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ASSESSING IF WOODCHIP DENITRIFICATION WALLS ARE A VIABLE EDGE OF FIELD NITRATE MITIGATION PRACTICE IN GRAVEL AQUIFER SETTINGS

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Abstract

Woodchip denitrification walls are an *in situ* groundwater nitrate remediation concept that has been successfully demonstrated for shallow sandy aquifer systems. Some of the earliest experimentation was conducted here in New Zealand (NZ), in the Waikato region (e.g. Schipper and Vojvodić-Vuković, 1998). We perceive woodchip denitrification walls to be a potentially useful edge-of-field nitrate-mitigation practice for addressing the challenge of farming within catchment nutrient limits.

Aquifers composed of outwash gravels represent the most common and important groundwater systems in NZ, particularly on the South Island where there are plentiful examples of them having exceeded their capacity to naturally assimilate nitrate leached from intensive land-use. There are no published cases of woodchip denitrification walls ever having been emplaced in gravel aquifer systems. To address this limitation and assess whether woodchip walls are a viable edge-of-field N-mitigation practice, we are undertaking a pilot study of a woodchip denitrification wall applied in a shallow gravel aquifer setting.

The experimental woodchip denitrification wall at Silverstream Reserve, North Canterbury, measures 25 m long x 5 m wide and was built in November 2018. It is entrenched through highly permeable gravel outwash, deposited by the Waimakariri River. Being 3 m deep, it penetrates about 2.5 m below the water table. We estimate that somewhere between 179 and 195 m^3 of groundwater flows through the wall each day, under the natural hydraulic gradient of 0.002. This flux is significantly more than any reported for other woodchip wall studies, hence our wall is ageing faster than other examples and rapid depletion of reactive organic carbon is evident in the time-series water chemistry data we have been collecting. Over its first year, the wall has demonstrated effective nitrate removal of between 93 and 100%, for influent concentrations that have ranged from 7.1 to 8.8 mg NO_3-N/L. It is too early to make reliable predictions of the longevity of the denitrification wall, yet our initial calculations made using findings from our field study tend to suggest that within the suite of known N-mitigation practices, woodchip denitrification walls rank as a relatively cost-effective mitigation option.

Introduction

Woodchip denitrification walls are an *in situ* groundwater nitrate remediation concept that has been successfully demonstrated for shallow sandy aquifer systems (e.g. Robertson and Cherry, 1995; Schipper and Vojvodić-Vuković, 1998; Jaynes et al., 2008; Vallino and Foreman, 2008; Schmidt and Clark 2012). There are no existing examples however of woodchip denitrification walls having been trialled in gravel aquifers, such as constitute the most common and important groundwater systems in NZ (Rosen and White, 2001; White et al., 2004). To address this limitation and assess whether woodchip walls are a viable edge-of-field N-mitigation practice that might be applied to the challenge of farming within catchment nutrient limits, we are undertaking a pilot study of a woodchip denitrification wall applied in a shallow gravel aquifer setting.

Methods

Environmental Setting

In November 2018, an experimental woodchip denitrification wall was constructed at the 3.5 ha Silverstream Reserve, Clarkville, North Canterbury (43.4122°S,172.6016°E). As recently as 1867 the site was an active part of the North Branch Waimakariri River. Consequently, surficial deposits at the site comprise alluvial gravel outwash and form a shallow unconfined aquifer of approximate 5 m thickness. The base of the shallow aquifer is marked by a layer of silt belonging to the Christchurch geological formation.

The water table at the site typically rests within 0.5 m of ground level and has a hydraulic gradient of 0.002. Whilst the hydraulic gradient at the site is effectively constant, the water table demonstrates fluctuations of +/-0.2 m, as a response to aquifer recharge events. Based on the results of a constant rate aquifer test made at the site in October 2018, we estimate the outwash gravel deposits to have an effective hydraulic conductivity of approximately 1,332 m/d. Background groundwater nitrate concentrations at the site have been measured between the range of 5 and 9 mg NO_3-N/L, or more precisely, 7.1 to 8.8 mg NO_3-N/L in the immediate vicinity of where the woodchip wall is positioned. This is consistent with the concentrations that Canterbury Regional Council typically detect in the nearby Silverstream, which is sourced entirely from groundwater (Dodson et al., 2012).

