Meeting cultural and water quality objectives for greywater treatment with a wetland and advanced infiltration zone

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Abstract

In New Zealand's founding document, the Treaty of Waitangi, the government promises to uphold the values of New Zealand's Tangata Whenua (people of the land). Thus wherever possible, treatment of human wastewater should conform to Māori cultural aspirations that treatment include a significant land-based infiltration component, including their marae (traditional communal dwellings/meeting houses). However, upgrading of existing systems often strain the finances of marae communities. In addition, occupancy of an individual site can be highly variable (ranging from daily use of only a few people, up to major events such as funerals where several hundred people may be present). This can place considerable strain on existing wastewater infrastructure. We present information for a coastal marae location where improvements to the existing wastewater system (septic tank and infiltration field) were sought. The local family grouping did not want to connect to the nearby town WWTP because they objected to discharge of the wastewater directly into the mouth of the harbour (their traditional food basket) adjacent to their ancestral lands. An on-site gravel bed constructed wetland with a novel infiltration swale was constructed to receive greywater which was diverted from the existing septic tank and infiltration zone, markedly reduced loading and flushing effects on this system. Water quality monitoring of the system was aligned with events at the marae. The constructed wetland reduced nitrogen by 72-99%, phosphorus by 75-98% and TSS by ~89-95%. Effluent concentrations of Escherichia coli were rarely above 1000-2000 per 100 ml, despite inflow concentrations which were sometimes >1,000,000 per 100 ml although increases were recorded when inflow concentrations were low. However within the Soil Infiltration Zone *E. coli* were absent in more than half the samples and never greater than 100 MPN per 100 ml.

Keywords

Greywater; constructed wetland; marae; on-site treatment; Māori

INTRODUCTION

On-site wastewater treatment is used by 270,000 households throughout New Zealand (MfE 2013), and is generally undertaken where access to municipal wastewater treatment such as sewers and centralised sewage treatment is lacking. Many systems are old style septic tank systems followed by an infiltration field, where removal of solids and associated biochemical oxygen demand may be adequate, but microbe removal is frequently poor. Typically an infiltration field receives the overflow from the tank, with some remediation via plant uptake and microbial processing. Overloading, poor maintenance or improper installation can all contribute to system failure, with 42,000 considered presently to be failing (MfE 2013).

A marae community of Tainui-a-Whiro tribe which operate a community camp/educational centre at a coastal township (Raglan) saw the need to upgrade water and wastewater facilities at their site. One particular concern was the existing septic tank system, which was appropriately sized for the small to medium sized events at the site, but was undersized when larger groups were present. The community have long exercised guardianship of the area, and realised the need to have an effective waste treatment system. Connection to the local sewerage system was a possibility, however Māori cultural/spiritual values require human wastes to be treated by land, as Papatūānuku (the earth mother) cleanses them as they pass through her. The discharge from the town sewage treatment system was into the harbour entrance, immediately by the marae site, thus a major cultural affront.

Rather than connect to a system they had long objected to, the marae community chose to upgrade their own water and wastewater facilities in a land based system which conformed to their cultural beliefs. The upgraded system reduced the load (particularly the hydraulic load) on the existing septic tank system by constructing a separate grey water treatment constructed wetland.

Inflows and outflows to the system were monitored during five events at the centre, two in summer (Feb and Dec 2013), two in winter (June 2013, July 2014) and one in spring (October 2014).

MATERIALS AND METHODS

Construction

Water use (and thus wastewater generation) was monitored using flow meters installed at key locations throughout the marae site. Flows were recorded on a Campbell meter and telemetered daily to the research facility (NIWA Hamilton). Greywater (showers and hand basins only) were separated from the blackwater at source, and piped to a separate treatment system constructed on site, although wastewater from the urinals was also treated in this system.

The treatment system consisted of a gravel bed constructed wetland planted with native plants, followed by a planted infiltration system. The wetland was 7 x 4 m, and 0.4 m deep and was sized to accommodate the volume from three day events of up to 60 people.

The wetland was planted with a mixture of native vegetation (*Carex secta*, *C. virgata* and *Cyperus ustellatus*). Water exiting the wetland entered an infiltration area consisting of a large buried 20 m long drainage arch (450 mm), buried in a trench in the centre of a shaped swale. The outer edges of the swale were raised to prevent other water entering the system during periods of overland flow. The centre of the swale was excavated in a shallow "v", which permitted water in the arch to exit to the surface of the swale if infiltration rates were too low during major events. The swale was planted with the culturally important plant species, the New Zealand lowland flax (*Phormium tenax*) or harakeke in Māori. The infiltration zone ran parallel to the shoreline at a minimum distance from open water of 80 m. Groundwater depths were measured at >2.5 m beneath the surface.

