slurries. Envirolink tools report AGRX0901. AgResearch.

Howse, S.W., Isherwood, P., Miller, D.B, Wells, J.L., Riddick, C.M., Thomson, N.A., Clark, D.A. 1996: Pasture silage in New Zealand – targets and current practice. Proceedings of the New Zealand Grassland Association 57: 157-160.

IPENZ. 2011: Farm dairy effluent pond design and construction. Version 1, IPENZ Practice Note 21. Institute of Professional Engineers New Zealand Inc., Wellington. www.dairynz.co.nz/page/pageid/2145869375?resourceId=686

IPENZ. 2013: Farm dairy effluent pond design and construction. Version 2, IPENZ Practice Note 21. Institute of Professional Engineers New Zealand Inc., Wellington. www.dairynz.co.nz/page/pageid/2145869375?resourceId=686

Kira, A., Roth, H., Botha, N. 2008: A regional analysis of NZ dairy farmers' practises that may negatively impact on the environment. AgResearch report for P21.

Laurenson S, Houlbrooke D.J. 2013: Assessing the risk of nutrient and microbial runoff from rainfall following surface application of effluent solids that vary in dry matter content. AgResearch Limited, Invermay.

Ledgard SF, Penno JW and Sprosen MS (1999) Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *Journal of Agricultural Science* 132, 215-225.

Longhurst, R.D., O'Connor, M.B., Roberts, A.H.C., Waller, J.E. 1999: Farm dairy effluent: findings of recent research studies in the Waikato. In *Best Soil Management Practices for Production* (Eds L D Currie, M J Hedley, D J Horne and P Loganathan). http://flrc.massey.ac.nz/publications.html.
Proceedings of Fertilizer & Lime Research Centre Workshop Occasional Report 12: 273-282. Massey University, Palmerston North.

Longhurst, B., Nicholson, B. 2011: Rapid method of assessing NPK content of dairy effluents for land application. In: *Accurate and efficient use of nutrients on farms*. (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 24. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 8p.

Longhurst, B., Glassey,C.,Taukiri, S., Roach, C., Wynn, K.,Luo, J., Ross, C., Rapp, D. 2013: Evaluation of physical, chemical and microbial characteristics of stand-off pad materials during winter use and relationship with cow behaviour. In: *Accurate and efficient use of nutrients on farms*. (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 9p.

McLeod, M., Aislabie, J., Ryburn,J., McGill, A. 2008: Regionalising potential for Microbial bypass flow through New Zealand soils. *Journal of Environmental Quality 37*: 1959-1967.

Monaghan R.M, Houlbrooke DJ, Smith L.C. 2010: The use of low-rate sprinkler application systems for applying farm dairy effluent to land to reduce contaminant transfers. *New Zealand Journal of Agricultural Research 53,* 389-402.

Monaghan, R.M., Smith, L.C. 2004: Minimising surface water pollution resulting from farm dairy effluent application to mole-pipe drained soils. II. The contribution of preferential flow of effluent to whole-farm pollutant losses in subsurface drainage from a West Otago dairy farm. *New Zealand Journal of Agricultural Research 47*: *417-428.*

Monaghan, R.M., Smith, L.C. 2012: Contaminant losses in overland flow from dairy farm laneways in southern New Zealand. *Agriculture, Ecosystems and Environment*, 159: 170-175.

Muirhead RW, Monaghan, RM, Donnison AM, Ross, C. 2008. Effectiveness of current best management practices to achieve faecal microbial water quality standards. In

Carbon and nutrient management (L Currie Ed) Occasional report 21. FLRC, Massey University, Palmerston North.

Ray, D.E., Balks, M.R., Barkle, GF., Selvarajah, N. 1997: Why do dairy farm effluent treatment ponds leak? Proceedings of New Zealand Water and Wastewater Conference: 273-275.

Scholefield, D., Tyson, K.C., Garwood, E.A., Armstrong, A.C., Hawkins, J., Stone, A.C. 1993: Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input, field drainage, age of sward and patterns of weather. *Journal of Soil Science 44*: 601-613.

Stewart, G., Rout, R. 2007: Reasonable stock water requirements; guidelines for Resource consent Applications. Technical Report for Horizons Regional Council. www.horizons.govt.nz/assets/horizons/Images/one-plan-tech-reports-public/Reasonable Stock Water Requirements Guidelines for Resource Consent Applications.pdf

Tikkisetty, B., Kuperus, W. 2004: Environmentally friendly silage management. Proceedings of SIDE Conference. South Island Dairy Event.

Vanderholm, D.H 1984: Agricultural Waste Manual. NZAEI Project Report No. 32. New Zealand Agricultural Engineering Institute, Lincoln College, Canterbury.

Wheeler, D.M., Ledgard, S.F., Monaghan, R.M., McDowell, R.W. and de Klein, C.A.M. 2006: OVERSEER nutrient budget model – what it is, what it does. In *Implementing sustainable nutrient management strategies in agriculture* (Eds L.D. Currie and J.A. Hanley). http://flrc.massey.ac.nz/publications.html. Occasional report No. 19. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. pp 231-236.

WRC. 2012: Waikato Regional Council dairy winter grazing survey 2011. Venus Research & A Davies. Technical Report Waikato Regional Council Technical Report 2012/30. www.waikatoregion.govt.nz/Services/Publications/Technical-Reports/