The 'Nitrate Catcher'

Design and installation of a bioreactor to monitor nitrate-N removal from drainage water

Prepared for DairyNZ and Living Water DoC-Fonterra Partnership

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Executive summary

A field-scale denitrification bioreactor 'Nitrate Catcher' was designed and constructed on a farm in the upper Waituna Catchment in Southland. It will be used to treat subsurface tile drainage from a ~9 ha dairy farm sub catchment to demonstrate the concept and monitor nitrate-N removal performance. This is the first full scale bioreactor trial on a pastoral farm in New Zealand.

The 'Nitrate Catcher' is a 1 m deep square (10 x 10 m) lined pit, filled with woodchips. Woodchips are added to the pit and water level controlled to promote saturated conditions suitable for microbial denitrification. Construction and installation of monitoring equipment was undertaken between 17 February and 20 March 2015.

The 'Nitrate Catcher' is instrumented to measure inflowing and outflowing nitrate concentrations and loads. Water levels are measured at v-notch weirs in the inlet and outlet boxes and converted to flow using a stage-discharge rating curve. Water quality monitoring includes continuous measurement of water temperature, electrical conductivity and turbidity supplemented with grab and flow proportional samples collected by automatic samplers.

Factors that must be considered when designing a filter, and steps that must be taken prior to and during construction are identified. Indicative prices for a 'Nitrate Catcher' installation are provided.

Construction was closely followed by an official opening on 23 March 2015 as part of a well-attended joint Environment Southland, DairyNZ, Living Water (DoC-Fonterra) Field Day, where the role of this project in the Living Water Programme was outlined.

1 Introduction

Excess inputs of nitrogen (N) and phosphorus (P) into waterways are undesirable because of proliferation of nuisance plants and periphyton in streams and eutrophication of downstream lakes and estuaries. The NPSFM has clearly signalled that water quality is to be managed to achieve certain values. To make this possible, inputs of nutrient from various land uses need to be managed. Various on-farm tools are available to reduce the N and P in water leaving paddocks and entering streams, including constructed and natural wetlands, riparian buffers, or addition of reactive materials (McKergow et al. 2008).

While the science behind many attenuation tools is reasonably well understood, their performance at the field-scale is less so. Farmers require greater certainty regarding the efficacy and cost-effectiveness of different mitigation options, before they will adopt new strategies for reducing contaminant losses. Field trials are required under conditions relevant to New Zealand pastoral farming to verify performance, refine design, demonstrate applicability and provide realistic information regarding construction and maintenance costs.

On-going research in the Waituna catchment aims to provide cost-effective and practical solutions for farmers to enable them to reduce their environmental footprint and contribute towards the long-term management of the Waituna Lagoon. A scientific workshop led by DairyNZ and attended by 14 scientists from NIWA, AgResearch, DoC, Environment Southland and DairyNZ in October 2013 identified denitrification and phosphorus sorption filters as having significant potential to reduce nutrient loading to Waituna Lagoon, alongside other on-farm nutrient management tools. Tile drains are an important feature of Southland's agricultural landscape, providing drainage essential for pasture production. Improved drainage also accelerates the transport of nutrients off-farm, particularly nitrate-nitrogen. This form of nitrogen is readily mobilised through the soil profile with drainage water. The use of in-drain treatment systems to intercept and treat tile drain discharges would have wide scale applicability if it could be demonstrated that this was a cost-effective mitigation tool.

Nutrient attenuation or removal can be enhanced by the addition of reactive materials to flowpaths, such as tile drains. Materials are added to target one nutrient attenuation process, typically the addition of carbon for N removal by denitrification, and binding of P to reactive materials (adsorption).

Adsorption is the physical or chemical binding of molecules to the surface of solids (soil, sand, clay, pumice, limestone, shells, and modified materials such as aluminised clays). A wide range of materials are available, but any material selected should have a moderate to high affinity for P, be relatively abundant, be readily available at low cost, be non-toxic, be suitable for reuse with no risk to soil or water quality in either the short or long term, and ideally, be a renewable and natural material (Ballantine and Tanner 2010). Melter slag, fly ash and alum have been through basic 'proof of concept' testing, but field scale performance assessments are required.