A sand trap was installed on the inflow pipe before the wetland, which acted as a convenient upstream sampling location, while the outflow was sampled from a water control structure at the outlet of the wetland. Sub-surface sampling piezometers (~ 2m deep) were installed in upstream and downstream locations around the infiltrations trench (Figure 1).

Event Sampling

Ice filled automatic samplers (ISCO 3700, Teledyne ISCO Inc, USA) were installed at the inflow and outflow of the constructed wetland, collected hourly composited samples (4 samples per bottle) starting prior to people arriving at the site. Samples were returned to the NIWA Water Quality Laboratory in Hamilton at the end of each event for analysis and analysed for electrical conductivity (EC), turbidity, suspended solids (SS), nitrate (NO_3-N), total ammoniacal-N (NH_4-N), total nitrogen (TN), dissolved reactive phosphorus (DRP), total phosphorus (TP), and *Escherichia coli*. Groundwater was collected from the pre-installed piezometers at the beginning and end of each event (except Feb 2013 when groundwater levels had fallen below the depths of the piezometers).

RESULTS

Details of the monitored events are shown in Table 1. Inflow and outflow data are presented in Tables 3 and 4 (summer events) and Tables 5-7 (winter and spring events). Summary data include averages or geometric means (*E. coli* only) and standard deviations. Mass removal rates have been calculated for each event. The wetland had a void space volume of 4.2 m^3. Thus events smaller than this would be mostly displacing water from a previous event.

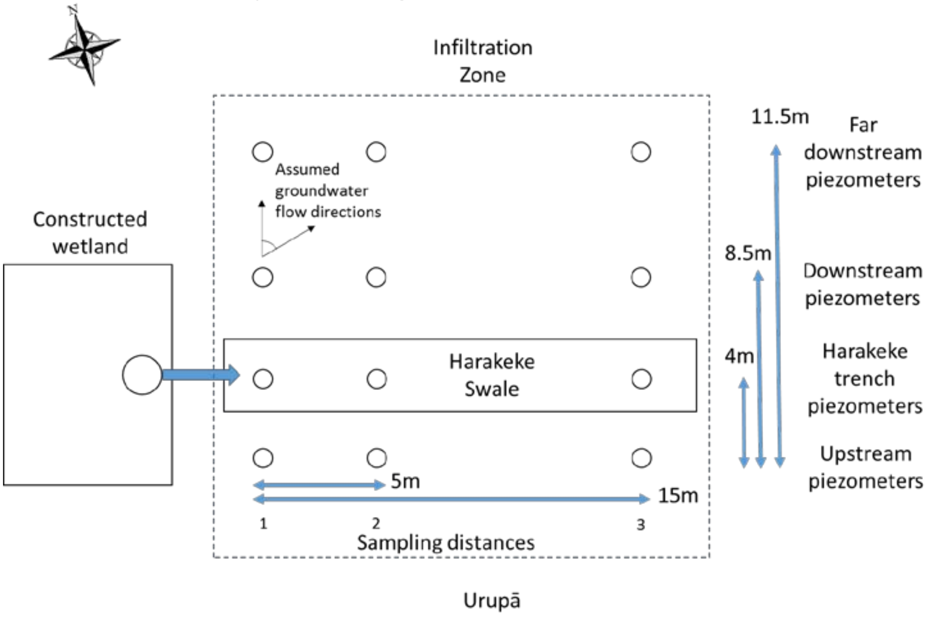

Figure 1. Layout of wetland and infiltration zone, showing position of sampling piezometers.

