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SENSITIVITY ANALYSIS OF THE SEEPAGE WETLAND MODULE IN OVERSEER

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Abstract

The potential for seepage wetlands to remove nutrients from pasture runoff has been identified (McKergow & Hughes, 2016) and in 2008 a wetland module was included in OVERSEER. However, the effectiveness of seepage wetlands has not been quantified as accurately as the effectiveness of constructed wetlands. In 2016 DairyNZ contracted NIWA to investigate the sensitivity of the OVERSEER wetland module to input variables and to identify major information gaps. Nitrogen removal was found to be most sensitive to four input parameters, ranked: Wetland area ~ By-pass flow ~ Wetland condition > Flow convergence. Two methods are used to estimate by-pass flow which require data on aquitard depth and drainage class (Method 1) or the area of the catchment that drains to the wetland (Method 2). OVERSEER assumes a maximum areal uptake rate of 250 mg m^{-2} d^{-1} which is modified by wetland condition, flow convergence and temperature factors. Where soils or vegetation are damaged and/or flow becomes channelized, wetlands become less effective at removing nitrogen. The required input parameters are difficult to estimate. Five input parameters were found to have only a small effect on nitrogen removal.

Removal estimates are highly uncertain but in keeping with the spirit of OVERSEER, enable the user to assess the potential of seepage wetlands to reduce nitrogen losses from farms. OVERSEER predicts that seepage wetlands occupying 5% of the catchment area can remove 10-20% of catchment nitrogen loss from pasture depending on the intensity of land use and the condition of the wetlands. The potential for seepage wetlands to remove nitrogen has been clearly demonstrated and a strong case can be made to protect and enhance them. The management of seepage flow offers the best prospect for reducing nitrogen losses and can be enhanced by preventing damage by stock, promoting the growth of wetland vegetation (e.g., through periodic harvesting), preventing channelization within the wetland, and reducing channelization of surface flow upslope from the wetland. It may be worthwhile to quantify the effectiveness of seepage wetlands better and in more parts of the country, and to make it easier for users to estimate key input variables.

Keywords

attenuation, denitrification, OVERSEER, nitrate, nitrogen, removal, wetlands,

Background

Seepage wetlands (also known as natural or riparian wetlands) are naturally occurring areas, usually alongside streams, characterised by saturated soils and wetland vegetation (e.g., reeds and sedges). Stock can become trapped in their fragile soils and many seepage wetlands have been drained or fenced to avoid this. Although their potential to remove nutrients from pasture runoff has been identified (McKergow & Hughes, 2016), their ability to reduce nitrogen losses has not been quantified as accurately as for constructed wetlands. In 2008 a seepage wetland module was developed by NIWA and implemented into OVERSEER by AgResearch (Rutherford & Wheeler 2011). In 2016 DairyNZ contracted NIWA to investigate the sensitivity of the wetland module to input variables and to identify major information gaps so that DairyNZ can better articulate to stakeholders the benefits of protecting seepage wetlands, have a better understanding of the strengths and weaknesses of the wetland module in OVERSEER, and can plan studies to fill major information gaps.

A desk-top study was conducted to determine the sensitivity of nitrogen removal by seepage wetlands to input variables in the OVERSEER wetland module. Sixteen variables that affect nitrogen removal by wetlands are considered in OVERSEER. Four relate to rainfall and evapotranspiration, five to soils, five to wetlands, and two to the catchment (Table 1). The wetland module in OVERSEER runs with a daily time step although annual nutrient losses are reported and inputs are often monthly. The module assumes that runoff enters the wetland along two pathways: shallow sub-surface (seepage) and surface flow. Nitrogen concentration in seepage and surface flow is the annual average concentration in runoff estimated by OVERSEER. The wetland module calculates daily seepage flow (viz., shallow sub-surface flow) at the foot of the hillslope using Darcy's Law, and then estimates the proportion that enters the wetland. It estimates daily surface flow using an 'infiltration excess' model, and the proportion that enters the wetland using hillslope and convergence. A proportion of runoff by-passes the wetland either as groundwater or surface flow.