Denitrification Wall Specifications

The woodchip wall was constructed by entrenching a mixture of coarse woodchip processed from *Pinus radiata* and gravel larger than 20 mm nominal diameter, 3 m into the top of the unconfined aquifer. The ratio of wood/gravel was 50/50, as per the recommendations of Burbery et al. (2014). The wall is oriented perpendicular to the local groundwater flow direction and measures 25 long and 5 m wide. To mitigate disturbance of the aquifer structure that might otherwise compromise its hydraulic function, steel sheet-piles were used as a trench-stabilisation measure, during the construction phase. Sheet-piles were toed into the top of the silt aquitard, such that effective dewatering of the open excavation was possible. This allowed the wall media to be deposited under dry conditions, and uniform mixing of the wood and gravel components. Barkle et al. (2008) showed this to be the best method by which to emplace denitrification wall fill.

Representative samples of the wall media were tested in large-scale permeameters following the methods described by Burbery et al. (2014). Results from these tests showed the wall media to have a hydraulic conductivity in the range 20,000 to 30,000 m/d. Accordingly, the woodchip denitrification wall is much more permeable than the aquifer sediments into which it is entrenched.

Results

Mass Fluxes and Nitrate Removal Efficiency

For a 1-D flow problem, the specific discharge q through a unit section of aquifer is calculated from Darcy' Law:

$$q = K\frac{dh}{dL} \qquad (1)$$

Where K is the hydraulic conductivity and dh/dL is the hydraulic gradient. At Silverstream Reserve, we estimate q = 2.7 m/d. When scaled up over the saturated cross-sectional area the woodchip wall (58 - 64 m^2) has covered over its first year of operation, we calculate the volumetric flux to have been in the order of 155 - 169 m^3/d. It is worthy to note that when we substituted the wall into a 3-D numerical MODFLOW model we originally calibrated to the constant rate aquifer test data from the site, we found from conducting a flow budget that the highly permeable wall induces 15% more flow. Correcting for such enhanced flow effects, we assume it is more likely that between November 2018 and November 2019, the wall filtered somewhere between 179 and 195 m^3 of groundwater per day. This implies the mean hydraulic residence time of groundwater in the wall was likely 41 - 49 hours.

Since October 2018, a comprehensive suite of groundwater chemistry parameters has been routinely monitored in a set of three piezometers, positioned: 5 m up-gradient; within, and 5 m down-gradient, of the woodchip wall. Figure 1 plots the results for dissolved oxygen, nitrate and dissolved organic carbon for the first year of the walls operation. Influent concentrations of nitrate to the wall have exhibited a small increasing trend, and ranged from 7.1 to 8.8 mg NO_3-N/L. From the difference in the nitrate concentration measured in the up-gradient and down-gradient well, we calculate the nitrate removal efficiency of the woodchip wall was 100% for the first 39 weeks of its operation, declining to 93% by the end of year 1.

Over the course of its first year, we estimate the woodchip denitrification wall at Silverstream has removed between 458 – 575 kg nitrogen (average 501 kg N/yr). Assessed on a monthly basis, we determine the nitrate removal rate to have varied between 4.2 - 5.4 g N/m^3 wall/day, and so far to have displayed no significant temporal trend.

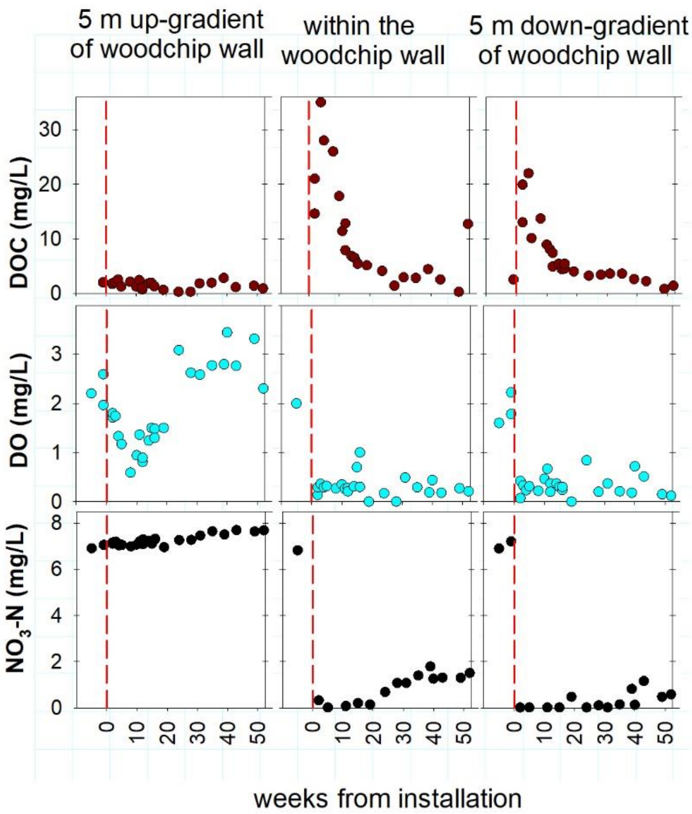

Figure 1: Time-series for water chemistry parameters: dissolved organic carbon (DOC), dissolved oxygen (DO) and nitrate, measured in groundwater up-gradient; within, and down-gradient of the woodchip wall. Hatched line marks the time of woodchip wall installation.

