ASSESSING THE PERFORMANCE OF STORMWATER TREATMENT FACILITIES IN SUBURBAN CHRISTCHURCH

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ABSTRACT

This paper discusses the findings from a monitoring program at two stormwater treatment facilities constructed for Christchurch City Council (CCC) in the last 10 years in predominantly new residential subdivisions in Christchurch. Both facilities contain first-flush basins (FFBs) followed by a wetland. The purpose of the monitoring program was to quantify the effectiveness of treatment provided by these facilities and to inform future decision-making on capital/operational investment for these devices. Specifically, the sites investigated for this study were:

- Prestons stormwater treatment facility, consisting of a Wet FFB and a wetland, and
- Knights Stream stormwater facility, consisting of a Dry FFB and intermittent wetland.

ISCO Autosamplers were used to collect samples across both facilities over nine rainfall events between 2018 and 2023. Composite samples at each autosampler site were prepared and analysed for a suite of common stormwater contaminants including metals, metalloids, nutrients, and total suspended solids (TSS).

The results from this study show that the greater reduction in contaminants occurred in Prestons Wet FFB, with lower treatment efficiencies occurring at the Dry FFB and treatment wetlands. These results indicated that the stormwater treatment wetlands exhibit lower treatment performance than was observed in comparative international research (Clary et al., 2020; CCC, 2014). However, the contributing catchments to both Prestons and Knights Stream facilities have relatively low vehicle movements and new residential housing. It is suspected that this contributes lower influent concentrations. In turn, this may result in a comparatively lower level of treatment. While wetlands and Dry FFBs provide great amenity value, flood retention and attenuation of stormwater, wetlands may not achieve the typical treatment efficiencies, specifically when the stormwater catchment contaminant concentrations are lower than typical older catchments.

These observations have implications for CCCs stormwater management strategy. Traditionally, offline wetlands were considered necessary to treat stormwater; they act as buffers to filter stormwater contaminants before they enter a water body. However, the high influent quality observed in this study challenges this assumption. It may be possible to use a Wet FFB in place of a wetland and achieve the same water quality outcomes. This doesn't undermine the importance of wetlands, which provide critical habitats for many species. Instead, it opens possibilities for more integrated stormwater management strategies, where Wet FFBs and wetlands can achieve different but compatible outcomes. In appropriate locations, the Wet FFBs could handle the initial treatment of stormwater, reducing the contaminant load, while wetlands could serve as secondary online treatment systems and wildlife habitats. This approach could optimise the use of resources, enhance

biodiversity, and still ensure the protection of water quality. Further research is needed to validate these findings and explore their full implications.

KEYWORDS: WETLANDS, FIRST FLUSH BASINS, STORMWATER QUALITY, STORMWATER TREATMENT, URBAN RUNOFF

1 INTRODUCTION

Christchurch City Council (CCC) approached Pattle Delamore Partners Limited (PDP) to assist with stormwater monitoring of stormwater treatment facilities serving urban catchments in Christchurch. This monitoring was aimed at investigating how the stormwater treatment devices are performing over a range of storm events, which is required under CCC's Comprehensive Stormwater Network Discharge Consent (CSNDC) (CRC231955).

PDP undertook monitoring of Prestons and Knights Stream stormwater facilities between 2018 and 2023. Nine rainfall events were sampled, using six ISCO 6712 automatic samplers and one Liquiport 2000 automatic sampler in locations situated at key points within the two treatment facilities.

2 BACKGROUND

2.1 HISTORICAL PRACTICES

When the first European settlers arrived in Christchurch, the place where the city now stands was a flat area filled with springs, swamps, and natural waterway systems. As the population grew and the settled areas expanded, waterborne disease, high groundwater levels, and flooding became a serious issue (Watts, 2011).

In October 1875 the Christchurch Drainage Board (CDB) was established to combat these issues through land drainage and wastewater management. For more than 100 years, the CDB focused on draining flood waters quickly and efficiently to combat flooding and protect public health. This resulted in hundreds of kilometres of open drains, concrete and timber-lined channels, and pipelines. Rivers were straightened, stop banks were constructed, and pump stations were installed (Watts, 2011).

In 1989 the CDB was merged with CCC, and adverse environmental effects from the straightening of the lower Heathcote (referred to as the Woolston Cut) increased public appetite for 'non-structural' approaches to flood mitigation. The adverse environmental effects included bank erosion and plant die-off. A barrage was constructed to divert the lower Heathcote back to its original meandering position whilst enabling the Woolston Cut to be used during large flood events, and water-sensitive design solutions were implemented within the catchment to reduce flooding instead. This included development restrictions, and the installation and expansion of wet ponds, detention basins, and soakage systems in both the Ōpāwaho/Heathcote River and Ōtākaro/Avon River catchments to manage the effects of urban development on both flooding and water quality (Watts, 2011).

The public response to the environmental impact of the Woolston Cut occurred as New Zealand began to develop resource management law, and public interest in environmental issues increased. This period led to an increase in water-sensitive urban design (WSUD) through the 1990s (Watts, 2011). In February 2003, the first iteration of the Christchurch Wetlands, Waterways and Drainage Guide (WWDG) was published to encourage innovation and sustainability in river and stormwater design practices. Wetlands and detention basins are now common practice stormwater management devices, with numerous facilities installed across Christchurch and New Zealand. Christchurch, in particular, is well suited to wetlands and wet ponds due to its history as a system of waterways and wetlands.

2.2 LITERATURE REVIEW

While WSUD systems such as wetlands were initially utilised in Christchurch for their flood mitigation benefits, they have been used as treatment systems since the 1950s in Germany. Constructed wetlands' role in water quality treatment became internationally recognized in the 1990s and early 2000s (Vymazal, 2022).

Chapter 6 of the WWDG includes treatment performance estimates for several stormwater treatment devices from data collected in studies (CCC, 2012). The International Stormwater Best Management Practice (BMP) database (ISBMPD) produced a report in 2020 (Clary et al., 2020), which analysed the removal efficiency of BMP devices using data from international studies. ISBMPD data has been compared with the WWDG treatment efficiencies, as summarized in Table 1 (CCC, 2014).

Table 1: Summary of relevant removal efficiencies found in the International Stormwater BMP (Clary et al., 2020), and the WWDG (Table 6-6) (CCC, 2014)

Treatment System	International Stormwater BMP Median Removal Efficiencies				CCC WWDG representative removal capability[1]			
	TSS	**Phosphorus[3]**	**Nitrogen[4]**	**Metals[5]**	**Solids**	**Phosphorus**	**Nitrogen**	**Metals**
Dry Detention Basin	70	10 - 30	0-30	10 - 60	40-80	40-60	20-40	20-60
Extended Wet Detention Basin	80	50	20-60	30-70	60-80	40-80	40-60	40-80
Wetlands	60	10 - 30	0-40	20-60	60-80	40-80	20-60	40-80

Notes:

1. The level of pollutant removal will be subject to the level of provisions of treatment system volume or surface areas relative to catchment runoff. As a general rule, the higher the concentration of in-flowing pollutants, the greater the degree of removal (CCC, 2012)
2. Range represents the range of median removal efficiencies between Total Phosphorus and Dissolved Phosphorus
3. Range represents the range of median removal efficiencies between Total Nitrogen, Total Kjeldahl Nitrogen, NO_x as N, and Ammonia as N
4. Range represents the range of median removal efficiencies between Total and Dissolved zinc, copper, and lead.

2.3 CSNDC COMPLIANCE

As these WSUD stormwater facilities are largely based on natural systems and biological processes, their treatment efficiency is likely to vary. Factors influencing treatment performance may be sensitive to location, and other factors such as groundwater interactions, soil conditions, surrounding land-use type, wetland age, plant species, hydraulic loading rates, and influent loading rates.