One of the most important variables in determining nitrogen removal by seepage wetlands is the proportion of seepage flow that enters the wetland, which OVERSEER estimates in two ways. Method 1 is used when data are available on aquitard depth and soil drainage characteristics (Table 4). Aquitards are soil layers of low permeability on the hillslope above the wetland that restrict drainage (e.g., iron pans, hard packed alluvial gravels and bedrock). Field observations indicate that seepage wetlands are abundant where there is a shallow aquitard. In the wetland module the proportion of seepage flow that by-passes wetlands in deep groundwater increases with aquitard depth. Method 2 uses the ratio of wetland area to effective catchment area (Table 5) and is the default method used when aquitard depth or soil drainage class are not known. The effective catchment area refers to that part of the catchment whose drainage all enters the wetland. Field survey data of seepage wetlands indicate that wetland area is correlated with wetland outflow while wetland inflow and outflow are strongly correlated. The wetland module has been programmed so that when the user increases the area of the wetland while holding the effective catchment area constant, OVERSEER increases the amount of water and nitrogen that flows into it. With Method 2 the user is not free to specify the area of the wetland independently of the amount of water and nitrogen flowing into it. The (small) proportion of total runoff that flows as surface runoff into a wetland is determined from soil properties and field estimates of convergence (Table 6).

OVERSEER assumes a spatially homogeneous rate of nitrogen removal from wetlands. The wetland cannot remove more than the uptake rate multiplied by the wetland area, or the mass inflow, whichever is smaller. Based on a review of New Zealand and overseas studies, Rutherford et al. (2007) estimated a maximum rate of 250 mg N m^{-2} d^{-1} for seepage wetlands which is the median value reported for constructed wetlands. McKergow & Hughes (2016) note that reported uptake rates are highly variable. In OVERSEER the maximum uptake rate applies only under ideal conditions and the actual uptake rate is determined by wetland Class and temperature. For a Class 1 (good condition), Type A (permanently wet) wetland the uptake rate is 90% of the maximum and as wetland condition declines the removal rate decreases (Table 2).

Table 1 Hillslope variables in the wetland module.

Catchment area [1]	User specified					
Wetland area [2]	User specified					
Variable	Choices available in 'drop down' menus					
Soil type [3]	Sedimentary	Volcanic	Pumice	Podzols	Sand	Peats
Soil depth	Deep	Shallow	Stony			
Hydrophobicity	Never	Occasionally	Frequently			
Aquitard depth	0-1 m	1-2 m	2-3 m	3-5 m	>5 m	
Drainage class	Well	Imperfect	Moderate	Poor	Very poor	
Convergence [4]	None	Little	Some	Moderate	High	

Notes

[1] Area of the catchment draining to the wetland (ha). [2] Area of the wetland (ha). [3] More detailed soils information can be entered. [4] Extent to which surface flow becomes channelized on the hillslope before flowing into the wetland.

Table 2 Wetland condition.

	Fencing	Vegetation & Stock	Surface flow	Channels	Factor
Class 1	Fenced	Well vegetated. No stock access	Evenly distributed	None	90%
Class 2	Unfenced	Lightly grazed by sheep only	Evenly distributed	No pugging	75%
Class 3	Unfenced	Lightly grazed by sheep or set stocked cattle	Minor pugging	No major channels	50%
Class 4	Unfenced	Accessible by cattle	Signs of pugging	Some channels	20%
Class 5	Unfenced	Inflowing water by-passes vegetation	Highly channelized	Deeply incised	10%

Table 3 Wetland type.

	Flow	Vegetation	Stock
Type A	Always flows	Sedge & reed. May contain flax & willow	Avoided by sheep. Easily damaged by cattle
Type B	Dry in droughts	Dominated by sedge & reed	Cattle pugging. Avoided by sheep
Type C	Dry in summer	Abundant sedge & reed, some pasture grass	Winter: cattle pugging. Summer: sheep grazing
Type D	Ephemeral	Dominated by pasture grass	Grazed by sheep except in winter

Table 4 Method 1: proportions of total runoff that flow into wetlands.

Aquitard depth	0-1 m	1-2 m	2-3 m	3-5 m	>5 m
Soil Drainage Class					
Well	0.1	0.05	0.03	0.01	0
Moderate	0.15	0.1	0.05	0.03	0.01
Imperfect	0.2	0.15	0.1	0.05	0.03
Poor	0.25	0.2	0.15	0.1	0.05
Very poor	0.3	0.25	0.2	0.15	0.1

Table 5 Method 2: proportions of total runoff that flow into wetlands.

	Type A	Type B	Type C	Type D
Wetland/catchment area				
0-1%	0.05	0.03	0.02	0.01
1-2%	0.15	0.1	0.03	0.02
2-4%	0.2	0.15	0.05	0.03
4-6%	0.25	0.2	0.1	0.05
>6%	0.3	0.25	0.15	0.1

Table 6 Proportion of surface flow that by-passes wetlands.