Nitrate-Removal Cost

It is normal practice for N-mitigation practices to be cost accounted assuming a 20-year operational life (pers. comm. Richard McDowell, AgResearch, March 2020). Being the first recorded example of a woodchip denitrification wall ever being installed in a fast-flowing gravel aquifer however, the nitrate treatment system at Silverstream has no precedent from which a reliable prediction of its longevity can be obtained. Furthermore, performance indicators (e.g. Figure 1) have displayed no obvious trend that would allow for extrapolation into the future. As a comparison, and to illustrate the quandary, the pioneering experimental woodchip wall built in 1996 at Blairdowie Farm, Cambridge, Waikato region (Schipper and Vojvodić-Vuković, 1998) has long served as a reference by which woodchip denitrification walls are judged. It has provided evidence for the general prognosis that woodchip walls can provide effective nitrate removal for 30-years or so (e.g. Schipper et al., 2010). For that case study however, the specific discharge at the field site is 0.22 m/d (Schipper et al., 2005), i.e. just 8% of the groundwater flows experienced at Silverstream Reserve. Considering the scale of water flows, we estimate that in the course of just one year, the woodchip wall at Silverstream has filtered as much water as it took the woodchip wall at Blairdowie Farm to filter over 12 years. For this reason, we presume the woodchip wall at Silverstream will age significantly faster than any pre-existing denitrification wall examples. How it ages however, and for how long it might continue to provide effective nitrate removal, is anybody's guess. Assessing the longevity of the woodchip wall is a long-term objective of our study. At this stage, rather than speculate on the wall's lifetime, for the purpose of gauging an initial estimate of the nitrate removal cost, we make a very conservative assumption and perform calculations on what it has cost to date, i.e. assume one-year operation life.

An advantage of denitrification walls is that once built, they require no on-going maintenance, other than any compliance monitoring that might be required. When a woodchip wall does reach the end of its operational life, the cost-effective solution is to write off the old one and construct a new one. Equally, being an edge-of-field N-mitigation measure and buried beneath the ground, they can be installed in manner that does not take out any productive land and so they incur no opportunity cost.

Construction of the experimental woodchip denitrification wall at Silverstream took 4 days, and cost approximately $200,000, for materials, labour and other project management expenses. At $100,000, sheet-piling accounted for 50% of the build-cost. In Canterbury region, excavation below the water table and burial of organic matter in to an aquifer are restricted activities that require resource consent which cost us $8,500 to obtain. Whilst considerable expense was spent investigating ground conditions at the Silverstream site prior to installation of the woodchip wall, this was done for the purpose of conducting rigorous scientific study rather than out of strict necessity. For costing model purposes, we assume water monitoring at three observation wells. A breakdown of costs is provided in Table 1.

For now, we estimate the N-removal cost for the experimental woodchip denitrification at Silverstream to so far have cost in the order of $357 – $448 per kilogram of nitrogen removed. Assuming land surface recharge at Clarkville to be approximately 200 mm/year (i.e. ~30% of annual rainfall), we infer that the groundwater intercepted by the woodchip was sourced over a recharge area in the region of 36 - 39 ha. When scaled against the effective land drainage area the woodchip wall intercepts, we estimate the cost so far to be in the region of \$9.03 - \$12.28 /kg N removed/ha/year.

Table 1: Breakdown of cost for construction and operation of 350 m^3 woodchip denitrification wall at Silverstream Reserve for first year.

