Ongoing efficiency of nitrogen processing in treatment wetlands of the Wet Tropics

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1. Executive Summary

Treatment systems such as constructed wetlands can efficiently remove nutrients, and suspended solids derived from agricultural land uses. However, the performance of these systems relies on certain conditions such as adequate soil carbon and an established plant and microbial community. These conditions can only be achieved months or years after construction. In this study, we assessed the performance of three treatment constructed wetlands (CW02, CW03 and Landscape wetland, LW01) in the Tully and Moresby catchments in the Wet Tropics. We analysed the latest monitoring period (June 2020 to February 2021) and compared the changes in the performance of these wetlands since construction (the period 2019-2020 has been previously reported in Adame et al. 2020a).

We compare the concentrations between in-and outflows of nutrients, including total ammoniacal (NH_3-N + NH_4^+-N), nitrate (NO_3^--N), dissolved inorganic N (DIN = NH_3-N + NO_3^--N), dissolved organic nitrogen (DON), and phosphorus (orthophosphate, OP; total, TP). We also analysed differences in physicochemical properties such as temperature, conductivity, pH, redox, turbidity and total suspended solids (TSS).

Our results show that wetlands CW02 and LW01 have consistently and increasingly removed NO_3^--N from the water column reducing concentrations by $\geq$ 90% and 67%, respectively. The site CW03 had low N flows and sporadic DIN removals, detected only during periods of rainfall when NO_3^--N and NH_4^+-N concentrations increased to 0.1 mg L^{-1} and > 0.04 mg L^{-1}, respectively. However, CW03 was a sink of TP, probably due to sedimentation. The reduction of NO_3^--N concentrations in CW02 and LW01 was associated with a significant decrease in DO% and an increase in pH as the water moved through the wetland. Site CW02 also significantly reduced NH_4^+-N concentrations, although LW01 slightly increased them. Both CW02 and LW01 were minor sources of DON, probably due to the productivity of plants and microbes. Overall, CW03 was a significant sink of TP, and CW02 and LW01 were sinks of DIN. Highest NO_3^--N removals in CW02 and LW01 occurred during the summer months, where concentrations of NO_3^--N and temperature were highest, and DO% and redox were lowest.

These results have shown that constructed treatment wetlands require at least a year to be fully established and reach their potential for removing DIN. We estimated that CW02 removes between 1,373 and 1,825 kg of DIN every year. This estimation includes water flow rates and seasonal and interannual variability of DIN removal. Because CW02 has been consistently efficient at removing DIN at a relatively low cost, continued monitoring should be prioritised for this site. Monitoring could also include co-benefits (e.g. biodiversity) and potential disservices (e.g. nitrous oxide emissions or fauna traps). Constructed wetlands like CW02 or LW01 could significantly reduce DIN from agricultural activities within the Wet Tropics.

2. Introduction

Nitrogen (N) pollution is a global problem that has caused unprecedented water quality degradation and is currently surpassing what is considered safe for humanity (Röckstrom et al. 2009). The leaching of excessive fertilisers from agriculture is one of the leading causes of N pollution and has resulted in extensive degradation of aquatic systems (Kulkarni et al. 2008; Galloway et al. 2003). Improved land-use practices, such as changes in fertiliser application quantities, type, and timing, can reduce N leaching. However, agricultural lands are likely to release N at times still; thus, complementary solutions to N pollution are required.

Wetlands are known to improve water quality by removing N (Land et al. 2016). In some regions, they can be five times more efficient at reducing nitrate (NO_3^-) loads than land management strategies (Hansen et al., 2018). The restoration of 5% of wetland area within a catchment could remove 20 to 50% of its N inputs into the coastal zone (Mitsch et al. 2001, Adame et al. 2019). Globally, there has been a substantial investment for constructing artificial wetlands to decrease the costs of treating water, improve the condition of waterways, and sustain human health (Jones et al. 2012). However, few studies have been conducted in treatment systems of tropical climates, which have high year-round temperatures, high primary productivity, and variable hydrology (e.g. Adame et al. 2019).

In our previous work with Terrain Natural Resource Management, we analysed the in-vs outflows of the recently constructed wetlands (2019-2020) to determine their efficiency to reduce N and improve water quality (Adame et al. 2020a, b). We found that the adequate conditions for N removal include an established microbial community, soil organic carbon ≥ 2%, soil nitrogen ≥ 0.2%, C:N >10, and anoxic soils (-100 to 300 mV). Some of these conditions, especially establishing a microbial community, can only be achieved years after construction (Duncan and Groffman 1994).

Here, we continue this analysis by including data from 2020-2021. The objective was to assess if the efficiency of the wetlands has increased with time. We expected that as the vegetation and microbial community established, the wetland performance would improve. We assessed if the factors we previously identified as key for water quality improvement are still relevant a year after construction. Finally, we recommend how to optimise N reductions and overall water quality improvement from these treatment wetlands.

3. Background

The Queensland Government established the Major Integrated Projects (MIPs) to reduce nutrient loads into the waterways of the Wet Tropics. Terrain NRM coordinated these efforts to create with landholders on-ground projects to improve water quality in the Moresby and Tully catchment. The project includes the creation of three treatment wetlands (Fig. 1):

Constructed Wetland 2 (CW02): a wetland within the Moresby Catchment of 1.6 ha that drains 15 ha of sugarcane (wetland: catchment of 0.11). The site has a high potential for denitrification, as it has soil rich in carbon (2%C, 0.1 %N, C:N of 17) and receives NO_3^- concentrations > 0.1 mg L^{-1} (Adame et al. 2020b). Site CW02 was constructed in December 2019 and removed nitrate (NO_3^--N) three months after construction.

Constructed Wetland 3 (CW03): a constructed treatment wetland within the Tully catchment with an area of 1.2 ha, targeting 37 ha of banana plantations (wetland: catchment of 0.03). This site had intermediate potential for denitrification due to low NO_3^--N concentrations (< 0.1 mg L^{-1}), low soil redox (-99 mV) and low C:N (11, 1.7% C, 0.2% N). This site was constructed in February 2019 and has had a variable performance for N removal, with better removal after rainfall events when NO_3^- concentrations increase. This site is efficient at removing total suspended solids (TSS) and phosphorus (P).

Landscape Wetland (LW): a large (8.5 ha) constructed wetland that targets 368 ha of mixed agricultural use (wetland: catchment of 0.02) in the Tully catchment. LW01 has high potential for denitrification due to its peat soils with high organic carbon (9% C, 0.3% N, C:N of 34) and high NO_3^--N concentrations > 0.25 mg L^{-1} (Adame et al. 2020a,b). This site has shown consistent NO_3^--N removal since its construction, but also export of dissolved organic nitrogen (DON) and occasionally NH_4^+, especially after rainfall events. The site has a series of channels to allow for fish passage and deeper ponds that provide habitat for reptiles and fish species.

Figure 1. Treatment wetlands in the Tully and Moresby catchment within the Wet Tropics, constructed wetland 2 (CW02), constructed wetland 3 (CW03) and landscape wetland (LW01).

4. Methodology

Water sampling was conducted by Terrain NRM between; site CW02 was sampled 13 times, CW03 was sampled 34 times, and LW01 was sampled 18 times. One inlet point was sampled for CW02 and CW03, and two inlets were sampled for LW01 (Fig. 2). Groundwater was assessed through water extracted from bores with a piezometer. The CW02 wetland is mostly groundwater-fed; consequently, surface and groundwater samples were included as inflows. We compared the differences in inlet-outlet from the recent monitoring period to our last analyses, which included sampling since 2019 (Adame et al. 2019a).

We included in our analyses the following parameters: pH, redox (mV), dissolved oxygen (DO%), electrical conductivity (EC, µS cm-1), turbidity (FNU), N (total ammoniacal [NH_3-N + NH_4^+-N]; nitrate, NO_3^--N; dissolved inorganic N [DIN = NH_3-N + NO_2^--N + NO_3^--N]); dissolved organic nitrogen, DON, P (orthophosphate, OP; total, TP), and total suspended solids (TSS). Most total ammoniacal is NH_4^+-N at pH < 7, so this form is included throughout the report. The concentrations of NO_2^--N were not included in the analyses as they were below detection limits (< 0.01 mg N L^{-1}).