Denitrification is the conversion of simple organic carbon and an electron acceptor (such as nitrate), to energy, carbon dioxide and gaseous oxides (nitric oxide (NO) and nitrous oxide (N_2O)) or nitrogen gas (N_2). In nature a diverse range of microorganisms (bacteria, proteobacteria, archaea and fungi) are capable of denitrification. Optimal denitrification conditions for these specialist microbes include:

1. A slow release carbon source.
2. Nitrate source.
3. Anoxic (low oxygen) conditions.

Passive filter systems have been extensively trialled at laboratory- and mesocosm-scales around the world. Recently, larger-scale trials have been initiated in the US for treatment of diffuse agricultural run-off and drainage from cropped lands, and preliminary implementation guidelines have been developed (Christianson et al. 2012a; Christianson et al. 2012b). Although performance is promising, it is expected to be highly dependent on the seasonality and variability of drainage flows. To date these systems have not been applied to treat agricultural tile drain runoff in New Zealand.

Denitrification walls and small scale woodchip filters have been evaluated under New Zealand conditions. Denitrification walls (trench filled with sawdust and soil mix) are best constructed where the full extent and flow direction of nitrate-polluted groundwater can be determined, such as sites used for intensive land application of wastewater, cattle feedlots, and old fertiliser dumps (e.g., Schipper and Vojvodic-Vukovic 1998). Small-scale woodchip filters have been evaluated in the Waikato (Sukias et al. 2005; 2006). Three medium (1.2% of catchment area) and one small (0.6% of catchment area) pilot-scale woodchip filters receiving tile drainflow on a dairy farm in the Waikato were monitored. Annual mass loads of nitrate-N were reduced by 55-79% for over a two year period, representing average annual removal rates in the range of ~0.09-0.3 g $N/m^3/d$. Increases in levels of ammonium-N and, in the first year of operation, organic-N, reduced the efficacy of total N removal (16-49%). Higher denitrification rates (in the range of 2-10 g $N/m^3/d$) have been recorded in other field-scale trials under continuous flow where nitrate concentrations are non-limiting (Schipper et al. 2010).

1.1 This project

This project aims to provide empirical data that may be used to assess the field-scale performance of two end-of-tile-drain nutrient attenuation tools in the Waituna Catchment – a woodchip bioreactor (also known as the "Nitrate Catcher") and a phosphorus filter. These tools are intended to enable farmers to reduce their environmental footprint in a cost-effective and practical manner. Alongside other actions, these tools will contribute towards the long-term sustainable management of the Waituna Lagoon and catchment. The two filters have similar designs – a lined pit, filled with materials that have been demonstrated to promote nutrient removal from drainage water; woodchips are used in the 'Nitrate Catcher', while a P-sorbing material will be added to the P filter.

The 'Nitrate Catcher' is a shallow lined pit receiving tile drainage. Woodchips are added to the pit and the water level controlled within the pit to promote conditions suitable for microbial denitrification. Bioreactors are most suitable for subsurface drains where the bulk (typically 80%) of the nitrogen (N) exported is in the nitrate form. The key drivers of bioreactor denitrification rates are inflowing water temperature, nitrate concentration, and the carbon source volume (Schmidt and Clark 2013). Woodchips are generally preferred over other media (e.g., maize cobs, wheat straw, green waste) because they have a longer life span and are likely to result in fewer adverse effects (e.g., N_2O emissions, organic carbon export; (Schmidt and Clark 2013)).

NIWA was contracted to deliver the project, which has five main tasks:

1. assist with site selection
2. design and oversee construction
3. install and maintain monitoring equipment
4. undertake water quality sampling
5. data analysis and reporting.

This report documents tasks 2 and 3 for the ‘Nitrate Catcher’. The site selection process for the ‘Nitrate Catcher’ is outlined in Tanner et al. (2014). A similar report will document the P filter once construction goes ahead.

2 'Nitrate Catcher' site

A site identified on the Pirie Farm, on the upper Waituna Stream, Southland was investigated and deemed suitable for a woodchip demonstration trial (Figure 1). A site inspection revealed a well-defined catchment and gully system on the north side of the valley flowing south to the stream. The gully narrows at the west end of a shelter belt which is at the margin of the rolling higher terrace ground and the flatter flood plain area (see Tanner et al. 2014 for more details).

The tile drain could not be located during initial site visits and a couple of hours was spent locating it on the day the 'Nitrate Catcher' was constructed. Two 3 inch flat bottomed (pre-WWII) tiles drain the gully, rather than the 4 inch tile anticipated.