Convergence	
None	0
Some	0.15
Moderate	0.2
Poor	0.25
Highly	1

Rainfall

Figure 1 shows wetland nitrogen removal (as a percentage of hillslope loss) as a function of rainfall for two representative soil types. The proportion of seepage flowing into the wetland was estimated using Method 1 for an aquitard depth of 1-2m and moderately drained soils. OVERSEER predicts that Class 1 wetlands remove 10-12% of catchment N loss irrespective of rainfall. On average 10% of seepage, plus 5-10% of surface flow, enters the wetlands and they remove 40-60% of the inflowing nitrogen. Removal is as highest for Class 1 and lowest for Class 5 wetlands. As wetland condition deteriorates, not only does nitrogen removal decrease, but the effect of rainfall on nitrogen removal becomes more pronounced. Thus for Sedimentary soils, Class 5 wetlands remove 5% of catchment N loss in high rainfall regions, but 7% in low rainfall regions. Overall Rainfall has a minor impact on nitrogen removal in Class 1-2 wetlands, but Class 4-5 wetlands remove a smaller proportion of nitrogen loss in high rainfall regions than in low rainfall regions. Note that for a given farming enterprise nitrogen losses increase as rainfall increases, but in these simulations nitrogen losses were specified independently of rainfall.

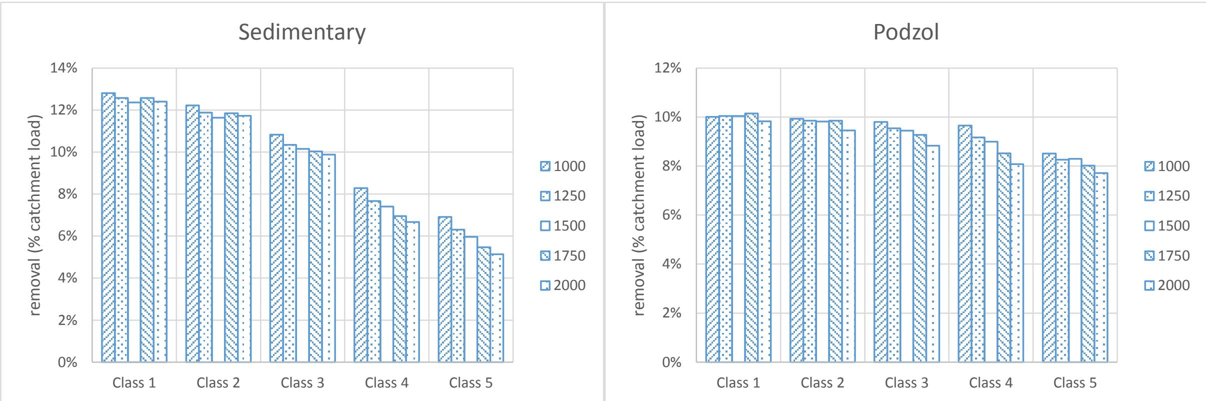

Figure 1. Effect of rainfall (mm yr^{-1}) on nitrogen removal (% of catchment load). Method 1. Soil Depth = Deep, Drainage Class = Moderate, Slope = Easy, Hydrophobicity = Never, Convergence = Some, Aquitard Depth = 1-2m, Catchment = 100 ha, Wetland = 5 ha, Loss = 50 kg ha^{-1} yr^{-1}.

Aquitard Depth and Soil Drainage Class

Where aquitard depth and soil type are both known, OVERSEER uses those data to estimate the proportion of seepage that flows into the wetland (Method 1, see Table 4). Figure shows that nitrogen removal decreases with aquitard depth. The reason is that the deeper the aquitard, the larger the proportion of runoff that by-passes the wetland and hence the smaller the proportion of catchment nitrogen loss that flows into the wetland. For aquitard depths >5 m on well drained soils, all shallow groundwater by-passes the wetland, the only inflow is surface flow, and nitrogen removal is low. As soil drainage class decreases, wetland removal increases. The reason is that a greater proportion of catchment runoff and nitrogen loss enters wetlands where soils are poorly drained.

