Performance of a constructed wetland intercepting run-off from a Lichfield dairy farm

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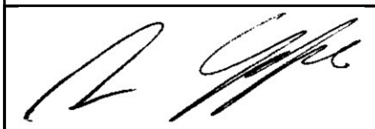	Approved for release by:	Rupert Craggs

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Executive summary

The constructed wetland complex on the Baldwin Farm (Lichfield) is designed to reduce environmental degradation by capturing and removing contaminants from farm runoff.

Baseflow into the wetland consisted of the outflows from a group of upstream seepage wetlands as well as groundwater entering through the base of the wetland. Groundwater flow was larger than expected, and was not directly sampled, although its contaminant concentration was able to be estimated based on the diffuse inputs to the seepage wetlands, which were sampled. During storm events an additional input was runoff from two major farm races. These contributed large amounts of sediment, faecal material and associated nutrients.

The initial three wetland cells acted as sedimentation ponds, and were highly effective at removing sediment, much of which was entering the system as runoff from the farm races during rainfall events.

Nitrogen inputs were much higher during rainfall events (467 kg) than during baseline flow (102 kg), with removals of 48% and 36% respectively. The lower removal during baseline flow is probably a reflection of the already low concentration inputs of nitrate entering from upstream wetlands where denitrification would have removed nitrate from the incoming groundwater. Also, the shallow water depths on sloping areas of the constructed wetland (around 73% of the total wetland area) may not have been as effective at removing nitrate as permanently submerged areas which would have been more anoxic. However nitrate removal was estimated at 17%, quite close to the average performance removal of constructed wetlands occupying 0.75% of a catchment as predicted in the New Zealand Guidelines for Treatment of Tile Drainage (Tanner, Sukias et al. 2010). Overall removal of total nitrogen within the wetland was even more effective, at around 45%, due to high capture rates of organic nitrogen fractions. Phosphorus removal was even higher at 77%, probably associated with sedimentation of particulate fractions.

Inputs of sediment to the wetland were similarly much higher during events, at over 30,000 kg compared with 583 kg during baseline inflows. Removal was also higher during events, at 81% compared with a still respectable 37% during baseline flow.

Removal of the faecal indicator bacterium, *E. coli*, was less than 1 order of magnitude (85%) at baseflow conditions. However during storm events, when inputs were much higher, removal rates reached a maximum of 99.97%, or nearly 4 orders of magnitude due to higher input concentrations and settling/removal of faecal associated solids.

Based on measured and estimated inputs, contaminant removal during the 2017/18 drainage season equated to:

~24,700 kg of suspended solids

~284 kg of total nitrogen, and

~104 kg of phosphorus.

The wetland provided considerable protection to the environment by removing faecal pollutants, solids and nutrients, both during baseflow and during high flow events. In addition, the wetland also buffered flows so that peak flows in the downstream receiving water occurred later than the initial storm event. The shallow sedimentation ponds are likely to require desludging soon due to the build-up of captured sediments.

1 Introduction

Natural and constructed wetlands offer significant potential as a management tool to reduce farm nutrient losses to surface waters. Constructed wetlands remove nitrate contained in runoff drainage water through bacteria-mediated processes as well as plant uptake. Wetlands can also trap sediment and phosphorus contaminants, and the extent of faecal bacteria loading to water bodies is also reduced by wetland filtration of surface runoff. The protection, restoration and creation of on-farm wetlands can therefore make an important contribution towards reducing agricultural nutrient losses and improving the water quality and health of downstream water bodies in addition to the direct ecological benefits they provide.

The science behind the design and functioning of wetlands as nutrient treatment systems is well understood. This however does not mean that wetland designs are standardised, as each on-farm situation is likely to contain unique landscape factors, so that a design for one farm may differ in a number of ways from that of a different farm. The practical elements of wetland design, project planning and implementation (e.g., hydraulic loading, wetland size and dimensions and plant specifications) are nonetheless crucial to ensuring wetlands function at their full potential as natural treatment systems.

The overall objectives of this study were to provide greater knowledge around wetland design, performance and practicality to Waikato dairy farmers and the community through the development of a practical case study to reduce agricultural nutrient loads from a 267 ha dairy farm to the Ngutuwera Stream. The project was undertaken in partnership between DairyNZ, Baldwin Family Trust, Opus International Consultants (Hamilton) and Hill Laboratories, together with Waikato Regional Council, NIWA and other organisations.

2 Brief

Dairy NZ contracted NIWA to assess the contaminant fluxes and removal performance of the constructed wetland on the Baldwin Family farm, Lichfield, under a range of environmental conditions (base flow, event flows, seasonal variability) for the constructed and seepage wetland areas, to help inform guidelines for constructed wetland treatment of dairy farm run-off.

3 Site description

The dairy farm constructed wetland was designed and construction supervised by Roger McGibbon, Opus (MacGibbon 2014, Burger, MacGibbon et al. 2016) for DairyNZ, and was completed in early 2015. The constructed wetland site is at the base of a valley system and consists of 3 small sedimentation ponds followed by two large shallow wetland cells, all arranged in series (see Figure 1). NIWA implemented a telemetered system to monitor flows and water quality entering and exiting the wetland. There are two major inputs to the wetland along with various minor inputs. One of the major inputs which flows throughout most of the year consists of outflows from a series of natural seepage wetland systems. The seepage wetlands are fully fenced to exclude stock, however they are dominated by pastoral plant species, with few native wetland plants, indicating previous stock access. The outlet from these seepage wetlands enter the first cell of the constructed wetland and is referred to as Input A.

The other major input (Input B) to the constructed wetland is from runoff from a raceway which runs down the length of the valley. The raceway is 750 m long to the point at which input enters the first cell of the wetland. Two other raceways also join onto this raceway above the input to the wetland. As major stock traffic route on the farm, the raceways have the potential to accumulate significant volumes of faecal matter and urine. In addition, various paddocks are accessed from the raceways with soil pugging and higher densities of faecal deposition adjacent to the gateways, as is normal on dairy farms. During rain events and for periods between events during the wetter months, water runs over the raceways into a side drain which enters the first cell of the wetland via a culvert. During these events this input carries significant amounts of faecal matter and urine, as well as some sand and soil from the raceways.

The outlet of the wetland complex flows into the Ngutuwera Stream in the headwaters of the Pokaiwhenua Stream, and then into the Waikato River at the top of Lake Karapiro.

There is a fall in topography of around 3 m from the inlet of the constructed wetland to the outlet, and the constructed wetland is divided into a number of cells separated by bunds. The first three cells are smaller (see Table 1) and deeper than the other cells in the system and are essentially wet ponds for much of the year. They slow inflow velocities and enhance settling of incoming suspended solids. The inflow from the raceway culvert runs through a stand of emergent vegetation, which assists with slowing and dispersing this flow. The inflow from the seepage wetlands enters on the other side of this cell. Because of their depth, emergent wetland vegetation is only found in shallower areas of these first three cells.

Following these deeper cells, there are two wide, large, shallow, meandering cells. Due to the fall between the inflow and outflow ends of these cells, water depth is only 5-10 cm between the plants, except at the outflow end where it is deeper (20-30 cm), and thus there is an open water area at each outlet. These cells are planted with a variety of native wetland species. Plant cover is much higher in these cells than the previous deeper ones.

When the wetlands were initially constructed, there was a further, final, shallow cell. However unexpectedly high flows during an early rain event caused complete failure of the bund at the outflow end of this cell, which was unable to be repaired. This cell was not included in the monitoring. It did however, retain wetland vegetation and thus probably provide some additional treatment after the outlet monitoring point. Some minor wetland cells were also constructed on the western side of the system, which flowed into the final damaged cell. These cells also have not been included in the monitoring of the system.

Wetland vegetation comprised native species including *Carex virgata* (swamp sedge/pukio), *Juncus pallidus* (giant rush), *Juncus sarophorus* (broom rush), *Cyperus ustulatus* (Giant umbrella sedge), and *Machaerina articulata* (jointed twig rush, previously *Baumea articulata*).

A complete description of the wetland design and planting scheme is provided in Burger et al. (2016).

Table 1: Constructed wetland cell areas. Monitored cells only. Total areas are those supplied by Opus (MacGibbon 2015).

Wetland Cell	Total area (m^2)	Vegetated area (%)	Permanently submerged area (m^2)	% of cell area permanently submerged
Cell 1 (pond)	419	66%	232	55%
Cell 2 (pond)	367	63%	367	100%
Cell 3 (pond)	153	50%	153	100%
Cell 4	1719	0%	158	9%
Cell 5	765	88%	112	15%
Total	3423	82%	935	27%

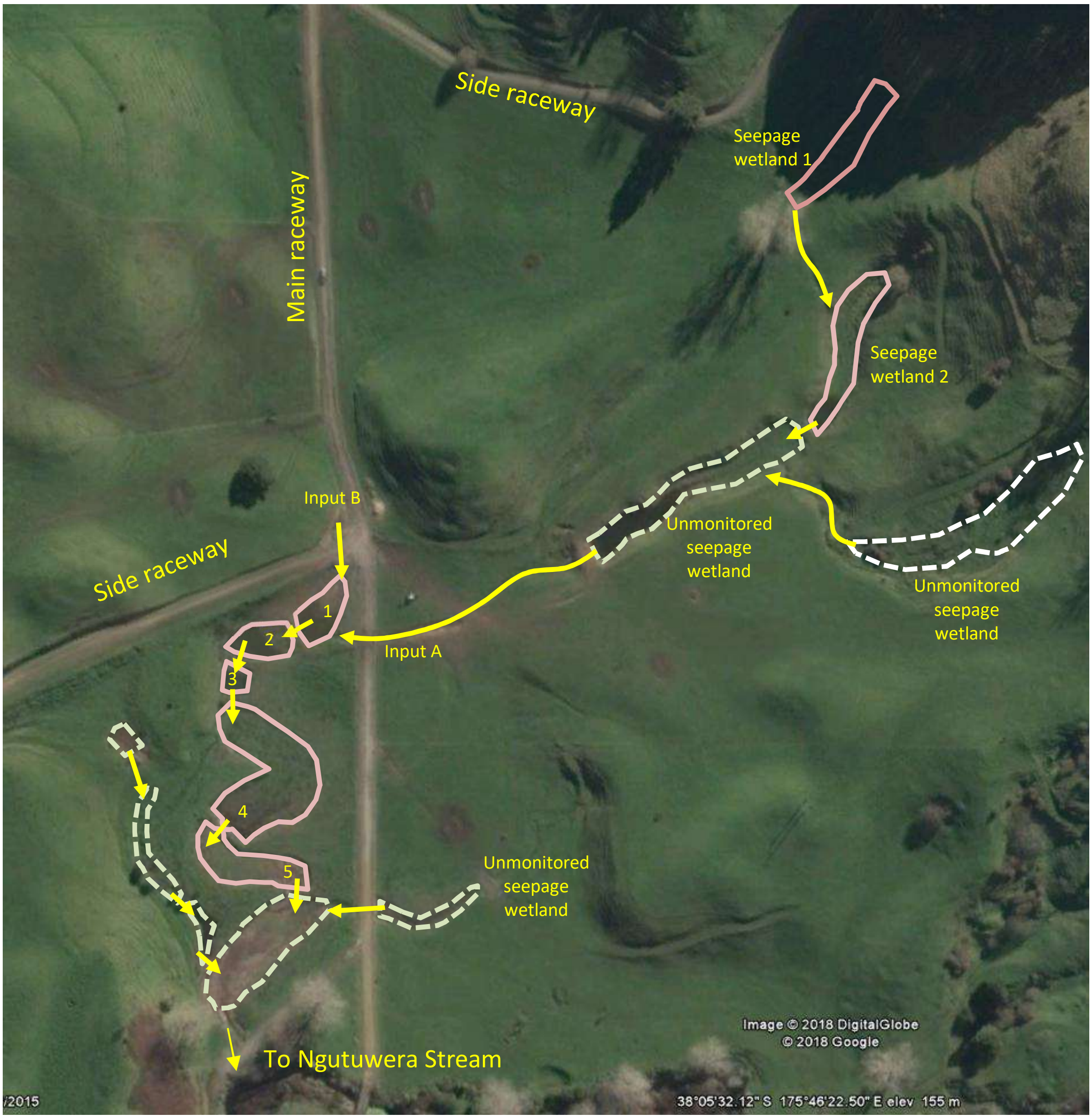

Figure 1: Individual cells of the wetland complex. Monitored locations are Input A and B, as well as the outlet from each of the constructed wetland cells (labelled 1-5). In addition, two labelled seepage wetlands were monitored. Unmonitored cells are outlined with a dashed line. Flow paths are shown with yellow arrows.

Figure 2 shows the contributing catchment for the combined wetland areas. The total River Environment Classification (REC2) calculated catchment area is 45.9 ha, thus the monitored constructed wetland (cells 1-5) equate to around 0.75% of the catchment. A further 6.5 ha of surface runoff is intercepted via the lower side raceway and side drain (total of 52.4 ha). In addition to the monitored wetlands, there is an additional 7063 m^2 of unmonitored seepage and constructed wetlands in the catchment (including the bottom damaged cell which still retains a wetland character), resulting in a total wetland area of 10,486 m^2, or ~2% of the catchment.

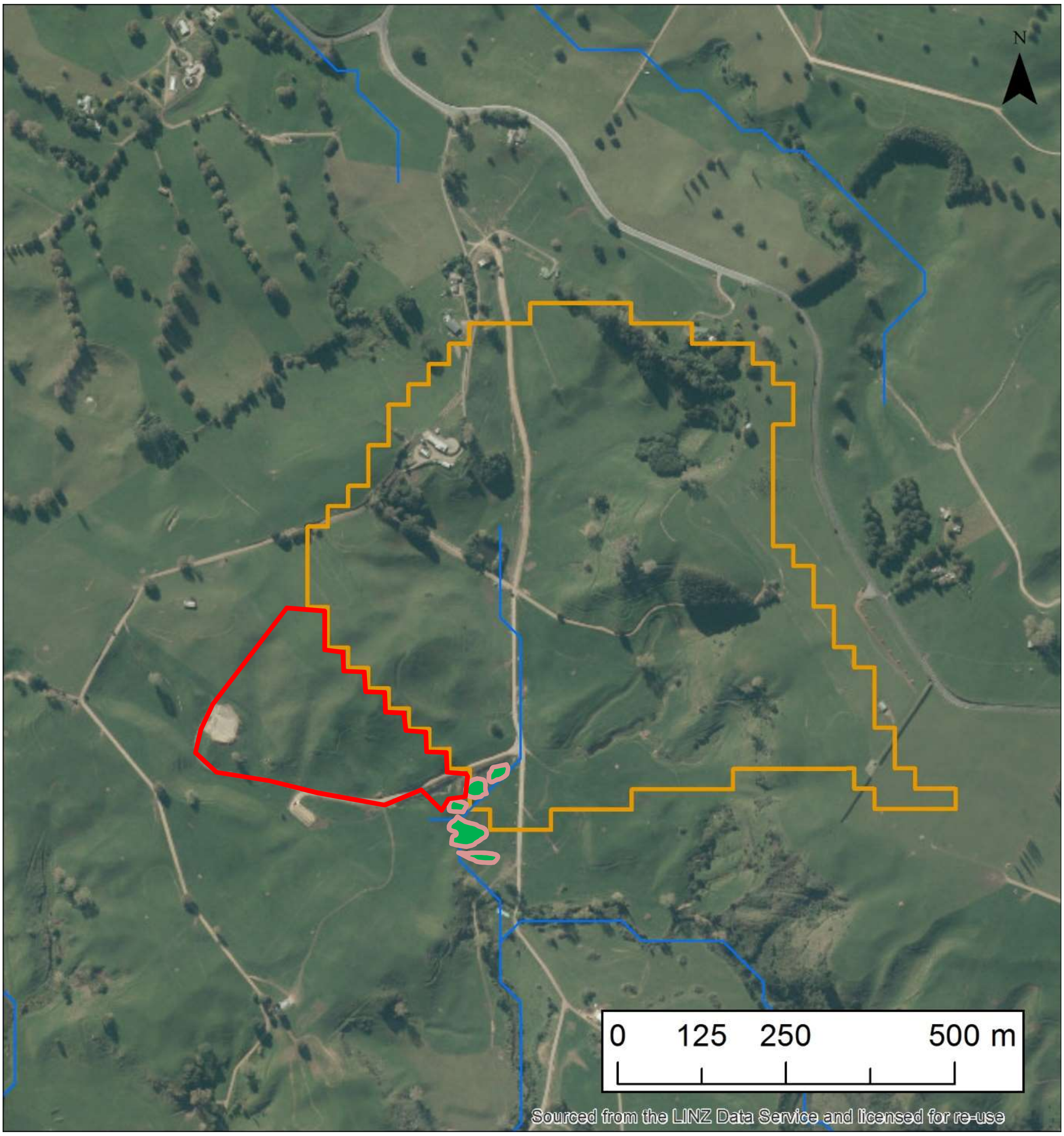

Figure 2: Catchment area of the constructed wetland. The catchment area as defined by REC2 (River Environment Classification) is shown in gold. An additional area to the west (in red) also contributes overland flow to the wetland due to the east-west raceway running down the hill, with a side drain which also enters via the culvert during high rainfall periods. Constructed wetland cells are shown in green with a pink outline (shown at approximate sizes).

4 System Monitoring

Two permanent monitoring stations were established in the constructed wetland (see Figure 3). These were at the outflow from Cell 1, and the outflow of Cell 5 (sampling locations 1 and 5 respectively in Figure 1). Each system consisted of a v-notch weir in the outlet bund. Water flow was calculated based on water depth relative to the bottom of the “V”, with depth measured using a float and counterweight attached to a digital encoder enclosed in a stilling well. Data was collected by a data logger (Neon unit) which telemetered it back to NIWA. Routine (approximately monthly) sampling data from these locations was used to measure baseflow inflows and outflows.

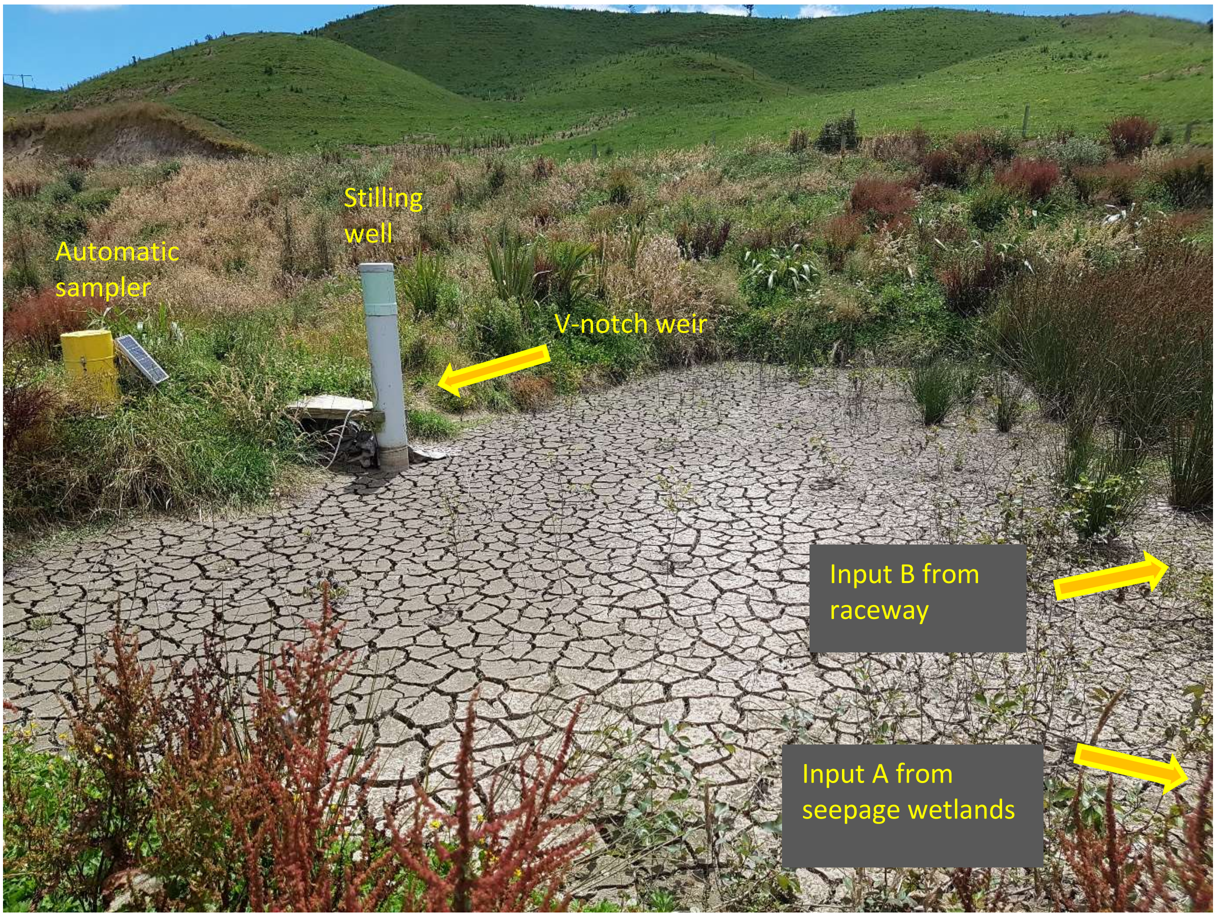

Figure 3: Monitoring system at upstream sampling point. Note the float stilling well and automatic sampler (Site 1). Photo was taken during a summer dry spell. The v-notch weir is obscured by the stilling well.