Average nitrogen values in the inflow to the wetland were close to or exceeded the very high values reported by Halalsheh (138 g m^{-3}, 2008) for three of the events (Feb 2013, 136 g m^{-3}; Jul 2014, 157 g m^{-3}; Oct 2014, 174 g m^{-3}; Tables 2, 5 & 6). These comprised mostly ammonium-N, clearly due to the inputs from the urinals, and thus not representative of solely grey water inputs. Of the two other events (Table 3 & 4), one was recorded as being a weaving workshop, thus likely to contain mostly women, explaining at least for this event why concentrations were much lower. Regardless of the inflow concentration, removal was high, ranging from 89% to 99% on a concentration basis, and 77% to >99% of a mass loading basis. There was no indication that removal was lower during the winter events. Evidence for conversion of total ammonia to nitrate was minimal, with higher (but still low) effluent concentrations in one summer event and one winter event. However effluent nitrate concentrations were low compared to influent ammonia concentrations in all instances. Removals of other key pollution indicators were similarly to the high levels seen with TN, with removal of TP ranging from 75% to 99% and TSS from 89% to 96%, both on a concentration basis.

Inflow concentrations of *E. coli* were highly variable, sometimes as low as 11 per 100 ml, whereas in another event the geometric mean was 530,000 per 100 ml. Effluent concentrations were much less variable, but were around 1,000-2,000 per 100 ml for 3 events, and 10-20 per 100 ml in the other two events. Of the three events with effluent >1000 per 100 ml, two had the very low influent concentrations, thus effluent concentrations were much higher.

Assessments of the above ground biomass of the wetland plants were undertaken in February 2016. Below ground measurements could not be undertaken without destroying the plants, thus were not undertaken. Based on the areas of each plant, dry biomass of *Carex spp.* was 65.5 kg and *Cyperus sp.* was 18.8 kg.

Groundwater data

For each of the events groundwater sampling was undertaken at the beginning and end of the sampling (except Feb 2013 when groundwater levels had fallen below the depths of the

Table 1. Event details.

Date	Season	Attendance	Flow (Q, m3)
8-12 Feb, 2013	Summer	80 for 3 days 40 for 2 days	10
6-9 Dec, 2013	Summer	15	2.5
4-7 Jun, 2013	Winter	20-30	16
25-28 Jul, 2014	Winter	35	3.2
6-10 Oct, 2014	Spring	60	16.6

Table 2. Summary of inflow and outflow data, summer (Feb 2013) sampling.

Concentration	EC µS cm^{-1}	Turb NTU	TSS g m^{-3}	NH_4-N g m^{-3}	NO_3-N g m^{-3}	TN g m^{-3}	DRP g m^{-3}	TP g m^{-3}	*E. coli* MPN 100 ml^{-1}
Inflow	1,227 ± 702	19 ± 17	54 ± 38	117 ± 114	0.017 ± 0.036	136 ± 103	5.8 ± 4	7.03 ± 4.54	530,000 SD 4,060,000/69,300
Outflow	479 ± 32	8 ± 7	6 ± 3	0.08 ± 0.15	0.001 ± 0.002	0.751 ± 0.222	0.301 ± 0.285	0.42 ± 0.319	1,260 SD 23,500/295
% Removal	61%	58%	89%	99.94%	94%	99.4%	95%	94%	99.76%
Mass			g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	
Loading			2.2	5.47	0.0007	6.38	0.29	0.35	
Removal			1.9	5.47	0.0006	6.35	0.28	0.33	
% Removal			87%	99.97%	87%	99.5%	96%	95%	

n=80, composited to 20 samples.

Values are average ± 1 standard deviation, except for E. coli which are geometric mean, along with upper and lower 1 (geometric) standard deviation.

Table 3. Summary of inflow and outflow data, summer (Dec 2013) sampling.

Concentration	EC µS cm^{-1}	Turb NTU	TSS g m^{-3}	NH$_4$-N g m^{-3}	NO$_3$-N g m^{-3}	TN g m^{-3}	DRP g m^{-3}	TP g m^{-3}	*E. coli* MPN 100 ml^{-1}
Inflow	611 ± 457	40 ± 44	85 ± 65	30 ± 45	0.03 ± 0.05	40 ± 58	1.9 ± 2.7	2.4 ± 3.1	11 SD 69/2
Outflow	537 ± 725	3 ± 1	5 ± 2	3 ± 0.3	0.12 ± 0.15	3.7 ± 0.3	0.4 ± 0.1	0.6 ± 0.1	1,900 SD 5,830/665
% Removal	12%	93%	94%	90%		91%	79%	75%	
Mass			g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	
Loading			0.49	0.12	0.00025	0.16	0.013	0.016	
Removal			0.45	0.10	-0.00050	0.14	0.011	0.013	
% Removal			92%	86%		86%	84%	80%	

n=76, combined to 19 samples.

