Land Treatment of Phosphorus, the Third Dimension.

Daryl Irvine [A]

[A] Pattle Delamore Partners Limited
Level 5, PDP House, 235 Broadway, Newmarket, Auckland
Email: daryl.irvine@pdp.co.nz

ABSTRACT

Wastewater, Land Treatment, Phosphorus, Soil

Land treatment systems have traditionally been sized and managed based on hydraulic and nitrogen, loading and treatment capacity, however, phosphorus is becoming a relevant nutrient, more frequently requiring considered management within land treatment systems.

With the now common use of models such as OVERSEER®, providing model estimates of phosphorus migration to surface water from land treatment systems, the risk that phosphorus presents on surface water systems is quantifiable and can no longer hide behind assumptions of continued adsorption onto soils.

This paper provides a summary of the mechanisms of phosphorus behaviour in soils, what the respective soil tests indicate, phosphorus migration pathways, and potential mitigation tools that are available for land treatment systems to minimise phosphorus migration to surface water. In addition this paper also explores potential methods for identifying sustainable phosphorus loading rates for respective land uses, considering factors in addition to plant phosphorus uptake.

INTRODUCTION

Land treatment systems have traditionally been sized and managed based on hydraulic and nitrogen, loading and treatment capacity, however, phosphorus is becoming a relevant nutrient, more frequently requiring considered management within land treatment systems.

During the 1980's in New Zealand, the key focus when positioning and sizing of land treatment system was disposal driven, as limited by hydraulic loading. This saw the implementation of high rate irrigation methods such as border dyke irrigation. During the 1990's and 2000's the effects of nitrogen loading on land treatment systems was becoming more evident, with increasing nitrate levels in groundwater and surface water systems. Nitrogen loading limits then became a common constraint within land treatment processes. During this period there was a general perception that New Zealand soils are phosphorus short with sufficient capacity to retain phosphorus loaded from land treatment systems. However, the potential effects of phosphorus migrating from land treatment systems are becoming more evident, particularly for land treatment systems that have operated for many years.

With the now common use of models such as OVERSEER®, providing model estimates of phosphorus migration to surface water from land treatment systems, the risk that phosphorus presents on surface water systems is more easily identified. It can therefore be expected that phosphorus limits should be more commonly utilised in the management of land treatment systems, however, with phosphorus removal methods in wastewater treatment systems incorporating high operational costs it is important to explore the functions by which phosphorus behaves in soils and migration pathways to surface water. This is essential for investigating land treatment options for new systems and for understanding the mitigation measures for managing phosphorus existing land treatment systems.

This paper provides a summary of the mechanisms of phosphorus behaviour in soils, phosphorus path ways to surface water and potential mitigation measures for managing risks presented by phosphorus in land treatment land treatment, along with exploring what loading rates may be appropriate for ongoing land treatment operations.

PHOSPHORUS SOURCES AND TREATEMENT COSTS

Phosphorus is present in most waste streams utilising land treatment systems. In municipal wastewater it is present at concentrations in the order of 10 to 15 ppm in raw wastewater. Through conventional biological treatment processes (that do not target phosphorus removal) it can be expected that phosphorus would be reduced to levels in the order of 6 to 10 ppm.

Industrial wastewater systems incorporating land treatment in the New Zealand more commonly incorporate either meat and by-product processing plant wastewater or dairy plant wastewater. In meat plant wastewaters, the phosphorus results from grass based wastewater sources (green waste streams), including paunch, stockyards and rendering. Once combined with other waste streams, phosphorus concentration range from 20 ppm to 40 ppm.

For the dairy industry, phosphorus sources are present from either the release of calcium phosphate from the casein molecule during product manufacture, released in the resultant whey processes, or resulting in the wastewater from the use of phosphoric acid based cleaning products (where utilised to replace nitrogen based products). While highly variable, depending on manufacturing processes, phosphorus concentrations can be expected to range from 50 ppm to 200 ppm.