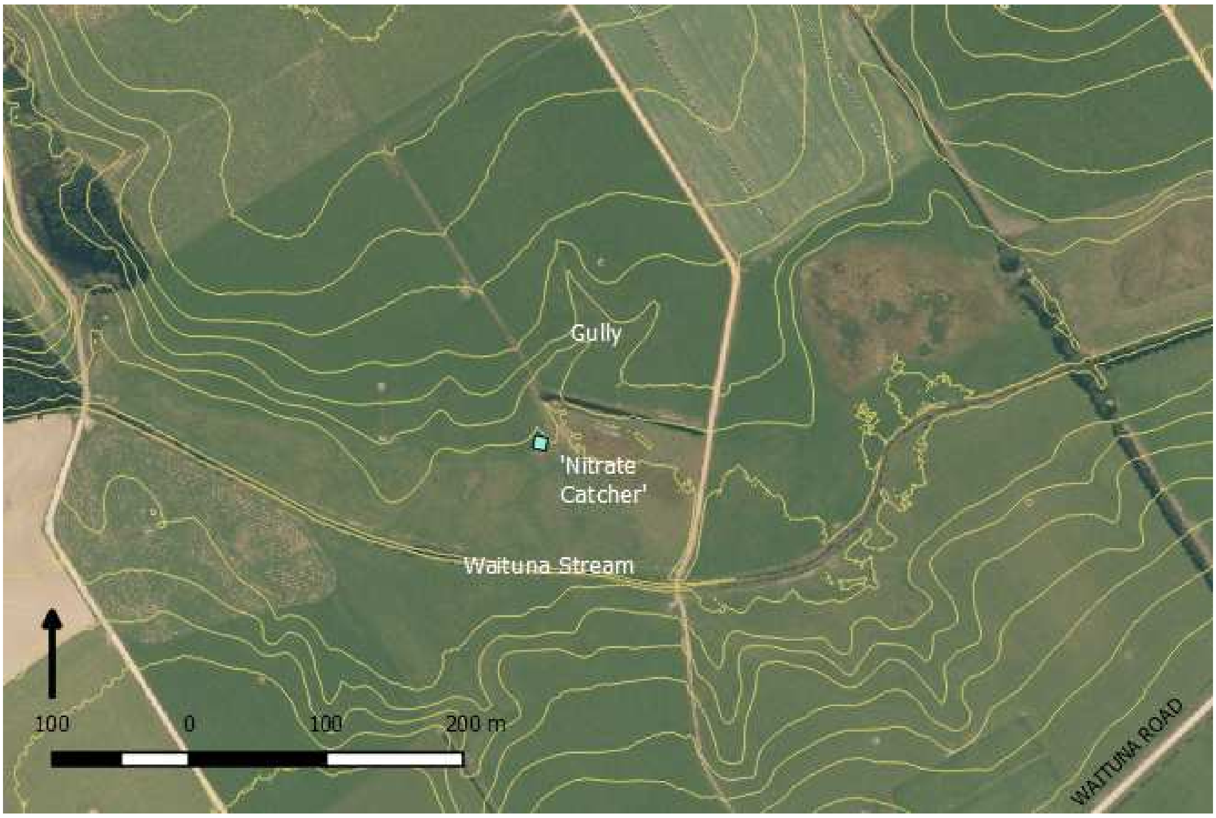

Figure 1: Annotated aerial photography of 'The Nitrate Catcher' location.

2.1 Site selection steps:

We have identified six basic steps that must be fulfilled before construction of a bioreactor should proceed:

1. Discuss the location of tile drain outlets and likely tile drain catchment area and flow characteristics with the farmer. Additional useful tools might include LIDAR, aerial photographs and GIS flow accumulation techniques to predict catchment areas (Tanner et al. 2014).

2. Sample the tile drain outflow and test nitrate concentration. Basic sample protocols include: Label a clean bottle, fill the bottle and empty twice, refill leaving no headspace and secure the lid. Store the sample in a chilly bin with ice/ice pack and deliver/courier to an accredited laboratory.

3. Check drainage network - history can make this difficult. Some possibilities include: (i) excavating the site, (ii) a field site visit during rain or snow to look at the natural drainage lines and soil, (iii) check early aerial photographs, (iv) use historical information to predict what is likely to be underground, for example, historically three tiles come out of a gully (one central, one left, one right).

4. Take levels to assist with final design and costing.

5. Check that the soil will support a bioreactor structure–dig soil pits and check soil maps.

6. Confirm basic feasibility – access suitable, ground conditions, etc.

Detailed site selection criteria and design considerations will be developed at the end of the project.

3 Design and construction

Woodchip filters are typically constructed as long rectangular beds. This configuration is prone to significant head loss during passage through the bed, causing the water level in the filter to drop significantly between the inlet and outlet. As a consequence, large volumes of the woodchips are not in contact with nitrate-rich water, and therefore not fully utilised (Christianson et al. 2013).