Automatic samplers were present at each of these locations (Site 1 & 5) and were used for sampling of high flow events. In addition, NIWA placed an automatic sampler at the inflow from the main raceway culvert (Input B) during targeted sampling of high flow events. Flow was not always present from this input, even during some small rainfall events.

Inflows to the seepage wetlands were sampled from installed large sampling wells. Outflows from the seepage wetlands combine and form Inflow A.

Sampling was undertaken at each site (when flow was occurring) during “base-flow” periods. These occurred between high flow events. During winter months, flows never fell to the low flow values recorded during warmer months. Flow entirely halted during much of the summer, and only a single sampling was possible during this period. During on-site sampling, measurements were made of pH, conductivity, dissolved oxygen and temperature using hand-held meters (TPS PTY Ltd, Brendale, QLD, Australia). Water quality samples were returned to the laboratory in ice filled containers and analysed for turbidity, suspended solids (total, volatile and inorganic), phosphorus (dissolved reactive and total), nitrogen (ammonium, nitrate and total), total coliforms and the faecal indicator bacterium, *Escherichia coli* (*E. coli*).

Samples from high flow events were analysed for the same suite of water quality parameters noted above in most instances.

4.1 Event Turbidity

Turbidity was measured through several events during winter 2017 using a short-term deployment (18/7/17 – 14/8/17) of a range of turbidity sensors attached to loggers (Starlogger, Unidata, O'Conner WA, Australia). The turbidity sensors used, and their ranges were:

Greenspan TS1200, Aquamonix, Milperra NSW, Australia	0-500 NTU
Greenspan TS1000, Aquamonix, Milperra NSW, Australia	0-1000 NTU
OBS-3, Campbell Scientific, Logan, Ut, USA	0-1688 NTU.

Sensors were arranged so that those with the greatest range (but least sensitivity) were placed in locations where turbidity was expected to be highest (i.e., influent culvert- Input B, and Sites 1-3). All instruments were pre-calibrated using an appropriate range of formazin standards[1].

4.2 Seepage wetland areal nitrate removal assessment

Potential rates of nitrate removal within the seepage wetlands was assessed using a "Push-Pull" technique on two occasions, modified from the method of Addy et al. (2002). This involved isolating a section of wetland by inserting a chamber (or mesocosm, 0.25 m^2, see Figure 4) with an open top and bottom into the soil, and, after allowing the wetland to recover for a period of 2-3 weeks, adding a known mass of nitrate and a conservative tracer. In this instance a 5 L solution containing potassium nitrate (~16-24 ppm) and lithium bromide (~32 ppm) was used. Mesocosm locations were determined by the availability of suitable wet locations but were spaced as evenly as possible, as shown in Figure 5. As noted by Rutherford (2017), this technique requires input nitrate values to be much higher than ambient values[2], and an adjustment needs to be made to correct for this as well as for temperature effects.

Water and air temperature were recorded at selected mesocosms using portable temperature loggers (Hobo Temperature Pro v.2, Onset, Massachusetts, USA) to assess its effect on nitrate removal.

After set periods (1, 3 and 8 days), a sample of the water was collected and analysed for nitrate, bromide and dissolved organic carbon. The change in the ratio of nitrate to bromide indicates removal.

[1] These sensors are in addition to those deployed at the outlet, and laboratory measurement of turbidity. A relationship between turbidity and suspended solids is based on those physical samples.

[2] Median ambient input nitrate concentration for this wetland was 3960 mg m^{-3}, thus the tracer was around 8 times higher than background inflow concentrations.

At the end of the experiment, soil samples were taken to measure total organic carbon using loss on ignition[3]. Samples were air dried at 80°C for 7d or until no further change in weight was recorded. Samples were then ashed for 8 h at 450°C, allowed to cool and reweighed.

Figure 4: Mesocosm being installed in a seepage wetland.

[3] No sample was taken at the beginning of the experiment as total organic carbon does not normally change to any significant degree during the period of this trial, and also to minimize disruption to the experimental sites.

Figure 5: Mesocosm chamber locations in seepage wetlands. Wetlands are outlined in red. The outflow from the upper wetland flows over the pasture into the second wetland as shown with a dashed line.

4.3 Vegetation Assessment

Transects across the wetland in pre-determined locations (Figure 6) were surveyed in winter (July) and summer (December). Across each transect, plant species and density were surveyed, and standard sized quadrats (0.5 x 0.5 m, 0.25 m^2) used to cut above ground vegetation for each species (except for *Carex* species where this was not practical) and weighed wet. For *Carex*, ¼ of the above ground biomass of a representative plant was harvested. Each bag of plant material was then dried for 7-10 days at 80°C and reweighed. Total biomass for each wetland cell was calculated based on representative areas of the transects from that cell.

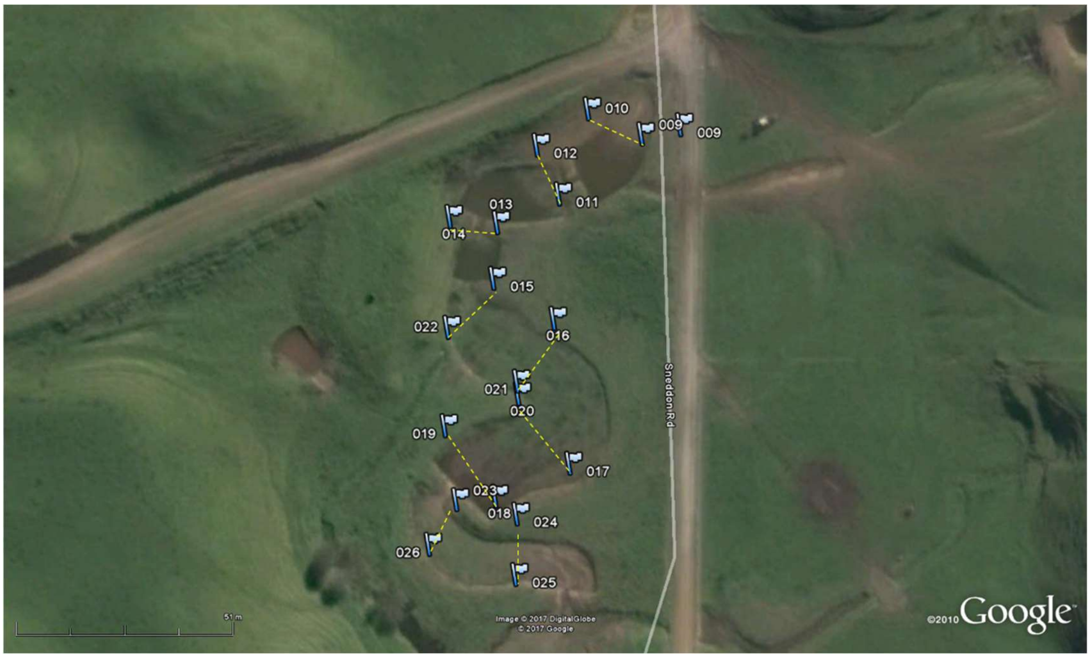

Figure 6: Vegetation transect locations. The first 3 sedimentation pond cells had one transect each. Cell 4 had 4 transects and Cell 5 had 2 transects. (Note Waypoint 009 had to be calculated twice to obtain acceptable accuracy).

4.4 Pond Sediment Accumulation

Sediment samples were collected from 0.01 m^2 quadrats from 3 locations across two transects (6 samples in total) in each of the first three pond cells. In addition, an extra sample was taken from the inlet zone of the first pond cell (i.e., 7 samples in total), to include an accumulation of coarse sand/gravel which had washed off the raceway. Samples were weighed wet and dry (after 7 d drying at 80°C). The entire sample was then ashed for 8 hrs at 450°C (loss on ignition, LOI, as a measure of total organic component). This temperature was chosen compared with the higher 550°C sometimes used to prevent loss of “structural water” associated with clay minerals.

5 Results and Discussion

5.1 Flow

Flow entering and exiting the wetland complex generally reflected local weather patterns. During summer months there was little or no flow entering the wetland, either from the upstream seepage wetlands or from the raceway inflow. At times there was a minor amount of flow exiting the constructed wetland (at the downstream monitoring site), which must have entered as groundwater, although this had entirely dried up by December 2017 (see Figure 3). Outlet flows had a greater baseflow component than the inlet associated with the groundwater inputs directly entering the wetland, as well as some direct rainfall inputs. However, flow peaks were, in most instances, higher at the inflow. Flow buffering within the wetland tended to delay these peaks reaching the outlet. In addition, larger events typically had an input from the culvert (Input B). Where this was the case, peaks at Site 1 tended to be around 10% higher than at the outlet (Site 5).

As contaminant removal processes differ under baseflow and during rain induced peak flows, it was necessary to sample these periods differently. Combining these two types of data to assess the performance of the wetland requires us to define these different flow types. We identified periods where "direct runoff" (a combination of surface runoff and interflow) or rain induced peak flows were present, and periods when flows comprised primarily groundwater-fed "baseflow". These baseflows were often less than 2.5 L s^{-1}, increasing to around 3.5 L s^{-1} in the September-October period (as higher rainfall caused higher groundwater levels). On this basis, we selected 3.0 L s^{-1} as a convenient cut-off point to separate periods of baseflow from when direct runoff was occurring.

Baseflow occurred 63% of the time, with no flow recorded 12% of the time. Flows between baseflow and 50 L s^{-1} occurred 23% of the time, often following a large flow event. Flows between 50 and 100 L s^{-1} only occurred 0.39% of the time, with flows greater than 100 L s^{-1} only present for 0.18% of the time, demonstrating how short a time these peak flows are present. The highest flow recorded exceeded 250 L s^{-1}.

Of the 129 days when flows above baseline were recorded (40% of days with flow), ~48 million litres (i.e., 48,000 m^3) was direct flow (i.e., flow above baseline). Total flow at the site was 96 million litres (i.e., 96,000 m^3), thus over the full drainage season baseflow and direct flow inputs to the wetland were essentially equal[4].

Rainfall at the nearby Lichfield rainfall monitoring station recorded annual rainfall (March 2017 -Feb 2018) at 1927 mm. Based on a catchment of 45.9 ha, around 884,447 m^3 would have landed directly on the catchment, with only about 11% of this recorded entering the wetland. A higher runoff coefficient was expected considering calculated delivery to the river (400-600 L/ha, Woods, Hendrikx et al. 2006), however some of the rainfall is likely to enter deeper groundwater which would bypass the wetland (i.e., flow underneath it), but still end up in the river.

Rainfall was highly seasonal, with a very wet autumn. This resulted in higher flows to the wetland in autumn (Figure 7), with peak flows correlated to zero groundwater deficit induced runoff (Figure 8).

[4] The similarity between baseline and direct flow is entirely coincidental.

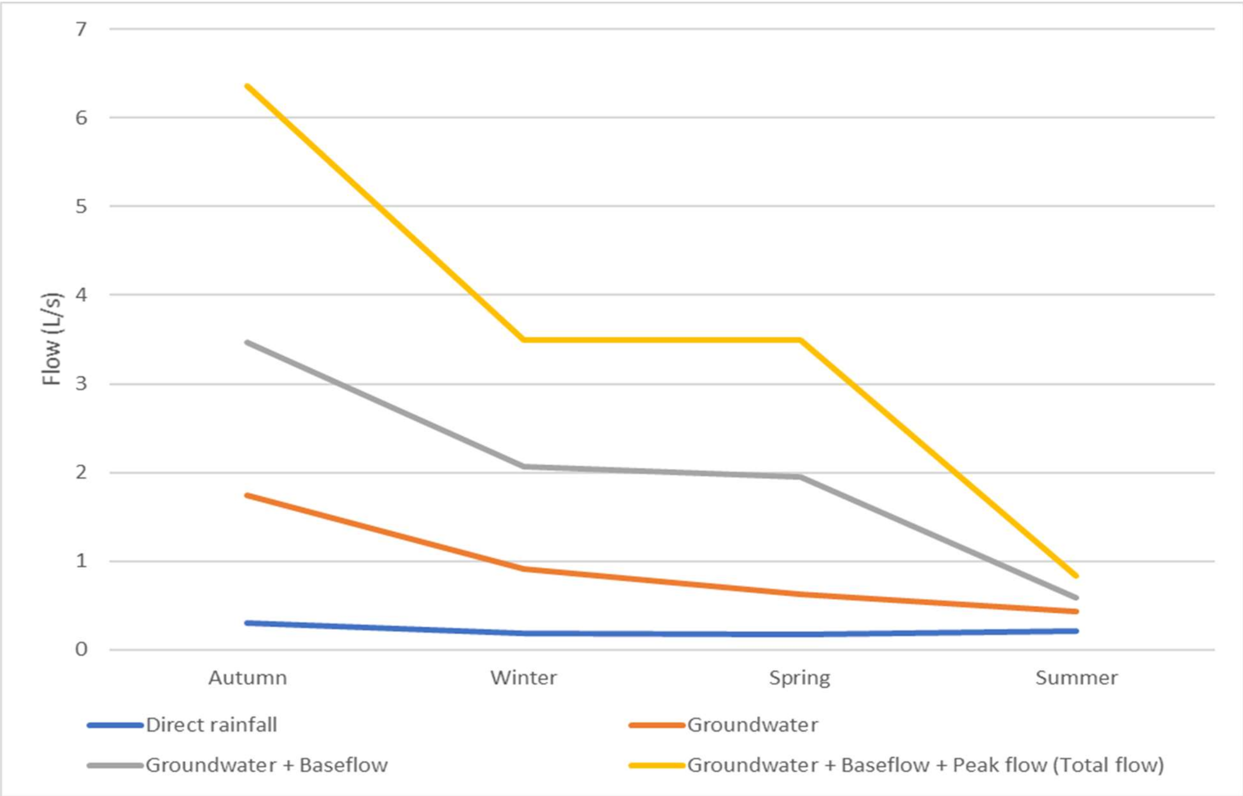

Figure 7: **Seasonal runoff.** Stacked chart of runoff from the wetland[5].

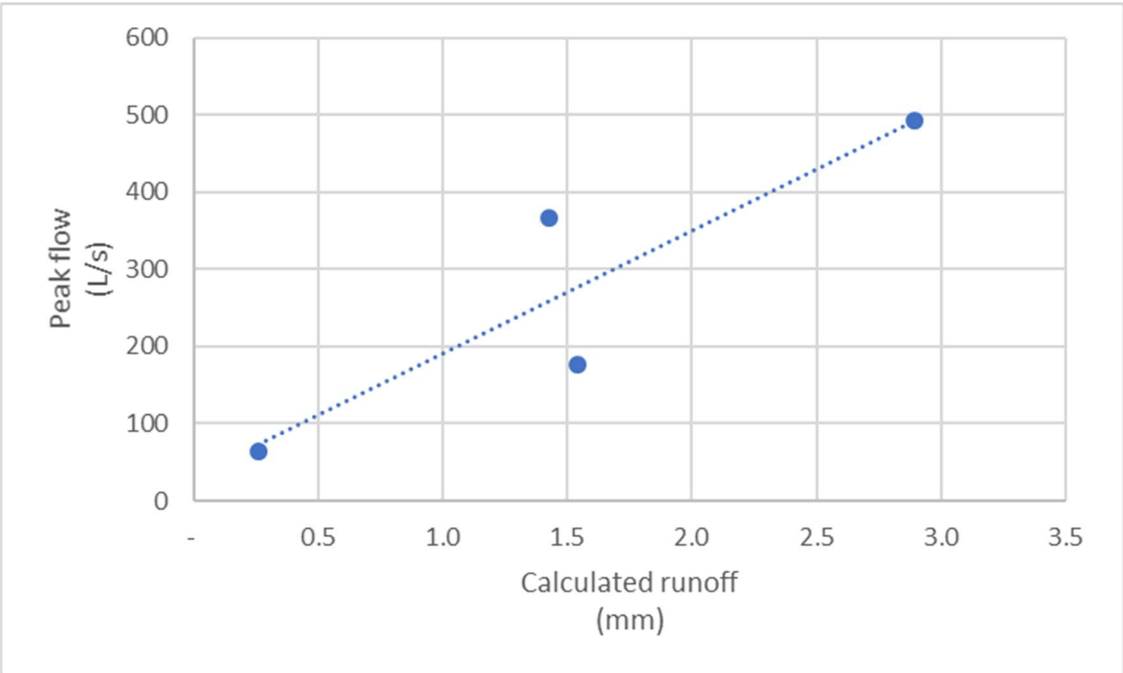

Figure 8: **Peak flow runoff v calculated runoff.**

[5] Note: Although the wetland was mostly dry during summer, some flows did occur during infrequent rain events allowing sampling on one occasion.

5.2 Routine WQ monitoring

The wetland system routine water quality was monitored on a monthly basis during the period when flow was recorded. This normally coincided with low-flow (non-storm event) periods[6]. During wetter months, flow would also enter the wetland from off the raceways (Inflow B), and this was sampled at the culvert (Figure 9) for WQ analysis. Data for the WQ analysis from the various sampling sites are presented in table and graph format. In the graphs the input concentrations from Input B are generally much higher than the other sites, causing details of the other sites to not be discernible. Therefore, each analyte is shown at two different scales to allow values from the other sites to be seen. Many of the contaminants measured were highly variable due to sometimes being taken during periods of very low flow, or at other times during extended wet periods (e.g., during autumn 2017). This is apparent where the contaminant data has high standard deviations compared with average (mean) values. In general, we will refer to median values, which are less skewed by high values.

Mass removal values were calculated from the percent removal between Cell 1 and Cell 5, which has been multiplied by total baseflow.

Figure 9: Input B (culvert outflow) during a storm event.

[6] High flow events were targeted separately as low flow and high flow events typically have different influent and effluent water quality, as well as different dominant contaminant removal mechanisms.

5.2.1 Turbidity

Turbidity data[7] from routine water samples are shown in Figure 10. Water entering the first pond from the upstream seepage wetlands had low turbidity (Input A), as would be expected from most wetland outflows, particularly when they are fenced. Occasional inputs from the farm race (Input B) showed exceptionally high values due to mobilised sand, soil and faecal matter. These inputs combined in the first pond and were still considerably elevated at the outflow (Site 1), despite high settling of suspended solids in the pond.

Between Site 1 and Site 5, turbidity showed no reduction during routine monitoring, being largely associated with low-flow periods when input turbidity was generally low.

Table 2: Routine sampling turbidity concentration data.