Table 4. Summary of inflow and outflow data, winter (June 2013) sampling.

Concentration	EC µS cm^{-1}	Turb NTU	TSS g m^{-3}	NH$_4$-N g m^{-3}	NO$_3$-N g m^{-3}	TN g m^{-3}	DRP g m^{-3}	TP g m^{-3}	*E. coli* MPN 100 ml^{-1}
Inflow	421 ± 111	22 ± 14	41 ± 28	8 ± 7.8	0.005 ± 0.006	42 ± 41	3.22 ± 3.85	3.91 ± 4.17	34,400 SD 1,210,000/976
Outflow	324 ± 4	3.1 ± 1.0	4.4 ± 1.9	0.43 ± 0.08	0.031 ± 0.025	0.75 ± 0.11	0.04 ± 0.06	0.09 ± 0.08	17 SD 60/5
% Removal	23%	86%	89%	95%		98%	99%	98%	99.95%
Mass			g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	
Loading			2.63	0.475	0.0003	2.549	0.1960	0.238	
Removal			2.61	0.473	0.0002	2.546	0.1959	0.238	
% Removal			99.4%	99.7%		99.9%	99.9%	99.9%	

n=72, combined to 18 samples.

Table 5. Summary of inflow and outflow data, winter (July 2014) sampling.

Concentration	EC μS cm^{-1}	Turb NTU	TSS g m^{-3}	NH$_4$-N g m^{-3}	NO$_3$-N g m^{-3}	TN g m^{-3}	DRP g m^{-3}	TP g m^{-3}	*E. coli* MPN 100 ml^{-1}
Inflow	14,900 ± 2,121	68 ± 40	95 ± 34	136 ± 20	0.027 ± 0.028	157 ± 30	5.7 ± 0.1	9.7 ± 0.1	746 SD 513/0
Outflow	368 ± 20	4 ± 2	9 ± 11	3.6 ± 0.5	0.015 ± 0.016	4.4 ± 0.8	0.5 ± 0.1	0.6 ± 0.1	13 SD 138/1
% Removal	98%	94%	91%	97%	44%	97%	91%	94%	98.26%
Mass			g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	
Loading			1.2	2.5	0.0001	2.9	0.09	0.16	
Removal			1.0	2.4	-0.0001	2.8	0.08	0.15	
% Removal			85%	98%		97%	92%	93%	

n=48, combined to 12 samples.

Table 6. Summary of inflow and outflow data, spring (Oct 2014) sampling.

Concentration	EC μS cm^{-1}	CBOD g m^{-3}	TSS g m^{-3}	NH$_4$-N g m^{-3}	NO$_3$-N g m^{-3}	TN g m^{-3}	DRP g m^{-3}	TP g m^{-3}	*E. coli* MPN 100 ml^{-1}
Inflow	1,618 ± 870	135 ± 70	186 ± 187	128 ± 101	0.101 ± 0	174 ± 116	7.52 ± 5	14 ± 10	159 SD 555/46
Outflow	566 ± 197	5 ± 4	10 ± 6	11.0 ± 17	0.026 ± 0	19.0 ± 55	2.12 ± 2	2.90 ± 4	1,920
% Removal	65%	96%	95%	74%	89%	72%	91%	SD 11,100/332	
Mass		g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	g m^{-2} d^{-1}	
Loading		4.0	11.1	7.81	0.007	10.2	0.43	0.80	
Removal		10.5	10.5	7.31	0.006	9.6	0.31	0.66	
% Removal		95%	95%	94%	77%	94%	71%	82%	

n=48, combined to 12 samples.

piezometers). As specific flow patterns are not certain, data have been shown in graph form, following the general layout of the piezometers.

Effluent concentrations of total ammonia (Fig 2 a, c, e and g) were significantly higher than in the groundwater in and around the infiltration zone, whereas the reverse was true for nitrate (Fig 2 b, d, f and h). In general, there was little difference in groundwater (piezometer) concentrations or patterns for these water quality measurement between the beginning and end of any particular event. There was a small indication that the constructed wetland may have been influencing concentrations total ammonia concentrations near to the input point to the infiltration zone in the Jul and Oct events (peaks in and upstream of the trench), but this appears to have been assimilated or converted to nitrate by the time it had travelled to the outer regions of monitoring. The effluent from the constructed wetland had a similar or lower concentration of Total Nitrogen to the receiving groundwater. Figure 3 shows total phosphorus concentrations in the groundwater monitoring piezometers. TP concentrations were notably higher in the effluent than the receiving groundwater, however again there is no clear indication that this was having a substantial effect at the limits of the infiltration zone.