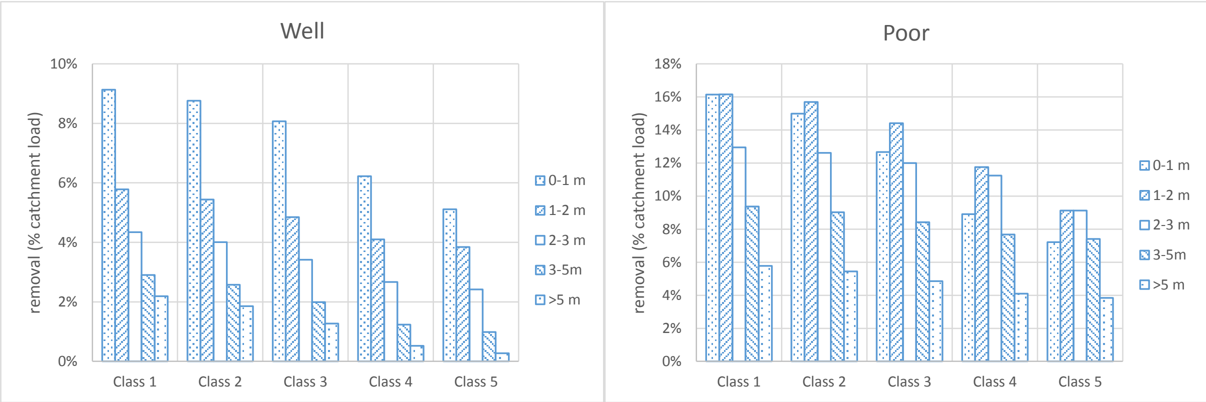

Figure 2. Effect of aquitard depth and drainage class on nitrogen removal for sedimentary soils. Rainfall = 1500 mm yr^{-1}, PET = 725 mm yr^{-1}, Soil Depth = Deep, Slope = Easy, Hydrophobicity = Never, Convergence = None, Catchment = 100 ha, Wetland = 5 ha, Loss = 50 kg ha^{-1} yr^{-1}.

Wetland and Catchment Area

Where aquitard depth is not known, OVERSEER estimates the proportion of seepage flowing into the wetland from wetland/catchment area ratio and wetland type (Method 2, Table 5). The underlying paradigm is that in catchments where soils are deep and well drained, natural seepage wetlands tend to be small, whereas in catchments where soils are shallow and poorly drained they tend to be more numerous and larger. Figure 3 shows that as wetland area increases, the proportion of catchment nitrogen loss removed increases – as would be expected. Nitrogen removal is highest for Type A, and lowest for Type D wetlands of the same Class because a greater proportion of catchment runoff flows into Type A wetlands.

Large wetlands remove a higher proportion of the nitrogen that enters them than small wetlands. In OVERSEER the nitrogen removal rate per unit area is constant for a given Class. If wetland area multiplied by areal removal rate exceeds the nitrogen inflow, then all the inflowing nitrogen is removed and this is more likely in a large wetland than a small one. In OVERSEER the default method for estimating the proportion of catchment nitrogen loss that flows into a wetland is Method 2, which bases the estimation of inflow on the wetland/catchment area ratio and wetland Type. Thus the proportion of catchment runoff and nitrogen loss that flows into the wetland increases with wetland size. This might be expected to reduce the percentage nitrogen inflow removal. However, the increase in area more than outweighs the increase in flow, and removal increases with wetland area.

Condition Factor

Class 1 wetlands are effective in removing nitrogen, and even small Class 1 wetlands remove most of the nitrogen that enters them (Figure 4). However, small wetlands intercept a small proportion of total catchment runoff and hence total nitrogen loss. Nevertheless, if there are numerous small wetlands in good condition within the catchment, then nitrogen losses can be significantly reduced. Wetlands in poor condition (notably Classes 4 and 5) remove a small proportion of the nitrogen that enters them. This is usually because channelization allows water to flow through the wetland quickly without prolonged contact between runoff and the organic-rich wetland soils where denitrification occurs.

