School of Engineering and Information Technology

Bachelor of Engineering Honours (BE(Hons)) in Environmental Engineering

Analysis of nutrient recovery by filter media and their suitability to be implemented in a vertical flow constructed wetland in Ellenbrook, WA

ENG470: Engineering Honours Thesis

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Declaration

I, Georgia Jane Smith, declare that this report is an account of my own original research, unless otherwise stated. This thesis has not been published or submitted for any other degree at any other institution.

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29/11/2021

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Abstract

The vertical flow constructed wetland in Ellenbrook was constructed in 2014 to reduce nutrient concentration within the Ellen Brook and, therefore, eutrophication within the Swan River. The current filter media was selected for its ability to sorb and remove phosphorus from the Ellen Brook. Over the period of operation, the filter media has declined in phosphorus removal efficiency and the rate of infiltration has decreased. The spent filter media will require replacement within the next two years.

The study investigates the performance of several filter medium employed in pilot scale vertical flow constructed wetlands with specific focus on phosphorus removal. Five pilot trial wetlands, containing four different filter medium, were assembled inside intermediate bulk containers. The filter media underwent soil characterisation surveys for analysis of particle size distribution and physical and chemical parameters. Each wetland was fed influent water from the Ellenbrook and the effluent was sampled for analysis of the water chemistry. Measurements were taken to determine the infiltration rate of each pilot trial wetland.

Infiltration rates ranged between 217.0mm/h and 2418.9mm/h. Phosphorus removal efficiency was, on average, between 13.7% and 68.3%. A significant correlation between infiltration rate and phosphorus removal efficiency was observed - pilot trial wetlands with a lower infiltration rate appeared to remove significantly more phosphorus. Taking both factors into account, phosphorus removal on an hourly basis was calculated and ranged between 18mg/h and 404mg/h. Nitrogen removal ranged between 43mg/h and 450mg/h. The release of other contaminants was observed from all filter media. Comparison with several literature and guideline values indicated that no filter media conformed to the specified limits. This may result in operational issues overtime and restrict the ability to repurpose filter media once it is saturated with phosphorus.

The results from this study will assist the Department of Biodiversity, Conservation and Attractions in the decisions and planning to replace the filter media within the Ellenbrook wetland.

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Summary of Acronyms

Al	Aluminium
BOD	Biological Oxygen Demand
Ca	Calcium
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
C_u	Uniformity coefficient
CW	Constructed Wetland
d10	Effective particle size: diameter in which 10% of particles are finer than
d60	Diameter in which 60% of particles are finer than
DBCA	Department of Biodiversity, Conservation and Attractions
DO	Dissolved oxygen
DON	Dissolved organic nitrogen
EBC	Ellen Brook Catchment
EBW	Ellenbrook Wetland
ET	Evapotranspiration
Fe	Iron
FRP	Filterable reactive phosphorus
HF	Horizontal Flow
HLR	Hydraulic Loading Rate
HRT	Hydraulic Residence Time
IBC	Intermediate Bulk Container
IMG	Iron-Man Gypsum
LOR	Limit of reporting
Mg	Magnesium
N	Nitrogen
N2	Nitrogen gas
NH4+	Ammonium
NO2	Nitrite
NO3	Nitrate
NOx	Nitrate and Nitrite
NUA	Neutralised Used Acid

OM	Organic Matter
ORP	Oxidation Reduction Potential
P	Phosphorus
PRI	Phosphorus Retention Index
PSD	Particle Size Distribution
PTW	Pilot Trial Wetlands
QA/QC	Quality assurance and quality control
Q_{in}	Inflow rate
Q_{out}	Outflow rate
SA	Surface Area
SCC	Swan Canning Catchment
SCRS	Swan Canning River System
SF	Surface Flow
SPC	Specific Conductance
SSA	Specific Surface area
SSF	Subsurface Flow
TN	Total Nitrogen
TOC	Total organic carbon
TP	Total Phosphorus
TSS	Total Suspended Solids
VF	Vertical Flow
XRF	X-ray fluorescence

1. Introduction

The Swan Canning River System (SCRS) is the centre of Perth, Western Australia. With over 40,000 years of cultural significance, *Derbarl Yerrigan* and *Djargarra/Dyarlgarro* (Swan and Canning Rivers respectively) contain a number of significant sites to the Whadjuk Noongar people, the original custodians of the land and waters (Department of Parks and Wildlife and Swan River Trust, 2015). Today, the SCRS provides habitat for native animals and supports industries such as agriculture, light industry, mining, horticulture, forestry, recreation and tourism (Department of Parks and Wildlife and Swan River Trust, 2015).

Significant alterations of the Swan Canning Catchment (SCC) have affected the natural surrounding ecosystems. Land clearing, urbanisation and agricultural practices have increased nutrient loads to the SCRS, contributing to ongoing eutrophication and toxic algal blooms. Two major blooms in 2019 and 2020 resulted in high levels of paralytic shellfish toxins, posing a fatal threat to humans and animals (Trayler and Cosgrove, 2021). To preserve the health of the river, several projects have been initiated in an attempt to mitigate the influx of nutrients. The Ellen Brook Catchment (EBC) is of particular interest due to its high nutrient loads into the river system.