Turbidity	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
(NTU)	Constructed wetlands							Natural seepage wetlands	
Median	6	246	9	11	14	10	10	23	6
Average	8	485	42	23	17	12	13	40	8
Standard deviation	7	627	75	33	18	9	10	38	7
Number of samples	10	6	11	9	9	8	11	10	7

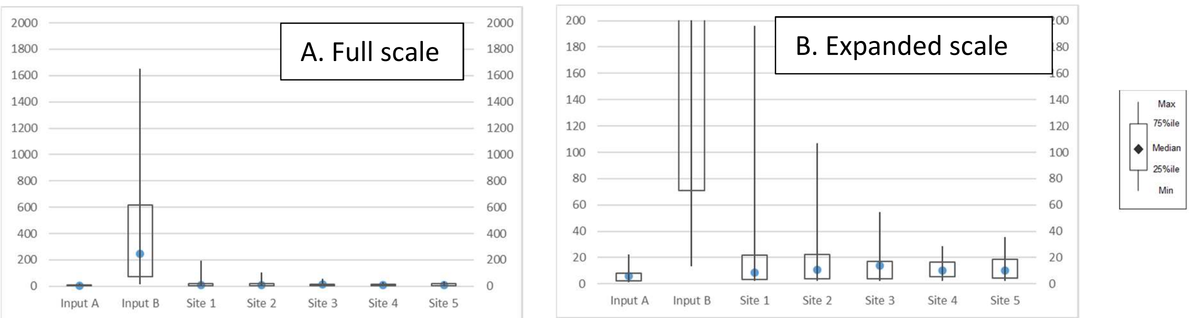

Figure 10: Turbidity at each constructed wetland sampling location. Turbidity is measured as NTU. Routine sampling data. Note differing range for full scale (A) and expanded scale (B) graphs. Expanded scale used to show detail, particularly for sites 1-5.

5.2.2 Suspended solids

Suspended solids data is shown in Table 3 and Figure 11. Removal (from Site 1 to Site 5 median values) was 37%. This equates to an annual removal of 214 kg of SS during baseflows[8].

[7] Note: this data is from laboratory measurement of baseflow samples. Turbidity measurements during events using field deployed instruments is presented later.
[8] See summary table in section 6.

Table 3: **Routine sampling suspended solids concentration data.**

Suspended solids (g m^{-3})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
			Constructed wetlands					Natural seepage wetlands	
Median	7	230	12	11	14	15	8	42	14
Average	13	757	65	49	27	17	17	76	22
Standard deviation	15	1133	116	99	38	12	19	82	24
Number of samples	10	6	10	9	9	8	10	10	7

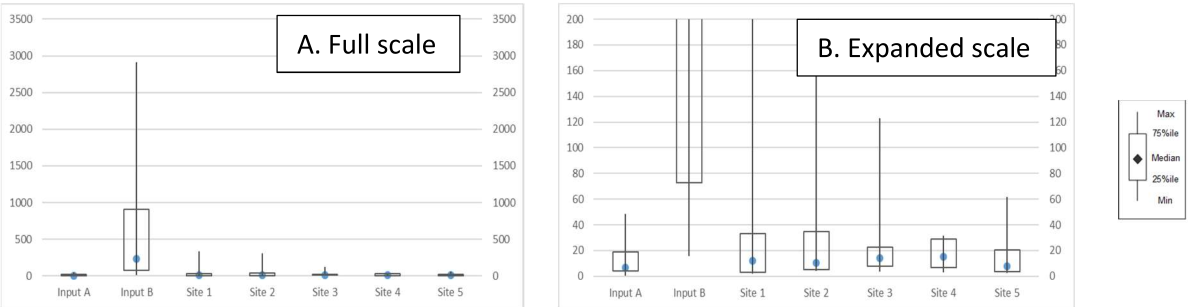

Figure 11: **Suspended solids at each constructed wetland location.** Routine sampling data. SS is measured as (g m^{-3}). Note differing range for full scale (A) and expanded scale (B) graphs. Expanded scale used to show detail, particularly for sites 1-5.

There was a strong correlation between suspended solids and turbidity as shown by Figure 12. Although the relationship was dominated by the high values of Input B, when these are excluded, the slope was remarkably similar (y=0.5294x + 3.283).

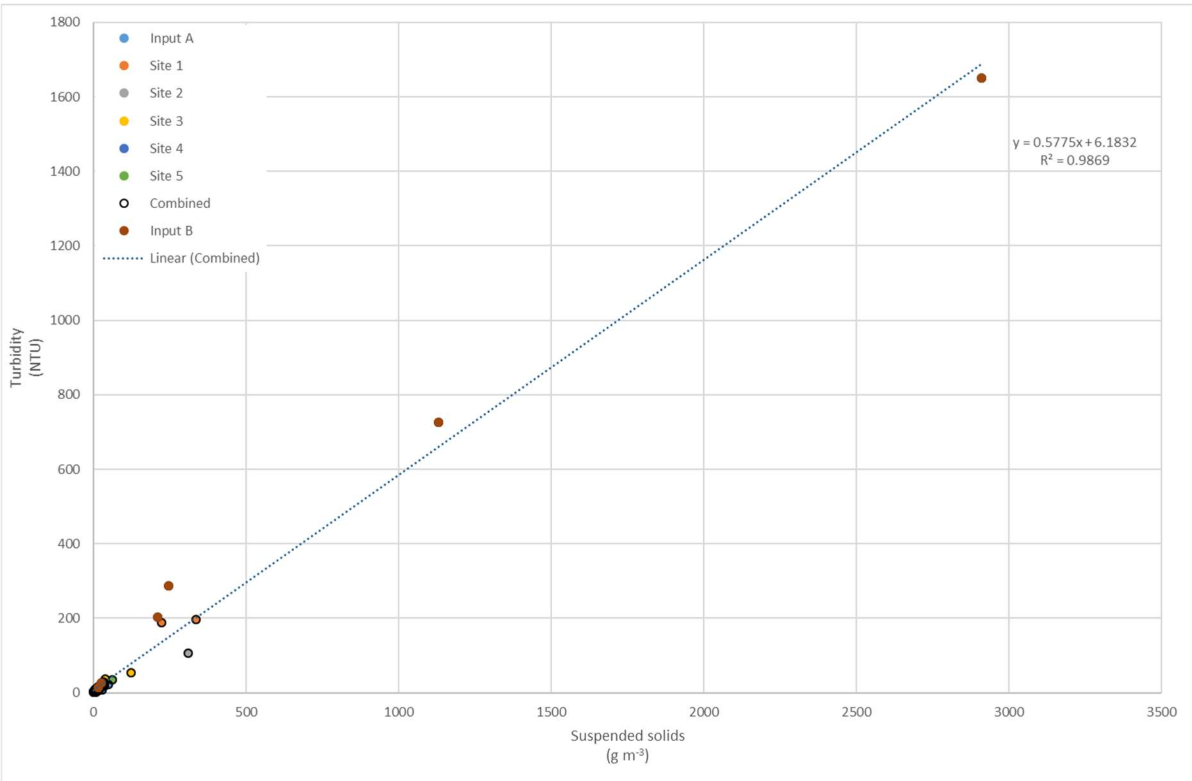

Figure 12: **Suspended solids v. turbidity.**

5.2.3 Volatile and inorganic suspended solids

Volatile suspended solids (Table 4) represent the organic fraction of total suspended solids, with the remainder as inorganic suspended solids (Table 5). Percentage of total suspended solids is based on median values in both tables. The inorganic fraction comprised the majority of the suspended solids in the inflow. The inflow from the race (Input B) would likely carry considerable sand, soil and fine inorganic particles from the race surface and drains. These rapidly settled in the first (and subsequent ponds), leaving volatile solids as an increasing proportion of the total. This would also likely be supplemented by some biogenic production of organic solids from bacterial and algal biomass and decay of plant detritus. The natural seepage wetlands, which combine to form Input A, did not appear to be exporting much particulate organic material.

Table 4: **Routine sampling volatile suspended solids concentration data.**

Volatile suspended solids ($g\ m^{-3}$)	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
			Constructed wetlands					Natural seepage wetlands	
Median	2	107	4	3	4	3	3	14	4
Average	3	132	13	15	13	5	7	27	6
Standard deviation	4	138	20	32	24	4	11	28	7
Number of samples	10	6	9	9	9	8	10	10	7
% of total suspended solids	24%	47%	30%	30%	30%	21%	39%	34%	27%

Table 5: **Routine sampling inorganic suspended solids concentration data.**

Inorganic suspended solids ($g\ m^{-3}$)	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
			Constructed wetlands					Natural seepage wetlands	
Median	4	123	5	10	10	12	5	29	10
Average	10	626	54	33	14	12	9	49	16
Standard deviation	11	1002	100	67	14	8	9	55	17
Number of samples	10	6	9	9	9	8	10	10	7
% of total suspended solids	64%	53%	45%	95%	68%	79%	61%	69%	73%

5.2.4 Nitrogen

Total nitrogen (TN) concentrations in the constructed wetland system are shown in Figure 13 and Table 1. There was no reduction in median TN values between Site 1 and Site 5 during routine sampling[9] which likely reflects the fact that inflows from the seepage wetlands already had some nitrate removed. However during baseflow periods there were significant amounts of diffuse inputs, which were likely of higher concentration than the surface inputs (note Seepage Wetland 2 median TN of 4560 mg m^{-3}). Average flow during baseflow sampling occasions at Site 1 was 4.2 L s^{-1}, while at

[9] In fact a slight increase was recorded.

Site 5 it was 8.8 L s^{-1}. Thus overall, at least half the flow entering the wetland system during baseflow occurred below the sampling location at Site 1 (note: average[10] daily rain directly into the wetland would only equate to 0.2 L s^{-1} additional flow). Using an average of the two seepage wetlands inflow concentrations as likely groundwater concentrations would result in diffuse inputs of around 64 kg in addition to measured inputs of 102 kg over the drainage season. Removal during baseflow was thus estimated to be 59 kg, or 36%[11].

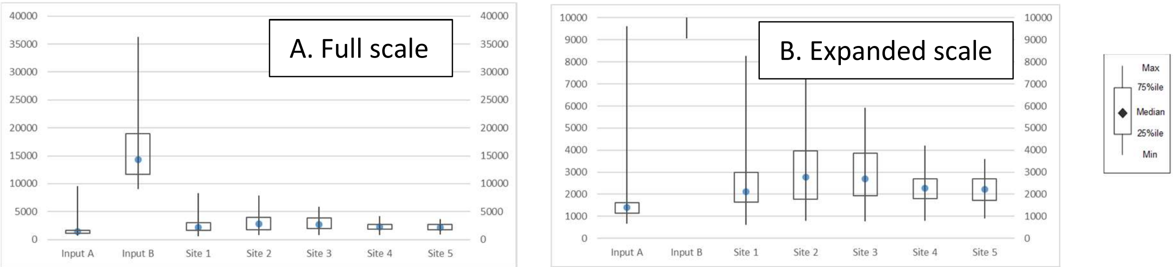

Figure 13: Total nitrogen at each constructed wetland location. Routine sampling data. TN is measured as mg m^{-3}. Note differing range for full scale (A) and expanded scale (B) graphs. Expanded scale used to show detail, particularly for sites 1-5.

Table 6: Routine sampling total nitrogen concentration data.

Total nitrogen (mg m^{-3})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
	Constructed wetlands							Natural seepage wetlands	
Median	1415	14300	2120	2780	2710	2275	2220	1220	4560
Average	2146	17545	2709	3510	3058	2358	2163	1428	4559
Standard deviation	2645	9959	2109	2475	1585	1016	826	941	1641
Number of samples	10	6	11	9	9	8	11	10	7

The different forms of nitrogen are detailed in Table 7. Ammonium-N was a minor component of the inflow, with nitrate-N and organic-N being the dominant forms and of similar importance, with the exception of raceway inputs measured at Input B, where organic-N was more than 3 times higher than nitrate-N and ammonium-N was a greater portion of the total. There was no "apparent" removal of organic-N or nitrate between Sites 1 and 5 based solely on concentration values. This is likely to reflect the fact that Input A had already flowed through the seepage wetlands, removing some of the nitrate in the inflow. However it is likely that additional inputs of nitrate would have occurred in the groundwater inflows to the constructed wetland cells below Site 1. If these inputs had a value close to the medians of the Seepage wetland inputs (see Table 7), concentrations around 2195 mg L^{-1} would be expected. Thus average inputs may have approached 1579 mg L^{-1} ((2195+963)/2). While it is difficult to rely on this methodology, removal would have been around 269 mg L^{-1} (1579-1310) or 17%. The New Zealand Guidelines for Constructed Wetland Treatment of

[10] Median values cannot be used, as most days had no rain, thus median rainfall was 0 mm.
[11] Calculating removal on assumed values for diffuse inflows is imperfect, we consider these to be relatively conservative values because groundwater values are not likely to vary greatly over the short distance between the seepage wetland inflows and the constructed wetland.

Tile Drainage (Tanner, Sukias et al. 2010) predicts nitrate removal for a wetland of 0.75% of the catchment at around 15%, so very close to the value calculated.

Removal of organic-N may have occurred via physical filtration through the wetland vegetation, although no removal was recorded[12]. Ammonium-N, which was a minor component of the inflow during routine monitoring, recorded 57% removal, probably via a combination of nitrification and plant uptake.

Table 7: Routine sampling nitrogen fractions concentration data.

	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
			Constructed wetlands					Natural seepage wetlands	
Ammonium-N (mg m^{-3})									
Median	29	1146	104	116	97	90	45	93	22
Average	47	2270	180	192	186	170	79	231	136
Standard deviation	62	2823	212	182	210	160	73	405	297
Nitrate-N (mg m^{-3})									
Median	1006	2165	963	1120	1330	1221	1310	86	4304
Average	1062	4558	1136	1411	1455	1386	1087	228	4040
Standard deviation	765	5657	1037	1086	1088	987	809	270	1924
Organic-N (mg m^{-3})									
Median	355	8410	533	587	593	665	786	792	248
Average	1036	10717	1393	1907	1416	802	998	969	382
Standard deviation	1926	9983	1427	2381	1488	471	707	625	277
Number of samples	10	6	11	9	9	8	11	10	7

5.2.5 Phosphorus forms

Total phosphorus concentrations in the constructed wetland system are shown in Figure 14 and Table 8.

[12] Inputs of organic-N from groundwater would likely be negligible.

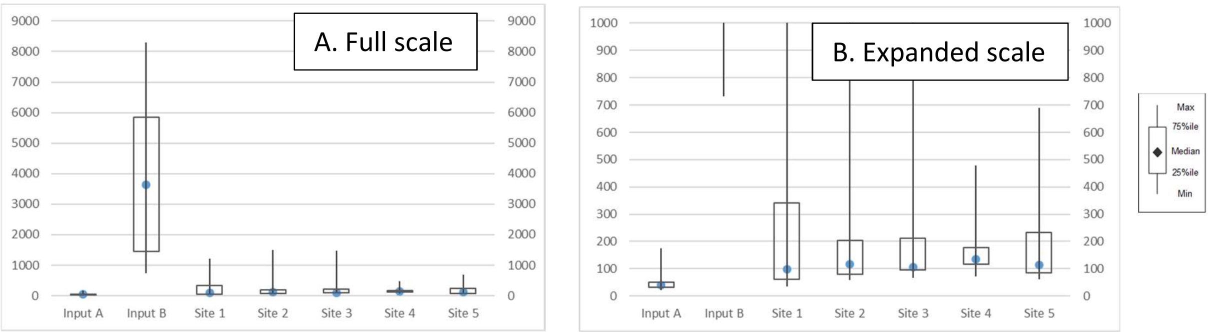

Figure 14: Total phosphorus at each constructed wetland location. Routine sampling data. TP is reported as mg m^{-3}. Note differing range for full scale (A) and expanded scale (B) graphs. Expanded scale used to show detail, particularly for sites 1-5.

Table 8: Routine sampling total phosphorus concentration data.

Total phosphorus (mg m^{-3})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
	Constructed wetlands							Natural seepage wetlands	
Median	40	3635	97	118	107	137	114	130	74
Average	63	3930	274	319	314	180	200	166	329
Standard deviation	55	3008	369	471	460	131	184	159	643
Number of samples	10	6	11	9	9	8	11	10	7

Median TP inputs of 97 mg m^{-3} equated to annual surface inputs of around 4.7 kg, of which between 20% and 37% was dissolved. An additional 8.4 kg was calculated to have entered as diffuse inputs based on measured differences in flow between the two flow sampling locations, and applying the nutrient concentrations found in the inflow to the seepage wetlands. Overall removal was around 8 kg, or 58%.

Table 9: Routine sampling dissolved reactive phosphorus concentration data.

Dissolved reactive phosphorus (mg m^{-3})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
	Constructed wetlands							Natural seepage wetlands	
Median	11	744	33	43	38	41	39	4	22
Average	17	837	53	49	46	46	43	5	252
Standard deviation	21	383	54	32	29	19	26	4	557
Number of samples	10	6	11	9	9	8	11	10	7
% of total phosphorus	28%	20%	34%	37%	36%	30%	34%	3%	30%

5.2.6 Total coliforms and *E. coli*

The influence of the constructed wetland complex on faecal indicator bacteria concentrations during routine sampling is illustrated in Figure 15. *E. coli* is the preferred indicator of microbial pollution, although total coliform data can also be instructive. Table 10 and Table 11 include geometric means, the preferred averaging metric for faecal bacteria.

Table 10: Routine sampling total coliform concentration data.

Total coliforms (MPN 100mL^{-1})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
	Constructed wetlands							Natural seepage wetlands	
Median	7,832	701,500	17,731	22,811	17,329	6,488	2,500	3,055	5,172
Average	7,161	6,606,798	232,296	43,774	56,917	14,512	6,507	6,059	22,265
Geometric mean	5,347	646,166	24,957	17,948	19,631	8,520	3,520	4,272	8,130
Standard deviation	4,789	12,271,829	581,498	57,371	88,486	18,637	7,831	5,905	39,075
Number of samples	8	4	10	8	8	7	10	8	5

Percentage removal of total coliforms during base-flow sampling using geometric means was 85% (or a little less than 1 order of magnitude) between Site 1 and Site 5. Removal was similar for *E. coli*, at 88%. Final *E. coli* concentrations had a geometric mean of 278 MPN 100 ml^{-1}, which is relatively low, considering the influent geometric mean of ~650,000 entering at Input B, and a maximum recorded value of 2,224,000 MPN 100 ml^{-1} (see Figure 15). Inputs from groundwater were likely to be minor, as shown by the inflow values to the seepage wetlands.

Table 11: Routine sampling *Escherichia coli* concentration data.

E. coli (MPN 100ml^{-1})	Input A	Input B	Site 1	Site 2	Site 3	Site 4	Site 5	Seepage 1	Seepage 2
	Constructed wetlands							Natural seepage wetlands	
Median	530	438,530	1,931	2,234	1,467	657	238	153	161
Average	1,520	777,716	31,733	13,667	12,786	2,714	752	278	332
Geometric mean	672	65,402	2,288	4,378	2,604	1,038	184	95	238
Standard deviation	2,195	1,037,222	78,392	22,016	25,188	5,280	1,428	401	344
Number of samples	8	4	10	8	7	7	10	8	5

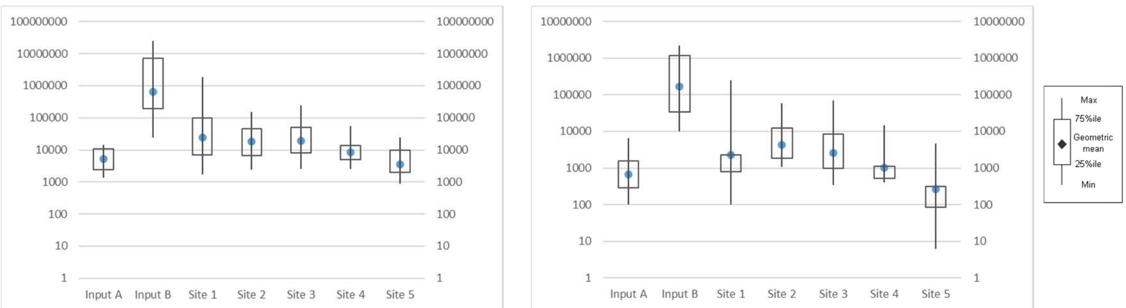

Figure 15: Total coliforms and *E. coli* at each constructed wetland location. Left graph, TC. Right graph, EC. Note Log vertical scale. Average value is the geometric mean.