Inflow concentrations of *E. coli* to the infiltration zone (i.e. effluent from the CW) in Figure 4 are the closest corresponding sample in time (i.e. not average values from Tables 2-6), as the values from the piezometers are also from grab samples rather than averages. Inflow concentrations ranged from as low as 3 MPN to 27,500 MPN per 100 ml. The highest concentration measured anywhere in the infiltration zone was recorded as <100 MPN[1]. More than half the samples (56 of 84) were <1 MPN per 100 ml.

DISCUSSION

Constructed Wetland

The average influent TN concentrations ranged from 40 g m^{-3} to 174 g m^{-3}. Regardless of the influent concentrations, removal of TN ranged from 77% to >99% with average removal of 104 g m^{-3}. Using total flows data of 823 m^{-3} since the system was constructed, if TN removal was similar in non-monitored events, nitrogen removal within the wetland would equate to around 85 kg of N. Of this total, above ground plant nitrogen (at 1-3% of dry weight) was only 1-3 kg only. Thus while plant uptake may have played some role in nutrient stripping, other mechanisms such as sequential nitrification and denitrification are likely to be of much greater significance. Removal of the other key nutrient, phosphorus, was similar, ranging from 75% to 99%, with average removal of 6.5 g m^{-3}, equivalent to 5.3 kg of phosphorus removal over its 4 years of usage. Again, plant uptake will have played some role, but only 0.1 kg of phosphorus was present in above ground biomass, indicating other mechanisms such as microbial uptake and storage, and adsorption to inorganic binding sites are likely to have been more important.

TSS had removals >89%, however turbidity, when it was measured, could be similar or noticeably lower, with a range from 58% up to 94%. Removal of the faecal indicator bacterium, *Escherichia coli*, within the wetland was not as straight forward. Occasionally influent concentration were very high (e.g. geometric mean 530,000 MPN per 100 ml), but were sometimes less than 100 MPN per 100 ml. High values were reduced to within the 500-2,000 MPN per 100 ml, however where influent concentrations were low (e.g. 10-100 MPN per 100 ml) effluent concentrations were still in the 500-2,000 MPN per 100 ml. This is somewhat higher than the residual 50 MPN per 100 ml suggested in Kadlec and Knight’s (1996) k-C* model, but conforms to a similar pattern that residual background levels are typically present in the effluent.

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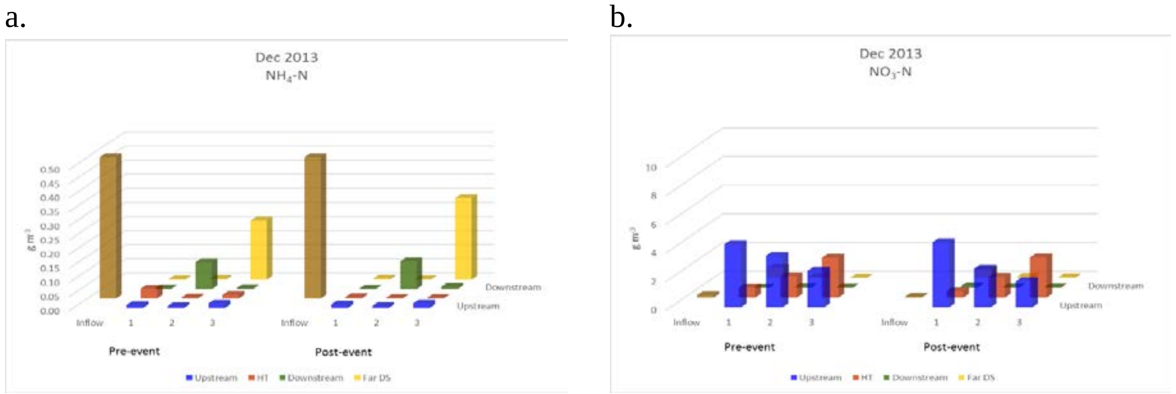
[1] Note: this represents a range of 0-99 MPN per 100 ml.

Summer event



Winter and spring events.