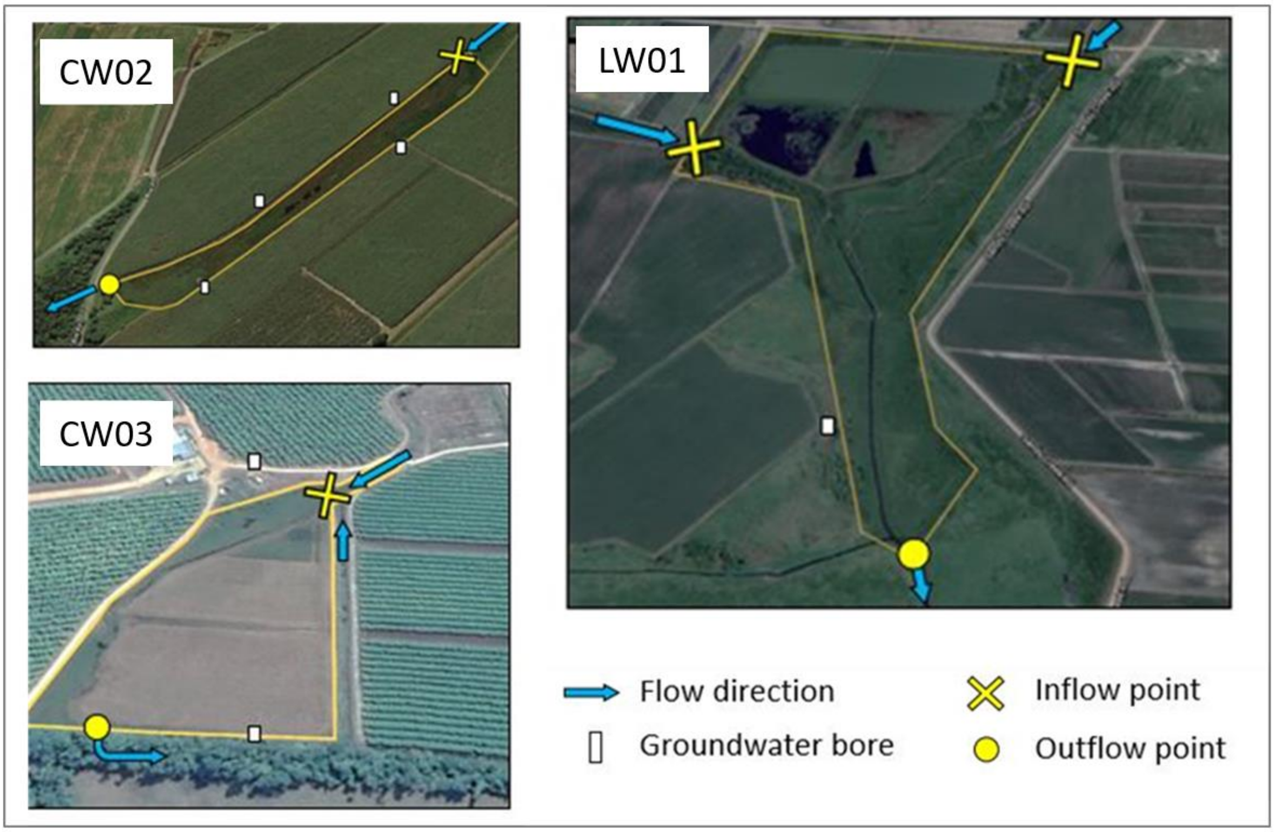

Figure 2. Sampling design in the inlet and outlet of three treatment wetlands. The “X” signs show the sampling points for surface water (in/out), and the rectangle denotes the sampled groundwater bores.

DIN removal (kg yr^{-1}) for CW02

Removal of DIN in kg per year was estimated for CW02 with the removal rates established for this site and groundwater flows. The directions and volume of groundwater flow were assessed by Rob Lait and Associates Pty Ltd (RLA) for 19th November, 24th December 2020 (the lowest groundwater level on record) and 4th January 2021 (the highest). We considered the flow volumes of 9.8 and 18.4 $m^3\ d^{-1}$ as the low end for the groundwater flow of the wet season (Jan to June) and dry season (July to Dec), respectively. The DIN removal was estimated as the average for each season from Adame et al. 2020a and this study, and estimated over the length of the aquifer as follows:

DIN removal (kg) = Groundwater flow ($m^3\ d^{-1}$) * DIN concentration (mg L^{-1}) * Length (m)

The mass removal of nutrients was estimated for the dry and wet seasons of 2020, and the wet season of 2021. The mass removal for both seasons were added up to obtain total mass of DIN (kg) of removal in year 2020 and the projected removal for 2021.

Statistical analysis

Normality and homogeneity of variance were tested using residual plot analyses, Shapiro-Wilk and Kolmogorov-Smirnov tests. When variables were normal, differences among the inlet, outlet, and groundwater were tested with a paired sample for means t-test. When a variable was not normal, a non-parametric one-sample Wilcoxon signed-rank test was conducted. Regression was used to determine the relationship between removal and inlet concentrations. We conducted a stepwise multiple regression after checking for autocollinearity among parameters to assess the influence of physicochemical parameters and removal rates. A scatterplot of the residuals was checked for homoscedasticity of residuals in the regression. Statistical analyses were performed with SPSS (v24, IBM, New York, USA). Data are shown as mean ± standard error (SE).

5. Results

Physicochemical characteristics of constructed wetlands

The average physicochemical characteristics of the inflows during the sampling period (June 2020 to February 2021) are shown in Table 1. There were differences among the inlets of the three sites. Notably, pH, temperature, and EC in CW02 and LW01 were lower than in CW03, possibly indicating groundwater influence in these sites. Groundwater was, in general, more acidic and colder (Table 2). Nutrients were highest in the groundwater, and at CW02, they accounted for all the detectable DIN into the wetland. The OP and TP of the inlets were very low at all sites except in CW03 (Table 3,4); this site also had the highest turbidity and TSS (Table 3).

Table 1. Physicochemical characteristics of the inlet of three constructed wetlands between June 2020 and February 2021. Sites CW02 and CW03 had one inlet, and LW01 had two (see Fig. 2). Values are means ± SE of time series for CW02 and CW03, and the mean of the time series for the two inlets in LW01.

EC = electrical conductivity, DO = dissolved oxygen, TSS = Total suspended solids.

	Temperature (°C)	EC ($\mu S\ cm^{-1}$)	pH	Redox (mV)	DO (%)	Turbidity (FNU)	TSS ($mg\ L^{-1}$)
CW02	26.5 ± 2.0	60.5 ± 0.6	5.7 ± 0.1	177 ± 14	76 ± 15	7.2 ± 2.0	9.7 ± 1.7
CW03	27.5 ± 2.9	113 ± 5	6.1 ± 0.1	171 ± 28	28 ± 3	31.9 ± 6.0	21.9 ± 3.2
LW01 (n = 2)	26.2 ± 0.9	43.2 ± 7.5	5.8 ± 0.3	148 ± 4	80 ± 19	14.5 ± 5.3	6.8 ± 1.4

Table 2. Physicochemical characteristics of the groundwater of three constructed wetlands between June 2020 and February 2021. Site CW02 had four bores, while CW03 and LW01 had one (see Fig. 2). Values are means ± SE of the bores, which were means of each time series. Turbidity and TSS were not included, as sampling with a piezometer caused sediment resuspension, which may have caused extremely high values.

EC = electrical conductivity, DO = dissolved oxygen

	Temperature (°C)	EC ($\mu S\ cm^{-1}$)	pH	Redox (mV)	DO (%)
CW02 (n = 4)	26.9 ± 0.2	180.1 ± 71.5	5.1 ± 0.2	168 ± 31	17 ± 5
CW03 (n = 1)	25.0 ± 1.0	153.5 ± 18.0	5.4 ± 0.2	313 ± 12	83 ± 20
LW01 (n = 1)	24.5 ± 1.2	54.2 ± 0.5	4.8 ± 0.0	129 ± 58	35 ± 16

Table 3. Nutrient and TSS concentrations in the inlets to three constructed wetlands in the Wet Tropics between June 2020 and February 2021. Values are means ± SE of the time series for CW02 and CW03 and the mean ± SE of the time series for the two inlets in LW01.

	NO_3^--N ($mg\ L^{-1}$)	NH_4^+-N ($mg\ L^{-1}$)	DON ($mg\ L^{-1}$)	OP ($mg\ L^{-1}$)	TP ($mg\ L^{-1}$)
CW02	< 0.01	< 0.02	0.49 ± 0.04	< 0.01	-
CW03	0.14 ± 0.03	0.04 ± 0.01	0.29 ± 0.03	0.02 ± 0.00	0.14 ± 0.02
LW01 (n = 2)	0.40 ± 0.07	0.02 ± 0.00	0.23 ± 0.02	0.03 ± 0.00	0.06 ± 0.01

Table 4. Nutrient concentrations of groundwater of four constructed wetlands in the Wet tropics between June 2020 and February 2021. Values are means ± SE of the bores, which were means of each time series.

	NO_3^--N (mg L^{-1})	NH_4^+-N (mg L^{-1})	DON (mg L^{-1})	OP (mg L^{-1})	TP (mg L^{-1})
CW02 (n = 4)	0.74 ± 0.56	0.11 ± 0.08	0.07 ± 0.03	< 0.01	0.07 ± 0.02
CW03 (n =1)	0.01	0.02	0.27	0.01	0.12
LW01 (n =1)	2.02 ± 0.19	0.04 ± 0.01	0.12 ± 0.01	< 0.01	0.07 ± 0.03

Inlet vs outlet

CW02

In CW02, DO saturation was significantly higher in the inlet compared to outlet and groundwater, which had the lowest saturation (t =4.13, df =12, $p < 0.001$; t = 2.27, df = 12, p = 0.042; t = -3.62, df = 12, p = 0.004). EC was highest in the groundwater compared to the in- and outlet (t =-25.7, df =12, $p < 0.001$; t = 27.70, df =12 $p < 0.001$). Redox, temperature, and TSS were similar between in and outlet (Fig. 3, 4B).