There are several options for removing phosphorus from wastewater prior to discharge, including enhanced biological phosphorus removal (EBPR) or chemical precipitation, utilising aluminium of iron based salts, or high pH precipitation utilising calcium (calcium phosphate precipitation). EBPR requires specific capital investment for development of multi stage activated sludge processes, often beyond the capacity of local authorities or industries to fund and operate. If phosphorus removal is required, utilisation of metal salts, such as alum, is more common in the New Zealand (at a cost of a round $8/kg of phosphate removed). Lime precipitation is less commonly utilised, and requires the pH of the wastewater to be raised to >9.0 pH units. The cost of lime precipitation is dependent of the concentration of the phosphorus in the wastewater, however, based on a wastewater at 50 ppm phosphorus concentration, the cost of utilising lime precipitation can be in the order of $10/kg of phosphate removed.

Following precipitation steps, the precipitate must be removed from the wastewater, resulting in a sludge that requires disposal, resulting in additional cost.

When taking into account phosphorus management costs, irrigation to land can provide for both a lower cost disposal method while also providing a fertiliser value for the land use activity, while reducing the phosphorus load that would have traditionally been discharged to surface water. However, over a longer term period, if loaded above the land use utilisation rates, phosphorus can accumulate in soils to a level where there is an increase in migration of phosphorus to surface water.

PHOSPHORUS PROCESSES IN LAND TREATMENT SYSTEMS

In land treatment systems, phosphorus in treated or partially treated wastewater (predominantly in phosphate form) behaves quite differently to nitrogen. Unlike nitrogen, phosphorus cannot form a gas phase under normal atmospheric conditions, therefore, it can be expected that all phosphorus that exists a wastewater treatment system to be irrigated, will result in the soil, with no loss mechanisms such as volatilisation.

Phosphate is a triple negative charged anion, compared to the single negative charge of nitrate, and therefore will bind more readily to anion storage site within soil, displacing other anions such as sulphate and nitrate. The capacity of a soil to adsorb phosphorus is referred to as the anion storage capacity (or P retention). This is an important function in land treatment systems because excess nitrogen will readily migrate to groundwater with soil drainage (predominantly during winter), while phosphorus readily binds to soil particles and will not freely migrate unless the P exists in the soil in high concentrations.

The anion storage capacity (ASC) of a soil is dependent on the parent material of the soil and the level of soil weathering. Soils with higher aluminium or iron hydrous content (generally of volcanic origin) will have a higher ASC and soils with a higher level of weathering (finer particle size and more hydrous oxide) will have more anion storage sites.

When bound to anionic storage sites in soils, phosphate is predominantly held in labile form (plant available), and a smaller portion of the phosphate can be released (desorbed) back into the soil water solution to be up-taken by plants. The amount of P that can be desorbed into soil water solution is in equilibrium with the adsorbed P content of the soil. Therefore, as the adsorbed phosphorus content in the soil increases, through ongoing phosphorus loading, the available P content that can be released into solution for plant uptake (as measured as Olsen P) increases.

As the P content in the soils increases, the available adsorption sites are utilised to a point where there is a more significant portion of P available in the soil. The point at which this occurs is dependent of the ASC of the soil, as indicated in Figure 1 (FLRC 2018).