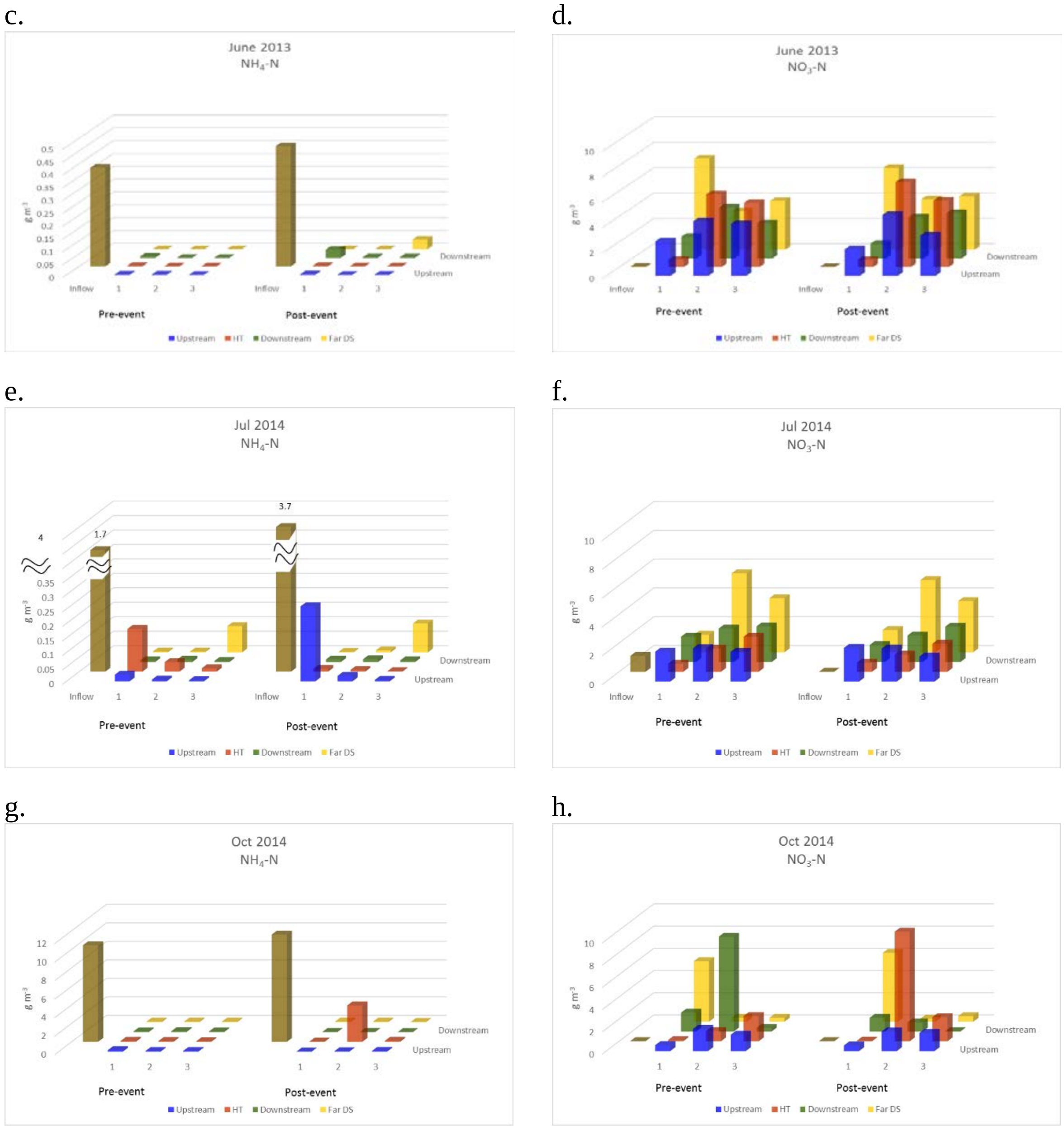


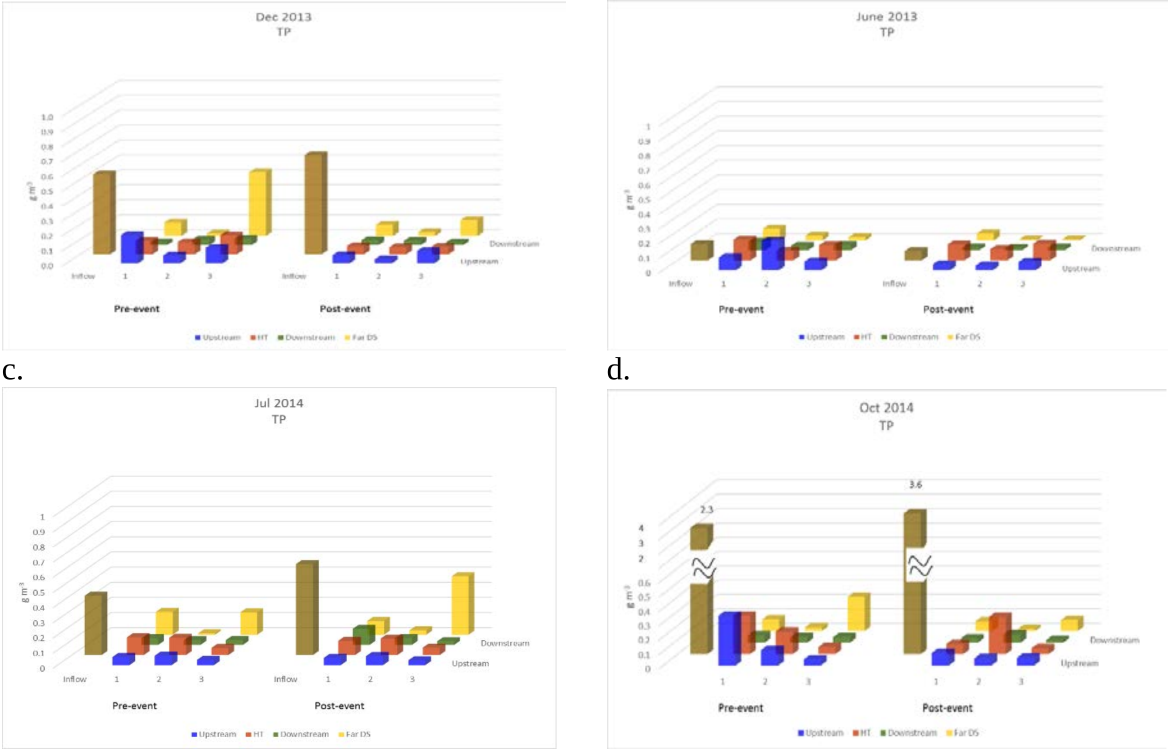
Figure 2. Total ammonia and nitrate concentrations in groundwater piezometers.

Summer event

a.

Winter and spring events.