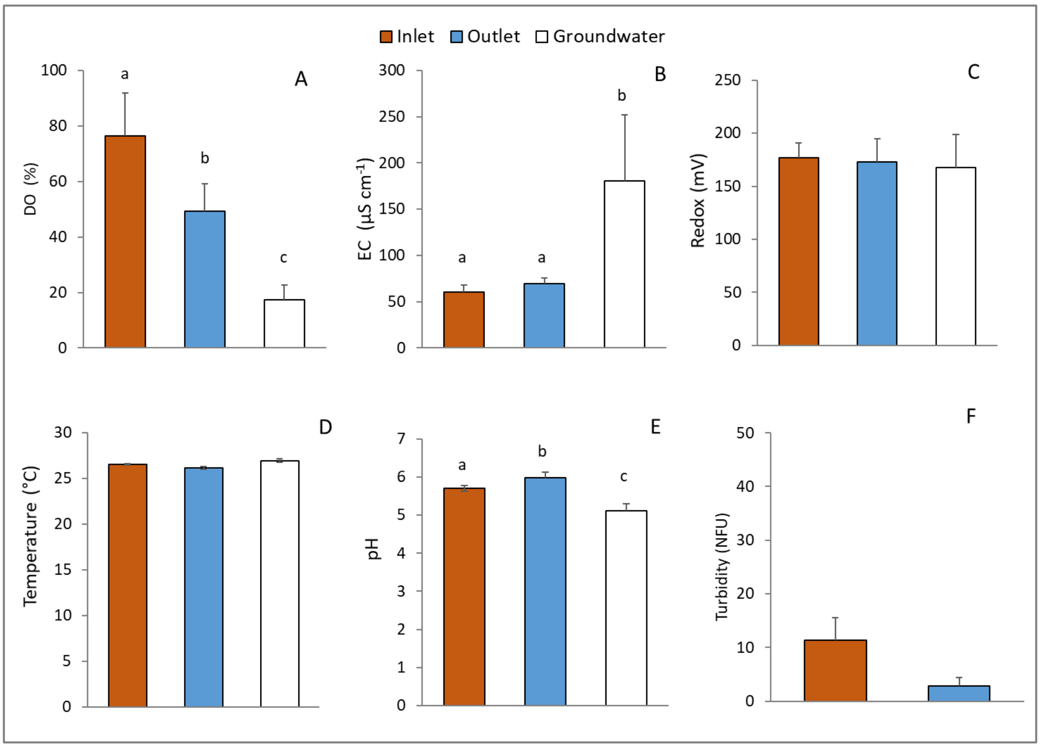

Figure 3. Differences in dissolved oxygen saturation (DO, %), electrical conductivity (EC, µS cm^{-1}), redox (mV), temperature (C°), pH and Turbidity (FNU) among inlet, outlet, and groundwater in CW02 from June 2020 to February 2021. Low case letters indicate significant differences ($p < 0.01$)

The inflows of nutrients for CW02 were mostly through groundwater, accounting for all DIN supplied to the wetland during the sampled period. Concentrations of NO_3^--N, NH_4^+-N in the outlet were significantly lower than those of groundwater by one or two orders of magnitude (Z = -2.27, n = 13, p = 0.023; Z = -3.18, n = 13, p = 0.001; Fig. 4), suggesting high uptake through plants and denitrification. Contrarily DON was highest in the outlet compared to groundwater (Z = -3.11, n = 13, p = 0.002), suggesting export due to plant or microbial production of organic matter (Fig. 4).

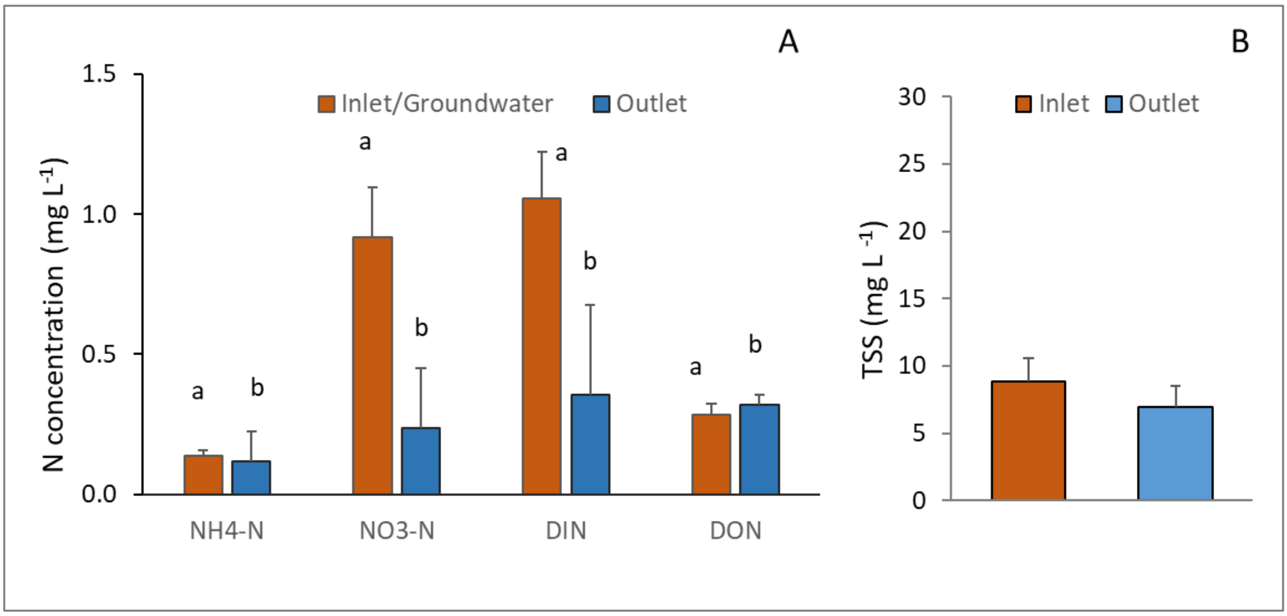

Figure 4. Differences in (A) nitrogen (N, mg L^{-1}) and (B) total suspended solids (TSS, mg L^{-1}) between groundwater and outlet in CW02 from June 2020 to February 2021. Low case letters indicate significant differences (p < 0.01)

The performance of CW02 has improved since construction with an increase in NO_3^--N and TP retention with time (Fig. 5). The average DIN removal increased from 0.28 ± 0.05 mg L^{-1} in the wet season 2020 to 0.76 ± 0.05 mg L^{-1} in 2021 (Fig. 13). One event was recorded of NH_4^+-N release at the beginning of the wet season in December 2020, coincident a very high peak of NO_3^--N input (5.6 mg L^{-1}).