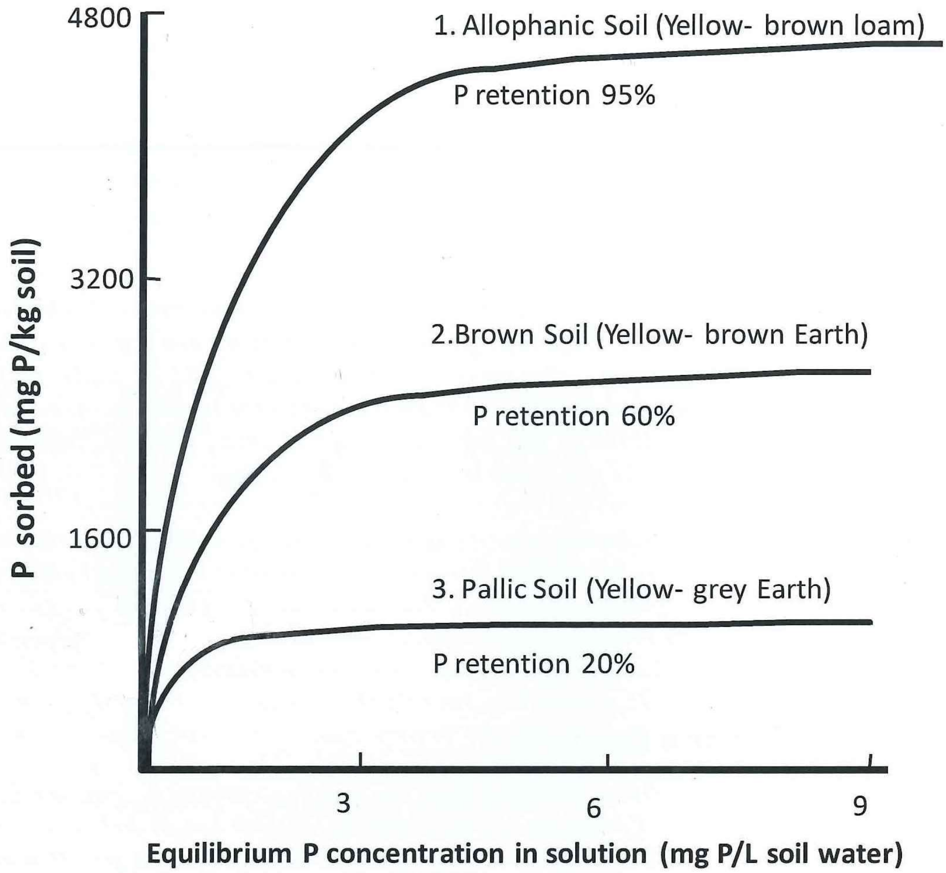

Figure 1: Phosphate Sorption Characteristics of 3 New Zealand Soil Orders

When assessing potential land treatment sites, Figure 1 provides a useful indication of potential lifecycle P loading rates before Olsen P concentrations will be rapidly increased.

As ongoing weathering of the soil occurs more hydrous oxide is produced resulting in ongoing coating of the adsorbed P, resulting in progressively absorbed P, which is then non-labile (cannot be desorbed), and generating more P adsorption sites.

P immobilisation can also occur when inorganic P is utilised in formation of organic complexes, becoming organic P (Po). In soils where the carbon content exceeds a ratio of 300 C : 1 Po, the organic P is likely to be immobilised. As the carbon content decreases to 200 C: 1 Po, mineralisation will increase. While only a general rule, P immobilisation through weathering and Po immobilisation are important considerations when assessing the capacity of a land treatment system to manage P loads.

PHOSPHORUS PATHWAYS TO SURFACE WATER AND RISK MANAGEMENT

Due to the ability for sorption of phosphorus in soils, not only in the top soil layer but also in sub soil layers, phosphorus tends not to migrate to groundwater in significant quantities, unless the soil is heavily loaded with P or groundwater levels are very shallow. Therefore, the dominant pathway for pathway for phosphorus to migrate to surface water is via overland flow paths (runoff) or lateral flow paths including artificial drainage pathways.

The migration of phosphorus to surface water is driven by mobilisation of particulates, primarily as a result of overland flow during in high intensity rainfall events, with 80% of the annual P loss to surface water as a result of such events (Sharpley *et al* 2008). The mass of phosphorus loss to surface water, however, is also a function of soil characteristic and phosphorus present in the soils.

The risk of P loss from soils via overland flow paths is dependent on P content present, soil type (texture index and slaking/dispersion index), and slope, and can be approximate by the following equation (McDowell *et al* 2005) as normalised to 100%.

P loss risk = ((Olsen P/P retention)*texture index * slaking/dispersion index* slope index)

From the above equation it can be seen that as the P sol water concentration increases (as indicated by Olsen P) the risk of P loss also increases. Alternatively, if the soil has a low P retention, there is a greater risk of P loss. The texture and slaking/dispersion indexes are characteristic to different soil types and work conducted assessing various soil orders (under the New Soil Classification System). An increase in slope also presents an increase in P loss risk.