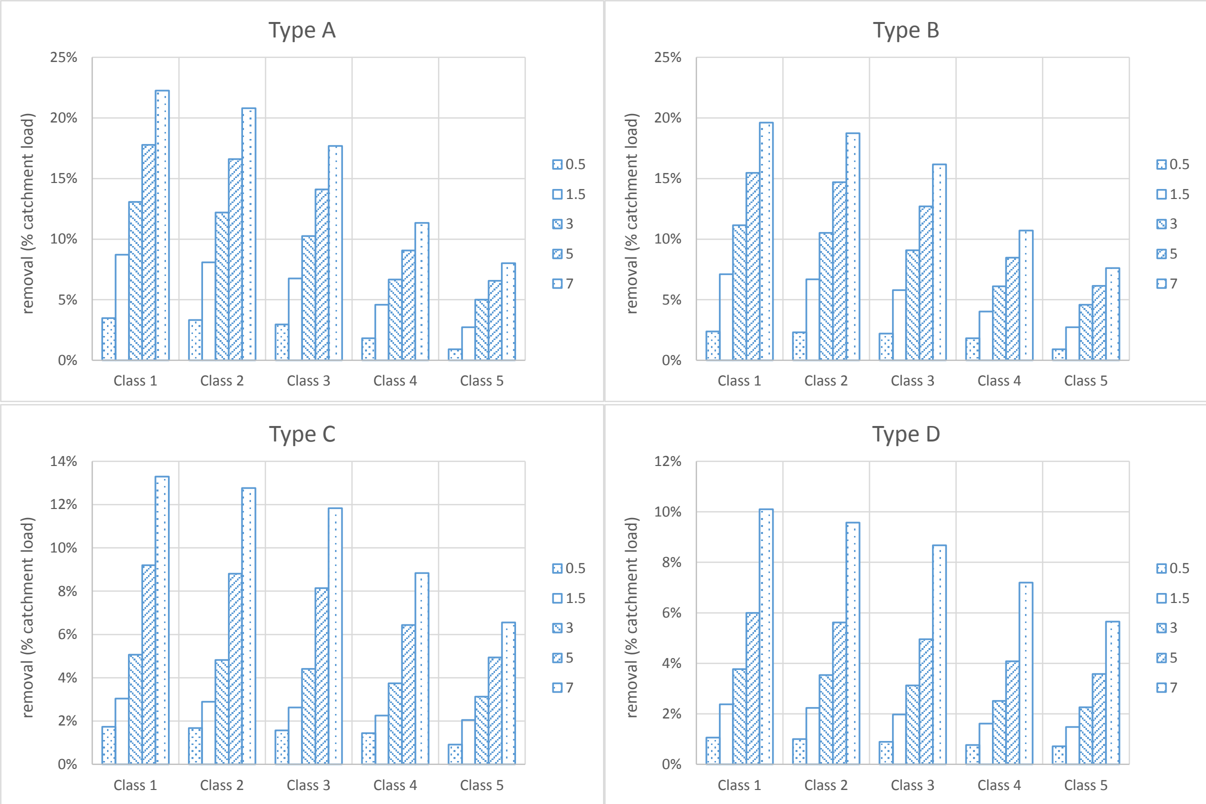

Figure 3. Effect of wetland area and type on nitrogen removal for volcanic soils. Wetland area = 0.5-7 ha, Catchment area = 100 ha, Rainfall = 1500 mm yr^{-1}, PET = 725 mm yr^{-1}, Soil Depth = Deep, Slope = Easy, Hydrophobicity = Never, Convergence = None, Loss = 50 kg ha^{-1} yr^{-1}.

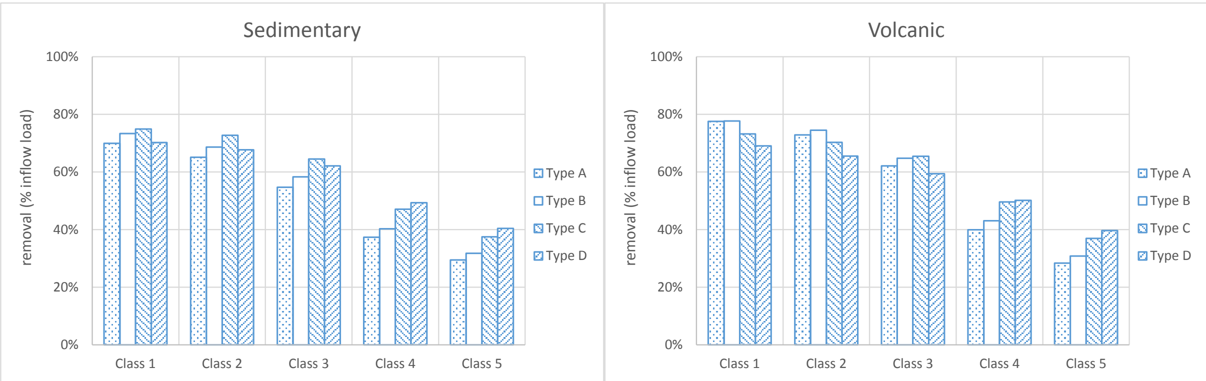

Figure 4. Effect of wetland condition and type on nitrogen removal. Note the y axis shows the percentage of inflowing nitrogen removed, not the percentage of catchment losses. Rainfall = 1500 mm yr^{-1}, PET = 725 mm yr^{-1}, Slope = Easy, Hydrophobicity = Never, Convergence = None. Aquitard depth, Drainage Class and Soil Depth have no effect on removal.

Convergence

The convergence factor is the proportion of surface flow from the catchment that by-passes the wetland. The convergence factor has no effect on the amount of seepage flow that enters the wetland. For the majority of New Zealand soils, surface flow occurs on only a few days per year and is responsible for transporting only a small proportion of runoff (typically 5-10%). In OVERSEER the average nitrogen concentration in seepage and surface flow is the same – the total nitrogen loss (kg ha^{-1} yr^{-1}) divided by the total runoff (seepage + surface flow) (mm yr^{-1}). As by-pass increases (viz., convergence decreases) removal decreases, as would be expected (Figure 5). There is only a slight decrease as convergence varies from None to Moderate, but where convergence is classified as High, removal is markedly reduced.