The 'Nitrate Catcher' installed in Waituna was designed by Chris Tanner. It was designed to capture 50% of the mean winter nitrate load, with an assumed mean drain NO_3-N concentration of 3.2 g/m^3 (Tanner et al. 2014). The 'Nitrate Catcher' is square to reduce the head loss between the inlet and outlet to manageable levels, whilst maintaining sufficient path-length to ensure adequate contact time between the water and woodchips, and avoid potential short-circuiting of flow (Figure 2). This configuration relies on good dispersion of flow across the width of the bed – this is achieved by the use of perforated pipes set in coarse gravel at the inlet and outlet of the bed (Figure 3).

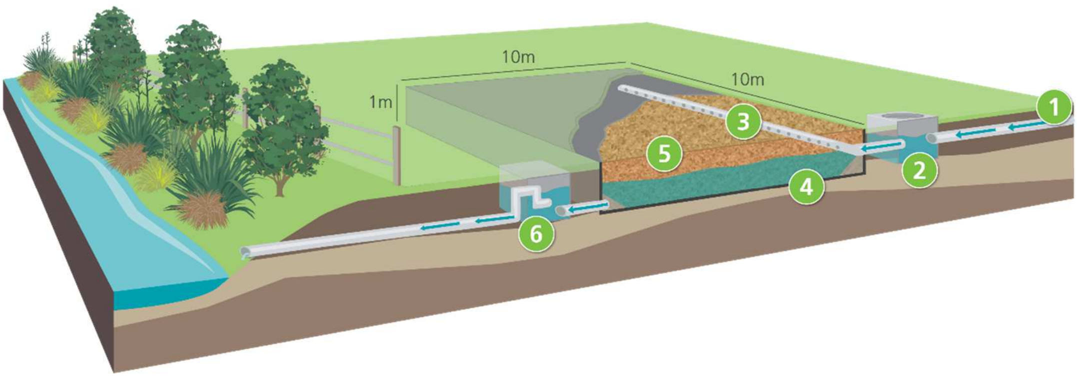

Figure 2: Schematic of the 'Nitrate Catcher'. . 1 is the incoming tile drain, 2 the inlet box, 3 the distribution pipe, 4 the liner, 5 the woodchips and 6 the outlet structure (Dairy NZ).

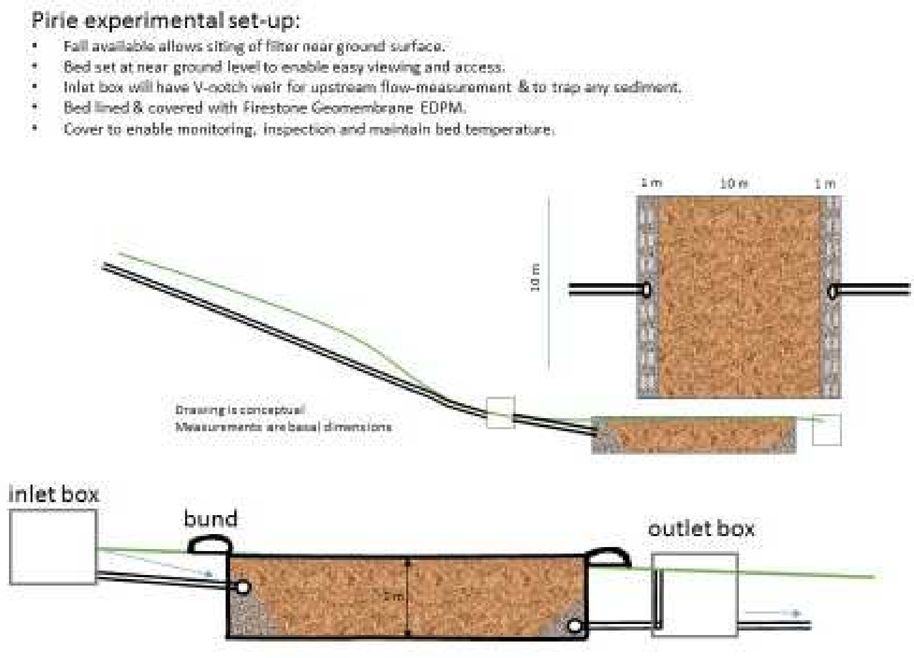

Figure 3: The 'Nitrate Catcher' - as constructed.

There are two control structures in the design (Figure 2, Figure 3). The inlet box brings the tile drain water into the bed and provides a place for sedimentation to occur. The water flows from the inlet box to a distribution pipe (100 mm PVC with 20 mm diameter holes at 300 mm centres) embedded in gravel which feeds water across the width of the 10 m bed. The outflow control structure helps to retain water in the 'Nitrate Catcher'. The outlet box (1 m x 1 m concrete box) contains a vertical standpipe, which may be adjusted to maintain a water level within the adjacent bed. Water leaves the outlet box and enters the Waituna Creek via a tile drain.