Based on field investigations (Taylor *et al* 2016) the risk of P loss represented by various soil orders is outlined in Figure 2.

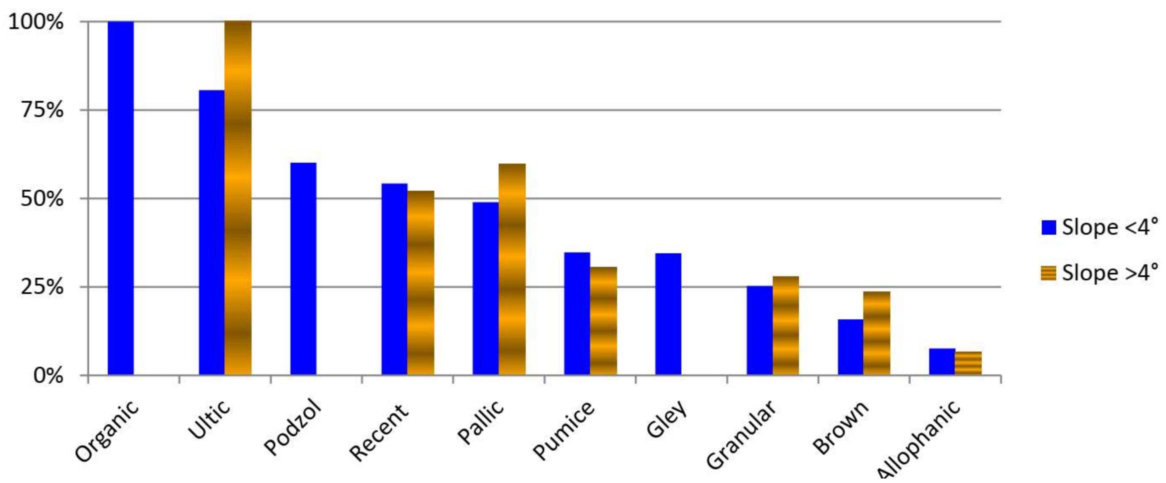

Figure 2: Relative P loss Risk by Soil Order for flat land (<4°) and slopes (>4°) using the Overland Flow Model Risk

It can be seen from Figure 2 that the risk of P loss increases rapidly based on soil type and slope, with soil type being the key contributing factor. While the Overseer P loss sub-model utilises similar factors, based on soil characteristics and P retention, along with additional factors such as under drainage, climate conditions etc. (Gray *et al* 2016), Figure 2 provides a good summary of risk presented by various soil types when assessing potential land treatment site options. For existing irrigation sites, it is more difficult to change away from irrigated soil types, however, it helps identify higher risk areas within land treatment systems where mitigation may be required.

MITIGATION MEASURES

When assessing the potential increase in P loss as a result of a land treatment system (compared with the underlying land use) it can be difficult to avoid a net increase in migration of phosphorus to surface water, however, there are some key steps that can be implemented which can help minimise the P loss from land treatment systems. Where new land treatment systems are proposed, it can be particularly important to consider the available mitigation tools when regional legislation may require net improvement, or betterment, such as when operating within the Waikato River and Waipa River catchments, with the requirements of the Vision and Strategy for the Waikato River.

If not already implemented, easy improvements such as fencing of waterways can provide a reduction in P loss to waterway for combined land treatment and grazed systems. Further mitigation tools are summarised as follows:

<u>Minimise pugging risk</u>
Pugging can result from grazing of pastures during wet conditions particularly with high stock number such as when strip grazing. Pugging compacts the soil and blinds macro-pores, decreasing the infiltration capacity of the soil to manage rainfall events, increasing the risk of runoff and mobilisation of soil particles.

Pugging can be minimised by amending grazing practices and/or installing stand-off feed pads to keep stock off wet soils. Going one step further, it may be more appropriate to implement a decrease in stocking rate to move to a more cut and carry based system, to prevent the risk of pugging.