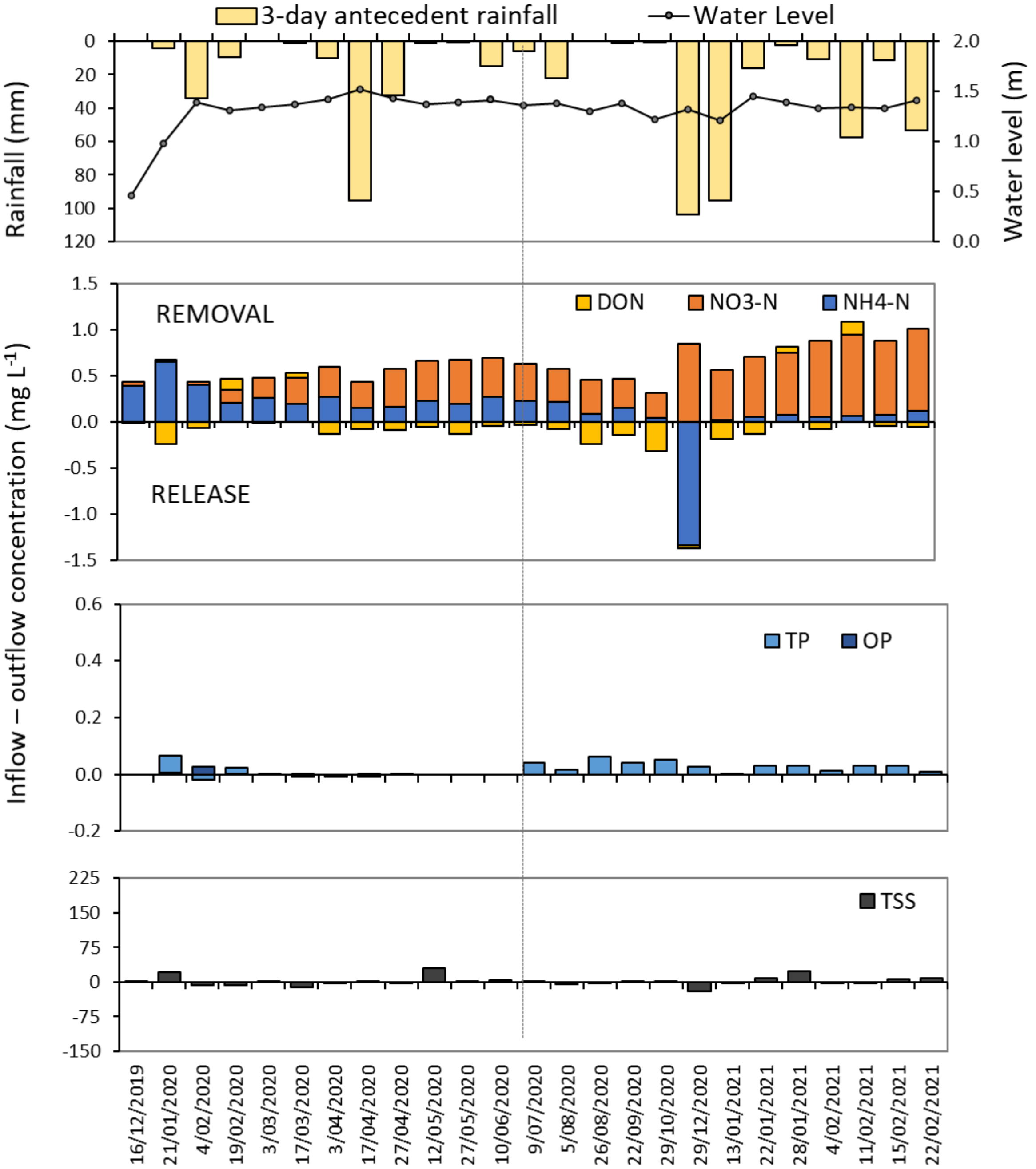

Figure 5. Differences between the inlet (groundwater) and outlet concentrations (mg L^{-1}) of nitrogen (DON, NO_3^--N, NH_4^+-N), phosphorus (TP, OP) and total suspended solids (TSS) in CW02 from December 2019 to February 2021. The hashed line indicates the starting date for the analyses in this report.

CW03

For CW03, there were no significant differences between in- and outlet for all the physicochemical parameters analysed, except EC, which was lower at the outlet (t = 5.03, df =17, $p < 0.001$). Nutrients in CW03 mainly were derived from runoff through the inlet, which had higher concentrations than groundwater (Table 3 and 4). Site CW03 had the lowest NO_3^--N concentrations of all the treatment wetlands measured and the highest TP (both at 0.14 mg L^{-1}; Table 3), TSS, and turbidity levels (Table 1, Fig. 6). TP was significantly lower in the outlet than the inlet suggesting retention (t = 2.34, df =33, p = 0.026). No other nutrient concentration in the outlet was significantly different from the inlet (Fig. 7).

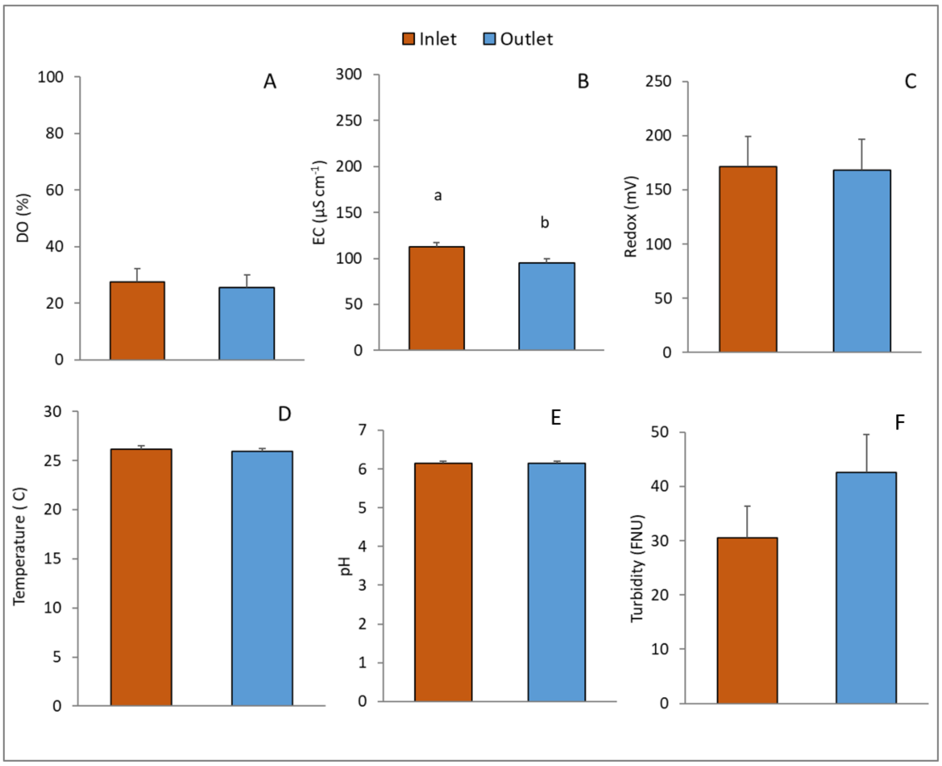

Figure 6. Differences in dissolved oxygen saturation (DO, %), electrical conductivity (EC, µS cm^{-1}), redox (mV), temperature (C°), pH and Turbidity (FNU) between inlet and outlet of CW03 from June 2020 to February 2021. Low case letters indicate significant differences (p < 0.01)

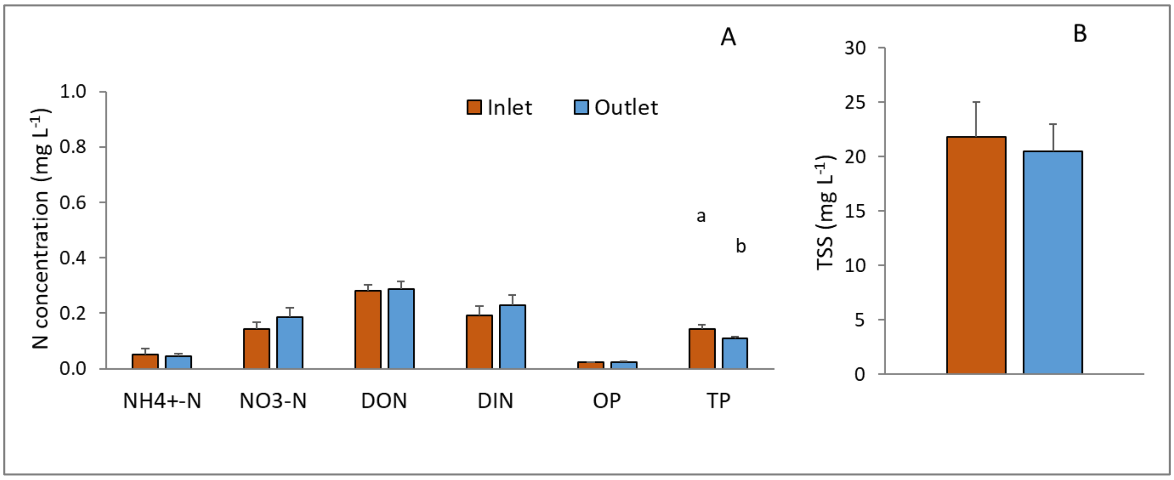

Figure 7. Differences in (A) nitrogen (N, mg L^{-1}) and (B) total suspended solids (TSS, mg L^{-1}) between the inlet and outlet in CW03 from June 2020 to February 2021. Low case letters indicate significant differences (p < 0.05)

Since its construction, CW03 has had low N flows and removals, except for brief periods in the wet season of 2020 (March) and, recently, in February 2021. However, this site is a sink of TP, probably because of sedimentation, which results in the deposition of sediments and the P associated with them (Fig. 8).