This pit is lined to reduce leakage and maintain water levels. The 'Nitrate Catcher' has a Firestone Geomembrane EDPM liner (a farmer might use a cheaper polypropylene liner). Boots were added to the liner at the inlet and outlet to seal the liner to the PVC pipes (Figure 8). The surface of the 'Nitrate Catcher' is covered to help maintain the bed temperature and stop inflow of eroded fine particles of soil etc., which might clog the pore-spaces in the woodchip media. The underlying membrane and the surface cover are held in position by burying the perimeter of the two sheets in a trench that lies outside and follows the perimeter of the pit.

The medium used for the 'Nitrate Catcher' is high quality pine woodchip (Figure 4), likely to be readily available across New Zealand. Woodchips are used in the bed, rather than sawdust, to provide a porous bed with sufficient hydraulic conductivity to ensure adequate through-flow of drainage waters during flow periods. Large woodchips (larger than 1 cm length) without significant proportions of fine materials, shredded materials and soil are preferred. Green materials such as leaves or pine needles are not recommended due to their potential to breakdown quickly, causing excessive initial release of organic matter, and their potential to reduce the permeability and treatment longevity of the bed.

Figure 4: Low quality stringy woodchips (left) and the high quality woodchips used in The Nitrate Catcher (right). (John Scandrett).

3.1 Pre-construction steps

1. Confirm design.
2. Peg out on ground.
3. Take levels at each corner and up the tile drain.
4. Calculate cut and fill for pit.
5. Write specifications for materials/machinery.
6. Check suitability of site for construction and machinery access, e.g., non-waterlogged soil; suitability of farm lanes and bridges; do fences need to be cut?
7. Arrange and coordinate contractor, materials (including pipes, liner, boots and vulcanising glue to make waterproof connections through liner) and labour.
8. Prepare H&S plan, including specifying requirements for all personnel to wear high viz clothing and appropriate footwear.

3.2 Construction steps

1. Strip topsoil from pegged area, including bund areas (Figure 5).
2. Excavate to depth at each corner of the pit (Figure 6), to find out if the soil varies and calculate fill volume required. Build bunds with excavated material.
3. Excavate tile drains.
4. Dig bed and perimeter trench for liner to be secured in.
5. Install liner (ensure position of inlet and outlet is marked on liner; Figure 7).
6. Anchor liner in perimeter trench - liner in, trim as necessary, then cover and fill.
7. Install inlet & outlet pipes (100 mm PVC). Install boots on liner at inlet & outlet. Mark the hole and use a small sheet of ply behind the boot to push against. Secure the pipe to the liner boot (Figure 8).
8. Attach PVC distribution galleries (100 mm PVC pipe with predrilled 20 mm holes at 300 mm centres) to inlet/outlet pipes and cover with coarse gravel, then pack and level galleries (Figure 9).
9. Connect inlet and outlet boxes to pit (Figure 10).
10. Laser level inlet tile drain pipe in (Figure 11), and secure and seal (e.g., using a clay collar).
11. Fill pit with good quality woodchips (Figure 12).
12. Reconnect outlet pipe to tile drain.
13. Secure cover (Figure 13), and landscape to divert surface water (as required).

Figure 5: **Topsoil removal.**(John Scandrett).

Figure 6: **Excavation of pit corners.** (John Scandrett).

Figure 7: **Liner installation.** (John Scandrett).

Figure 8: **Securing liner boot onto inlet pipe.** (John Scandrett).

Figure 9: Levelling inlet distribution gallery. (John Scandrett).

Figure 10: Connecting inlet pipe to inlet box. (John Scandrett).

Figure 11: Inlet tile drain replacement and grading. (John Scandrett).

Figure 12: Adding woodchips to the pit. John Scandrett.

Figure 13: Securing the (folded) cover. John Scandrett.

3.3 Cost

A goal of this study is to provide farmers with accurate estimates of the costs of installation and operation of bioreactors. A preliminary estimate of on-site construction costs for a basic lined rectangular (5 x 21 x 1 m) pit was $7.3 K (Tanner et al. 2014). This preliminary estimate was based on a preliminary design and did not include the woodchips, plumbing, cover, gravel, supervision and project management costs (Table 1).

The final “as-built” cost of the ‘Nitrate Catcher’ final cost is high compared to a bioreactor that might be installed by a farmer, due to the additional requirements of this experimental device (e.g., heavier liner, additional plumbing; Table 1).Once the design was finalised and suitable materials sourced, the cost was estimated at between $20 and $22K, depending on the time required to locate the incoming tile drain prior to construction. The actual on-site cost of construction was $13.9K and total construction cost was $21.5 K (ex GST). This included the inlet and outlet boxes, tile drain, cover and gravel required by the final design, plus project management, labour and on-site supervision fees.