	NZ\$ (excl. GST)
Capital cost	
Construction costs:	
175 m^3 woodchip	17,000
175 m^3 aggregate/screening	13,500
Sheet-piling (incl. trench excavation)	100,000
Other civil works costs (e.g. tipper; dewatering; project management)	55,000
Compliance costs:	
Resource consents (2 of)	8,800
Monitoring well infrastructure (assumes install 3 wells)	5,000
	199,300
Depreciation	**n/a**
Opportunity cost	**nil**
Maintenance cost	
Water quality monitoring	6,000
	6,000
TOTAL cost for first year	**205,300**

Discussion

Fast-flowing alluvial gravel aquifer settings represent a challenging environment in which to emplace a woodchip denitrification wall, due to the complexity of aquifer heterogeneity and risk of preferential flow effects, and civil engineering problems of excavating below the water table, combined with high mass fluxes of water, dissolved oxygen and nitrate - the effects of which conceivably promote rapid degradation of the organic woodchip. In our pilot study, to mitigate disturbing the aquifer architecture and risk jeopardising the hydraulic function of the shallow groundwater system, we employed sheet-piling as a trench-stabilisation measure during the construction phase of the woodchip wall. Indications are that this worked effectively, since piezometric contours converge about the wall, suggesting enhanced flow through the highly permeable woodchip.

A disadvantage of using sheet-piling methods however is the significant cost it adds to constructing a denitrification wall. Nonetheless, there are records of irrigation galleries being dug below the water table in gravel aquifers across NZ, without need for trench-stabilisation. This would suggest there are situations where such expensive civil engineering practices might not be necessary. As an on-going part of our viability study, we are exploring alternative, more cost-effective ways of burying woodchip below the water table to achieve similar results.

The mass fluxes of water, nitrate and dissolved oxygen in the shallow groundwater system at Silverstream exceed fluxes reported for any previous denitrification wall case study. Rapid depletion of reactive organic carbon is evident in the time-series water chemistry data we collected. Within just 28 weeks, DOC concentrations in pore water sampled from within the woodchip wall reduced to levels insignificantly different from baseline conditions. At the same time, measurable quantities of nitrate were detected in the pore water sampled from within wall, signifying some loss in its capacity to reduce nitrate. Whilst the internal capacity of the woodchip wall to drive denitrification may appear to have declined a bit, results suggest much of the residual nitrate is removed by reactions occurring immediately down-stream of the wall. We report a gradual decline in nitrate removal efficiency from 100% to 93%, although this result is confounded by the trending increase in background (influent) groundwater nitrate concentrations. From what we can deduce, nitrate reaction rates have not demonstrated any significant decline over the 12 months the wall has so far been operational. The rates computed of 4.2 - 5.4 g N/m^3 wall/day rank towards the top end of reaction rates (0.6 – 12.7 g N/m^3 wall/day) Schipper et al. (2010) collated for woodchip denitrification walls. We suspect the favourable reaction rates at Silverstream are likely to be biased by the young age of the woodchip wall. With time we anticipate nitrate reactivity will decline.

Even without corrections for inflation, it is clear the cost of N-removal (NZ$357 – NZ$449 kg/N) we have so far calculated for the woodchip denitrification wall at Silverstream, are significantly more than costs Schipper et al. (2010) reported for other woodchip denitrifying bioreactor systems. These were in the order of US$2.39 – 15. 17 kg/N (i.e. ~ NZ$3.78 – 24.0 kg/N). The principle reason for the exuberant cost we report, is because it represents the cost for the first year of operation, not spread over the lifetime of the woodchip denitrification wall (that Schipper et al. (2010) assumed was 20 years). Whilst we are reluctant to make such forecasts at such an early stage of our viability assessment, for the reasons explained above, should it prove the wall remains as effective at removing nitrate as it is now, for another 19 years, then the N-removal cost has potential to reduce to NZ$18-NZ$22 kg/N removed, which is closer to values reported by Schipper et al. (2010).

It may be helpful to note that being an experimental pilot study, little expense was spared on installation of the woodchip denitrification wall at Silverstream Reserve, as is reflected in the high project management costs we assigned to the construction. Besides the project management aspect of the woodchip wall installation, we foresee other areas where cost/effectiveness might be gained. For example, in cases where a woodchip denitrification wall is strategically placed to target nitrate remediation at a specific nitrate hot-spot (e.g. down-gradient of a stand-off, land-based effluent treatment), where there is opportunity to intercept higher N-loads. Capital cost savings could be made if a free-feed of woodchip and aggregate materials were available, for example if a land-owner sourced their own timber (e.g. from an old shelter-belt) and screened gravel excavated from the aquifer, on site. The most significant cost saving however is to be made if the need for expensive sheet-piling could be averted.