The Stormwater Quality Investigation Program outlined in CCC's CSNDC (CRC231955) lays out a framework for addressing some of the uncertainty surrounding these stormwater facilities. It is important to note that the stormwater quality investigation programme is one of several important studies that CCC is required to undertake. These studies have the potential to significantly improve the current knowledge in the performance and management of stormwater in the context of stormwater treatment.

3 METHODOLOGY

3.1 SITE SELECTION

The sample locations at Knights Stream and Prestons Stormwater Facilities are shown in Figure 1 below, along with the different treatment facility layouts.

Figure 1. Christchurch stormwater facility sampling locations

3.2 WATER QUALITY CONTAMINANTS

The sampling programme targets key pollutants of concern which are typically found in urban catchments. Stormwater samples were analysed for the following analytes:

- Turbidity
- Dissolved and Total Copper, Lead, and Zinc (Metals)
- Dissolved and Total Arsenic (Metalloid)
- Total Phosphorus (TP)
- Total Nitrogen (TN)
- Total Suspended Solids (TSS)
- Dissolved Inorganic Nitrogen (DIN)
- Dissolved Reactive Phosphorus (DRP)

Due to the volatility of petroleum hydrocarbons and the extended periods that the samples would spend in the samplers without being sealed, it was decided that these would not be included in the analysis. *E. coli* analysis was also not included due to the period between sample collection and analysis.

In established residential subdivisions, TSS is sourced from atmospheric deposition, vehicle traffic, and erosion during overland flow. Typically, TSS can decrease water clarity, smother the benthic layer of streambeds, and form a binding surface for metals, metalloids, and other contaminants (Charters, Cochrane, & O'Sullivan, 2015). It is therefore an important pollutant for determining the effectiveness of a treatment facility.

Dissolved metals are more bioavailable and therefore more toxic to the aquatic environment (ANZG, 2019). However, particulate metals can accumulate in streambeds and can dissolve or become re-suspended over time. Therefore, it is important to analyse the samples for both total and dissolved metals.

DIN and DRP are the dissolved inorganic forms of nitrogen and phosphorus that are available for immediate uptake by plants. TN and TP include bound forms of nutrients that are less bioavailable. Environment Canterbury's (ECan) current guideline for receiving water bodies includes guideline values for DIN and DRP in rivers and artificial water courses, and TN and TP in lakes. Both DIN and DRP can influence the growth of periphyton in rivers which can lead to excessive algae growth. This growth can cause issues such as a reduction in habitat for aquatic life, altered water chemistry, and obstructing the flow in waterways (ANZG, 2019). Therefore, it is important to understand the magnitude of nutrient removal provided by the stormwater facilities.

3.3 EQUIPMENT AND SAMPLING

The sampling programme used the following equipment:

- Six ISCO 6712 automatic samplers, with ISCO 730 Bubbler Flow Modules to measure the water depth; and
- One Liquiport 2000 automatic sampler, PS98i pressure transducer to measure water depth.

A trigger water level was set for each of the samplers, and when the Bubbler Flow Module or PS98i detects a level greater than the trigger level the sampling program begins. In some cases, due to damaged Bubbler Flow Module tubing or issues with the Liquiport programming, the samplers have been triggered manually or based on a programmed start time.

Due to the inability to measure flow at some of the sample locations, time-weighted composite samples were the chosen sample type. This method of sampling is not as accurate as flow-based sampling; however, collecting a large number of samples at each site per rainfall event can produce results similar to flow-based sampling regimes. Following a storm event, the autosamplers collected up to 72 time-weighted samples. NIWA (2021) peer reviewed the monitoring. Since flow monitoring was not feasible, NIWA recommended that autosamplers should collect at least 30 samples per storm event for each composite sample. The high number of samples collected enables an estimate of the event mean concentration (EMC) to be obtained within a 20% error, with greater sample numbers further reducing this error.

From these time-weighted samples, three 1 L composite samples were prepared and sent to an IANZ-accredited laboratory for testing. Two were analysed as duplicate samples to ensure the composite sampling method was consistent, and the third sample was held cold until the results of the other samples were reported. If there were major discrepancies in the two samples, the third sample was analysed. Otherwise, the average concentration between the two duplicate samples was reported.

3.4 STORM EVENT SUMMARY

NIWA (2014) recommends that only rainfall events with a rainfall accumulation exceeding 2.5 mm per day should be considered runoff-generating events. This is because the effects of evaporation and depression storage result in little (if any) runoff generation from events smaller than this. As such, antecedent dry days are also defined as days having less than 2.5 mm of rainfall.

Rainfall data for the Prestons stormwater facility was obtained from the Lower Styx rainfall station. This monitoring location is situated approximately 2 km from the Prestons monitoring sites and is the closest weather station with available and reliable data. The closest reliable weather station for the Knights Stream site was approximately 5 km away (Sparks Road).

Nine rainfall events have been sampled at the Prestons and Knights Stream monitoring sites (2018 – 2023). A summary of the rainfall characteristics of each of these events is provided in Figure 2. Graph legends include the number of antecedent dry days (ADDs) that preceded each event. The relative steepness of each graph shows the relative storm event intensities. A wide range of rainfall depths, durations, and antecedent dry days have been sampled at the Prestons and Knights Stream facilities, ranging from storms with over 90 mm of rainfall over 80 hours to 15 mm over 10 hours.

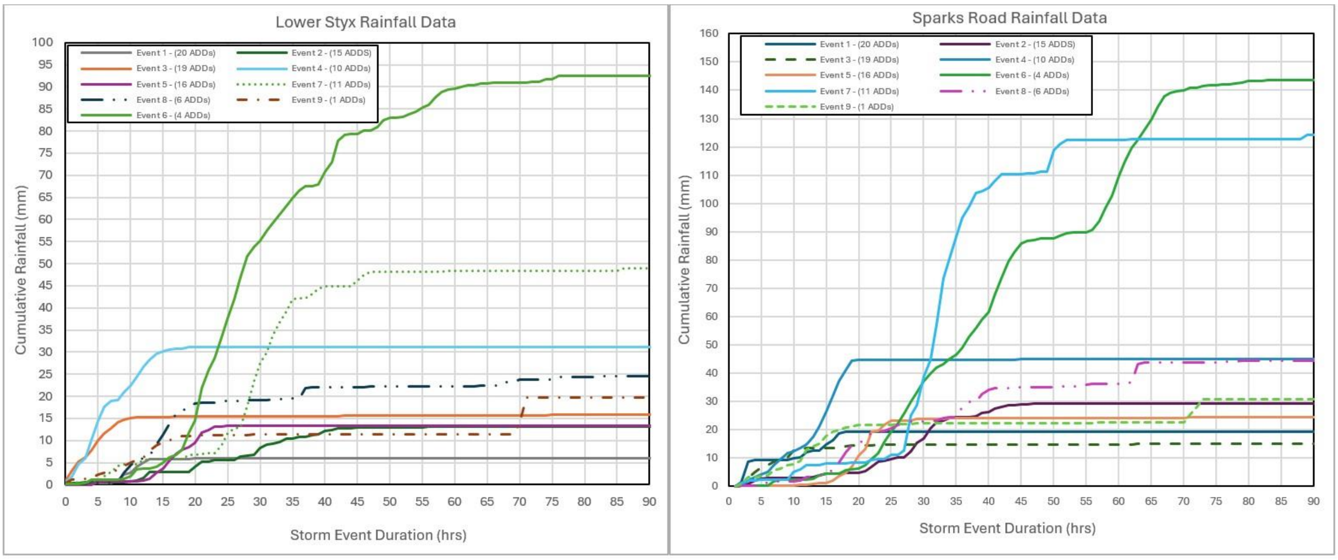

Figure 2. Lower Styx and Sparks Road rainfall data for all sampled events (2018 - 2023)

3.5 PERFORMANCE ANALYSIS

The performance of the stormwater facilities and treatment devices was assessed based on the analysis of distributions of influent and effluent water quality sample concentration data for individual events. The contaminant concentration and removal efficiency for each pollutant at each site were plotted using a box plot, with influent/effluent/removal efficiency medians, interquartile ranges, and 95% confidence intervals. The median and interquartile ranges were used as descriptive statistics for the BMP performance, as these are generally less impacted by extreme values than means and standard deviations (Clary et al., 2020).