Soil Type

Soil type affects drainage, the proportion of runoff that enters the wetland, and hence the proportion of catchment nitrogen loss removed. Using Method 1 to estimate inflow, for an aquitard depth of 1-2 m a Class 1 wetland removes 9-13% of catchment losses depending on soil type. Using Method 2 to estimate inflow, a Class 1 wetland removes 18-24% of catchment losses depending on soil type. The effect of soil type is smaller than the effect of condition, aquitard depth and wetland/catchment area, is comparable with the effect of convergence, and is larger than the effect of hydrophobicity.

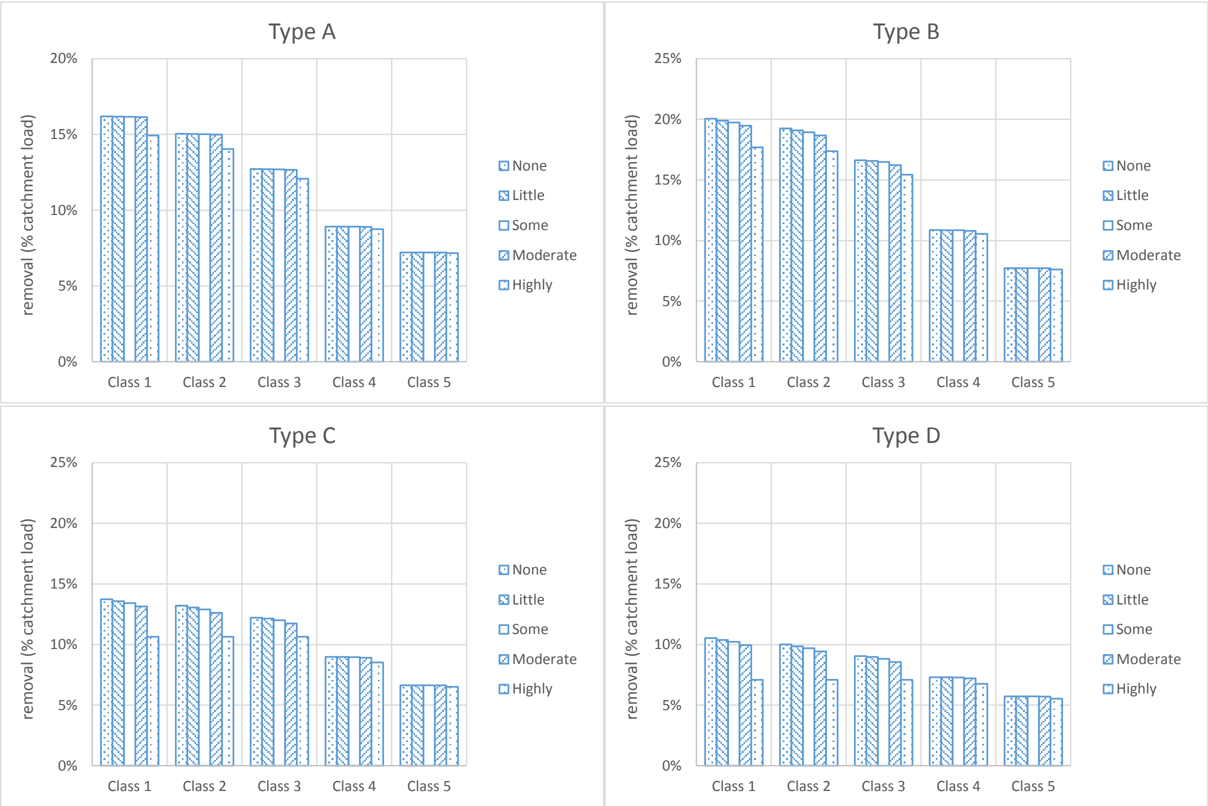

Figure 5. Effect of convergence on nitrogen removal. Soil Group = Volcanic, Soil Depth = Deep, Drainage Class = Well, Rainfall = 1500 mm yr^{-1}, PET = 725 mm yr^{-1}, Slope = Easy, Hydrophobic = Never, Catchment = 100 ha, Wetland = 5 ha, Loss = 50 kg ha^{-1} yr^{-1}.

Slope

As slope increases, the velocity of seepage flow in soils upslope from the wetland increases. Consequently, seepage flow into the wetland increases, a greater proportion of catchment nitrogen loss enters the wetland, and wetland removal increases. The only exceptions occur when nitrogen inflow exceeds the capacity of the wetland to remove nitrogen (as in small, Type D wetlands). On flat land, there is little surface flow and convergence has negligible effect on nitrogen removal. On steep land, removal decreases with increasing convergence, as would be expected. This counteracts the increase in seepage flow arising from the increase in slope. Thus removal rates are similar where land is flat and where land is steep but convergence is high.