The likely cost to farmers for an “easy” site with good access under good working conditions would be around $10K, increasing for more difficult sites where double handling of materials is required or where swampy soils occur. The ‘Nitrate Catcher’ site was a “moderate” site, with good access for heavy vehicles, but challenging soils and uncertainty about the tile drain history. A “difficult” site might have no heavy vehicle access (requiring double handling of materials), additional fill to create bunds, or poor, wet working conditions. Final costs would depend on many factors, including the availability of materials, labour and earthmoving equipment. A cheaper liner could be used, for example woven polypropylene costs $5/m². Simple inlet and outlet control structures might be used, similar to those described in NIWA’s constructed wetland guidelines (Tanner et al. 2010). Woodchips might also be sustainably sourced on-farm.

Table 1: Preliminary and actual on-site costs.

Item	Preliminary		'Nitrate Catcher'	
	Cost per unit	Total	Cost per unit	Total
Liner	$13.5/m²	$3500	$15.5/m²	$3600
Cover		-		$1250
Excavation		$2100		$2500
Plumbing		-		$1350
Woodchips (incl. transport)		-	$22/m³ + transport to site	$3000[1]
Inlet & outlet structures		$600	$400-500 each	$1300[2]
Gravel	-	-		$900
Contingency	20% (excl woodchips)	$1100		-
Project management, labour & supervision		-		$7600
Total		**7300**		**21500**

[1] No double handling required.
[2] Two truckloads from Oreti Beach.

4 Monitoring

The 'Nitrate Catcher' is instrumented to measure inflowing and outflowing nitrate concentrations and loads. Nitrate loads are calculated by direct computation, i.e., the product of volume and concentration. The performance of the system will be assessed as the difference in load as outlined below:

$$removal\ efficiency\ (\%) = \frac{inlet\ load - outlet\ load}{inlet\ load}\ x\ 100$$

Nitrate concentrations will be measured on discrete samples taken after passage of given flow volumes. The actual performance of the filter for N removal will be assessed at the end of project.

4.1 Monitoring and sampling

Water levels are measured at v-notch weirs (Figure 14) in the inlet and outlet boxes at 5 minute intervals and converted to flow using a stage-discharge rating curve. Water temperature, electrical conductivity and turbidity are also monitored at 5 minute intervals (Table 2). Rainfall is measured on site with a tipping bucket rain gauge.

Figure 14: Inlet weir and sampler intake during construction. (Evan Baddock, NIWA).

Water quality samples will be collected at the weirs. Samples will include (1) grab samples and (2) flow proportional samples collected by automatic samplers. All automatic sampler bottles will be pre-dosed with a biocide (mercuric chloride) to prevent biological growth. Samples will be retrieved at regular intervals and sent to the NIWA Hamilton Water Quality Laboratory for analysis and disposal of mercuric chloride. On each site visit 1 L grab samples will also be taken and analyzed for the full suite of N species and *E. coli* (a faecal indicator organism).

All nitrate-N samples will be filtered with a Millipore syringe and filter holder containing a GF/C glass fibre pre-filter (47 mm diam., 1.2 µm pore size), and a Sartorius cellulose acetate membrane filter (47 mm diam., 0.45 µm pore size). Total N and nitrate-N will be analyzed on a Lachat flow injection analyzer (Lachat Instruments). Total nitrogen samples will be digested with persulfate and reduced with cadmium before analysis. Detection limits are 0.001 mg/L for nitrate-N and 0.01 mg/L for total N.

Table 2: Monitoring instrumentation.

Parameter	Instrumentation	Resolution and measurement frequency
Rainfall	Tipping bucket rain gauge - Unidata 6506C	0.5 mm/tip, logged at 5 minute intervals.
Flow	Water level through sharp crested ½-90 degree v-notch weir. Measured with a float and encoder (Unidata 6541C) in a 250 mm stilling well. Water level converted to flow via rating.	1 mm water level (converted to mL/s), logged at 5 minute intervals.
Electrical conductivity & temperature	Temperature compensated EC - Unidata 6536E.	1 uS/cm & 0.06 °C, logged at 5 minute intervals.
Turbidity (inlet only)	Optical nephelometer (sidescatter) - FTS DTS12 with wiper.	0.01 NTU, logged at 5 minute intervals.
Nitrate (auto)	24 bottle ISCO automatic sampler.	To be triggered flow proportionally.
Other (grab)	Grab samples for *E. coli*, N suite.	Taken on site visits.