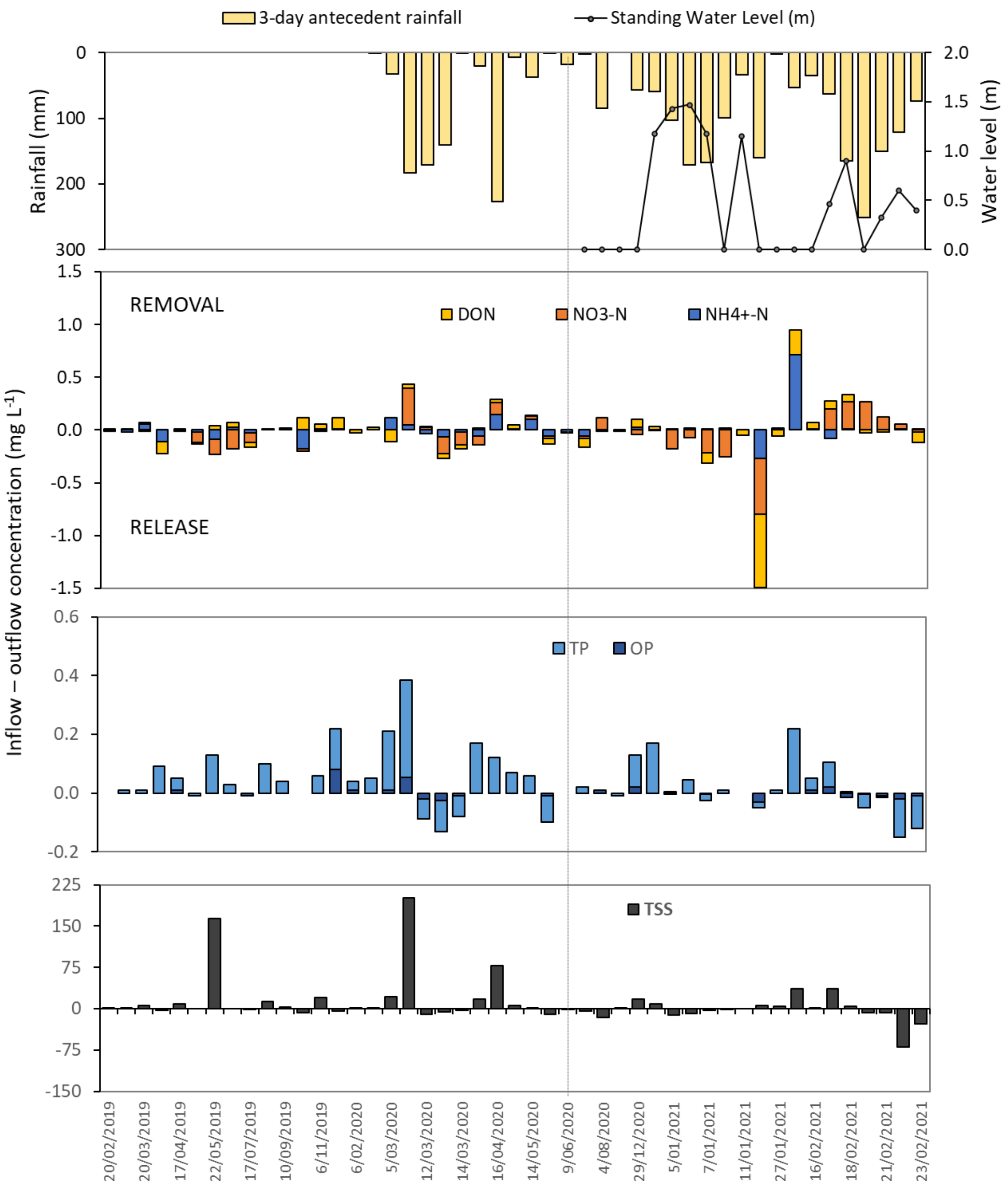

Figure 8. Differences in inlet and outlet concentrations (mg L^{-1}) of nitrogen (DON, NO_3^--N, NH_4^+-N), phosphorus (TP, OP) and total suspended solids (TSS) in CW03 from February 2019 to February 2021. The hashed line indicates the starting date for the analyses in this report.

LW01

In this wetland, DO%, redox, temperature and turbidity were significantly higher in the inlet compared to the outlet ($t = 17.93$, df =28, $p < 0.001$; $t = 4.27$, df = 24, $p < 0.001$; $t = 4.80$, df = 28, $p < 0.001$; $t = 4.40$, df = 28, $p < 0.001$). Contrarily, EC was highest at the outlet, consistent with evaporation ($t = -5.16$, df = 17, $p < 0.001$).

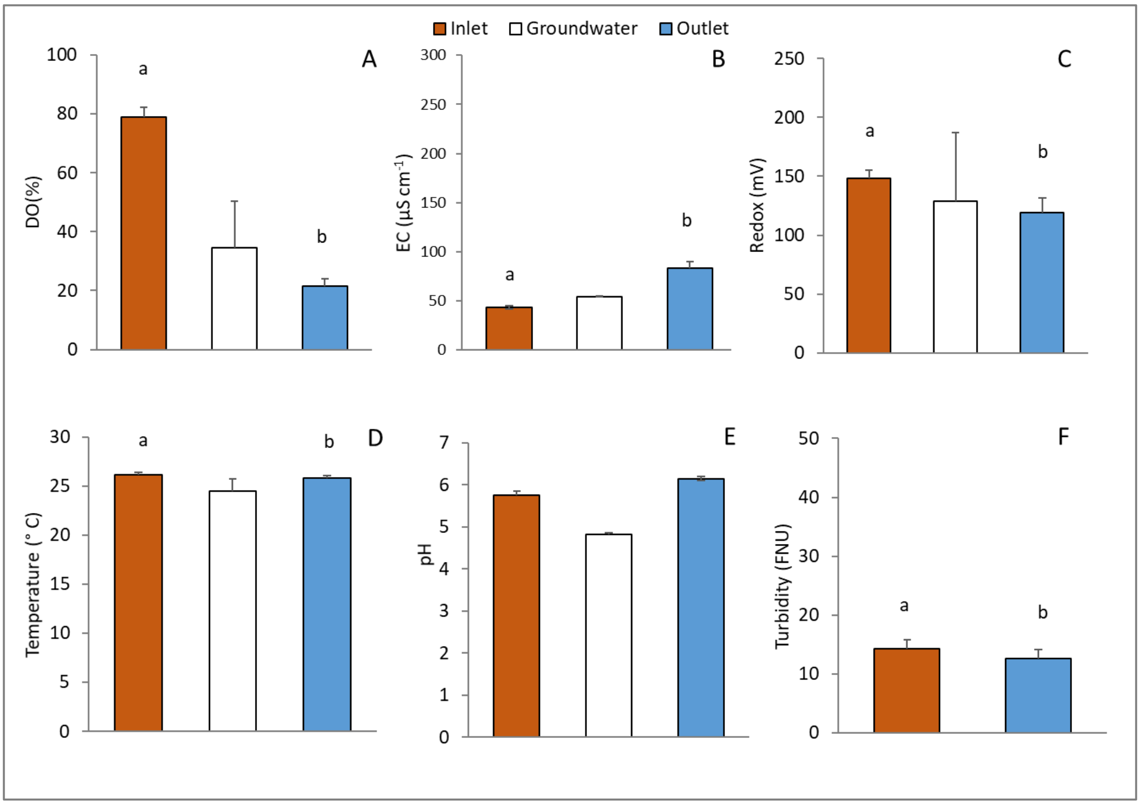

Figure 9. Differences in dissolved oxygen saturation (DO, %), electrical conductivity (EC, µS cm^{-1}), redox (mV), temperature (C°), pH and Turbidity (FNU) between inlet and outlet of LW01 from January 2020 to February 2021. Low case letters indicate significant differences ($p < 0.01$). Groundwater was not included in the statistical analyses due to limited data points (n ≤ 10).

In LW01, NO_3^--N concentrations were four times higher in the inlet compared to the outlet ($Z = -4.41$; $p < 0.001$) suggesting established denitrification in the treatment wetland. There was export of DON and a small export of NH_4^+-N, OP and TP ($t = -9.084$, df = 30, $p < 0.001$; $Z = -2.12$; $p < 0.034$; $Z = -3.46$; $p = 0.001$; $Z = -4.51$; $p < 0.001$; Fig. 10).

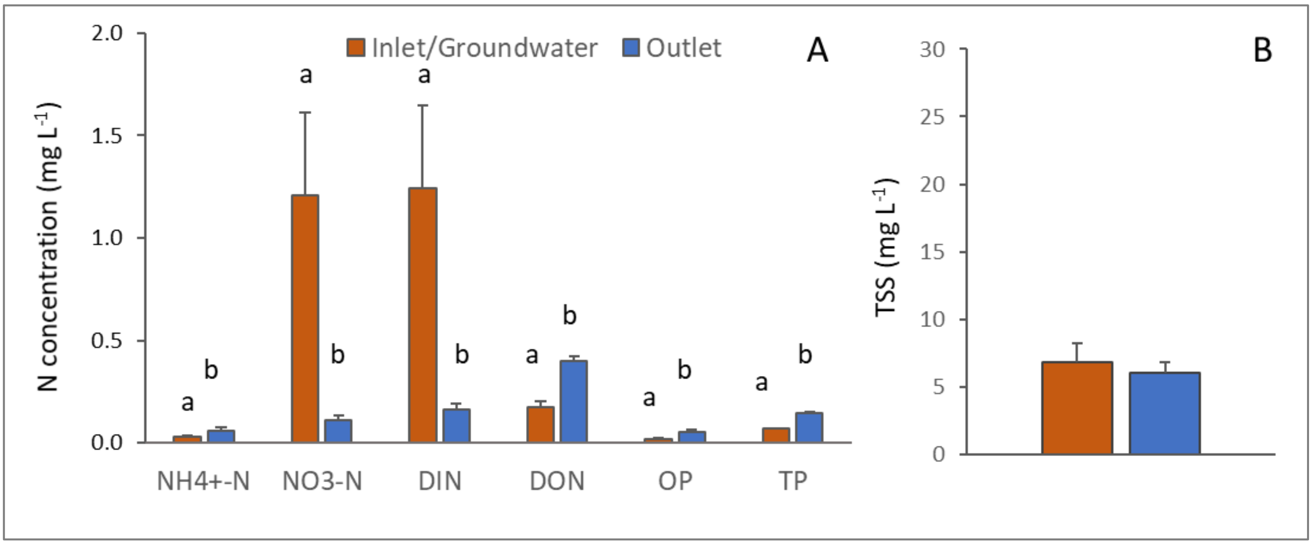

Figure 10. Differences in (A) nitrogen (N, mg L^{-1}) and (B) total suspended solids (TSS, mg L^{-1}) between the mean of inlet and groundwater concentrations and the outlet in LW01 from June 2020 to February 2021. Low case letters indicate significant differences ($p < 0.05$).