High Flow Events Water Quality Data

High flow events resulting from rainfall contain direct runoff, a combination of overland flow and interflow (interflow is shallow groundwater flowing through the unsaturated soil zone). At this site, they resulted in increased flows from the seepage wetlands, direct seepage into the base of the constructed wetland system, as well as (in most instances) direct runoff from the raceway. Individual events are detailed below, followed by a general high flow events summary. Mass removal values are based on influent concentrations and recorded flow at Sites 1 and 5 during each event. Where specific inflows were sampled from Input B, flow values have been assigned based on the flow and the ratio of dissolved components as measured at Site 1 prior to inflow occurring at Input B.

5.2.7 April 6th, 2017

A rain event occurred on the 6-7th April, 2017, with 15.7 mm falling, following on from 117 mm of rain in the previous 2 days. Outflow and sample times are shown in Figure 16.

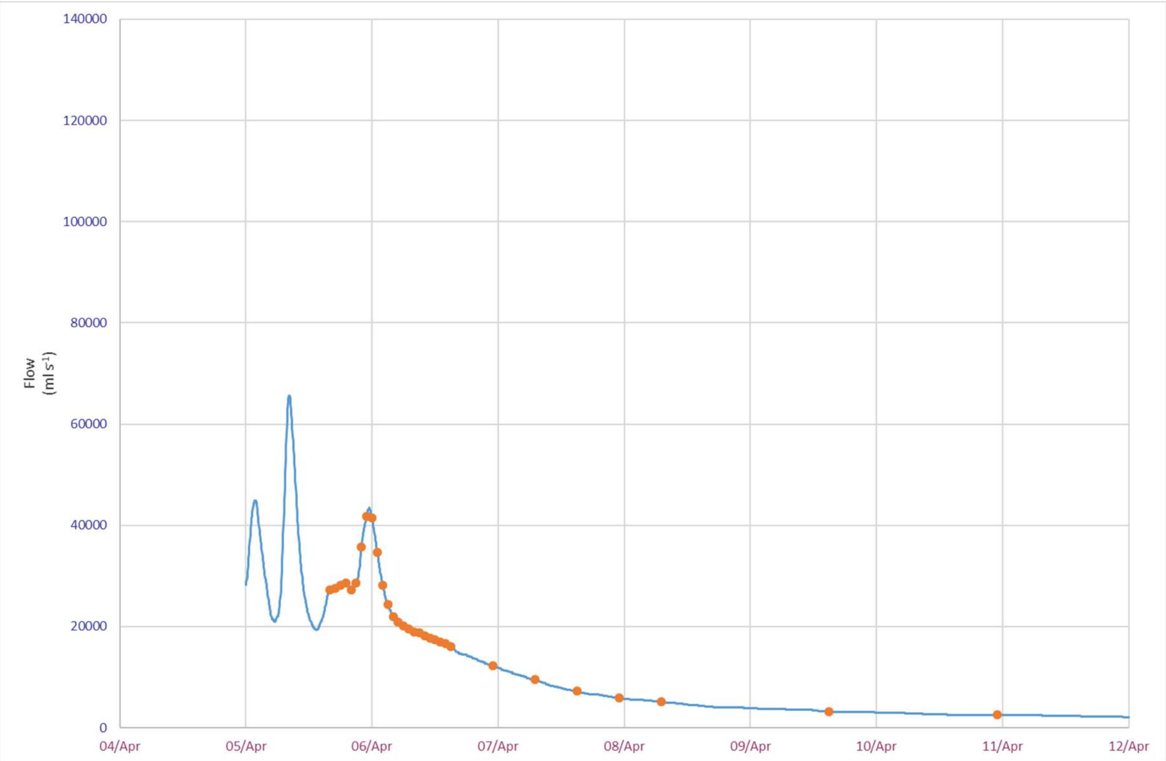

Figure 16: Constructed wetland outflow data for April 6th, 2017 rain event. Note: upstream flow data was not able to be recorded. Orange dots indicate sample times.

Water quality data is shown in Table 12. At this time, separate sampling of Input B had not been instituted. Thus removal in the first cell is not specifically accounted for. Regardless of this, a high percentage of solids present at Site 1 (outflow of the first cell) were removed (96%), equating to over 500 kg of solids. In addition, over 60% of total phosphorus was removed (around 0.5 kg). There was however a modest increase in total nitrogen (12% or 1.3 kg) apparently associated with release of nitrate. This is probably nitrate entering the wetland via seepage through the base. The influence of an unsampled event the previous day is uncertain.

Table 12: Water quality data from April 6th, 2017 rain event.

Site 1	Turbidity NTU	SS $g\ m^{-3}$	DRP $mg\ m^{-3}$	TP $mg\ m^{-3}$	NH_4-N $mg\ m^{-3}$	NO_3-N $mg\ m^{-3}$	Organic N $mg\ m^{-3}$	TN $mg\ m^{-3}$
Average	151	171	80	264	112	1791	1246	3149
Median	4	5	25	68	73	1925	754	3095
Standard deviation	290	329	110	379	121	947	1117	1351
Number of samples	28	28	28	28	28	28	28	28
Mass (kg)		541	0.2	0.8	0.6	5.6	4.9	11.1
Site 5								
Average	5.6	6.3	33.4	97.5	15.3	2887	601	3503
Median	4.7	5.4	10.0	63.0	14.0	2510	460	3390
Standard deviation	3.0	3.4	47.9	76.9	9.0	961	285	863
Number of samples	33	33	33	33	33	33	33	33
Mass (kg)		19.7	0.1	0.3	0.05	10.3	2.1	12.4
Mass removal (kg)		521	0.1	0.5	0.5	-4.7	2.9	-1.3
% removal		96%	55%	61%	91%	-84%	0.6	-12%

5.2.8 May 12th, 2017

A high flow event occurred from 11-16th 2017. Flow data and sample times are shown in Figure 22. Peak flow values exceeded the standard rating curve values for the v-notch weirs installed (max 68 L s^{-1}) as water overtopped the weir, and thus a modified rating curve was produced, using the bank contours to produce a flow value. This method is not as accurate as when flows are confined within the area of the v-notch, however the upstream and downstream weirs had similar bank contours, and thus values are broadly comparable. The maximum flow at the upstream location was 123 L s^{-1}, and at the downstream was 114 L s^{-1}. Due to other inputs (diffuse seepage and direct rainfall), there was more water exiting the wetland complex at Site 5 (7141 m^3 over the whole event) than was measured at Site 1 (5378 m^3). Only 3.4 mm of rain was recorded at nearby Lichfield, suggesting localised rainfall was probably much higher at the Baldwin farm.

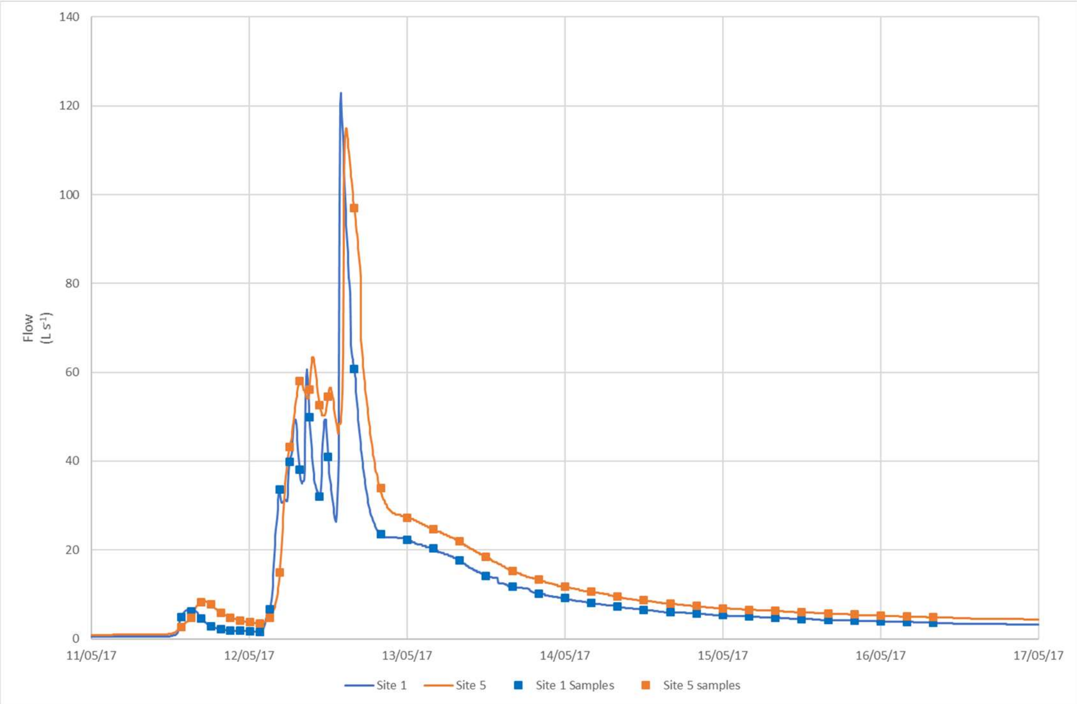

Figure 17: **Flow data for May 12th, 2017 event.**

Suspended solids concentrations at Site 1 and 5 are shown in Figure 18. Inflow concentrations were high[13]. At Site 1, 1041 kg of suspended solids was entering the wetland system, of which over 80% was inorganic material. Over 600 kg (59%) was removed by the constructed wetland system.

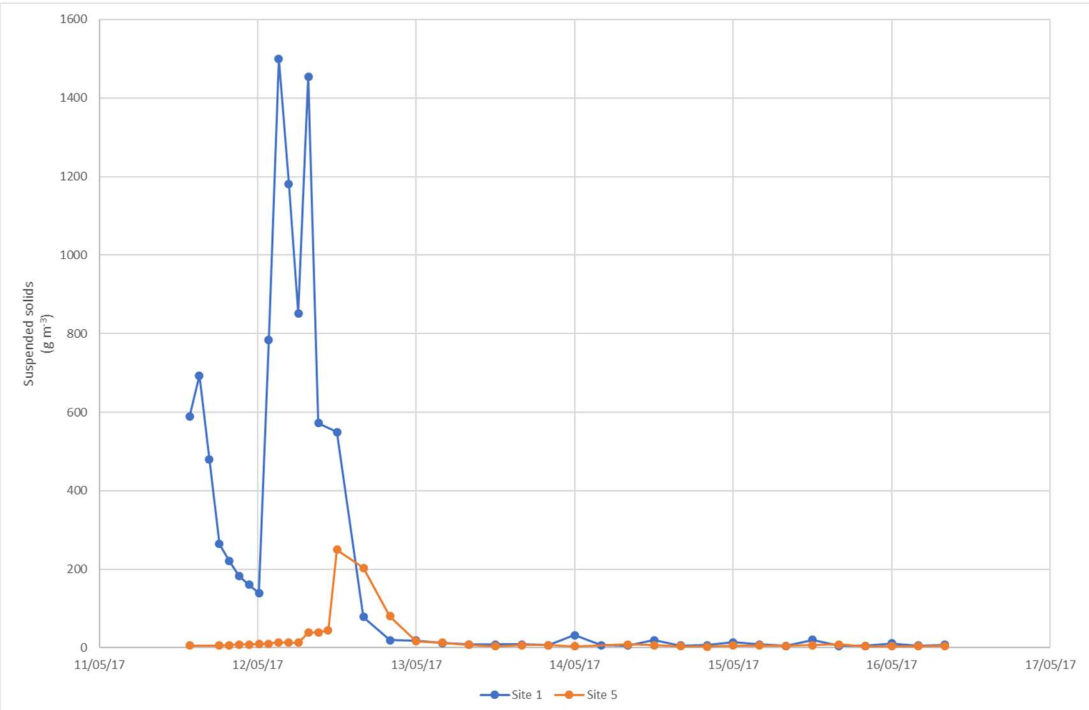

Figure 18: **Suspended solids concentrations during May 12th, 2017 event.**

[13] Most of this input was from the runoff from the race. At the time of this sampling, the race input was only sampled manually when deploying and collecting the automatic samplers.

Table 13: Water quality for May 12th event.

Site 1	Turbidity NTU	SS g m-3	VSS g m-3	Inorganic SS g m-3	DRP mg m-3	NH_4-N mg m-3	NO_3-N mg m-3	Organic N mg m-3	Total N mg m-3	Total P mg m-3	Total coliforms MPN 100 ml-1	*E. coli* MPN 100 ml-1
Average	228	262	11	64	130	391	1,776	1,963	4,130	631	4,676	2,242
Median	9	19	4	13	37	160	1,750	788	3,330	118	725	310
SD	367	416	24	153	174	388	684	2,132	2,168	835	1,320,973	206,128
Number of samples	38	38	9	9	38	38	38	38	38	38	14	14
Mass (kg)		1,041			0.6	1.3	11	8	20	3		
Site 5												
Average	23	24	6	27	19	40	1,619	603	2,262	102	3,034	422
Median	7	7	0.7	4	9	23	1,790	434	2,380	51	2,110	200
SD	50	52	16	65	29	44	871	389	836	138	80,287	19,468
Number of samples	36	36	9	9	36	36	36	36	36	36	13	13
Mass (kg)		429			0.2	0.5	12	6	18.9	1.5		
Mass removal (kg)		612			0.4	0.8	-1.1	1.3	0.9	1.1		
% removal		59%			64%	63%	-10%	17%	5%	42%	35%	81%

DRP and TP (Figure 19) show a similar pattern to suspended solids. Total inputs at Site 1 were 0.6 and 2.5 kg respectively. By Site 5 these had reduced to 0.2 kg (64% removal) and 1.5 kg (42% removal) respectively.

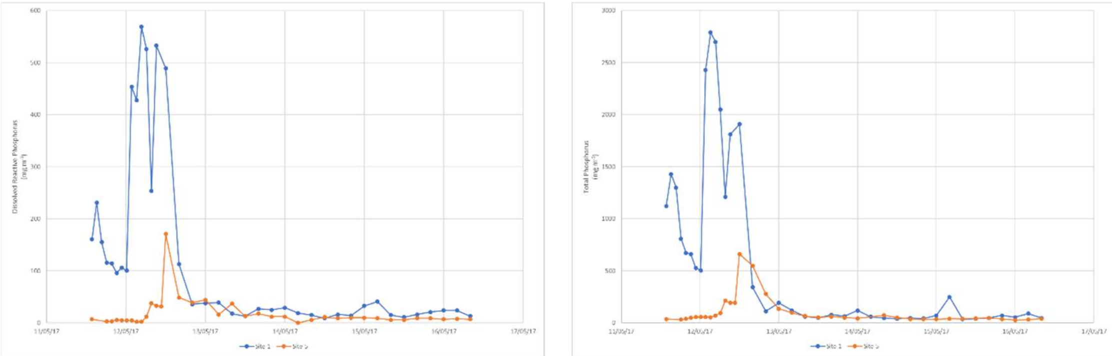

Figure 19: Dissolved reactive and total phosphorus concentrations during May 2017 event. Note differing vertical scales. Dissolved reactive (left) and total phosphorus (right) graph.

Of the dissolved nitrogen fractions, nitrate was the main component entering the constructed wetland (see Figure 20), even though the input from the seepage wetlands would likely have had some portion removed via denitrification. While there may have been some removal of nitrate, the diffuse inputs to the wetland outweighed this slightly, resulting in a 10% increase in nitrate mass by Site 5. Organic-N in the inputs however were even higher that the dissolved fractions, with most likely originating from the raceway. The overall input of total-N measured at Site 1 was 20 kg, which reduced only slightly to 19 kg during this event.

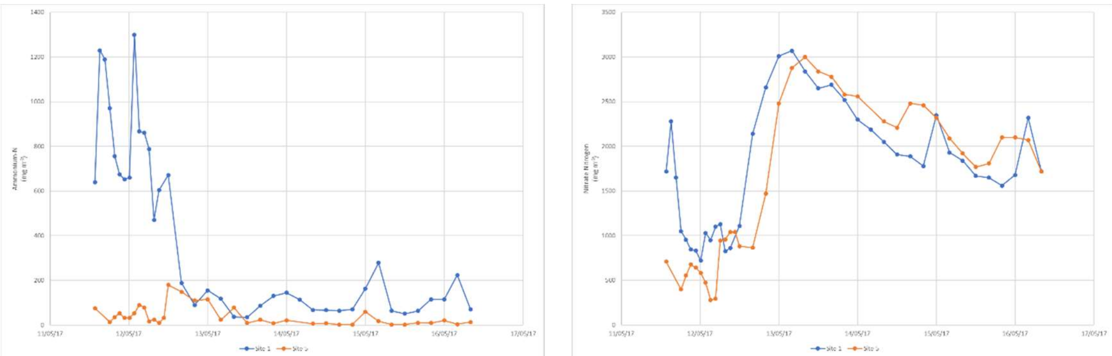

Figure 20: Ammonium-N and nitrate concentrations during May 2017 event. Note differing vertical scales. Ammonium-N (left) and nitrate (right) graph.

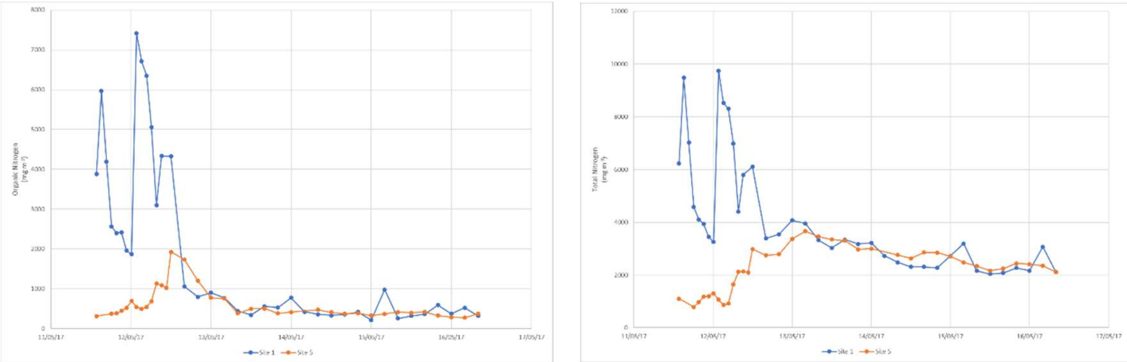

Figure 21: Organic and total nitrogen concentrations during May 2017 event. Note differing vertical scales. Organic (left) and total nitrogen (right) graph.

Both total coliforms and *E. coli* showed reductions between Site 1 and Site 5 (35% and 81% respectively). Higher removals would be evident if sampling had been undertaken in the inflow from the race, however a sampling system for that location was not established until after this event.

5.2.9 August 9th 2017

A high flow event occurred during the period from 9-11 August 2017, with 18.6 mm falling during this period. Flow data and sample times are shown in Figure 22. The main inflow during base-flow from the seepage wetlands increased >10-fold above baseline (from 0.7 L s^{-1} up to a peak of 7.6 L s^{-1}), however the inflow from the race (Input B) went from zero input to around 36 L s^{-1}, with flow from this source continuing for 18 hours. During this period, it contributed an estimated 984 m^3 of water, whereas the inflow from the seepage wetlands (Input A) was estimated at 763 m^3 over the 2.5-3 day high-flow event. In combination they equalled 1748 m^3 measured at Site 1. At the downstream flow measuring location (Site 5), flow over the 3 days equalled 2149 m^3, an increase of 402 m^3 or 23% above Site 1. These inputs are likely to be from seepage through the base and sides of the wetland, as well as some direct input from rain[14].

[14] Note: while diffuse subsurface inputs will have contributed some dissolved nutrients, direct inputs of particulate material from overland flow to the constructed wetland were considered negligible.