Figure 15: Inlet, outlet and complete monitoring installations. The float is inside the well (large vertical pipe with small solar panel) with encoder and NEON logger on top. Automatic samplers are stored in the green boxes. (Evan Baddock, NIWA).

Logged data is sent to the NIWA NEON Server by a NEON NRT 2G/3G (Spark) connection. This provides:

- transfer of data from the field to the office
- ability to view data from any browser on the internet
- automated email reports
- automated email/txt alarm notifications (e.g., when the bottle counter reaches 23)
- ability to reconfigure the logger, updating via the internet from any access point in the world.

A snapshot of the NEON screen for the 'Nitrate Catcher' is shown as Figure 16.

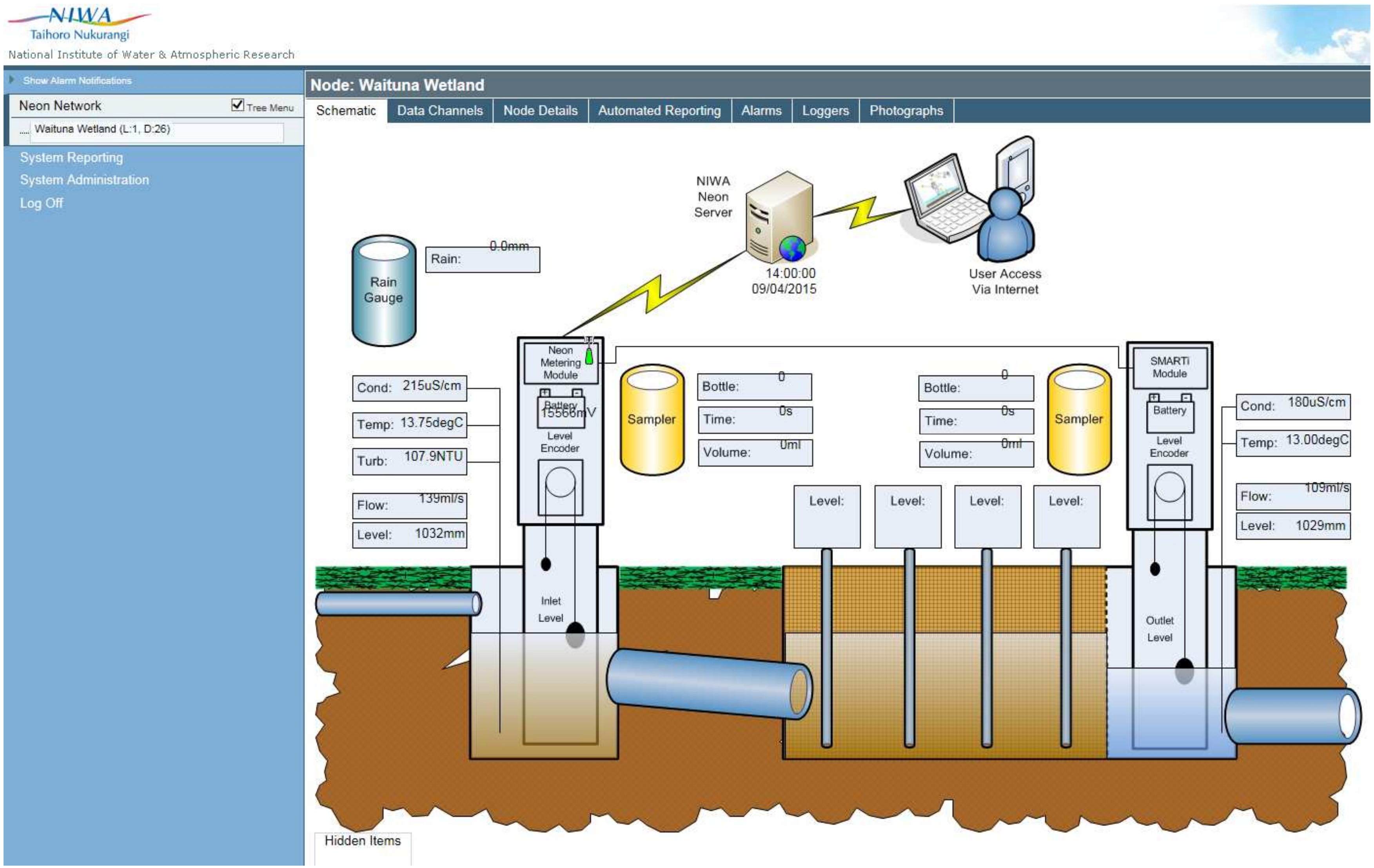

Figure 16: **Snapshot of the NEON screen for the 'Nitrate Catcher'.**

5 Waituna Field Day

Construction was closely followed by an official opening on 23 March 2015 as part of a well-attended joint Environment Southland, DairyNZ, Living Waters (DoC-Fonterra) Field Day. The role of this project in the Living Waters Programme was outlined by Nicola Toki of Fonterra and Geoff Ensor of DoC. David Burger (DairyNZ) noted the importance of such mitigation tools in finding viable solutions to assist farmers address environmental impacts of farming in the catchment. NIWA scientists Lucy McKergow and Chris Tanner described the function of the Nitrate Catcher and operation of the monitoring system, and answered wide-ranging questions from the participants. A fact sheet outlining the project and filter tool design was made available to attendees (Appendix A).

6 Summary

A field-scale denitrification filter ('Nitrate Catcher') was constructed on a farm in the upper Waituna Catchment in Southland to treating subsurface tile drainage from a ~9 ha dairy farm sub catchment. It will be used to demonstrate the concept and monitor performance. Construction and installation of monitoring equipment was undertaken between 17 February and 20 March 2015. This report documents the design, construction steps and monitoring design and equipment. A final report documenting the scientific results of the trial as well as recommendations for future filter designs and wide scale application will be completed at the end of the project in August 2016.