b.



c.

d.

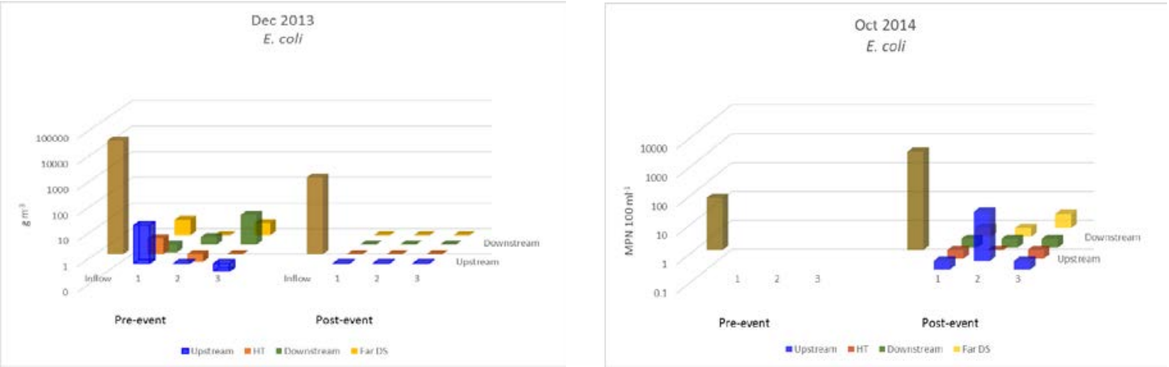
Figure 3. Total phosphorus concentrations in groundwater piezometers.

Summer event

a.

Spring event

b.



Winter events.

c.

d.