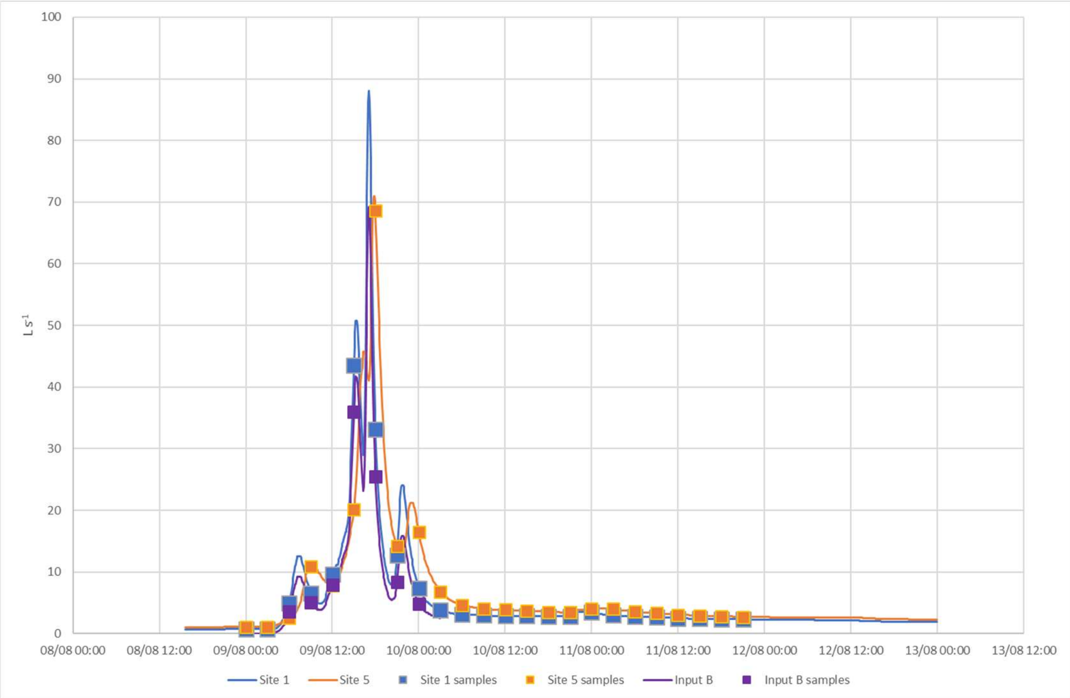

Figure 22: Flow data for August 9th, 2017 event. Samples were taken on a time basis (3 hourly).

Inflow from the race carried considerably higher concentration of contaminants than from the seepage wetlands. However, some contaminants were removed highly effectively (see Table 12). Turbidity can be considered a rough analogue for suspended solids. At Site 1, where turbidity was continuously monitored, the effect of the inflow from the race can be seen in considerably higher than background values. However, as can be seen from Figure 23, much of it was removed within the wetland system. On occasions, large amounts of sand and gravel entered the first wetland cell (configured as the first of three sedimentation ponds). A large amount of this debris would be visible near the inflow point, which had effectively been removed prior to even reaching the turbidity sensor. Thus the overall system was even more effective at removing turbidity (and also suspended solids) than is shown by this figure.

Table 14: Water quality for 9th August event.

Input B	Turbidity NTU	SS $g\ m^{-3}$	DRP $mg\ m^{-3}$	NH_4-N $mg\ m^{-3}$	NO_3-N $mg\ m^{-3}$	Organic N $mg\ m^{-3}$	Total N $mg\ m^{-3}$	Total P $mg\ m^{-3}$
Average	1,722	5,137	995	3,271	96	25,676	29,043	11,466
Median	2,400	3,040	894	2,173	26	27,729	29,400	14,000
SD	1,159	8,031	397	2,095	131	14,726	16,361	6,682
Number of samples	7	7	7	7	7	7	7	7
Mass (kg)		2,968	0.82	2.46	0.08	23.16	25.70	11.00
Site 1								
Average	469	685	362	1,048	575	5,679	7,302	2,639
Median	262	499	69	462	661	2,560	3,790	1,210
SD	530	732	505	1,424	330	7,237	8,279	3,558
Number of samples	20	10	20	20	20	20	20	20
Mass (kg)		1910	1.06	3.08	0.48	19.51	23.07	9.89
Site 5								
Average	57	66	103	389	1,814	1,617	3,819	489
Median	7	7	41	76	1,819	474	2,985	113
SD	97	132	137	491	681	2,072	1,994	749
Number of samples	18	10	18	18	18	18	18	18
Mass (kg)		682	0.55	1.76	2.43	8.07	12.26	2.84
Mass removal (kg)		1228	0.52	1.32	-1.94	15.09	13.44	8.16
% removal		41%	49%	43%	-401%	65%	52%	74%

Note: it appears the automatic sampler at Input B only captured some of the event. Thus percent removals are based on mass removal between Site 1 and Site 5.

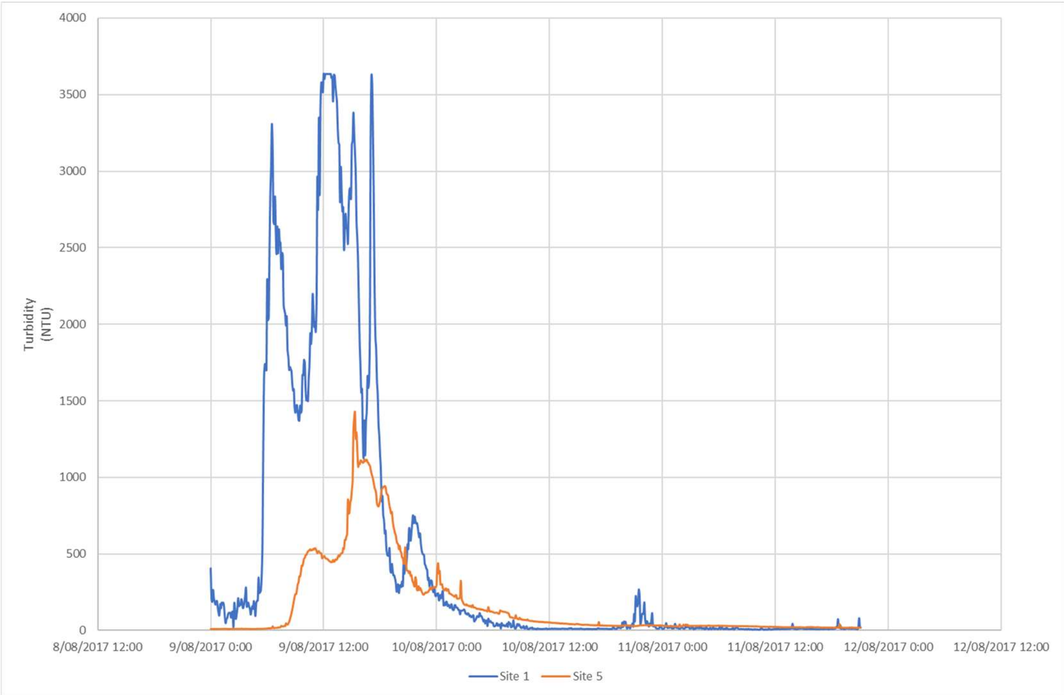

Figure 23: **Turbidity data for August 2017 flow event.**

Suspended solids concentrations are shown in Figure 24. Clearly runoff from the race (Input B) has the highest concentration, contributing an estimated 2,968 kg of material during this event. Significant amounts are removed by settling in the first wetland cell, along with some dilution from the input from the seepage wetlands. By Site 1 the flow is carrying an estimated 1,910 kg of suspended solids, so over 1,000 kg was removed by settling in the first cell. By Site 5, this had further reduced to 682 kg, thus the entire constructed wetland complex removed an estimated 2,286 kg of SS.

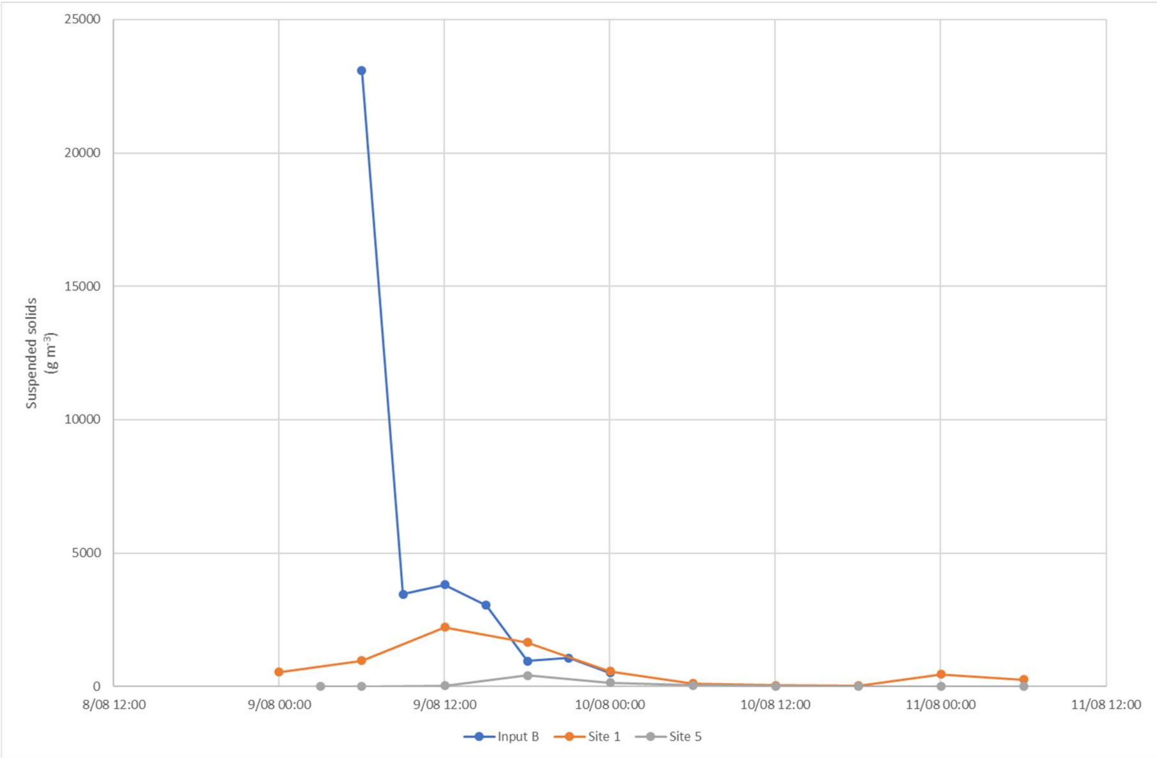

Figure 24: Suspended solids concentrations for August 2017 flow event.

DRP and TP levels rose considerably in the inflows during the high flow event (Figure 25). Total loads from Input B were 0.82 kg and 11 kg respectively. Inputs from the seepage wetland increased the dissolved fraction to 1.06 kg by Site 1, although particulate inputs were lower, and with settling, had reduced to 9.9 kg. By Site 5, the mass of DRP and TP had reduced to 0.55 kg and 2.8 kg respectively.

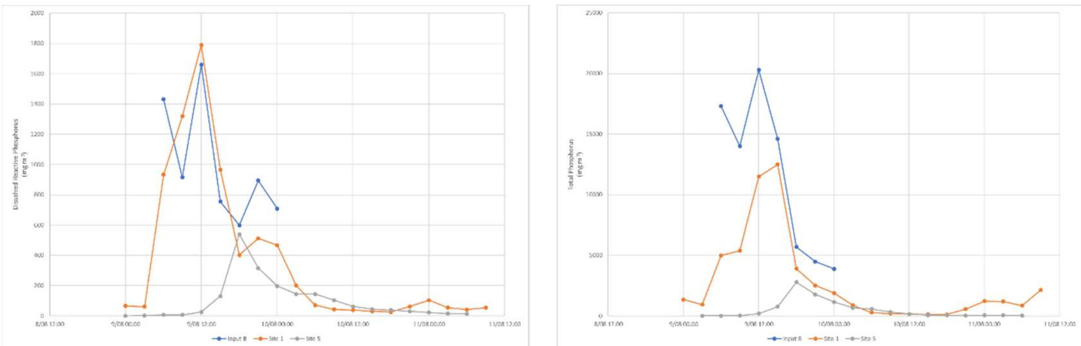

Figure 25: Dissolved reactive and total phosphorus concentrations during August 2017 event. Note differing vertical scales. Dissolved reactive (left) and total phosphorus (right) graph.

Figure 26 shows nitrate and ammonium N concentrations and Figure 27 shows organic and total nitrogen concentrations. Inflow from the raceway (Input B, Table 14) was primarily as organic-N (23 kg), with some ammonium-N (2.5 kg), however nitrate-N was negligible (0.08 kg), as might be expected where the main source of nitrogen is from urine and faecal matter. Total-N from the raceway was 25.7 kg. Inputs from the seepage wetland were largely as nitrate-N (which had increased to 0.48 kg) and ammonium-N (which increased to 3.1 kg). Total-N had reduced to 23 kg after some removal in the first wetland cell. Removal in the rest of the wetland was largely by removal of the organic fraction, which reduced to 8 kg by Site 5, however higher strength diffuse inputs caused an increase in nitrate-N to 2.4 kg. Total nitrogen at the outlet was just over 12 kg, thus with input from the race at 25.7 kg, net removal within the entire wetland system was 13 kg or 52% during the event.

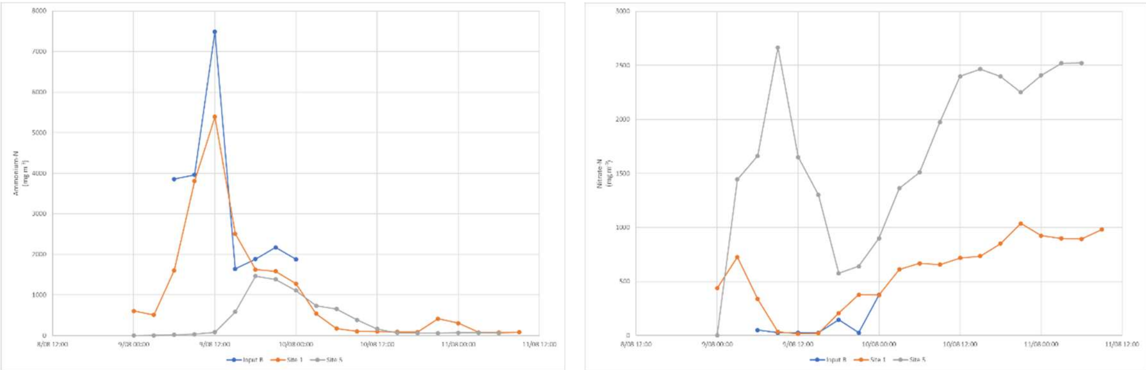

Figure 26: Ammonium-N and nitrate concentrations during August 2017 event. Ammonium-N (left) and nitrate (right) graph.

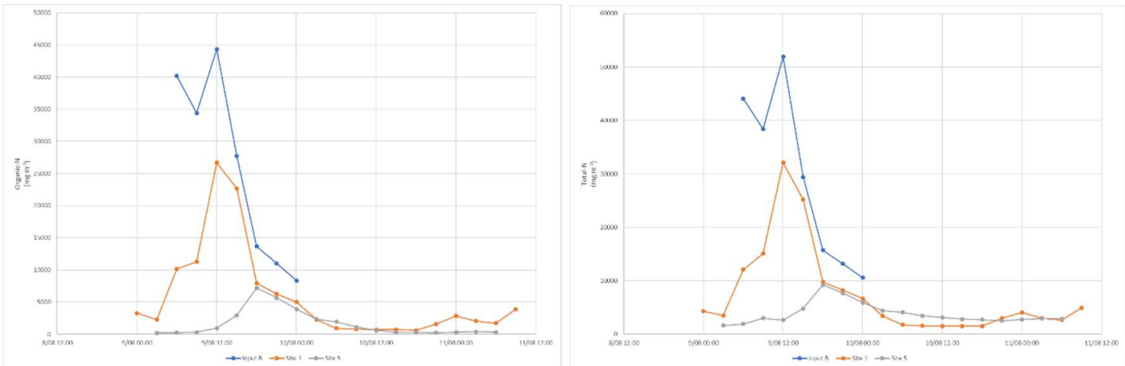

Figure 27: Organic and total nitrogen concentrations during August 2017 event. Organic (left) and total nitrogen (right) graph.

5.2.10 August 20th, 2017

A second flow event in August was sampled. Flow and sample times are shown in Figure 28. At its peak, a flow of nearly 10 L per second was recorded at Site 1, thus smaller than several previous events. Rainfall was 27.8 mm, following 20.5 mm on the previous day.

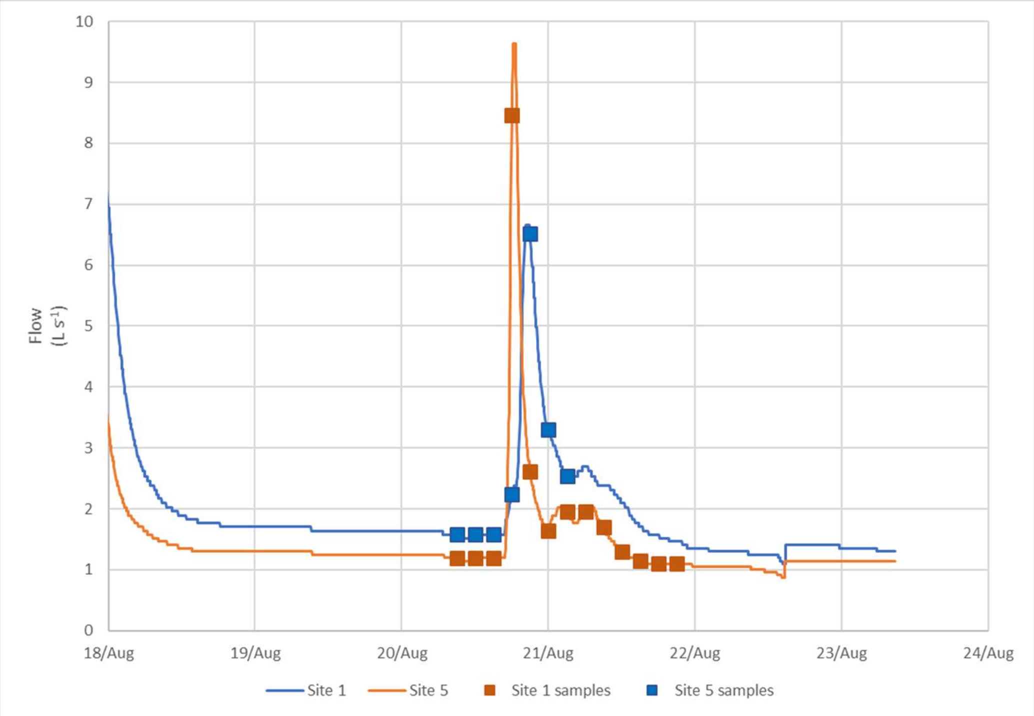

Figure 28: Flow during second event, August.

Turbidity recorded at Site 1 and 5 is shown in Figure 29. Values at Site 1 exceeded the range of the measuring instrument for some periods. Much of the turbidity had been removed by settling processes within the wetland prior to water reaching Site 5, indicating likely similar levels of SS removal.