7 Acknowledgements

This work is being funded by the Living Water DoC-Fonterra Partnership, DairyNZ and Clean Water Productive Land (Ministry of Business, Innovation and Employment), delivered by NIWA and supported by Environment Southland and Drakes Hill Farming. NIWA Instrument Systems provided key components of the monitoring and telemetry systems installed. We thank:

- Ewan Pirie for access to his farm to undertake the trial and assistance with background information, and
- Katrina Robertson, James Dare and colleagues from Environment Southland for assistance with site identification.

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Appendix A

The nitrate catcher trial: Drakes Hill Farm, Waituna

This field trial tests an innovative wood chip filter to remove nitrate from agricultural runoff. It aims to provide a cost-effective and practical tool for farmers to reduce their environmental footprint and ultimately help improve the health of the Waituna Lagoon.

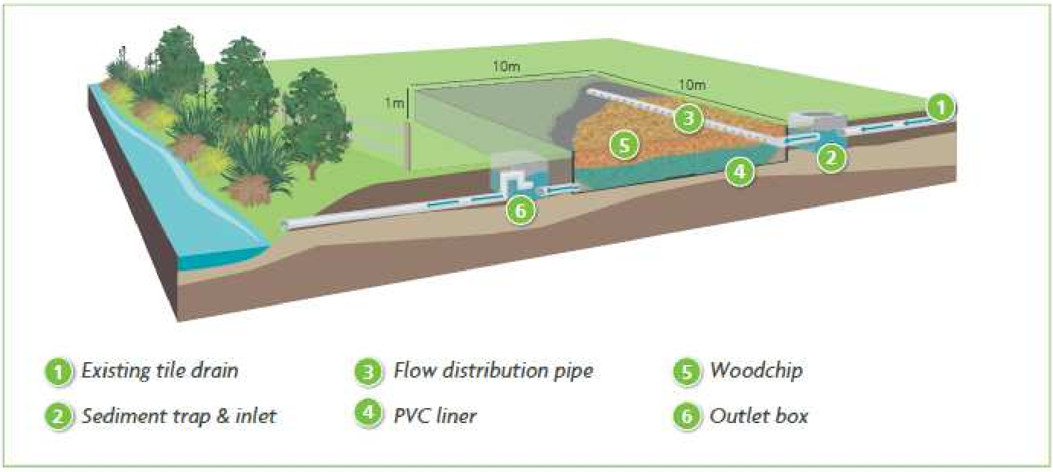
The study trials the 'nitrate catcher' under New Zealand conditions to help understand how much nitrate can be removed, what a well-designed system looks like and how much it will cost.

Background

Tile drains are an important feature of Southland's agricultural landscape. They provide essential drainage for pasture production. Drainage also accelerates the transportation of nutrients off-farm. Particularly nitrate, a form of nitrogen, readily leaches through the soil profile with water. To improve downstream water quality and ecosystem health, we're looking at ways to capture nitrates before they leave the farm.

How does the nitrate catcher work?

The 'nitrate catcher' removes nitrate as it passes slowly through a wood chip filter bed. Naturally occurring denitrifying bacteria, typically found in wet soils, convert nitrate to nitrogen gas. The bacteria use carbon from the wood chip as a food source and nitrate in the water as part of their respiration process. The two-year study will also look into how environmental conditions such as flow and temperature influence how much nitrate can be removed.



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