<u>Install grass buffer strips</u>
Grass buffer strips between irrigation areas and surface water drains have the ability to filter out particulates and utilise dissolved phosphorus, minimising loss to surface water by approximately 0% to 20% (McDowell and Nash 2012).

Grass strip can be promoted along fenced off water ways, allowing a wider strip where available, but also around farm drains, which are generally not fenced off, but act as short circuiting path ways. If grass strips are to be promoted, additional fencing will be required to exclude stock from these areas.

<u>Detention areas or Constructed Wetlands</u>

Where possible, runoff from catchment areas and farm drains can be directed to detention areas or constructed wetlands, to allow phosphorus bound in particulate form to settle prior to discharging to the receiving surface water environment. The efficiency of runoff detention or wetlands is dependent on the area of runoff that is able to be captured and the ability to remove the sediments on a regular (annual basis). If sediments are not regularly removed then phosphorus may progressively be remobilised back into the water column over a longer term, as may happen with a wetland.

Remove artificial drainage

Where possible, remove short circuiting pathways such as mole drains or tile drains. Overseer currently allows for an increase of 0.3 kg P/ha/yr in P loss to surface water associated with artificial drainage (Gray *et al* 2016), however P loss may decrease by as much as 50% (McDowell and Nash 2012).

It is not always possible to remove artificial drainage without compromising the risk of pugging. If soil drainage is required to avoid pugging, the soil drainage could be directed to addition mitigation facilities such as detention areas.

IDENTIFYING SUSTAINABLE P LOADING RATES

For both new and existing land treatment systems it is important to identify if phosphorus is the load limiting factor and, if so, what is a sustainable phosphorus loading rate for the system, to minimise loss of phosphorus to surface water.

As a rough guide, if phosphorus exceeds a concentration of approximately 10 g/m^3 and the nitrogen to phosphorus ratio is less than 3N:1P, then there is potential that phosphorus management requires careful consideration for the land treatment system (beyond hydraulic and nitrogen limits), requiring further assessment. This is on the assumption that hydraulic and nitrogen loading limitations would be in the order of 500 mm/yr and 150 kg N/ha/yr respectively.

The difference between hydraulic and nitrogen loading capacity and phosphorus loading capacity for a land treatment system is that due to the ability for phosphorus to adsorb to soils, the effects of elevated phosphorus loading can last for a number of years, whereas excess hydraulic load and nitrogen load pass beyond the soil profile much faster.

In a normal agricultural system, the available phosphorus in the soil (Olsen P) would be assessed on an annual basis and fertiliser P load adjusted to maintain suitable levels for the land use. With land treatment systems, it is not easy to manipulate the P loading rate on an annual basis and therefore, the ongoing sustainable P loading rate needs to be identified as part of the land treatment system.

As a starting point, it is necessary to identify the expected P load based on hydraulic and nitrogen load limitations and compare this with the land use requirements, in terms of P removed by plant uptake (maintenance P requirements). It is then important to consider what P loading may be required to increase the Olsen P level to optimal level for the land use and soil type (capital P requirements). The capital P requirement could be considered an operating requirement for the land use, or an available capacity for ongoing land treatment.

Expected land use P maintenance rates are summarised Table 1. In considering combined land uses, such as combined cut and carry and grazing, consideration needs to be given to the combined P demand of stocking rate and the pasture yield rate removed from farm.

Table 1: Land Use Phosphorus Maintenance Requirements

Landuse	P Maintenance Rate (kg/ha/yr)
Sheep and beef (16 SU/ha)[1]	21 - 34
Dairy Farm (3 cow/ha)[2]	34 - 45
Dairy Farm (4 cow/ha)[2]	54 - 65
Cut and Carry Silage[3]	42 - 48

Notes:

1. *Sourced from Fert NZ 2018*
2. *Sourced from Fert NZ 2016*
3. *Estimated based on a pasture P concentration of 0.3% to 0.4% DM and a yield rate of 12 tonne/ha*

If a soil within a land treatment system is below the optimum Olsen P level for the land use and soil type, there is available capacity for P loading until the optimum P level is reached for pasture growth. Table 2 provides a summary of the require/available phosphorus load to bring a soil up optimum Olsen P levels.