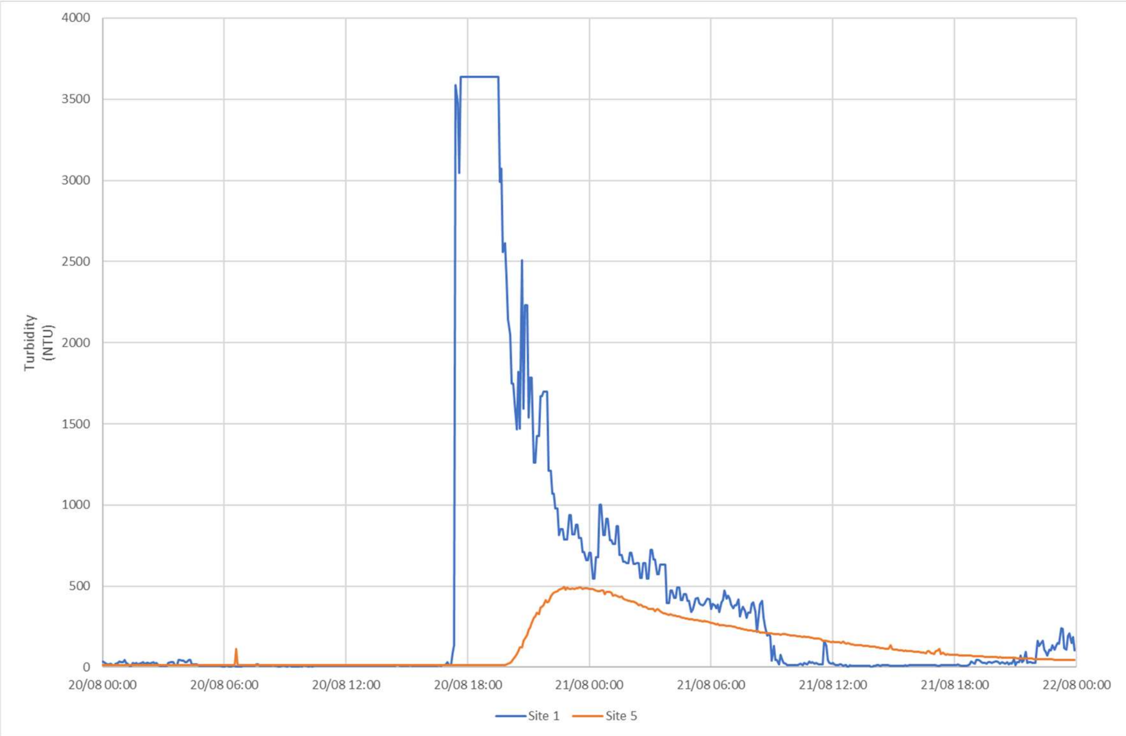

Figure 29: Turbidity for second August flow event.

The wetland effectively removed suspended solids and associated turbidity. Total Nitrogen inputs were not high (4.6 kg) from Input B. However, removal efficiency within the constructed wetland was high (99.7%), primarily by removal of organic nitrogen and ammonium. Nitrate was only a small proportion of the influent nitrogen load, and was not removed by the wetland, with some probably entering via diffuse seepage, again resulting in an increase of this contaminant.

Phosphorus was removed very effectively (>99%), mostly associated with removal of particulate fractions. Removal of *E. coli* was 99.97%, or nearly 4 orders of magnitude.

Table 15: Water quality data for August 19-20th, 2017.

Input B	Turbidity NTU	SS g m-3	DRP mg m-3	NH_4-N mg m-3	NO_3-N mg m-3	Organic N mg m-3	TN mg m-3	TP mg m-3	Coliforms MPN 100mL-1	*E. coli* MPN 100mL-1
Average	1,037	1,178	13,03	6,,028	6.3	30,791	36,825	11,475	250,000	250,000
Median	1,043	1,184	1,200	5790	5.5	28,578	34,850	11,950	250,000	250,000
SD	450	511	269	2,515	5.7	7,264	83,49	2,353		
Number of samples	4	4	4	4	4	4	4	4	4	4
Mass (kg)		101	0.15	0.97	0.0004	3.6	4.6	1.2		
Site 1										
Average	347	394	410	1,633	317	7,506	9,456	2,976	123,520	86,323
Median	200	227	181	905	402	3,966	5,210	1,720	173,287	129,965
SD	441	501	563	1,714	256	7,829	9,343	4,019	93,932	104,899
Number of samples	9	21	21	21	21	9	21	21	21	21
Mass (kg)		77	0.1	0.4	0.1	1.3	2.1	0.6		
Mass removal		24	0.1	0.6	-0.1	2.4	2.5	0.6		
% removal		24%	45%	64%		65%	55%	51%	51%	65%
Site 5										
Average	1.5	1.7	2.8	39.0	1,845	239	2,123	21.0	5,619	70.7
Median	1.4	1.6	2.5	36.0	1,920	268	2,160	19.5	6,015	50.0
SD	0.5	0.5	1.7	11.4	526	73	547	5.6	5,153	75.0
Number of samples	4	16	16	16	16	4	16	16	16	16
Mass (kg)		0.2	0.0003	0.005	0.3	0.01	0.3	0.003		
Mass removal		101	0.2	1.0	-0.2	3.6	4.3	1.2		
% removal		99.8%	99.8%	99%	-222%	99.6%	93%	99.7%	98%	99.97%

Note: removal of nitrate at Site 5 is based on values at Site 1 (rather than Input B), because the major input of nitrate appears to be from the seepage wetlands. Average values for total coliforms and *E. coli* are geometric means.

5.2.11 September 2nd, 2017

A flow event occurred on September 2nd, with peak flows of 53 L s^{-1} at Site 1, and 50 L s^{-1} at Site 5 (Figure 30). Rainfall was 17.8 mm.

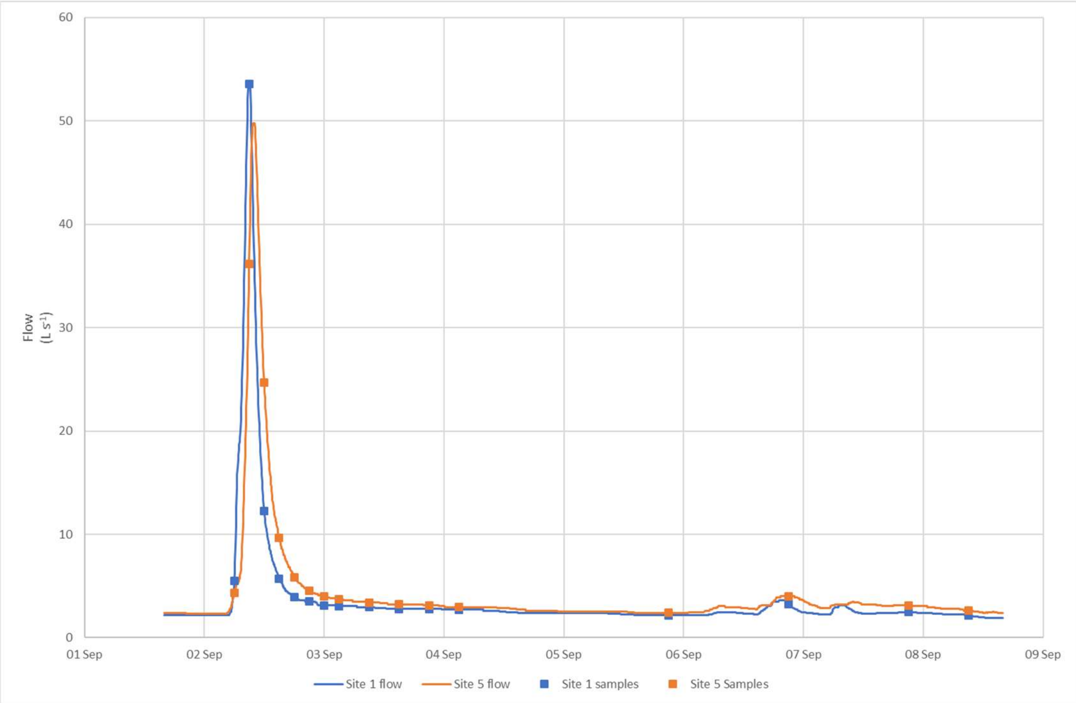

Figure 30: Flow and sample times during Sept 2nd flow event.

Turbidity during the event is shown in Figure 31. As seen in previous events, turbidity associated with inflowing suspended solids is very high at Site 1 (peak value 2,577 NTU) but has been effectively removed by Site 5 (peak value 980 NTU).

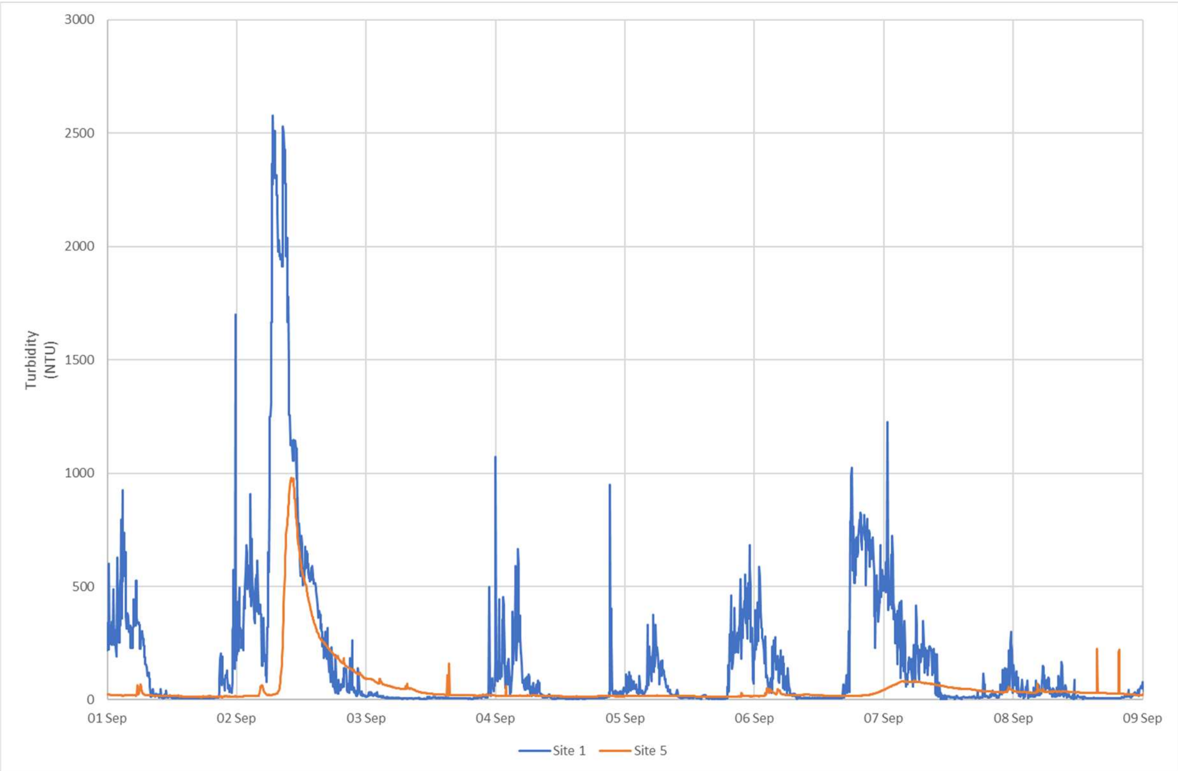

Figure 31: **Turbidity during Sept 2nd event.**

Water quality data for this event is shown in Table 16. Note that the inflow sampler at Input B only captured a portion of the event, thus mass inflow at this site could not be calculated. Percent removals have been based on concentration data. Removal of particulate associated compounds is high, even in the first wetland cell, with 75% reduction in suspended solids and total phosphorus, and 74% reduction of the organic fraction of nitrogen. Removal of microbial contaminants may be exaggerated due to the small number of samples at Input B but was still likely to be high. Nitrate inputs were likely to be from the seepage wetlands, and thus not reflected in water quality from Input B, however we again see inputs to the wetland after Site 1, resulting in increased concentrations of nitrate at Site 5. This may also be associated with some conversion of ammonium-N into nitrate within the large aerobic areas of the wetland system, although rates are generally low where hydraulic retention times are short.

By Site 5, removal of most compounds had increased, with suspended solids, dissolved reactive phosphorus, ammonium-N, organic N and total phosphorus all 95% or higher. Removal of microbial contaminants was close to three orders of magnitude.

Table 16: Water quality data from Sept 2nd, 2017 event.

Input B	SS g m^{-3}	Total Coliforms MPN 100 ml^{-1}	*E. coli* MPN 100 ml^{-1}	DRP mg m^{-3}	NH_4-N mg m^{-3}	NO_3-N mg m^{-3}	Organic N mg m^{-3}	TN mg m^{-3}	TP mg m^{-3}
Average	1,414	2,500,000	776,848	1,233	7,613	46	26,008	33,667	9,313
Median	1,140	2,500,000	866,400	1,120	7,640	23	19,307	27,400	6,710
SD	747		269,000	364	471	51	12,435	12,536	4,666
Number of samples	3	3	3	3	3	3	3	3	3
Site 1									
Average	350	109,011	28,722	416	2,411	390	6,799	9,599	2,348
Median	218	185,958	33,650	249	1,630	503	4,527	6,350	1,740
SD	420	418,552	228,218	431	2,493	310	6,703	8,826	2,512
Number of samples	16	16	16	16	16	16	16	16	16
Mass (kg)	1,429			1.4	7.2	0.6	24	32	8.8
Mass removal				Mass removal could not be calculated*					
% removal	75%	96%	96%	66%	68%	-754%	74%	71%	75%
Site 5									
Average	48	10,172	2,064	25	350	967	2,227	3,544	414
Median	6.3	5,195	1,780	13	148	1,305	399	1,865	68
SD	74	104,816	38,030	30	380	622	3,077	2,860	603
Number of samples	16	16	16	16	16	16	16	16	16
Mass (kg)	51.8			0.03	0.4	2.9	2.4	6	0.4
Mass removal	1,377			1.4	6.8	-2.3	22	26.4	8.4
% removal	96%	99.6%	99.7%	98%	95%	-369%	90%	82%	95%

*Note: Inflow sampling at Input B did not capture the whole peak. Thus, mass calculation values have not been able to be calculated. Percent removals are based on concentrations for this event only.

5.2.12 High Flow Events Summary

During high flow events, inputs to the wetland from the raceway and associated gates into paddocks, which may be muddy and saturated, tended to increase quickly with high concentrations of particulate material, faecal matter, organic N and P and ammonium-N. Inputs from the seepage wetlands and diffuse inputs to the constructed wetland also increased, but the responses were buffered, with a lower peak and longer response.

Figure 32: Gateway into paddock. These areas became muddy and could become a "hot-spot" source of suspended solids during rain events.

Within the wetland complex, the time available for microbial removal processes during high flow events is substantially reduced. However, due to much higher sediment inputs, removal rates ranged from one to nearly four orders of magnitude (81%-99.97% removal), with an average of around 2 log removal. Large particles of sediment and organic matter settled within the initial settling basins, with removals of 24–96% of SS within the initial basin, and 41 – >99% by Site 5. The magnitude of each event had a substantial influence on removal processes, with large events having higher flow velocities and reduced hydraulic retention times, that reduced the overall removal of pollutants. Thus, there is a negative relationship between event size and the efficiency of removal for most pollutants (Figure 33).

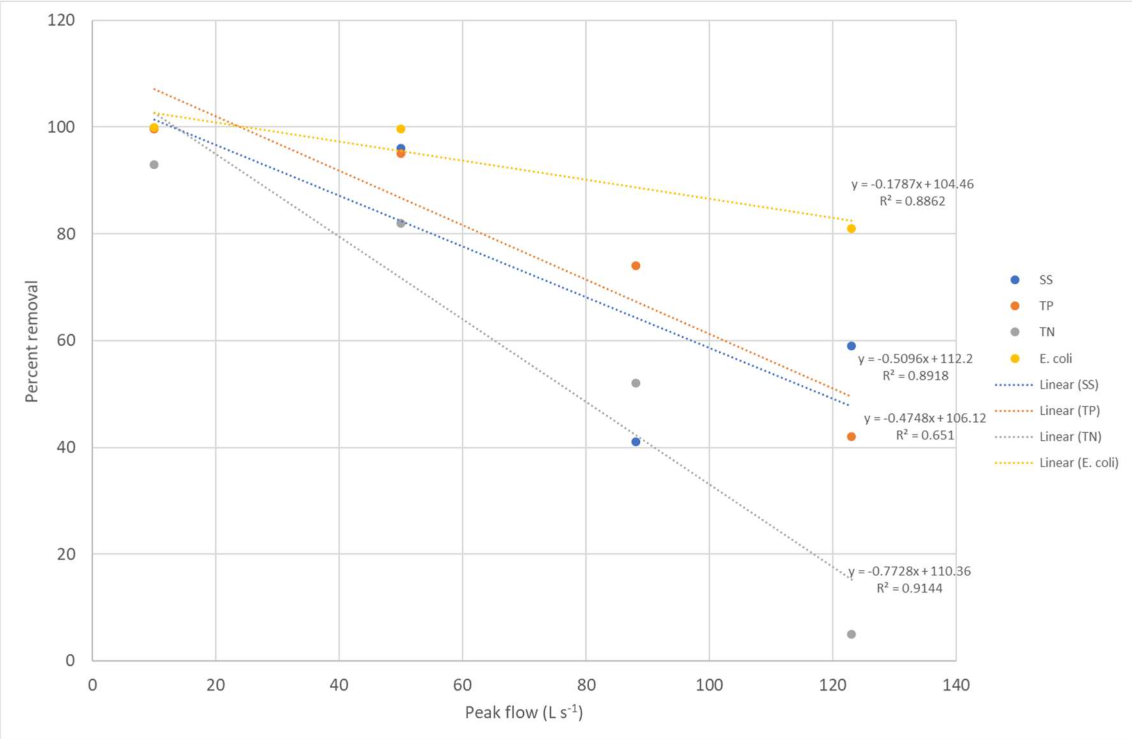

Figure 33: Influence of event size on contaminant removal efficiency. Peak flows have been used as a measure of the size of an event.

While removal efficiency (i.e., as a percent of influent) decreased, higher inflow concentrations were expected during high flow events, particularly for particulate associated compounds due to runoff from the raceway. While a positive trend for mass removal was apparent (Figure 34), it was too weak to be relied upon. The relationship between total phosphorus and flow was even weaker, and no relationship was found between flow and total nitrogen removal. Some of this variability will be associated with reduced hydraulic retention times associated with larger events.

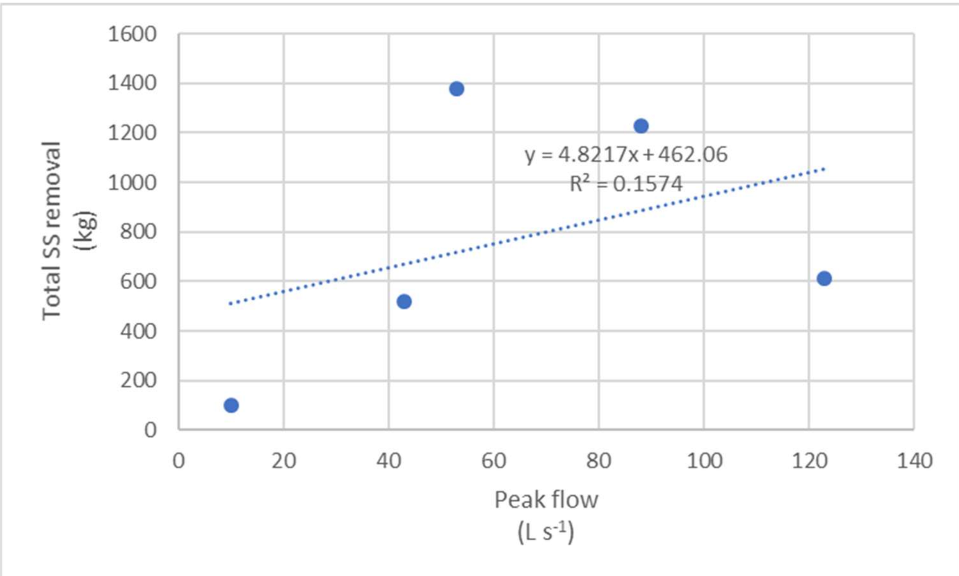

Figure 34: Relationship between event peak flow and total SS removal.

Table 17: Event contaminant removal.