Since monitoring started, the performance of LW01 for NO_3^--N removal has improved (Fig. 11), with a 0.2 mg L^{-1} increase in DIN removal from the wet season 2020 to the wet season 2021. Additionally, the exports of TSS observed in the first months after construction have been reduced. This result is probably a result of established denitrification and increased vegetation, stabilising the soil and reducing erosion, although there are exports of TP.

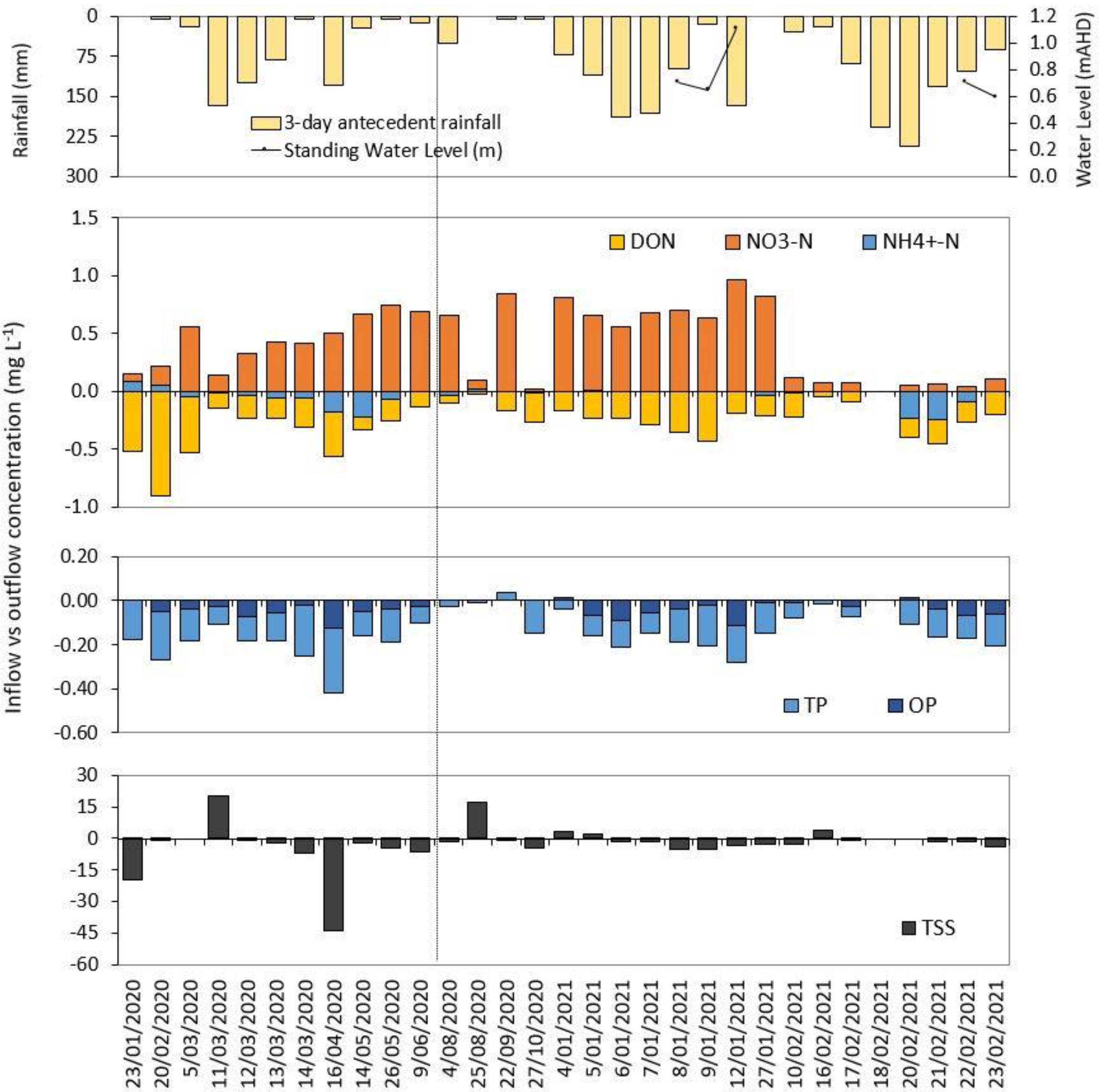

Figure 11. Differences in inlet (in and groundwater) and outlet concentrations (mg L^{-1}) of nitrogen (DON, NO_3^--N, NH_4^+-N), phosphorus (OP, TP) and total suspended solids (TSS) in LW01 wetland from January 2020 to February 2021. The hashed line indicates the starting date for the analyses in this report.

Factors associated with DIN and TP removal

From the three wetlands analysed, CW02 and LW01 have been consistently and increasingly removing NO_3^--N from the water column. Their removal is significantly and closely associated with NO_3^--N concentrations in the inlet of LW01 and the concentration in the groundwater of CW02 (Fig. 12, 13,14)

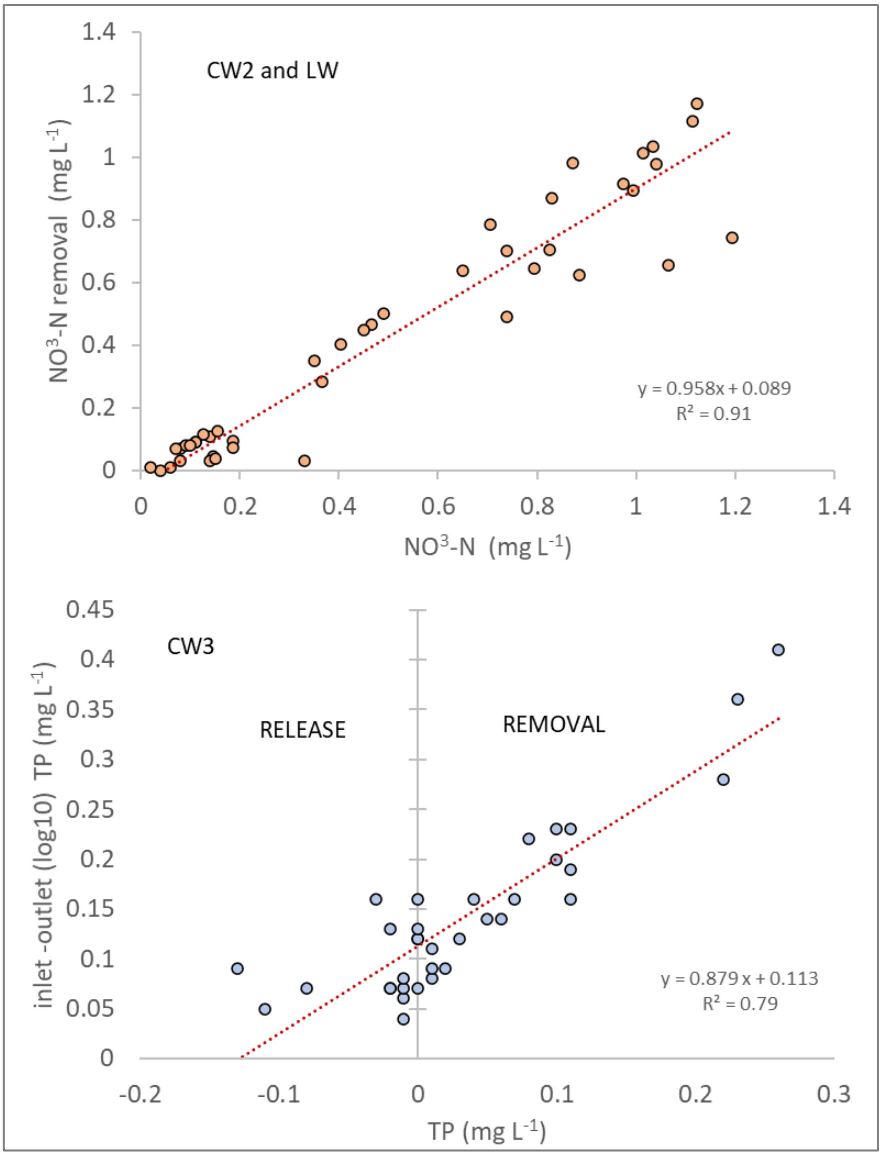

Figure 12. Association between NO_3^--N removal (inlet/groundwater concentration - outlet concentration, mg L^{-1}) in CW02 and LW01 ($p < 0.001$) and TP removal ([log10] inlet-outlet) and TP concentration in CW03.