To assess the performance of these stormwater facilities, the Mann-Whitney U test/Rank Sum test (Mann-Whitney Test) and the Wilcoxon sign ranked test (Wilcoxon Test) were utilised. These tests are both non-parametric hypothesis tests, which are used to assess significant median differences. The Mann-Whitney Test is suitable for independent data tests, while the Wilcoxon Test is used to pair influent and effluent data. These two tests were chosen for consistency with the methodology used in the ISBMPD (Clary et al., 2020).

The outcomes of the Mann-Whitney and Wilcoxon Tests may contradict each other when quantifying statistical significance. For stormwater facilities with short hydraulic residence times and limited storage, the Wilcoxon Test is considered more accurate, as it assesses influent and effluent data pairs. For stormwater treatment devices with longer residence times and more storage, the Mann-Whitney Test is considered more accurate as influences from different storm events might mix within the treatment device, before flowing out (Clary et al., 2020). For reference, Prestons FFB is a Wet FFB, and has a significant amount of storage as well as inflows from groundwater; whereas Knights Stream is a Dry FFB and will likely be best suited to the Wilcoxon Test.

The Mann-Whitney Test was carried out in Python using the scipy.stats.mannwhitneyu module (Virtanen, et al., 2020). An exact methodology was used to calculate the exact p-value by comparing the observed statistic against the exact distribution of the statistic under the null hypothesis. This method was chosen as the sample size was less than or equal to 8 for many of the locations. However, where there were ties in the data set, the asymptotic methodology was used instead, as it corrects for ties (where the exact method does not) (Virtanen, et al., 2020).

The Wilcoxon Test was carried out in Python using the scipy.stats.wilcoxon module (Virtanen, et al., 2020). To prevent roundoff errors, the influent–effluent subtraction was calculated outside of the scipy function. The method used for finding the p-value was the approximate method, due to the limited amount of data available. It is worth noting that the Wilcoxon Test cannot be applied when the difference between all contaminants is zero. Therefore, for some contaminants, it could not be applied, as all tests were below the detection threshold. Additionally, because it required influent and effluent pairs, if data was missing for an influent or effluent value, its corresponding pair had to be discarded. Where there were ties in the data, the exact p-value calculations could not be carried out, and normal approximations were utilized instead. This approximation creates a normal distribution, which is standard practice for large data sets. As this is not a large dataset, results should be interpreted with caution.

The bootstrap technique is a technique for estimating variance, bias, and percentiles for nonparametric data (Boos & Brownie, 1988). In the case of this study, the bootstrap methodology was applied to estimate percentiles by resampling the effluent and influent data for each contaminant up to 1000 times. "Resampling" refers to the process of selecting a subset or smaller dataset from a larger dataset. Resampling the original influent and effluent data 1000 times leads to a much larger randomized set of p-values, based on the original concentrations. By calculating the interquartile range of these p-values, 75th percentile and 25th percentile p-values were obtained and reported to illustrate uncertainty.

3.6 RECEIVING ENVIRONMENTAL GUIDELINES

Knights Stream and the Styx River are both classified as spring-fed (plains) streams, under the Environment Canterbury (ECan) Land and Water Regional Plan (LWRP). This means they require a 95% level of protection (LoP) for aquatic organisms (ECan, 2018). Based on this information, results were compared to the guidelines outlined in Table 2.

Table 2: Receiving Water Standards

Standard Applied	**Contaminants**
ECan LWRP Rule 5.95A, Condition 2 (a)	TSS
ECan LWRP Schedule 5 Table S5A	Nutrients
ECan LWRP Schedule 5 Table S5B	Metals and metalloids

The LWRP standards are for chronic (longer term) exposure and, except for Rule 5.95A, Condition 2 (a) of the LWRP, are intended to be applied to a discharge following reasonable mixing with the receiving waterway. A mixing assessment has not been undertaken, nor have the concentrations of contaminants within the receiving waterway been accounted for in this paper (ECan, 2018). Therefore, results must be interpreted with caution and are intended to be used as a guide for comparison. However, the results will aid in identifying which contaminants may be of concern for the receiving waterway.

The receiving water standards in the LWRP do not distinguish between dissolved metals and total metals. However, the LWRP values are comparable to the ANZG (2019) trigger values, which are based on the dissolved fraction. The collection of both the dissolved and total metal & metalloid concentrations adds to our understanding of the capture and removal of particulate metals or metalloids within the treatment system. Therefore, their values were applied to both dissolved and total metals. However, the LWRP does distinguish between different forms of arsenic. The limit for arsenic V was conservatively applied to the results as this limit is lower than for arsenic III (ECan, 2018).

4 RESULTS

4.1 KNIGHTS STREAM STORMWATER FACILITY

4.1.1 WATER QUALITY

The metal and metalloid concentrations at each sampling location at the Knights Stream stormwater facility are plotted in Figure 3.