Event	Peak L s^{-1}	Total flow m^3	SS				TN				TP			
			Load	Effluent	Total removal (kg)	% removal	Load	Effluent	Total removal (kg)	% removal	Load	Effluent	Total removal (kg)	% removal
April 2017	43	639	541	20	521	96%	11.1	12.4	-1.3	-12%	0.8	0.3	0.5	61%
May 2017	123	5378	1041	429	612	59%	20	19	0.9	5%	2.5	1.5	1.1	42%
Aug 2017a	88	984	2968	682	2285	77%	25.7	12.3	13	52%	11	2.8	8.2	74%
Aug 2017b	10	494	101	0.2	101	99.8%	4.6	0.3	4.3	93%	1.2	0.003	1.2	99.7%
Sept 2017	53	161	1429	52	1377	96%	32	5.7	26	82%	8.8	0.4	8.4	95%
Average					979				9				4	

As the relationships between the size of events (or peak flow) and total removal was weak, this could not be reliably used to estimate removal. Thus, we have had to use average removal values.

Although there were 129 days of above-baseline flow, true event peaks (above 10 L s^{-1}) were only present on 25 occasions[15]. Using average event removal values, around 24,479 kg of SS, 225 kg of TN and 97 kg of phosphorus are estimated to have been removed during high flow events.

5.3 Event Turbidity

Turbidity is a measure of the side scattering of light caused by fine particles suspended in water, resulting in a decrease in visual clarity as more particles are present (Davies-Colley and Smith 2001). Because turbidity is an inexpensive continuous measure, it is often used as a surrogate for visual clarity, and more particularly, suspended solids. However, it is well known that different particles scatter light differently, and that both dissolved and particulate organic matter absorb light, particularly in the short wavelength (blue) spectrum. In addition, different turbidimeters measure turbidity in different ways, resulting in variation between instruments (Rymszewicz, O'Sullivan et al. 2017). Despite these difficulties, measurement of turbidity is still a powerful tool for assessing water quality. As Rymszewicz et al. (2017) noted, these variations are less likely to be an issue when turbidity is being used as a surrogate for suspended solids.

In this instance we have had to use three different types of turbidimeters, as they were the only ones available. On the plus side, because of the different ranges of turbidity likely to be found from the inflow to the outflow of the wetland system, the different ranges and sensitivities of the instruments was used to our advantage.

Data from one event which occurred from July 27th – 28th is presented in Figure 35. No rainfall was recorded at nearby Lichfield on this date, but rain events in the preceding week ranged from 1.4 to 28.4 mm. At Site 1, direct flow (flow above baseline) occurred for 9 hours, and peaked at 11.5 L s^{-1}, while at the outlet (Site 5) flow peaked at 12.7 L s^{-1}. Turbidity of the inflow from Input B (Culvert from the raceway) is very high (see Figure 36) and exceeded the maximum of the highest ranging turbidity sensor available. Similarly, the peak from within the first wetland cell (the first pond), arriving around 1:50 hrs later, also exceeded the maximum of the sensor in that system, even though it was somewhat diluted by the inflow from the seepage wetlands (Figure 37). However, the relative width of the peaks gives an indication that there was substantial reduction in turbidity and associated suspended particles within the first cell. Turbidity further reduced in the next two cells (both sedimentation ponds, Figure 38), although only by a small amount in Cell 3, the smallest of the three sedimentation ponds. The peak at the outlet of Cell 4, arriving 5:40 hrs after first entering the wetland system also shows a reduction. This pattern continues in Cell 5, with a much-reduced peak, arriving at the outlet of the wetland system, approximately eleven hours after first entering the system.

[15] Some events were present over multiple days.

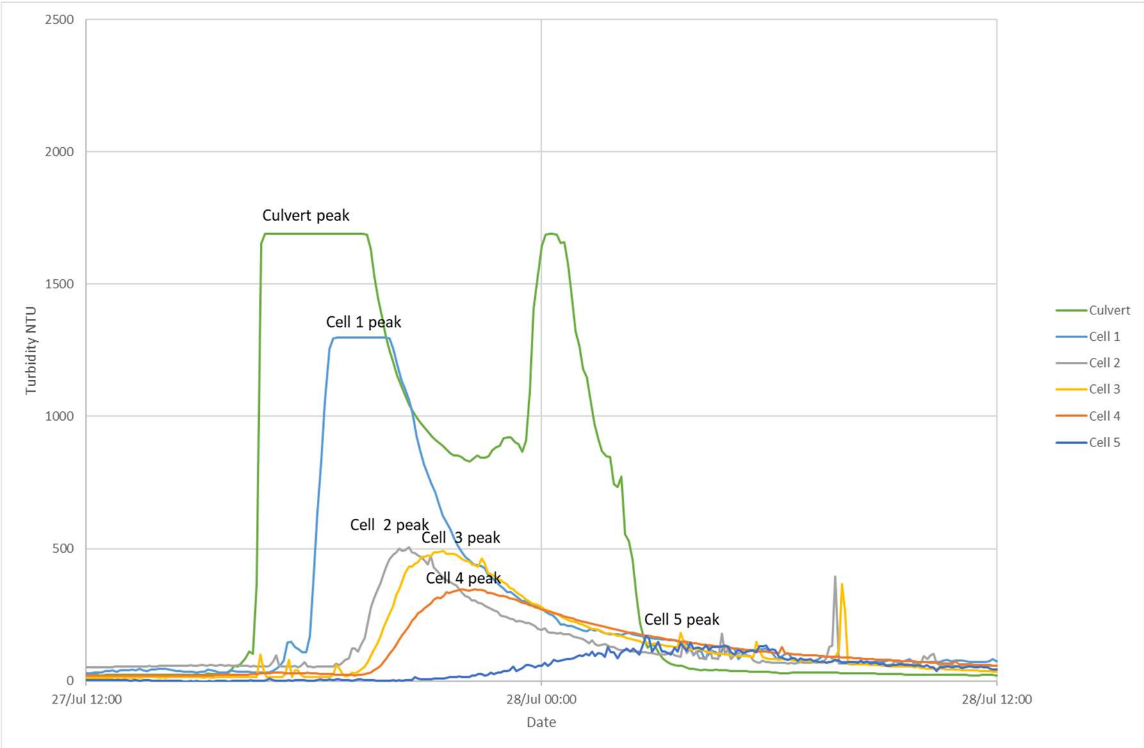

Figure 35: Turbidity through the wetland complex. During a storm event, 27-28 July 2017.

The first three cells of the wetland, designed to maximise sedimentation, showed considerable turbidity reductions. Interestingly, the following cells, where water flowed as a shallow sheet through the wetland plants, also had a notable contribution to reducing turbidity. This supports the earlier conclusion that these cells are also contributing to suspended solids removal.

The extended period of reduced flow velocities within the wetland complex permitted the settling of particulate material which entered the system. In addition to providing considerable direct protection to the environment (by removing solids and associated pollutants), the wetland also buffers flows, so that peaks in the receiving water downstream are lower and slower.

Figure 36: Inflow from culvert. The raceway runoff (Input B) carried high loads of suspended solids during rain events.

Figure 37: **Input A.** Water entering from the seepage wetlands carried much less particulate material than the runoff from the raceway.

Figure 38: First three wetland cells. The first three cells operating as sedimentation basins during a high rain event.

5.4 Seepage wetlands areal nitrate removal

By supplying nitrate in excess of what would normally be present in the wetland, the potential (or maximum) nitrate removal is able to be assessed. This was undertaken at 4 locations in the seepage wetlands, where inflow concentrations were difficult to monitor accurately (unlike in the constructed wetlands). This was undertaken in winter (August) and summer (December).

During the winter monitoring, air temperatures fluctuated between -2.84°C and 20.62°C with an average of 7.80°C. Water temperatures were less variable, fluctuating between 5.55°C and 14.71°C at the two sites monitored, with averages of 9.09°C and 10.65°C.

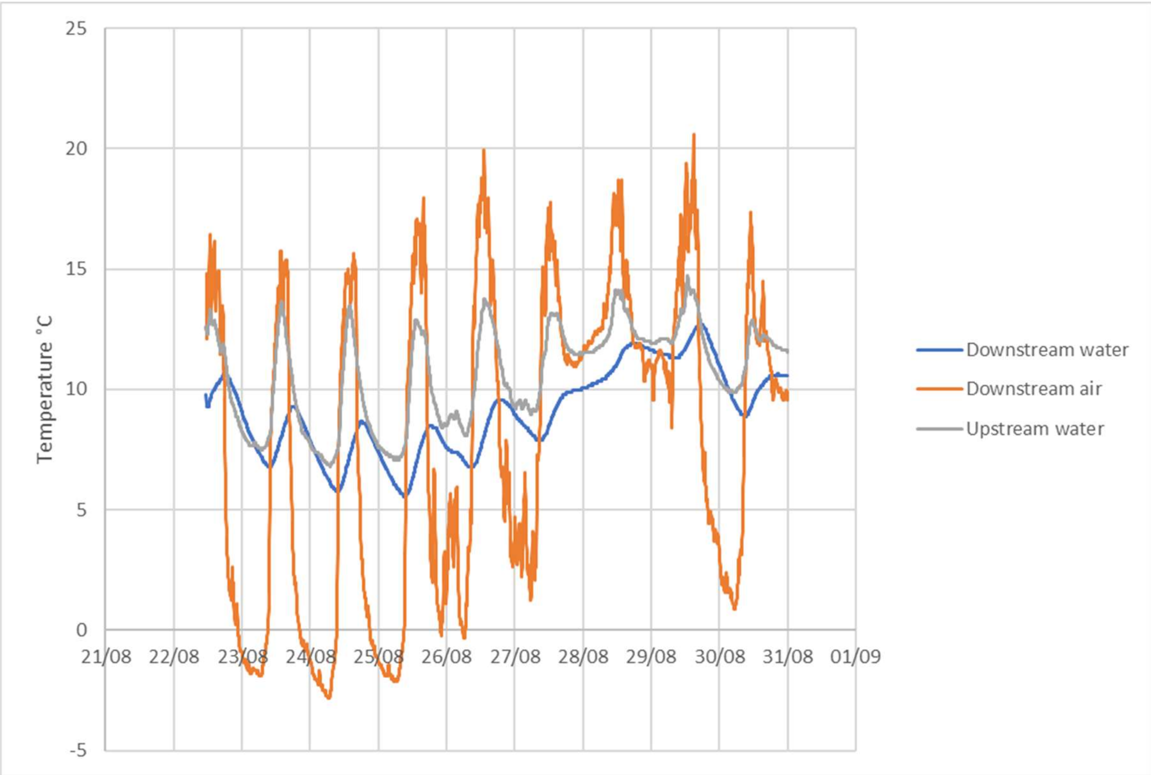

Figure 39: Air and water temperatures during winter monitoring.

During summer air temperatures in the mesocosm enclosure fluctuated between 9.67°C and 39.62°C (Figure 40). The peak air temperature values were probably higher than expected due to the metal walls of the chamber heating up. Smaller daytime peaks are seen with the wetland water temperature. Average temperatures were however, quite similar at 20.34°C in the air and 20.62°C in the water[16].

[16] Note: one of the temperature loggers (in the water) malfunctioned, and thus only one set of water data is available for the summer monitoring.

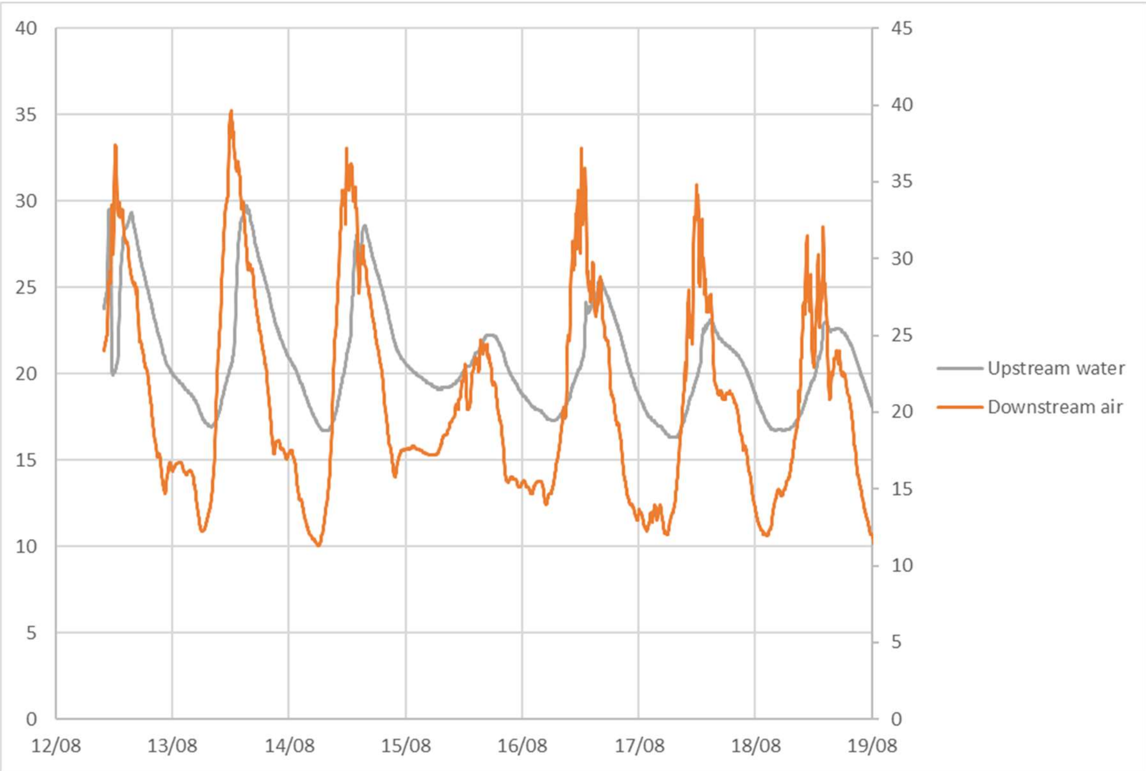

Figure 40: **Water and air temperatures during summer monitoring.**

Removal of added nitrate from the various mesocosms are shown in Figure 41 and Figure 42. While in both seasons final removal is between 65->99% after 8 days, initial rates of removal are noticeably less in the first few days under winter conditions. Under summer conditions, microbial removal is much greater. Some explanation is necessary for the results of both Chamber 3 and 4 in summer conditions (Figure 42, note arrows). Conditions became very dry in these chambers during this experiment, resulting in the necessity to add further water on days 3 and 8 in order to extract samples. It is assumed that the dry conditions inhibited our ability to access zones where denitrification was prevalent.

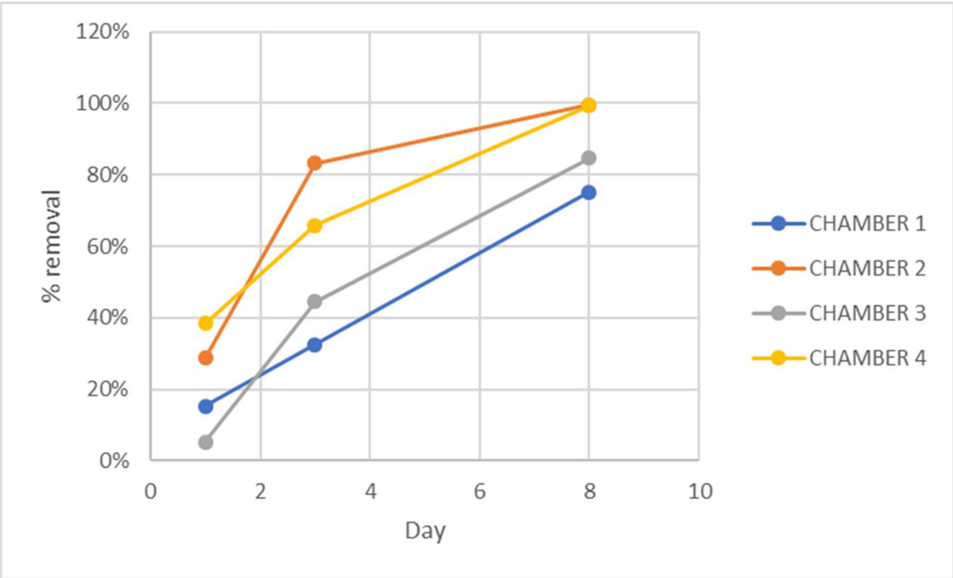

Figure 41: **Percentage removal of added nitrate under winter conditions.**

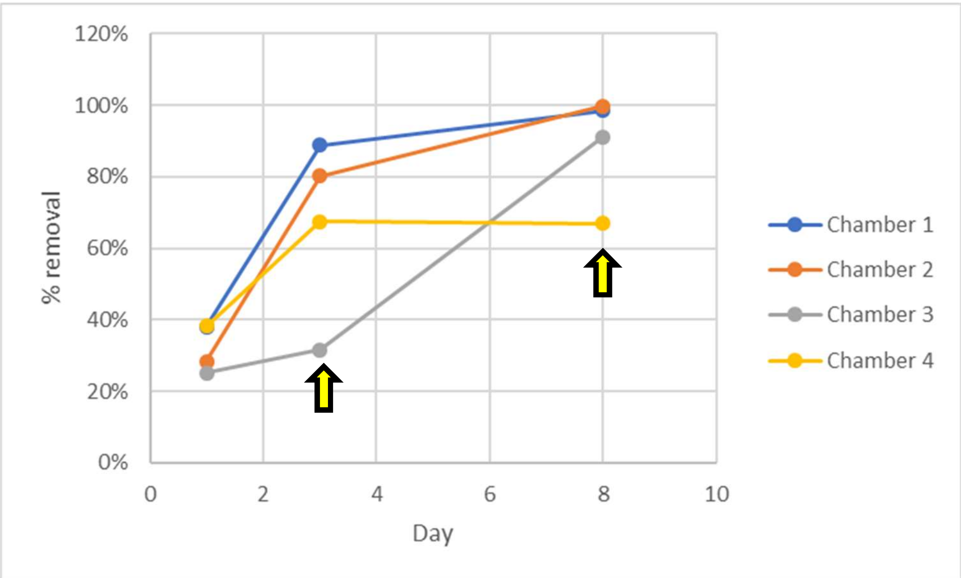

Figure 42: **Percentage removal of added nitrate under summer conditions.** Arrows indicate unusual sample results due to the wetland drying out.

Concentrations of dissolved organic carbon (DOC) varied day by day in the chambers. When daily values were compared with areal nitrate removal rates, there was little clear relationship between the two (Figure 43). The effect of temperature however was more apparent, with summer values overall higher than winter values.

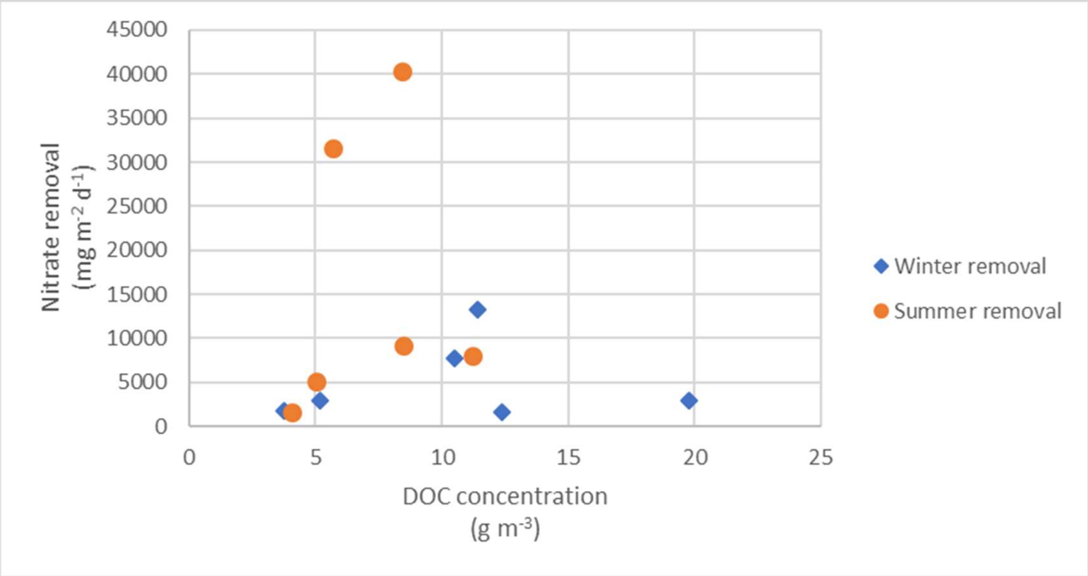

Figure 43: Relationship between DOC and raw (uncorrected) nitrate removal. For corrected values, see following text.