Additionally, for CW02, higher NO_3^--N removal was associated with low inlet EC and high temperatures ($R^2 = 0.81$, $p < 0.001$). In LW01, NO_3^--N removal was associated with higher temperatures and lower redox/DO% in the water. It seems that during the summer, when NO_3^--N concentrations, temperature, and productivity are highest, conditions for denitrification are optimal, resulting in high removals (Fig. 13).

CW03 did not show any significant correlation for N removal but had a trend of higher NO_3^--N removals at concentrations > 0.1 mg L^{-1} and higher NH_4^+-N removals at concentrations > 0.04 mg L^{-1}. Reduction of TP was highest when concentrations were higher than 0.15 mg L^{-1} (Fig. 12), pH > 6, EC > 150 us cm^{-1}, and at lower Redox values (< 200 mV) ($R^2 = 0.76$, $p < 0.001$) (Fig. 14).

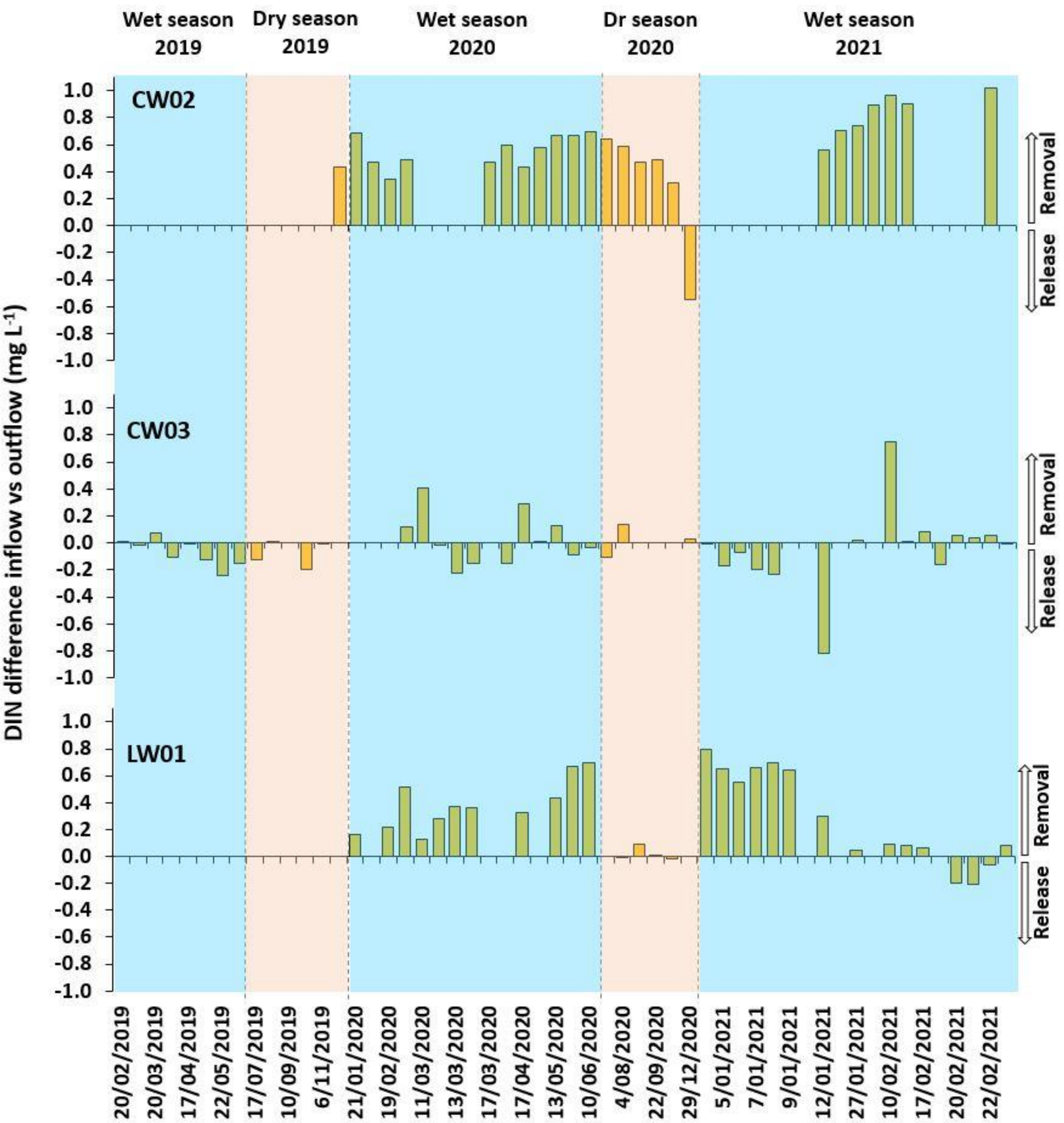

Figure 13. DIN removal performance (mg L^{-1}) of the CW02, CW03 and LW01 wetlands in two dry and three wet seasons between 2019 to 2021.

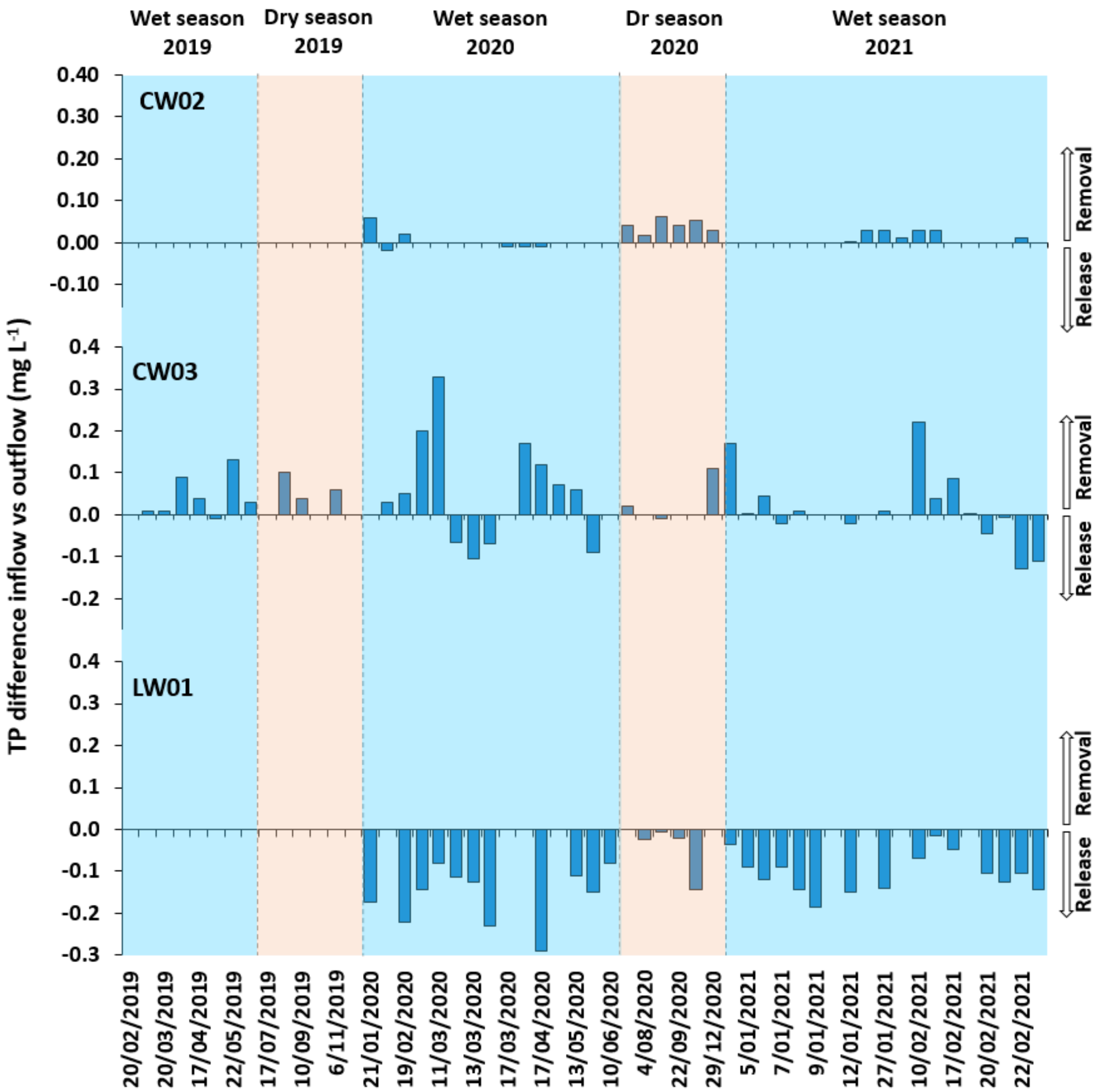

Figure 14. TP removal performance (mg L^{-1}) of CW02, CW03 and LW01 in two dry and three wet seasons between 2019 to 2021.