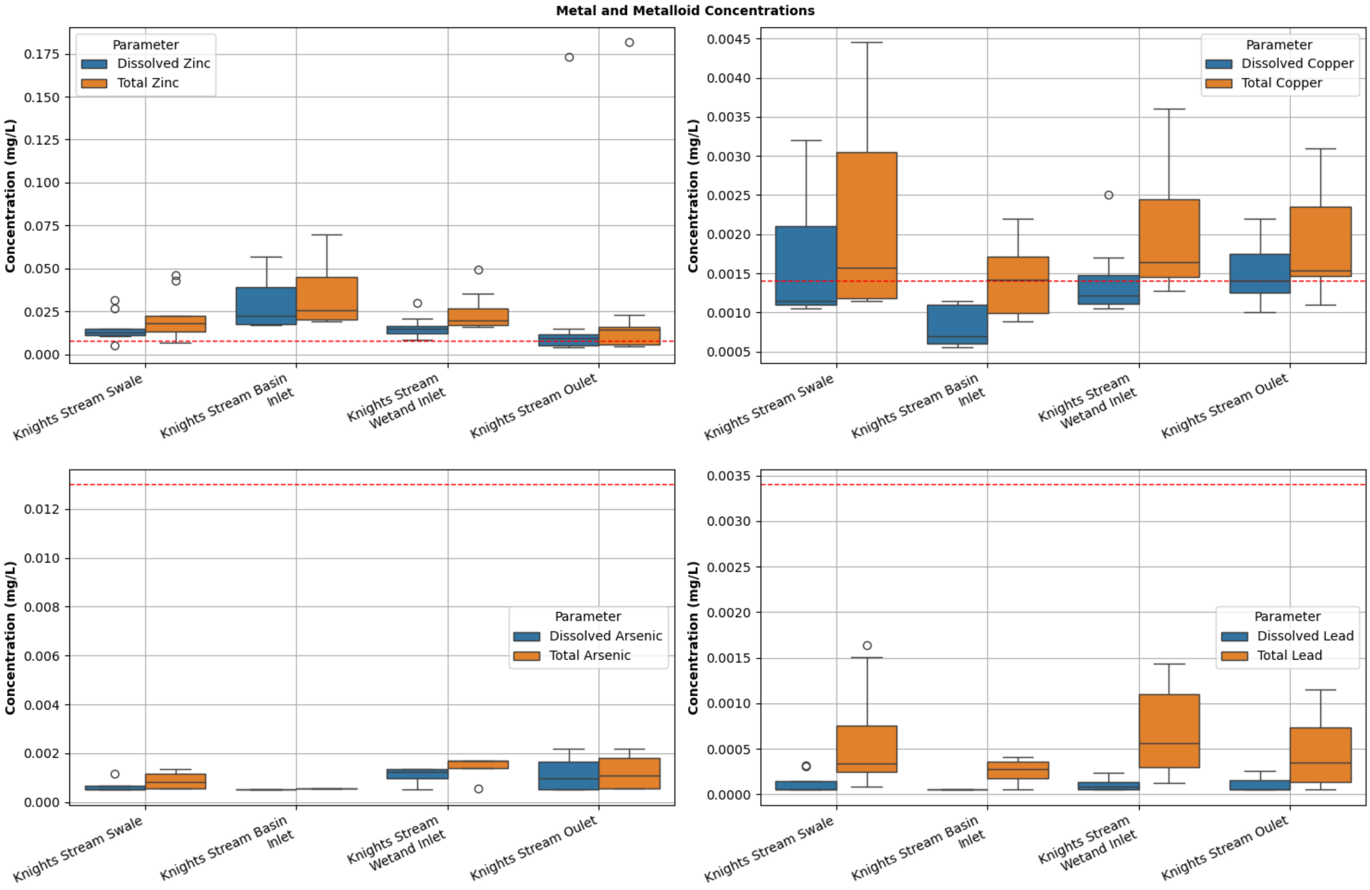

Figure 3. Metal and metalloid contaminant concentrations in the Knights Stream Stormwater Facility (the red dashed lines are the LWRP water quality limits (ECan, 2018))

The TSS and nutrient concentrations at each sampling location at the Knights Stream stormwater facility are plotted below in Figure 4.

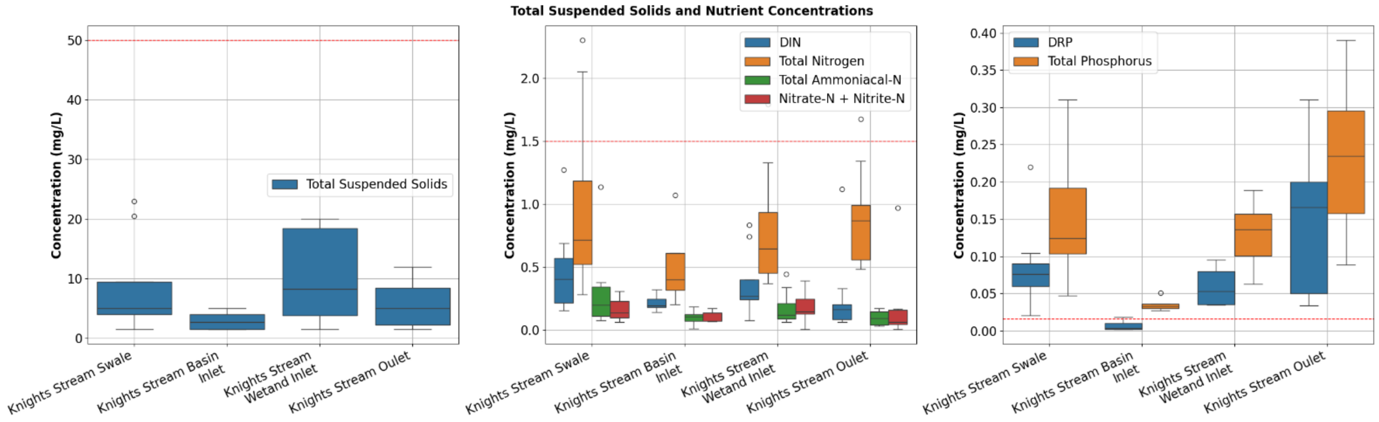

Figure 4. TSS and nutrients contaminant concentrations in the Knights Stream Stormwater Facility (red dashed lines are the LWRP water quality limits (ECan, 2018))

4.1.2 REMOVAL EFFICIENCIES

The observed contaminant removal efficiencies at the Knights Stream wetland and Dry FFB are plotted below in Figure 5. These removal efficiencies have been evaluated against the anticipated removal efficiency published in the WWDG (CCC, 2012).

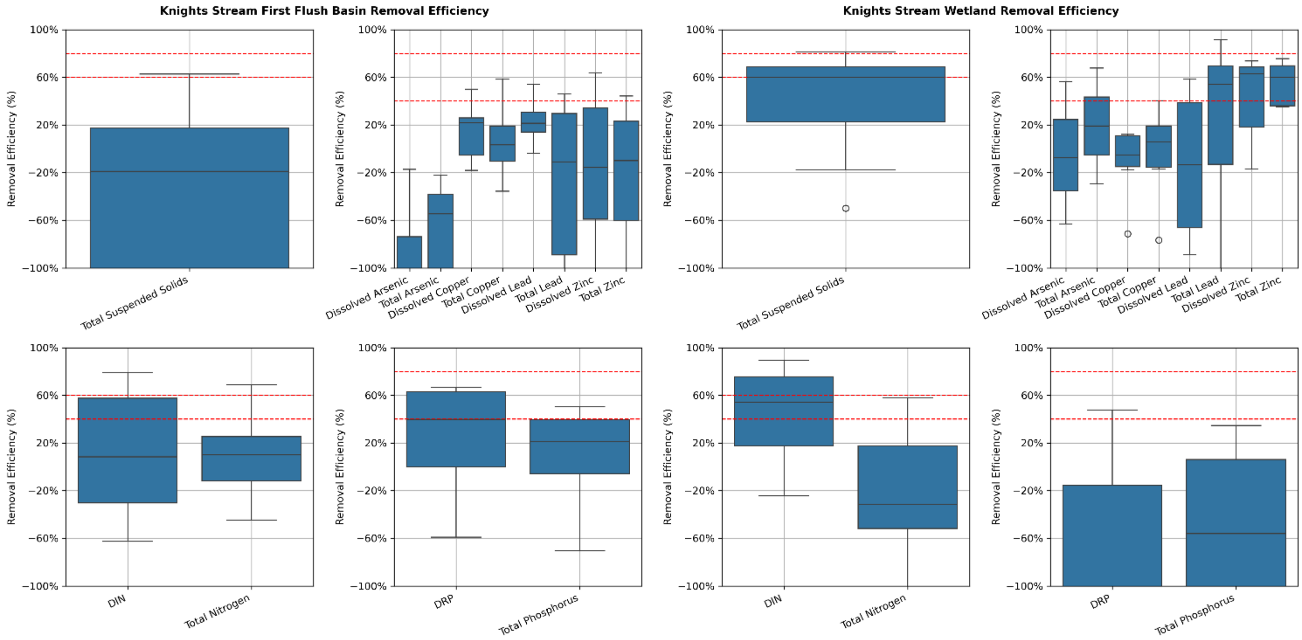

Figure 5. Knights Stream Dry FFB and Wetland removal efficiencies

4.1.3 STATISTICAL ANALYSIS

The statistical analysis for Knights Stream influent and effluent concentrations is shown in Table 3. The Wilcoxon Test was used to compare influent and effluent contaminant concentrations, as the stormwater of the events considered in this study were unlikely to have mixed. Specifically, the test was used to demonstrate if the effluent water quality was statistically lower than the influent water quality for the two treatment elements (Dry FFB & wetland), where the p-values quantify the statistical evidence against the hypothesis that effluent contaminant levels are less than influent concentrations. A p-value (<0.05) suggests strong statistical evidence for this hypothesis, indicating lower effluent concentrations. The key features of this analysis are as follows:

- Bootstrap method was used to calculate the 25th and 75th percentile p-values for influent and effluent contaminant concentrations, to illustrate uncertainty.
- p-values < 0.05 (green) show statistically significant contaminant reduction.
- p-values > 0.95 (red) indicate it is unlikely this contaminant is reduced through the device.
- p-values <0.6 (orange) indicate that there is more than a 60% probability that there is a contaminant reduction.

Table 3. Statistical hypothesis testing that the Knights Stream Dry FFB and Wetland produced a reduction in contaminant concentrations.