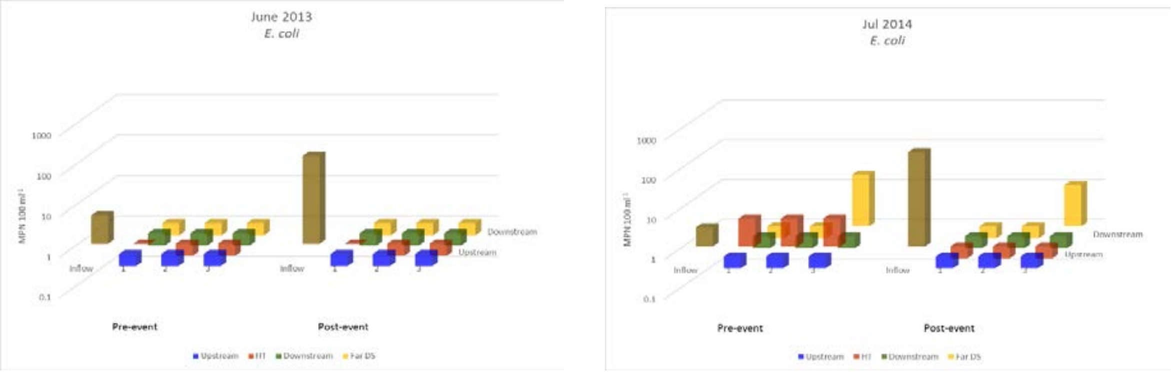


Figure 4. *E. coli* concentrations in groundwater piezometers. Note: Logarithmic scale. Also, during the spring pre-event there was insufficient sample for *E. coli* analyses.

Harakeke Infiltration Zone

The Infiltration Zone allows treated water to disperse into groundwater, but also permits further treatment before any wastewater reaches areas of potential human contact or food gathering locations (e.g. fish and shellfish from the harbour). Both the gravel bed wetland and soil based infiltration zone are important cultural/spiritual aspects of cleansing wastewaters, particularly those containing human faecal matter. While cultural cleansing is important to the Māori land owners, they also recognise that as guardians of the area, any wastewater treatment system they put in place should give equivalent or superior biogeochemical treatment to that which they advocate should be used by the wider community. Within the infiltration zone, groundwater was only sampled at the beginning and at the end of an event, which may only be 3-4 days later. In general there was only limited change in groundwater quality over this period. There was no strong signal of effluent discharged from the constructed wetland either traversing the length of the trench/drainage arch, and generally it appeared that the CW discharge was of a lower concentration than the groundwater it was discharging into (considered to be the blue bars on Fig 2 and 3). Clearly total ammonia concentrations are an exception, as groundwater concentrations are generally negligible for ammonia/ammonium, which is generally converted into nitrate. In three of the four events where groundwater was able to be sampled, background nitrate levels well exceeded inputs of total ammonia, and it was only in the Oct 2014 event where there is an indication that inputs of nitrogen from the CW may be adversely influencing groundwater concentrations within the infiltration zone. Occasional concentration peaks at the outer limits of the infiltration zone (e.g. Fig 2a for total ammonia and Fig 3f for total phosphorus) may be due to previous unmonitored events, thus establishing the effect of these discharges on groundwater may require addition of tracer material and continuous monitoring of groundwater.

A key water quality measure of the combined system is *E. coli*. Inflow concentrations were two to three orders of magnitude higher than seen in the zone itself, which were generally less than 10 MPN per 100 ml, and two thirds of samples were less than 1 MPN per 100 ml. That is, no *E. coli* were measurable in the samples. Clearly soil attenuation processes of these microbes were effective in reducing numbers to background levels.

CONCLUSIONS

The constructed wetland treating mostly greywater but with some addition of urine removed 72 - 99% of TN, which represents around 85 kg of N during its period of operation. TP removal ranged from 75% to 99%, equating to around 5.3 kg during the wetland period of operation. Plant uptake could only account for a fraction of these removals, thus mechanisms such as sequential nitrification and denitrification, and uptake into short and long term storage reservoirs. Nutrient removal was not as apparent in the soil Infiltration Zone planted with flax (harakeke), but conversion of total ammonia to nitrate was evident. Importantly, most samples from this area were negative for the faecal indicator, E. coli. The use of a gravel bed wetland and soil infiltration zone combined elements of western science with tikanga Māori (“appropriate way to do things”). The emphasis on land treatment and assimilation avoided contributing to discharges to the moana (“ocean”), which is unacceptable to local tangata whenua (“people of the land”). This wetland design and studies of its performance give Māori and other communities a tool to reliably treat wastes while recognising and valuing Māori cultural beliefs.

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