DIN removal in CW02 (kg yr^{-1})

The annual rates for DIN removal were higher in the wet than in the dry season, and higher in 2021 compared to 2020 (Table 5, Fig. 15). Changes in DIN removal are due to the increased N concentrations during wet periods and the increased maturity of the site in the last months of monitoring. Removals were highest for NO_3^--N than NH_4^+-N, confirming that denitrification is the key process that drives DIN removals in these treatment wetlands.

Table 5. Removal of DIN (kg yr^{-1}) during wet and dry seasons of 2020 and the projected removal for 2021 in CW02.

	Days	Groundwater flow vol. (m^3 d^{-1})		Removal (mg L^{-1})			Mass removal (kg yr^{-1})		
		Low flow	High flow	NH_4^+-N	NO_3^--N	DIN	NH_4^+-N	NO_3^--N	DIN
Wet Season 2020	181		18.4	0.27 ± 0.04	0.28 ± 0.05	0.55 ± 0.04	446 ± 72	466 ± 80	923± 60
Dry Season 2020	184	9.8		0.14 ± 0.04	0.34 ± 0.02	0.5 ± 0.06	129 ± 33	310 ± 19	450 ± 50
Wet Season 2021	181		18.4	0.06 ± 0.01	0.76 ± 0.05	0.83 ± 0.06	102 ± 18	1,259 ± 81	1,374 ± 103
Total 2020	365						576 ± 79	775 ± 82	1,373 ± 78
Total projected 2021	365						231 ± 37	1,569 ± 83	1,825 ± 115

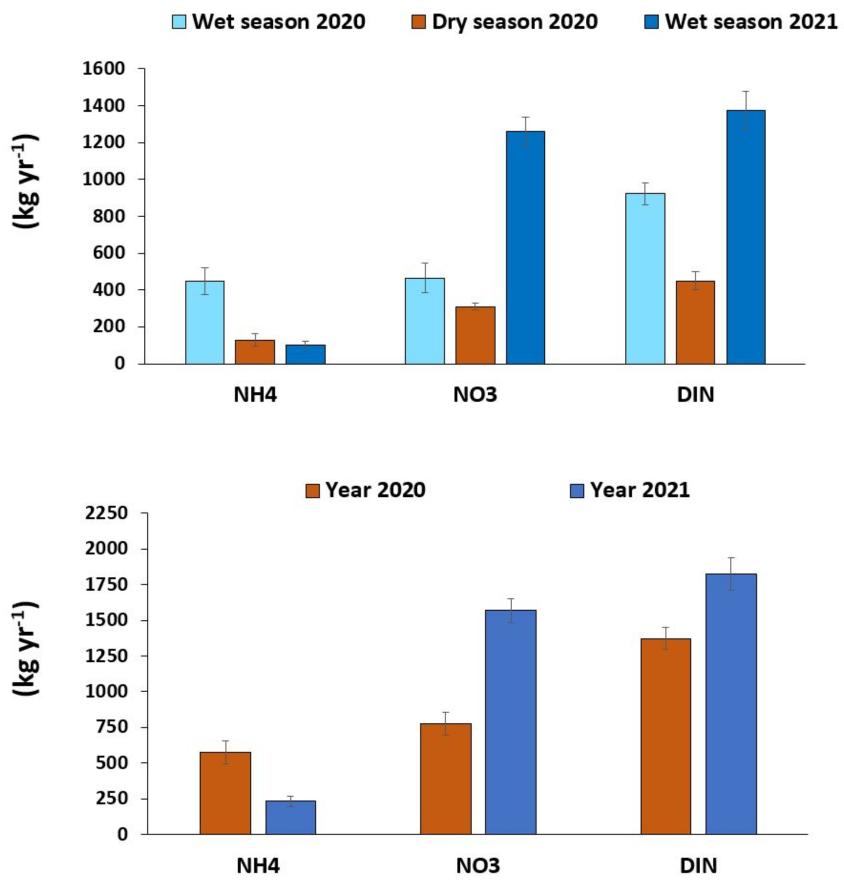

Figure 15. Removal of DIN (kg yr^{-1}) during wet and dry seasons of 2020 and the projected removal for 2021.

6. Discussion and management recommendations

After a year of monitoring, there has been consistent improvement in the capacity of CW02 and LW01 for removing NO_3^--N. Contrarily, CW03 has had only sporadic periods of removal, although it has continued to reduce TP. The conditions favouring N and TP removal are like those detected in early data analysed in Adame et al. (2020a). Higher NO_3^--N removals occur when concentrations are high, usually after rainfall events. Also, higher NO_3^--N removal was associated with lower DO% and higher pH in the outlet compared to the inlet. High pH suggests high primary productivity, which along with low oxygen and high NO_3^--N favour denitrification (Adame et al. 2021). For TP, high removal was associated with high TP concentrations and reductions of TSS, suggesting that CW03 is acting as a sedimentation basin, reducing sediment and P inputs into adjacent waterways.

CW02

This wetland was the most efficient at reducing NO_3^--N and NH_4^+-N by one or two orders of magnitude. Most of the DIN delivered to this wetland is from groundwater, where concentrations reached high values > 5 mg L^{-1}. However, it was during these peak N flushes where CW02 performed the best, removing > 90% of the NO_3^--N and between 29 to 100% of the NH_4^+-N. These results suggest that this wetland performs denitrification as or above the potential estimate of 175 kg ha^{-1} yr-^{1} measured in Adame et al. (2020b).

The estimation of water flows for this wetland by Rob Lait & Associates has allowed us to determine a removal rate of kg DIN per year considering seasonal and interannual variation (Table 5). Due to the high potential of this wetland to remove DIN and its relatively low cost of construction of this modified drain, it is strongly recommended continued monitoring of water quality, groundwater flows, and vegetation growth. Also, it would be important to assess co-benefits such as biodiversity and potential disservices such as nitrous oxide emissions, or whether these sites could be acting as “ecological traps” for some aquatic species.

CW03

This wetland has been acting as a sedimentation basin since its construction and efficiently reduces TP. This site had some potential for denitrification during our experiments (Adame et al. 2020b). Still, we early recognised that the soil was highly anoxic and soil carbon was low, which may limit NO_3^--N removal. After a year of monitoring and the establishment of vegetation, there is still no clear pattern of NO_3^--N retention, with only periodic reduction of NO_3^--N during periods of rainfall, when concentrations increase.

For CW03, we recommend conducting a test to sample different points of the wetland to establish if the current monitoring sampling points are adequately capturing DIN reduction. There may be a confounding source of water close to the sampling points affecting the nutrient concentrations observed. There is also the possibility that the high turbidity of the water and continuous sedimentation in the basin may be limiting the capacity of the soil microbial community to denitrify. Nevertheless, CW03 is removing 43% of the TSS and 29% of the TP and may be providing habitat for some aquatic species or birds. We also recommend measuring stream flow and the cross-section area at the same point. This information is essential to estimate annual mass removal (kg per year) of this site.

LW01

This wetland has shown a recent clear improvement in performance with almost a double increase in NO_3^--N removals compared to the first year and a reduction in TSS export, firstly observed after its construction. The increase in vegetation cover has probably reduced erosion and stabilised the soil enough to reach the high potential denitrification rates of 1,051 kg ha^{-1} yr^{-1} measured in Adame et al. (2020b). This site behaved in a very similar way to CW02, although LW01 has higher DON exports. LW01 removed 67 ± 5 % of the NO_3^--N that flowed through it. This site had no NH_4^+-N removal but some exports; this could be because the deeper lagoons at LW01 may create "pockets" of anoxic conditions where N is mostly in NH_4^+-N form, and thus, is not denitrified.

For LW01, we recommend continuing monitoring to detect if anoxia becomes persistent at some point, for example, during very dry periods. It would be essential to see whether these dry periods result in NH_4^+-N exports, especially after the first flush following rainfall. We also recommend measuring stream flow and the cross-section area at the same point. This information is necessary to estimate annual mass removal (kg per year) of this site. Finally, we recommend monitoring co-benefits. Due to its variability of microhabitats, including a fish passage, this site has a high potential to provide biodiversity co-benefits on top of their high potential for NO_3^--N removal.

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