Contaminants	Dry FFB			Wetland		
	25th % p-value	p-value	75th % p-value	25th % p-value	p-value	75th % p-value
Total Suspended Solids	0.25	0.55	0.74	0.04	0.05	0.31
DIN	0.15	0.55	0.74	0.11	0.25	0.64
DRP	0.05	0.18	0.46	0.02	0.05	0.20
Dissolved Arsenic	0.10	0.11	0.25	0.25	0.59	0.79
Dissolved Copper	0.17	0.18	0.74	0.20	0.74	0.74
Dissolved Lead	0.17	0.14	0.72	0.22	0.47	0.72
Dissolved Zinc	0.31	0.95	0.74	0.05	0.25	0.64
Total Arsenic	0.13	0.11	0.38	0.18	0.65	0.69
Total Copper	0.20	0.38	0.74	0.31	0.74	0.84
Total Lead	0.25	0.95	0.74	0.15	0.20	0.64
Total Zinc	0.20	0.95	0.74	0.04	0.20	0.64

Table 3 shows the probability that each contaminant is being reduced through the respective treatment devices. To analyse this further, a bootstrap of the influent and effluent values was used to quantify the percentage of samples for each contaminant that meets the LWRP water quality standards outlined in Section 3.6, as presented in Figure 6 (ECan, 2018).

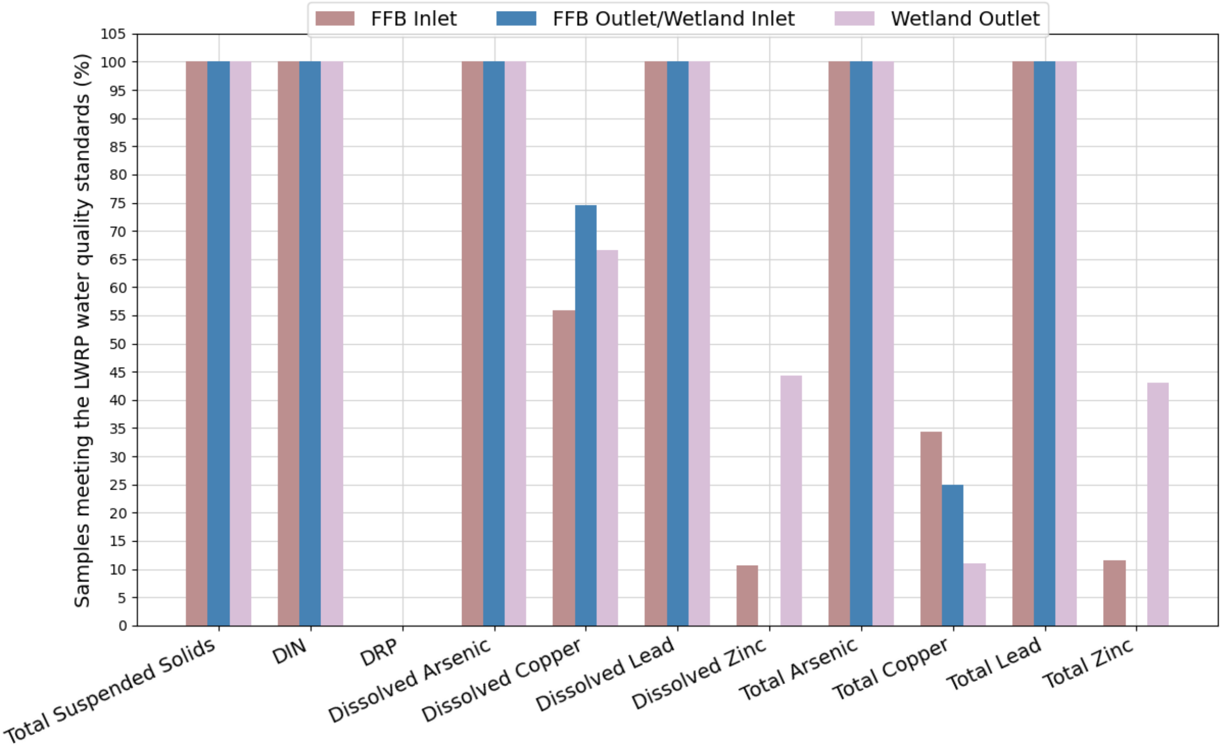

Figure 6. Knights Stream Stormwater Facility Compliance with LWRP Water Quality Standards (ECan, 2018).

4.2 PRESTONS STORMWATER FACILITY

4.2.1 WATER QUALITY

The metal and metalloid concentrations at each sampling location at the Prestons stormwater facility are plotted below in Figure 7. Where the red dashed lines are the LWRP water quality standards discussed in Section 3.6 (ECan, 2018).

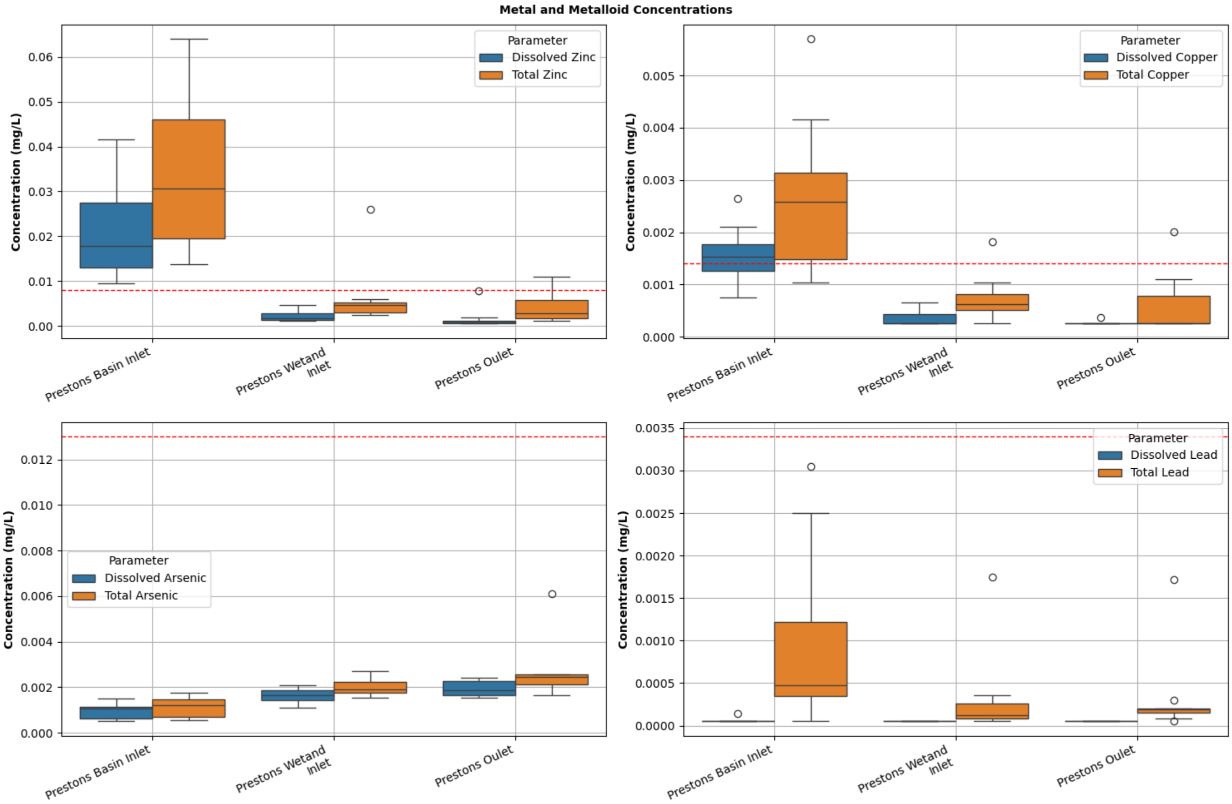

Figure 7. Metal and metalloid contaminant concentrations in the Prestons Stormwater Facility (the red dashed lines are the LWRP water quality limits (ECan, 2018))

The TSS and nutrient concentrations at each sampling location at Prestons stormwater facility are plotted below in Figure 8.