Soil Depth

Aquitard depth (viz., the depth of the low permeability layer (if any) in the soils upslope from the wetland) strongly influences the proportion of runoff that enters the wetland via seepage flow. Soil depth is specified separately from aquitard depth. Soil depth affects the moisture content of soils and hence seepage rates, but has negligible effect on wetland nitrogen removal.

Drainage Class

Drainage class is used, together with aquitard depth, in Method 1 to estimate the proportion of seepage flow that by-passes the wetland. It has no effect on nitrogen removal when Method 2 is used. For a given aquitard depth, increasing soil drainage increases the proportion of seepage flow that by-passes the wetland, and hence decreases nitrogen removal (Figure 6).

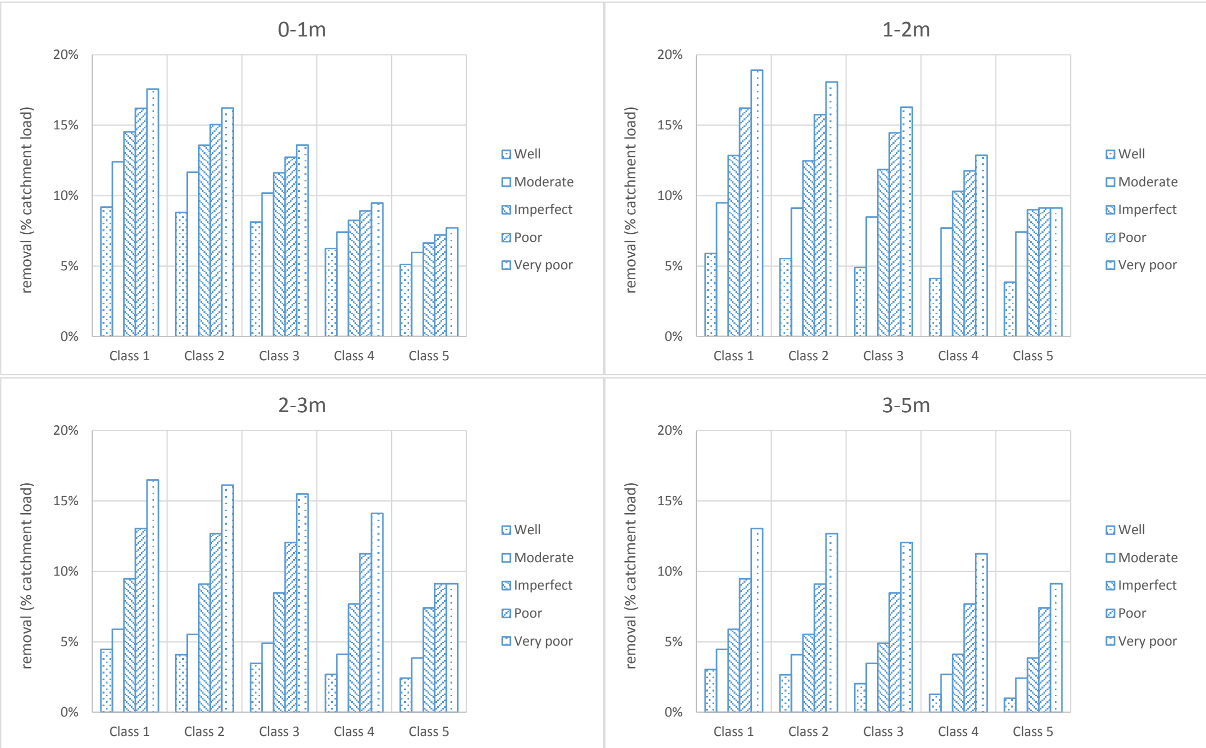

Figure 6. Effect of drainage class and aquitard depth on nitrogen removal estimated using Method 1. Rainfall = 1500 mm yr^{-1}, PET = 725 mm yr^{-1}, Soil Type = Sedimentary, Slope = Easy, Hydrophobicity = Never, Catchment = 100 ha, Wetland = 5 ha, Loss = 50 kg ha^{-1} yr^{-1}.

Nitrogen Loss

The amount of nitrogen removed per day by a wetland is the maximum removal rate x wetland area x condition factor, with an adjustment for temperature. As catchment nitrogen loss increases, all else staying the same, the amount of nitrogen that flows into the wetland increases. Eventually the wetland reaches its capacity for removal. For the Class 5 wetland in Figure 7, this occurs when catchment loss is 100 kg ha^{-1} yr^{-1}. Note the sudden increase in slope of the line for the Class 5 wetland in the left hand figure at a loss of 100 kg ha^{-1} yr^{-1}. The loss from the catchment at this point is 10 t yr^{-1}, the inflow to the wetland is 5.7 t yr^{-1}, the capacity of the wetland is 0.46 t yr^{-1}, and the wetland removes 4.6% of the catchment loss. The Class 4 wetland approaches its capacity when the catchment loss is 200 kg ha^{-1} yr^{-1} but the Class 1-3 wetlands receives less nitrogen than their capacity for removal.