In their assessment of strategies to mitigate the loss if contaminants from agricultural land to freshwaters, McDowell et al. (2013) argue evaluation of cost-effectiveness on the basis of $ per kg of N removed is problematic and therefore they reported costs on an areal basis. In their report they ranked denitrification beds (which includes denitrification walls) as the most effective N-mitigation option, but also the most expensive cost option. From the handful of denitrification bed case-studies available to review, they determined the cost of N-removal to be in excess of $270 kg N retained/ha/yr, suggesting denitrification beds to cost almost double a constructed wetland option. The findings from our denitrification wall pilot in a gravel aquifer setting provides evidence that as a farm-scale N-mitigation strategy, denitrification walls can be more cost-effective than has previously been considered. At \$9.03 - \$12.38 /kg N removed/ha/year, even our conservative evaluation of the N-removal cost offered by the woodchip wall at Silverstream over one year makes it a very-effective, relatively low-cost N-mitigation option for the farm-scale. The reason why the woodchip denitrification wall at Silverstream is markedly more cost-effective than previous denitrification bed examples McDowell et al, (2013) referenced, is because of the massive water flux that can be treated in fast-flowing gravel aquifer systems in combination with the large effective land area from which drainage can be intercepted. Reasons why they can be a significantly more cost-effective N-mitigation option than constructed wetlands include denitrification walls being low maintenance, and no opportunity costs are incurred from loss of productive land.

Conclusions

An experimental woodchip denitrification wall installed in the shallow gravel aquifer at Silverstream Reserve, North Canterbury is proving effective at removing nitrate. Nitrate removal efficiencies of between 93 and 100% have been recorded over its first year of operation. Mass fluxes of water, nitrate and dissolved oxygen through the wall are significantly higher than those reported for any pre-existing woodchip denitrification wall test site world-wide. Whilst it is too early to make reliable predictions of the longevity of the denitrification wall at Silverstream Reserve, initial calculations made using findings from the field study tend to suggest that within the suite of known N-mitigation practices, woodchip denitrification walls rank as a relatively cost-effective mitigation option.

References:

Barkle, G.F., Schipper, L.A., Burgess, C.P., Milne, J., Painter, B.D. (2008). In situ mixing of organic matter decreases conductivity of denitrification walls in and aquifers. Ground Water Monitoring and Remediation 28, 57–64.

Burbery L.F., Abraham P., Afrit B. (2014). Determining the Hydraulic Properties of Wood/Gravel Mixtures for Use in Denitrifying Walls. *Journal of Hydrology New Zealand* 53 (1): 1-21.

Dodson, M., Aitchison-Earl, P., Scott, L. (2012). Ashley-Waimakariri groundwater resources investigation. Environment Canterbury Report No. R12/69, June 2012.

Jaynes, D.B., Kaspar, T.C., Moorman, T.B., Parkin, T.B. (2008). In situ bioreactors and deep drain-pipe installation to reduce nitrate losses in artificially drained fields. Journal of Environmental Quality 37, 429–436.

McDowell, R.W., Wilcock, B., Hamilton, D.P (2013). Assessment of Strategies to Mitigate the Impact or Loss of Contaminants from Agricultural Land to Fresh Waters. Report RE500/2013/066 prepared for MfE, June 2013.

Robertson W.D. and Cherry J.A. (1995). In Situ Denitrification of Septic-System Nitrate Using Reactive Porous Media Barriers: Field Trials. Groundwater 33 (1): 99-111.

Rosen, M.R. and White, P.A. (*eds.*) 2001: Groundwaters of New Zealand. New Zealand Hydrological Society.

Schmidt C.A. and Clark M.W. (2012). Efficacy of a denitrification wall to treat continuously high nitrate. Ecological Engineering 41 (3): 724-731. DI 10.2134/jeq2011.0331

Schipper, L. and Vojvodić-Vuković, M. (1998). Nitrate removal from ground water using a denitrification wall amended with sawdust: field trial. J. Environ. Qual. 27, 664–668.

Schipper, L. A., Barkle, G. F., Vojvodić-Vuković, M. (2005). Maximum Rates of Nitrate Removal in a Denitrification Wall. J. Environ. Qual. 34:1270-1276. doi:10.2134/jeq2005.0008

Schipper L.A., Robertson W.D., Gold A.J., Jaynes D.B., Cameron S.C. (2010). Denitrifying Bioreactors – An Approach for Reducing Nitrate Loads to Receiving Waters. Ecological Engineering 36 (11): 1532-1543.

Vallino J. and Foreman K. (2008). Effectiveness of Reactive Barriers for Reducing N-Loading to the Coastal Zone: a Final Report Submitted to The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET).

White, P.A., Sharp, B.M.H., Reeves, R.R. (2004). New Zealand water bodies of national importance for domestic use and industrial use. GNS Science Report 2004/12, prepared for the Ministry of Economic Development. 78 pages.