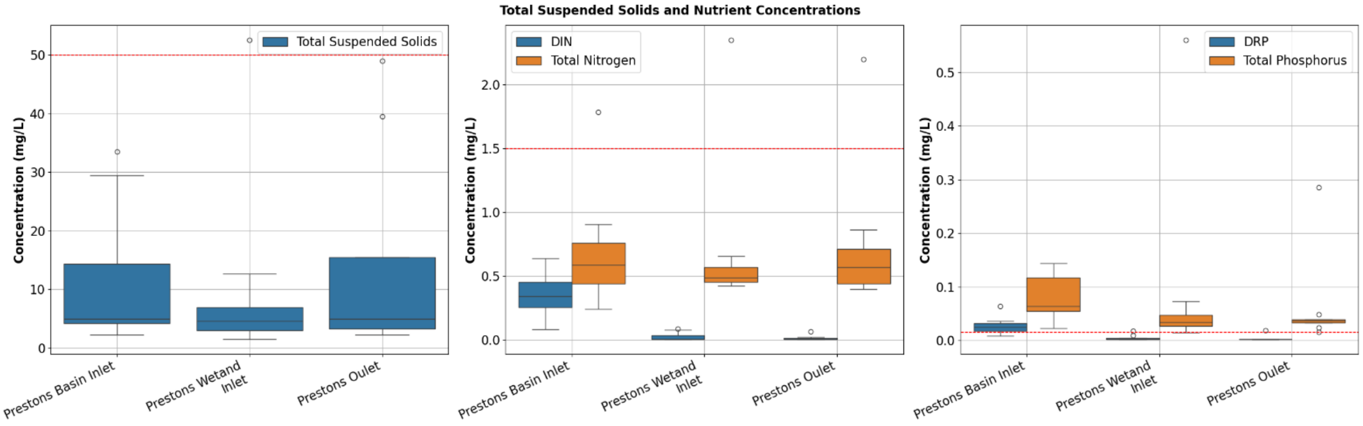

Figure 8. TSS and nutrient contaminant concentrations in the Prestons Stormwater Facility (the red dashed lines are the LWRP water quality limits (ECan, 2018))

4.2.2 REMOVAL EFFICIENCIES

The observed contaminant removal efficiencies at the Prestons wetland and Wet FFB are plotted below in Figure 9. These removal efficiencies have been evaluated against the anticipated removal efficiency published in the WWDG (CCC, 2012).

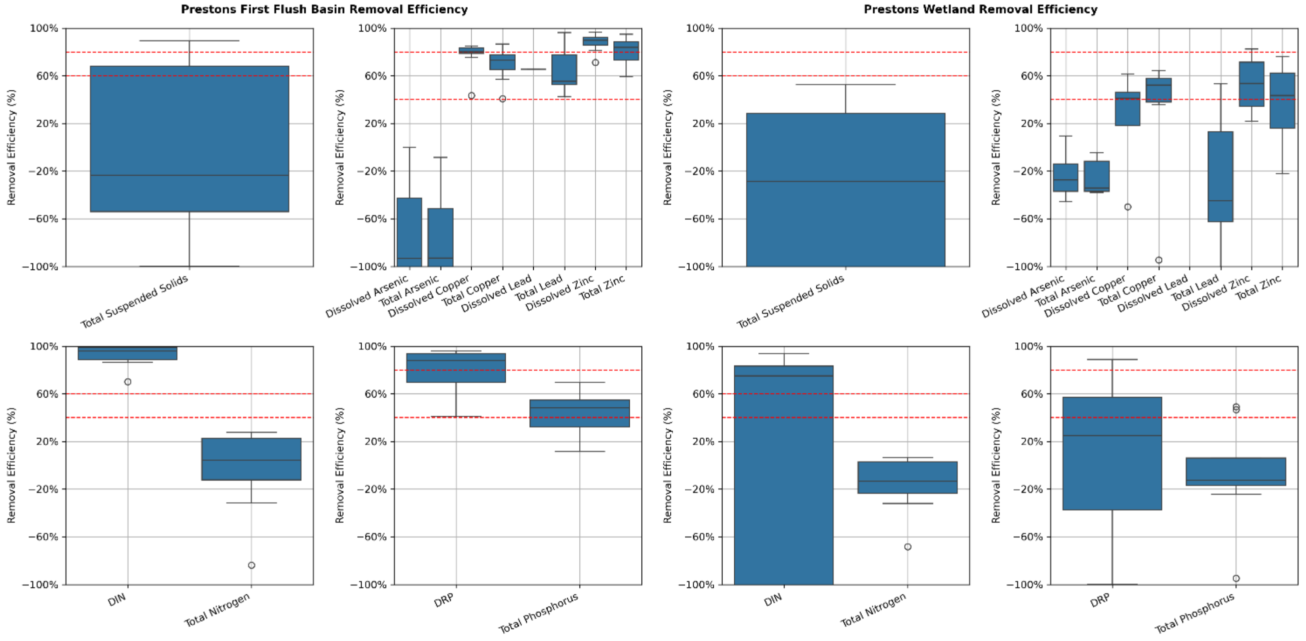

Figure 9. Prestons Wet FFB and Wetland removal efficiencies

4.2.3 STATISTICAL ANALYSIS

As outlined in Section 4.1.3, a similar statistical analysis of the observed Prestons Stormwater Facility influent and effluent water quality was undertaken. Table 4 shows the probability that stormwater contaminants are being reduced through the respective treatment devices. Specifically, this probability was calculated using the Mann-Whitney Test. This statistical test was applied to determine if the influent concentrations were greater than the effluent concentrations.

Table 4. Prestons FFB and Wetland Removal Efficiency Statistical Analysis.

Contaminants	**Wet FFB**			**Wetland**		
	25th % p-value	**p-value**	**75th % p-value**	**25th % p-value**	**p-value**	**75th % p-value**
Total Suspended Solids	0.11	0.32	0.58	0.44	0.73	0.91
DIN	0.00	0.00	0.00	0.14	0.36	0.63
DRP	0.00	0.00	0.00	0.03	0.17	0.31
Dissolved Arsenic	0.99	1.00	1.00	0.82	0.93	0.99
Dissolved Copper	0.00	0.00	0.00	0.03	0.09	0.17
Dissolved Lead	N/A	N/A	N/A	N/A	N/A	N/A
Dissolved Zinc	0.00	0.00	0.00	0.00	0.02	0.07
Total Arsenic	1.00	1.00	1.00	0.81	0.93	0.98
Total Copper	0.00	0.00	0.00	0.03	0.13	0.29
Total Lead	0.00	0.03	0.08	0.42	0.70	0.91
Total Zinc	0.00	0.00	0.00	0.03	0.14	0.30

To analyse this further, a bootstrap of the Wet FFB and wetland influent and effluent values was used to quantify the percentage of samples for each contaminant that meets the LWRP water quality standards outlined in Section 3.6. This information has been graphed below in Figure 10.