Table 2: Olsen P Adjustment Demand Based on Soil Type

Soil Type	Optimum Olsen P[1] (mg/L)	Olsen P Adjustment Requirements[1,2]
Ash	20-30	7 – 18
Sedimentary	20-30	4 – 7
Pumice	35-45	4 – 15
Peat	35-45	6 - 9

Notes:

1. *Sourced from Fert NZ 2016*
2. *Based on adjusting the Olsen P level by 1 mg/L*
3. *Based on a dairy farm operation*

Once the soil and land use based P requirements have been established, it is important to consider the Olsen P of the soils that will be maintained and the available mitigation measures on the site. Overseer can be a useful tool at this stage to identify what the resultant migration rate of P to surface water is, however, it must be remembered that Overseer is primarily a farm nutrient management tool and was not developed for the purpose of modelling land treatment systems.

In considering P loading limits for land management systems, consideration needs to also be given to P immobilisation from continued weathering and organic based immobilisation (particularly if soil organic matter is increasing as could be expected in a pasture system), allowance for operation loading variations (buffer allowance) and the ability for mitigation measures to capture P migration. For resource consents, a wider range of factors must also be considered relating to the social and economic implications of the P source and what improvements in P loading are practicable to achieve.

Regular (annual) Olsen P monitoring will help identify how the P loading rate is impacting on P levels in the soil and whether it is tracking in accordance with the expected rates outlined in Table 1 and 2.

CONCLUSIONS

Phosphorus loading is becoming a more common limiting factor for managing land treatment systems. While phosphorus in wastewater can provide a valuable fertilizer resource, phosphorus can also present a risk to the environmental, and must be considered as a potential limiting factor, along with hydraulic limitations and nitrogen limitations, if phosphorus concentrations exceed certain levels.

In considering the capacity of land treatment systems to receive phosphorus, soil type is a key consideration in identifying loading capacity and risk to the environment, with soils of volcanic origin providing for lower risk phosphorus management. To establish appropriate P loading rates in land treatment systems, land use P maintenance requirements and capital P requirements are key factors to be considered, along with P immobilisation potential and the best practicable option for any particular land discharge.

The dominant pathway for migration of phosphorus to surface water is via particulate mobilisation via overland path ways during higher intensity rainfall events. For new or existing land treatment systems, particularly for high risk soil types, there are a number of mitigation measures that can be implemented to reduce phosphorus migration.

REFERENCES:

Gray, C.W. Wheeler, D. McDowell, R.W. (2016) *Review of the Phosphorus loss Submodel in Oveseer*. Agresearch RE500/2015/050

Fertilizer and Lime Research Centre, Fertiliser Association of New Zealand. 2018. *Sustainable Nutrient Management in New Zealand Agriculture.* Palmerston North: Massey University.

Fertiliser Association of New Zealand 2016, *Fertiliser Use on New Zealand Dairy Farms*

Fertiliser Association of New Zealand 2018, *Fertiliser Use on New Zealand Sheep and Beef Farms*

McDowell R.W., Monaghan R.M., and Wheeler D. (2005) Modelling phosphorus losses from pastoral farming systems in New Zealand. New Zealand Journal of Agricultural Research 48, 131-141

McDowell RW, Nash D (2012) *A review of the cost-effectiveness and suitability of mitigation strategies to prevent phosphorus loss from dairy farms in New Zealand and Australia*. J Environ Qual 41:In press.

Sharpley AN, Kleinman PJA, Heathwaite AL, Gburek WJ, Folmar GJ, Schmidt JP (2008) *Phosphorus loss from an agricultural watershed as a function of storm size*. J Environ Qual 37:362-368.

Taylor, M.D. Drewry, J.J, Curran-Cournane F, Pearson L, McDowell RW, Lynch B , (2016). *Soil quality targets for Olsen P for the protection ofenvironmental values.* In: *Integrated nutrient and water management for sustainable farming*. (Eds L.D. Currie and R.Singh).