There was a positive trend of DOC measured with increasing soil LOI under summer conditions (Figure 44). The relationship was less clear under winter conditions, but sample numbers were relatively low.

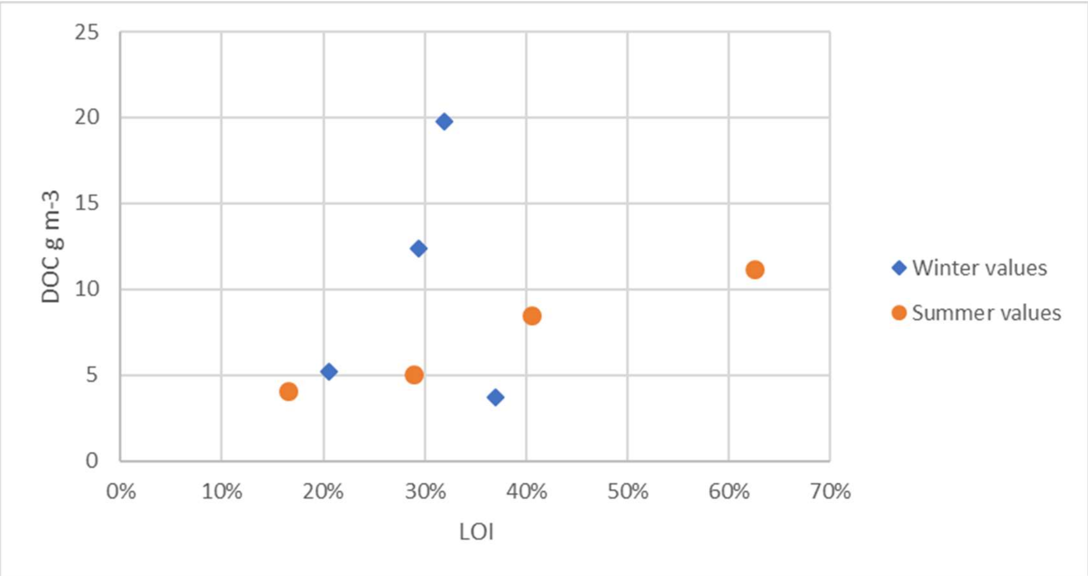

Figure 44: Relationship between DOC and LOI. DOC values were those taken on the final day of sampling.

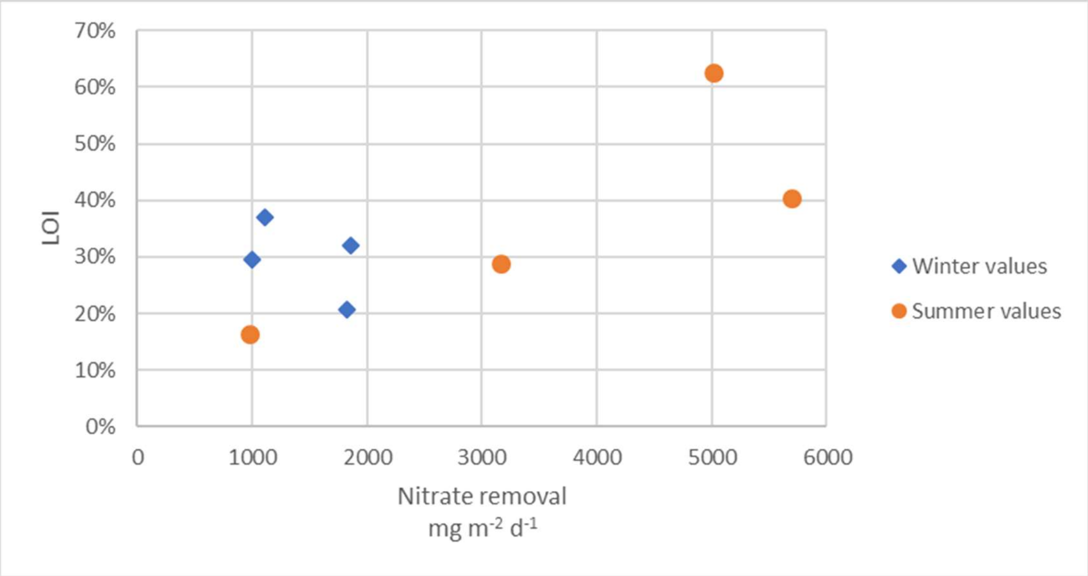

Figure 45: Relationship between LOI and raw nitrate removal. For corrected nitrate removal rates, see following text.

During summer there was a positive trend between nitrate removal and soil LOI (a surrogate for total carbon), but no clear relationship during winter.

Measured removal rates were between 1.6 g m^{-2} d^{-1} and 13.1 g m^{-2} d^{-1} under winter conditions, and between 1.5 g m^{-2} d^{-1} and 40.3 g m^{-2} d^{-1} under summer conditions. These raw values are influenced by the high nitrate input concentrations as well as temperature effects. The OVERSEER module for seepage wetlands (Rutherford, McKergow et al. 2008) provides the following equation for correction of raw values.

$$U_T = U_{20} 1.1^{T-20}$$

where *T*=temperature (°C, OVERSEER uses air temperature), U_T = uptake rate at temperature *T*, and U_{20} = uptake rate at 20°C. In addition to the correction for temperature effects, and initial correction for input concentrations (16.3 ppm in summer and 24 ppm in winter) needs to be made, as input concentrations affect removal rates. U_{20} values are presented in Table 18.

Table 18: Seepage wetland removal rates. at 20°C.

	U_{20} (mg m^{-2} d^{-1})
Winter removal average (8 days)	765
Winter removal maximum	6,961
Summer removal average	1,958
Summer removal maximum	9,479

In a review of removal rates of nitrogen in New Zealand seepage wetlands, Rutherford (2017) notes that all of the studies found the wetlands significantly reduced the concentrations of nitrate (51-98%). Removal rates found by Rutherford were highest where runoff first enters a wetland and nitrate concentrations were highest. Removal rates corrected to 20°C ranged from 31-4500 mg m^{-2} d^{-1}, with some uncorrected values (temperature correction not possible) up to 8100 mg m^{-2} d^{-1}. As can be seen from Table 18, average removal rates over the 8-day testing period were 765-1958 mg m^{-2} d^{-1}. These rates sit within the range measured elsewhere. However, the maximum removal rates were a little higher than recorded elsewhere and probably reflect the artificial conditions of the testing (e.g., high temperatures in the chambers), the short-term nature of the testing, the high input concentrations, as well as the correction factor used[17].

5.5 Vegetation Assessment

The main plant species established in the constructed wetland complex were *Carex virgata*, *Juncus pallidus*, *Juncus sarophorus*, *Cyperus ustulatus*, and *Machaerina articulata* (previously *Baumea articulata*). Total cover was 68% in winter, increasing to 88% in summer (2017/18). Various deep-water areas remained unvegetated, particularly in the first three cells. This will enable excavation of settled sediment within these areas at a later date. Also both of the vegetated wetland cells (4 & 5) had a deeper area at their outlets (near the bund), which were poorly vegetated[18].

Various adventive species were also noted, particularly in summer. The major species was Yorkshire fog (*Holcus lanatus*), although buttercup (*Ranunculus repens*), blackberry (*Rubus fruticosis*), lotus (*Lotus pedunculatus*) and willow weed (*Persicaria maculosa*) were present. These equated to 14% of total plant biomass in summer. These adventive species were not at nuisance levels, however the Yorkshire fog can smother wetland plants and may become a nuisance in the future.

Wet biomass in the wetlands was calculated to be 4.6 T in winter[19] and 4.1 T in summer, equivalent to dry biomasses of 1469 kg and 1537 kg respectively. Nutrient analyses were not undertaken on these samples, however, we have applied nutrient values obtained from a nearby (Lichfield Fonterra) wetland (Nitrogen 1.0-1.3%, Phosphorus 0.12-0.14%) to the Baldwin wetland plant data. On this basis, nitrogen in the standing plant biomass was estimated as 17.2-18.1 kg, and phosphorus 1.9-2.0 kg (winter and summer respectively).

The recorded values of nitrogen and phosphorus in standing plant biomass represent a only a small fraction of the total amount which the wetland removed in a single year (6% of TN and ~2% of TP[20]). Large areas of this wetland, dominated by shallow planted areas with water flowing down a gradual slope, was designed to maximise plant biomass and enhance plant uptake of nutrients (Roger McGibbon, pers comm), although it is clear that other removal pathways were more significant. It is probably the case that the plants are approaching maximum standing biomass, and that much of the nutrients in them has accumulated since the wetland was initially established 2 years previously. Harvesting of plant biomass to stimulate continued plant uptake is not recommended here as it would only result in a marginal increase in overall removal and, by removing the dominant native canopy species, would be likely to lead to subsequent weed proliferation relative to the preferred native vegetation. In addition, leaf litter falling into the wetland during plant die-back forms an

[17] A linear correction factor was applied in this instance. There is some evidence that an exponential factor should be applied. However, there was insufficient data in this study to generate a reliable exponential relationship.
[18] These deeper areas had standing water for much of the year, and probably contributed substantially to wetland denitrification.
[19] The winter value was slightly higher as the plant biomass samples had a greater moisture content, probably adhering to the plant surfaces from the time of harvest. Dry biomass was a little higher in summer.
[20] See summary data.

important source of organic carbon for denitrification, which may be increasingly important as the wetland matures.

5.6 Sediment Accumulation

The initial three stages of the constructed wetland were small and deeper than the following stages, resulting in standing water in these "ponds" for most of the year. As a result, these ponds acted to enhance sediment removal via settling. In addition, the first two ponds had a band of emergent plants at their inflow ends which reduced inflow velocities, further enhancing conditions conducive to sediment settling. It should be noted that, although these cells acted as settling ponds, they are shallower than would be typical for dedicated sedimentation ponds. Their shallow depth may actually have enhanced sedimentation, as settling solids have a shorter distance to fall to the base of the pond. However this can also have negative outcomes, as wind induced mixing can re-suspend solids in shallow ponds, and they require solids removal more frequently.

Sediment accumulation data is presented in Table 19. Total accumulation reduces through each stage, as is expected, with larger, denser particles settling out more readily in the first stage, and progressively less settling (and accumulation) in later stages. The differences between summer and winter values are probably associated with variability in sampling locations and difficulties associated with accurately determining the constructed wetland's clay base. Regardless of this, it appears these first pond stages accumulated in the order of 9-13 T of sediment, of which 10.7-10.8% was organic[21]. This was about half the estimated sediment load removal based on average inflow concentrations (see final summary below). The samples of accumulated sediment appeared to be mainly inorganic, with minimal organic content or detritus derived from wetland plant decomposition. This reflects their collection from areas primarily devoid of plant growth and intended for sediment settling. Thus, it is likely that the organic component was primarily from material washed off the raceway, although some smaller component is likely to have been contributed from wetland vegetation at the inflow of the first two ponds stages.

Based on our measurements the inorganic component of accumulated sediment was also mostly from the raceway (entering via the culvert, Input B), consisting of grit from the raceway, as well as eroded soil and dung particles from stock hooves and waterborne erosion from surface drainage swales down the side of the drains. The low turbidity of water entering from the fenced natural seepage wetlands suggested relatively low suspended solids inputs from these sources.

[21] The Loss on Ignition method to calculate % organic has some advantages with non-homogeneous samples containing coarse sediments, however it is a crude measure, and laboratory measurements of total organic carbon may have resulted in a more reliable estimate.

Table 19: Total and organic sediment accumulation in the first three wetland stages.

		Total Sediment Accumulation (kg)	Total Organic Accumulation (kg)	Percent Organic
Wetland/Pond 1	Winter	8696	883	
	Summer	4132	386	
Wetland/Pond 2	Winter	2887	342	
	Summer	3126	377	
Wetland/Pond 3	Winter	1441	168	
	Summer	1846	216	
Total	Winter	13024	1394	10.7%
	Summer	9104	979	10.8%

6 Summary and recommendations

The constructed wetland complex at this site includes a number of beneficial features including a multi-cell design (which enhances nutrient removal processes and minimises short-circuiting), deeper initial cells (to encourage particulate sedimentation) with dense plantings of *Carex* at the inflow point (to reduce flow velocities), along with a sinuous natural shape (creating an aesthetic appearance and "landscape fit", i.e., it looks like it should be there).

Inflows to the constructed wetland complex during the 2017/18 drainage season consisted of equal amounts of baseflow (below 3 L s^{-1}) and storm or event flows (both around 48,000 m^3). Baseflow was mainly from a number of seepage wetlands although there were some groundwater inputs entering through the constructed wetland base. The groundwater inputs were not directly sampled but were likely to be of similar quality to the inputs to the seepage wetlands, which were sampled.

The seepage wetlands had previously been fenced to exclude livestock, preventing grazing and treading disturbance as well as direct inputs of dung and urine, as occurs in unfenced wetlands. These upstream wetlands were shown to have high rates of denitrification and were likely to be effective at capturing any inputs of suspended solids and phosphorus. Thus inputs from this source were of generally good quality. However groundwater inputs to the constructed wetland were likely to be of some significance, as measured inputs to the seepage wetlands had average nitrate concentrations of 2.2 g m^{-3}. If these groundwater inputs were equivalent, then under baseflow conditions the constructed wetland complex appears to have removed around 59 kg of nitrogen (36%) and 8 kg of phosphorus (58%) during this drainage season. Some caution should be applied to these values as they were not directly sampled, but will be over the next drainage season. Suspended solids inputs during baseflow were not high, however around 214 kg (37%) was removed under these conditions.

During rain events, additional surface runoff occurs, particularly from the raceway which could be considered a significant point source of contaminants on this farm. This resulted in a maximum peak flow of 250 L s^{-1} recorded during the monitoring period. Overall, these storm-flows also accounted for ~48,000 m^3 distributed over 25 distinct events during the season[22]. Contaminant removal processes during these events are assumed to be different from during baseflow, as hydraulic residence times within the system would be reduced and flow velocities increased. Moreover, inputs of particulate associated material increased considerably, particularly with runoff from the raceway. Five events were successfully sampled, with SS removal ranging from 101 to 2,968 kg per event. Using average values, up to 24,479 kg of SS (81%) was removed by the wetland during flow events. Measurement of sediment accumulation in the first 3 ponds indicated between 9,000 and 13,000 kg captured in these wetland stages. Further removal would have occurred in subsequent wetland cells. In addition, up to 225 kg of total nitrogen (48%) and 97 kg of total phosphorus (79%) were estimated to have been removed from the discharge during rain events.

[22] The fact that the baseflow and direct flow values are the same is a coincidence, and would not necessarily occur in other years.

Table 20: Summary table.

	Surface inputs (kg)	Diffuse inputs (kg)	Combined inputs (kg)	Outputs (kg)	Mass removal (kg)	% Removal
Nitrogen						
Baseline flow	102	64	166	106	59	36%
Event flow	467	7	473	248	225	48%
Total flow	568	71	639	355	284	45%
Phosphorus						
Baseline flow	4.7	8.4	13	5.5	8	58%
Event flow	122	0.1	122	25.3	97	79%
Total flow	126	9	135	30.8	104	77%
Suspended Solids						
Baseline flow	583	0	583	368	214	37%
Event flow	30394	0	30394	5915	24479	81%
Total flow	30977	0	30977	6283	24693	80%

	Site 1 (Median)	Diffuse inputs (Median)	Outputs (Median)	% Removal	Log removal
E. coli					
Baseline flow	1931	157	238	88%	1 Log
Event flow	372,881	157	12,834	97%	2 Log

Thus, with baseflow and rainfall events combined, the constructed wetland complex has removed a total of 284 kg of nitrogen (45%), 104 kg of phosphorus (77%) and 24,693 kg of suspended solids (80%). *E. coli*, an indicator of faecal contamination was reduced in the wetland complex by around 1 log during baseflow, and around close to 2 logs during rain events, although when runoff from the raceway was very high nearly 4 log removals was recorded.

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8 Glossary of abbreviations and terms

Baseflow	Flow entering the wetland not influenced by rain events. Baseflow is also present during rain events, but direct flow typically causes a distinct peak during rain events. In this study, baseflow was sampled on a routine basis, choosing days without rain, or if during a rainy period, on a day of only light rain.
Denitrification	The loss or removal of nitrates or nitrites commonly by bacteria (as in soil) that usually results in the escape of nitrogen gas (N_2) into the air.
Direct runoff	Direct runoff is a combination of surface runoff and interflow. This causes rain induced peak flows or storm flows.
Dissolved organic carbon	DOC. Sometimes known as dissolved organic material (DOM), is a broad classification for organic molecules of varied origin and composition within aquatic systems. In a laboratory, samples are filtered through a pre-combusted (450°C) Glass Fibre filter of 1.2 µm pore size (GFC) to obtain the “dissolved” fraction.
Electrical conductivity	A measure of a material's ability to conduct an electric current. For wastewater, it is a measure of dissolved ions, indicating the general level of pollution.
Escherichia coli	Abbreviated to *E. coli*. A bacterium which is found in mammalian and bird guts. It is recognised as an indicator of faecal contamination.
Interflow	The rapid lateral flow of water along the unsaturated zone, or vadose zone.
Loss on ignition	LOI. The weight change of a sample after it has been heated to high temperature causing some of its content to burn or to volatilise.
Mesocosm	An enclosed experimental environmental or ecosystem that is on a larger scale than a laboratory microcosm.
MPN	The “most probable number” method, otherwise known as the method of Poisson zeroes, is a method of getting quantitative data on concentrations of discrete items from positive/negative (incidence) data. There are many discrete entities that are easily detected but difficult to count. Often used to calculate the most likely number of bacteria in a sample.
NTU	Nephelometric Turbidity Unit. This signifies that the instrument is measuring scattered light from the sample at a 90-degree angle from the incident light.
Organic-N	Nitrogen compounds produced by living things, thus containing N bound to carbon and hydrogen. Organic compounds are able to be combusted or volatilised.
Piezometer	Hollow tube inserted down to groundwater to allow water sampling. Ends may consist of a slotted pipe.
Suspended solids	SS. Small particles which remain in suspension in water as a colloid or due to the motion of the water. Analysed via filtration through a glass fibre filter.

Total coliforms	A group of bacteria that are found in soil and in water that has been influenced by surface water, and in human or animal waste. Faecal coliforms are the group of the total coliforms that are considered to be present specifically in the gut and faeces of warm-blooded animals.
Transect	A path along which one counts and records occurrences of the species of study (e.g., plants across the wetland).
Turbidity	The cloudiness or haziness of a fluid caused by large numbers of individual particles that are generally invisible to the naked eye.

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10 Appendix A

Seasonal Load Reduction

There was a degree of seasonality in various removal processes, as shown in Table 21. As seen in the seepage wetland mesocosm study, microbial nitrification and denitrification are higher in warm summer months and lower in winter months. Other processes are more associated with physical processes such as settling of suspended solids, which should not be greatly affected by temperature, although the rain events which generate the inputs have distinct seasonal drivers. While we have shown percent removal achieved by this wetland complex during the sampled drainage season, it is important to keep in mind that each value represents a small number of samples. In addition, loading associated with storm events varies significantly between years, thus we consider it would not be scientifically valid to provide aerial removal rates at this stage, and recommend caution if applying the percent removal rates outside of this study. Greater confidence in interpreting seasonal patterns of removal can only be achieved after several years of sampling have been undertaken.

Table 21: Seasonal load reductions.

	Suspended solids	Dissolved reactive P	Total-P	Ammonia-N	Nitrate-N	Organic-N	Total-N
Autumn	94%	34%	47%	74%	78%	59%	78%
Winter	52%	-142%	-42%	71%	-1%	-34%	5%
Spring	84%	56%	72%	74%	-5%	57%	50%
Summer	-24%	>99%	>99%	>99%	>99%	>99%	>99%