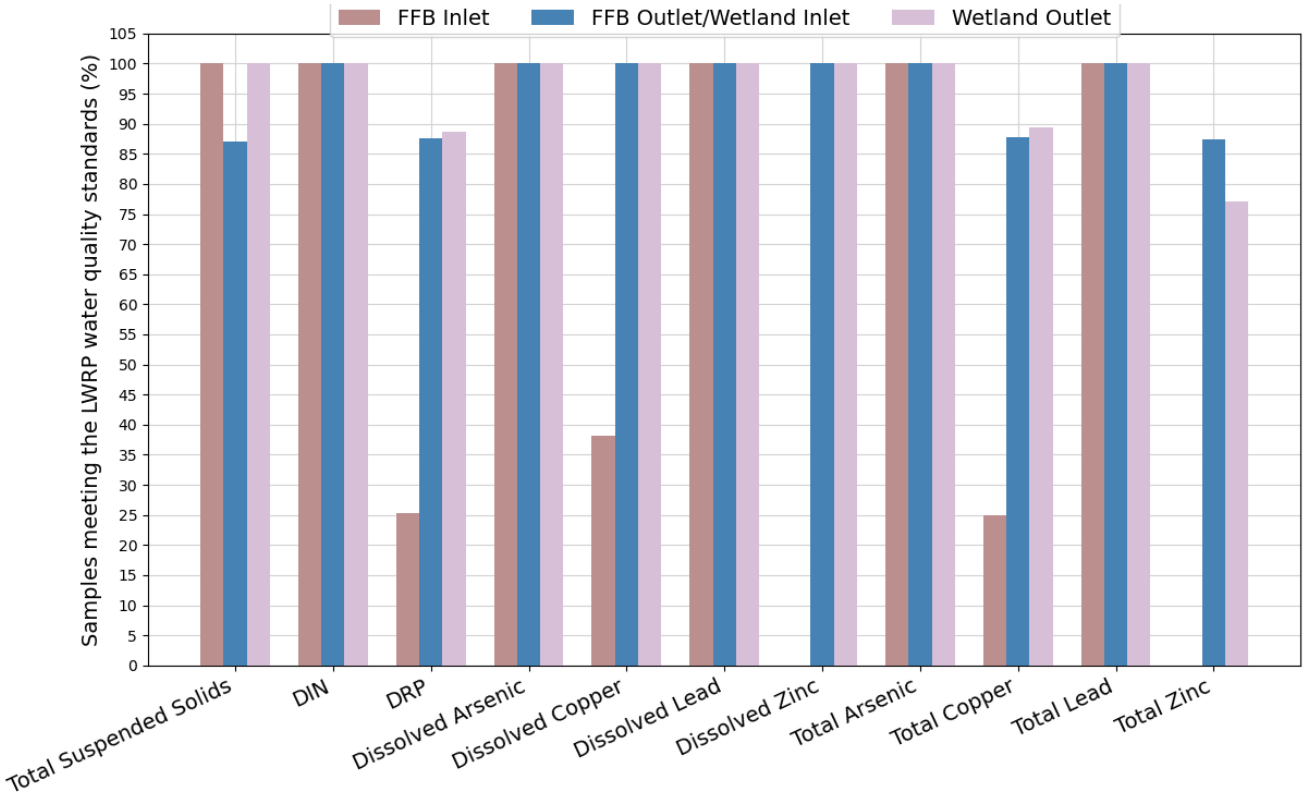

Figure 10. Prestons Stormwater Facility Compliance with LWRP Water Quality Standards (ECan, 2018).

5 DISCUSSION

5.1 FIRST FLUSH BASIN REMOVAL EFFICIENCY

The ISBMPD indicated that detention basins can provide:

- a statistically significant reduction in TSS
- a statistically significant reduction in total and dissolved zinc, total and dissolved copper, and total lead
- no statistically significant reduction in dissolved phosphorus, or dissolved nitrogen (Clary et al., 2020)

This is mostly consistent with Prestons Wet FFB, which showed a statistically significant reduction in all contaminants excluding arsenic and TSS. A comparison of the observed Wet FFB treatment efficiency and the WWDG demonstrated a similar or greater total and dissolved metals, DRP, and DIN removal efficiency, except arsenic which increased through the Wet FFB. This could be attributed to naturally elevated arsenic levels within the peaty soil of the area. Naturally occurring arsenic may be entering the Wet FFB via overland flow (erosion) and/or groundwater (PDP, 2018; PDP, 2022; Clary et al. 2020). To caveat this, it is unclear whether the other metal reductions are due to physiochemical processes within the Wet FFB, or due to groundwater dilution of contaminants. Further research on Wet

FFBs in different groundwater zones is recommended, to enhance understanding in their physiochemical processes.

The Knights Stream Dry FFB removal efficiencies shown in Figure 5 and Table 3 indicate that the treatment system has variable performance. No statistically significant reduction in contaminants through the Knights Stream Dry FFB was observed. However, the statistical analysis did indicate that:

- There was an 82% probability that DRP reduced through the system
- There was an 89% probability that total and dissolved arsenic reduced through the system
- There was an 82 – 85% probability that dissolved lead and copper reduced through the system.

The Knights Stream Wetland Inlet sampling point was located next to the wetland pump well. High flow generated by this pump may have resuspended sediment at this location, which in turn increased the suspended solids concentrations through the wetland. The pump well may need to be investigated, to determine whether it is contributing to elevated TSS concentrations and decreasing the overall calculated removal efficiency of the Dry FFB.

As previously noted, no statistically significant reduction in TSS in Knights Stream and Prestons FFBs was observed. The low TSS influent concentrations at Prestons and Knights Stream may have contributed to the low removal efficiency (CCC, 2014; Bilek et al., 2019; ANZG, 2019). The median influent sediment concentrations found in the ISBMPD ranged between 26 and 77 mg/L, whereas the median TSS concentration found at Prestons Wet FFB Inlet was just 4.6 mg/L (influent concentrations ranged from 3 – 53 mg/L). Likewise, the median TSS concentration at Knights Stream Swale was 9.5 mg/L, with a maximum of just 23 mg/L. Studies have shown that TSS influent concentrations are correlated with treatment performance (Yang, et al. 2023; Bilek et al., 2019; ANZG, 2019; Clary et al., 2020).

As shown in Figure 6 and Figure 10, the majority of stormwater contaminant concentrations were below the LWRP water quality standards prior to entering the stormwater treatment facility (ECan, 2018). Low influent and effluent concentrations can cause more variable removal efficiencies and higher sensitivity to sampling and measurement error. Where a small change in contaminant concentrations can translate to large changes in removal efficiencies. For example, if the TSS influent concentration was 0.01 mg/L, and the effluent concentration was 0.02 mg/L – the removal efficiency would be -100% despite a minute concentration change.

5.2 WETLAND REMOVAL EFFICIENCY

The observed Prestons and Knights Stream wetland removal efficiencies were not consistent with the ISBMPD or the WWDG; specifically, the observed lack of statistically significant total metals and metalloids, dissolved metals and metalloids, total suspended solids, or total phosphorus removal. However, some removal efficiencies were consistent with the ISBMPD, in terms of:

- the lower dissolved copper, and dissolved lead removal efficiencies; and
- that no statistically significant removal of Total Nitrogen, or TKN was observed.

At both stormwater treatment facilities, wetland influent contaminant concentrations were below LWRP water quality standards for most contaminants; and lower than the ISBMPD influent concentrations (ECan, 2018; Clary et al., 2020; CCC, 2012). As noted previously, studies have shown that influent concentrations are correlated with treatment performance. Low influent concentrations tend to lead to more variable removal efficiencies (Yang, et al. 2023; Bilek et al., 2019; ANZG, 2019).

Statistical analysis (Wilcoxon Test) demonstrated that Knights Stream wetland did not contribute a 'statistically significant ($p<0.05$)' reduction in any of the stormwater contaminants. Where a p-value of less than 5% means that there is more than a 95% probability that the wetland provides a reduction in contaminants (Andrade, 2019). While contaminant reductions were not statistically significant, Figure 3 and Figure 4 did indicate that:

- Total lead, dissolved zinc, and total zinc median removal efficiencies sat within the CCC WWDG ranges, and the statistical analysis showed there was a 75 – 80% probability that a reduction in these contaminants was observed
- The median DIN removal efficiency sat within the WWDG range, and there was a 75% probability that it was reduced through the wetland
- The statistical analysis showed DRP and TSS had a 95% probability that they were reduced through the wetland

Results showed that Prestons Wetland also did not cause a 'statistically significant reduction' in any of the stormwater contaminants, except for zinc. The analysis did indicate that some stormwater contaminants may be reduced (though not statistically significant). For example, the Prestons wetland removal efficiency box plots show the median wetland treatment efficiency for copper and zinc (dissolved and total) met the WWDG guidelines, and the statistical analysis showed there was an 86 – 91% probability that these contaminants would be reduced through the wetland.