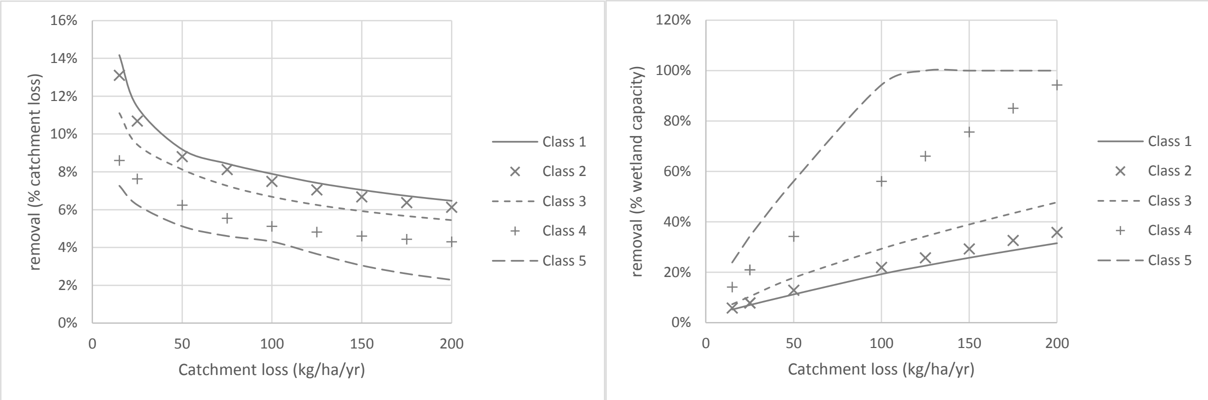

Figure 7. Effect of catchment nitrogen loss on wetland removal. Left: removal as a %age of catchment loss. Right: removal as a %age of wetland capacity. Rainfall = 1500 mm yr^{-1}, PET = 72 mm yr^{-1}5, Soil Type = Sedimentary, Slope = Easy, Hydrophobicity = Never, Catchment = 100 ha, Wetland = 5 ha, Soil Depth = Deep, Aquitard Depth = 0-1m, Drainage Class = Well.

Discussion

Rutherford et al. (2007) reviewed wetland uptake rates and found a very wide range. New Zealand studies reported nitrate removal rates of 5-120 mg N m^{-2} d^{-1} from tracer studies (where mixtures of nitrate and inert bromide were injected, and nitrate removal estimated from the change in nitrate/bromide ratio) and 950-8100 mg N m^{-2} d^{-1} from *in situ* denitrification measurements (where denitrification is measured directly). There is an order of magnitude difference between removal rates measured by these two different techniques. One possible explanation is that there are 'hot spots' in wetlands associated with locally high carbon sources (e.g., buried vegetation). If the *in situ* denitrification measurements were made on soil samples from such 'hot spots', this may explain the very high removal rates. The injected tracers would have come into contact with a range of conditions in the wetland which may include both 'hot spots' of high activity and 'cold spots' of low activity. McKergow and Hughes (2016) state '…Mature constructed wetland removal rates vary with season and hydraulic loading, but systems have average areal nitrate removal rates in the order of 230-280 mg m^{-2} d^{-1}. This rate is higher than the rates inferred from tracer experiments at seepage wetlands, which range from 5-120 mg m^{-2} d^{-1}. The range of likely areal removal rates is therefore wide, and can be expected to vary with season and loading….' OVERSEER assumes a maximum removal rate of 250 mg N m^{-2} d^{-1}. This rate applies only to Class 1 (good condition), Type A (permanently wet) wetlands. As wetland condition degrades (Class 2 to Class 5) and as Type changes (Type B to Type D) the removal rate decreases. There is a requirement to better understand and quantify areal removal rates in seepage wetlands. Nevertheless, the wetland module within OVERSEER enables comparison of the effectiveness of different types and conditions of wetlands for nitrogen removal, and semi-quantitative assessment of nitrogen removal. Nitrogen removal is most sensitive to four parameters: wetland area, by-pass flow, wetland condition and flow convergence. Five other parameters have a minor effect on removal: soil type, rainfall, slope, hydrophobicity and soil depth.

Acknowledgements

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