All dissolved lead results were below the detection limit, before and after entering the wetland. Therefore, the wetland could not visibly impact this contaminant, and the Wilcoxon Test could not be completed due to lack of data.

5.3 DISCHARGE WATER QUALITY

The Knights Stream Wetland and Dry FFB was unable to demonstrate a significant improvement in the treated water quality; specifically, the frequency the stormwater treatment system would comply with the LWRP water quality standards as the untreated water quality was of a high standard and already met many of the standards. This is shown in Figure 6, which indicates that:

- 100% of DIN, total and dissolved lead, total and dissolved arsenic, and TSS samples met the receiving environment guidelines at every sampled location.
- 25% of total copper, 75% of dissolved copper and 0% of dissolved and total zinc samples met the LWRP water quality standards at the Dry FFB Outlet.
- 11% of total copper, 67% of dissolved copper and 44% of dissolved and total zinc samples met the LWRP water quality standards at the Wetland Outlet. This is a:
  - 10% reduction in the percentage of copper samples meeting the limits, and between the Wetland Inlet and the Wetland Outlet
  - a 40% increase in the % of zinc samples meeting the limits Wetland Inlet and the Wetland Outlet.
- 0 % of DRP samples met the receiving environment guidelines at both the inlet and outlet of the facility.

These results should be interpreted with caution, as the LWRP water quality standards are intended to be applied to a discharge following reasonable mixing with the receiving waterway (ECan, 2018). Therefore, results are intended to be used as a guide for comparison. It should be noted that the LWRP, like most regional water quality plans allows for reasonable mixing of the treated stormwater with the receiving water body. For the purpose of this study no mixing has been considered as the comparison with LWRP water quality standards provides an adequate representation of the likelihood that compliance could be achieved with the relevant standard.

At the outlet of Prestons Stormwater Facility, the LWRP water quality standards were met at least 78% of the time (ECan, 2018). Figure 9 shows that:

- In the Prestons Wet FFB influent, 0% of zinc, 24% of DRP, and 24 – 38% of copper samples met the LWRP water quality standards.
- At the outlet of the Prestons Wet FFB, a minimum of 88% of all contaminant samples met the LWRP water quality standards, with 100% of dissolved zinc and copper meeting the standard.
- At the outlet of the wetland, the percentage of total zinc samples meeting the environmental standards decreased from 87 to 77%; whilst compliance with the TSS standards improved from 87% compliance at the inlet to 100% compliance at the outlet.

The analysis of the performance of Prestons Stormwater Facility shows the Wet FFB provided a meaningful increase in the number of samples meeting the LWRP water quality standards, whereas the Knights Stream Dry FFB, Prestons Wetland, and Knights Stream Wetland did not. This is either because the Dry FFB and the two wetlands are only providing light polishing treatment and this is not sufficient to reduce them below guideline values, or the inlet values were already below guideline values. Additionally, a statistical analysis indicated that there was no significant difference between the influent and effluent concentrations at these facilities, except dissolved zinc.

The water quality observations in this study have implications for Christchurch's stormwater management strategy. Traditionally, offline wetlands were considered necessary to treat stormwater, acting as buffers to filter contaminants and prevent them from entering water bodies. However, the high quality of the influent in this study challenges this assumption. If the effluent from Wet FFBs can effectively meet environmental standards in new subdivisions with low vehicle movement, then the requirement to provide offline wetlands and/or Dry FFBs, specifically to provide additional treatment for compliance with the LWRP water quality standards may need to be reevaluated.

This doesn’t undermine the importance of these devices, which provide critical habitats for many species, offer other environmental and social benefits, and attenuation of stormwater flows. Instead, it opens up possibilities for more integrated stormwater management strategies, where Wet FFBs and wetlands can work in tandem. The Wet FFBs could handle the initial treatment of stormwater, reducing the contaminant load, while wetlands could serve as secondary online treatment systems and wildlife habitats. This approach could optimise the use of resources, enhance biodiversity, and still ensure the protection of water quality. Further research is needed to validate these findings and explore their full implications.

6 CONCLUSION

Stormwater treatment facilities in urban Christchurch are affected by a plethora of different factors. These factors are responsible for the variability seen in contaminant removal efficiencies and performance. Between the different zonings, slopes, soil types, and groundwater conditions, every urban catchment's stormwater is different from the next. Even different individual storm events within the same urban catchment can result in wide performance variability. Understanding this variability is made more complex by the difficulty involved in monitoring stormwater (Bilek et al., 2019). The uncertainties associated with the results were amplified by various study issues including sampler measurement errors, sample timing errors, missing event data, and a relatively small number of data points. However, despite this inherent variability, it can be statistically demonstrated that the Prestons Wet FFB can generate a significant reduction in contaminants, even with low influent stormwater contaminant concentrations.

The results from this study indicate that the majority of contaminants meet receiving environment guidelines prior to stormwater entering the wetlands at Prestons and Knights Stream. No contaminants were reduced below guideline values between the Prestons and Knights Stream wetland inlets and outlets. The study suggests that in some locations Wet FFBs in Christchurch can effectively treat stormwater, challenging the need for offline wetlands. This could lead to more integrated strategies where Wet FFBs handle initial treatment, and wetlands serve as secondary online systems and habitats. This approach could optimise resources, enhance biodiversity, and maintain water quality. Some further research is recommended to validate the findings; specifically, to evaluate the possible interactions of groundwater inflow or outflows.

A key observation derived from this study pertains to the influence of loading rates on the efficiency of treatment. This report indicates that both stormwater treatment facilities exhibit a lower treatment performance when compared to international research findings (Clary et al., 2020). However, low influent concentrations may be contributing to this comparatively poor treatment performance (Yang, et al. 2023; Bilek et al., 2019). Additionally, the removal efficiency calculation is highly sensitive to the magnitude of concentrations. This means small changes in contaminant concentrations can translate to large changes in removal efficiencies. Therefore, the treatment facilities in this study may appear to have performed comparatively poorly, which may be due to the low influent concentrations.

The contributing catchments for both Prestons and Knights Stream have relatively low vehicle movements and are relatively new residential developments, which is principally attributed to the low concentration of observed influent stormwater contaminants. This study indicates that wetlands and Dry FFBs may not be well suited to treating low pollutant concentrations. While these devices provide great amenity value, flood retention, and stormwater attenuation, they may not provide significant and reliable treatment of event mean concentrations (EMCs) in catchments with low influent contaminant concentrations. International studies appear to indicate that wetlands are more effective with higher pollutant loading rates (Yang, et al. 2023; ANZG, 2019; Bilek et al., 2019).

7 RECOMMENDATIONS

Stormwater treatment facilities in urban Christchurch are affected by numerous different factors. These factors are responsible for the variability seen in contaminant removal efficiencies and performance. Between the different land uses, zonings, slopes, soil types, groundwater conditions and local climates, urban catchment stormwater quality is highly variable. This can in turn impact the published treatment efficiency of stormwater treatment facilities. To manage this variability, Councils could:

- Be wary of applying treatment efficiency guidance solely from international studies.
- Consider the influence that influent concentrations may have on the stormwater treatment facility design and likely treated stormwater water quality.
- If groundwater is likely to be intercepted, consider the possible movement of typical stormwater contaminants into and out of the groundwater.

Further studies may help quantify the factors that affect stormwater treatment variability. In particular, the following studies could shed more light on factors affecting stormwater facility performance in Christchurch:

- Flow-weighted composite sampling of wetland treatment facilities with higher contaminant loadings.
- Further research on FFBs, with a focus on Wet and Dry FFBs in different groundwater zones.
- Further research on the nature of the contributing catchment characteristics and stormwater inflow concentrations on facility performance.

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