1.1. Background

1.1.1. Ellenbrook Catchment

The EBC has a total area of 716km^2, approximately 1/3 of the total area of the 30 Swan and Canning coastal catchments (Kelsey et al., 2010) as depicted in Figure 1. More than half of the catchment has been subject to significant land alterations and clearing for agriculture and urban/residential purposes (Department of Water & Environmental Regulation and Department of Biodiversity Conservation & Attractions, 2019; Kelsey et al., 2010). Remnant areas have high conservation value due to the

presence of a number of threatened ecological communities and species including the Western Swamp Tortoise and Carnaby's Black Cockatoo (Department of Biodiversity Conservation & Attractions, 2018).

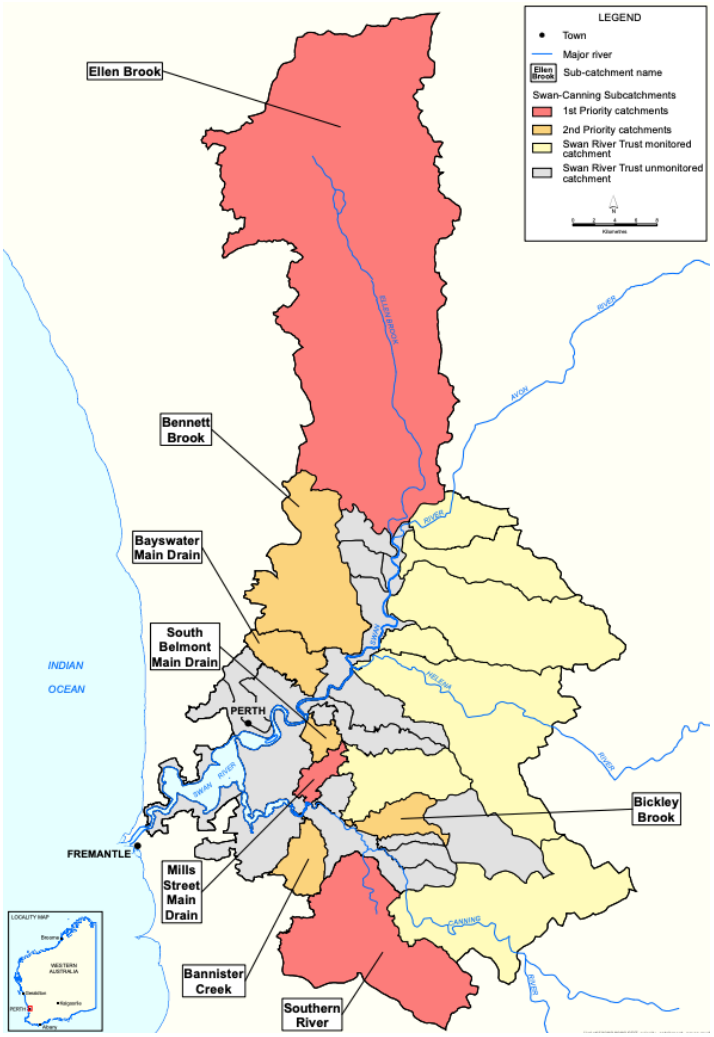

Figure 1: Coastal subcatchments of the SCC and their priority ratings (Department of Parks and Wildlife and Swan River Trust, 2015)

Soils of the EBC are predominantly Bassendean Sands. These sandy soils are relatively infertile and unable to retain nutrients due to their low cation exchange capacity (CEC), phosphorus retention index (PRI) and poor absorption characteristics (He, Gilkes, and Dimmock, 1998; SRT, 2005). To overcome this, nutrient rich fertilisers have been applied to optimise agricultural practices and increase crop yields within the catchment (O'Toole et al., 2013). Rainfall and storm events mobilise these excess nutrients and, as a natural consequence, enter the Ellen Brook.

The Ellen Brook is a major ephemeral waterway in the EBC which flows between May and December each year (Department of Water & Environmental Regulation and Department of Biodiversity Conservation & Attractions, 2019). The Ellen Brook has been identified as one of the largest contributors of nutrients discharging into the Swan River (Barron et al., 2009) (Figure 2 and Figure 3). With an average annual flow of 15.2 GL/year (Department of Biodiversity Conservation & Attractions, 2018), the Ellen Brook is responsible for 28% of total nitrogen (TN) and 39% total phosphorus (TP) entering the SCRS (Department of Parks and Wildlife, 2009; Swan River Trust, 2009). The source of these nutrients has been attributed to fertilisers, animal wastes and soil-bound nutrients (Barron et al., 2009). Modelling indicates that predicted urban expansion within the EBC could result in increases of TN and TP loads by 24% and 29% respectively (Department of Parks and Wildlife, 2009).

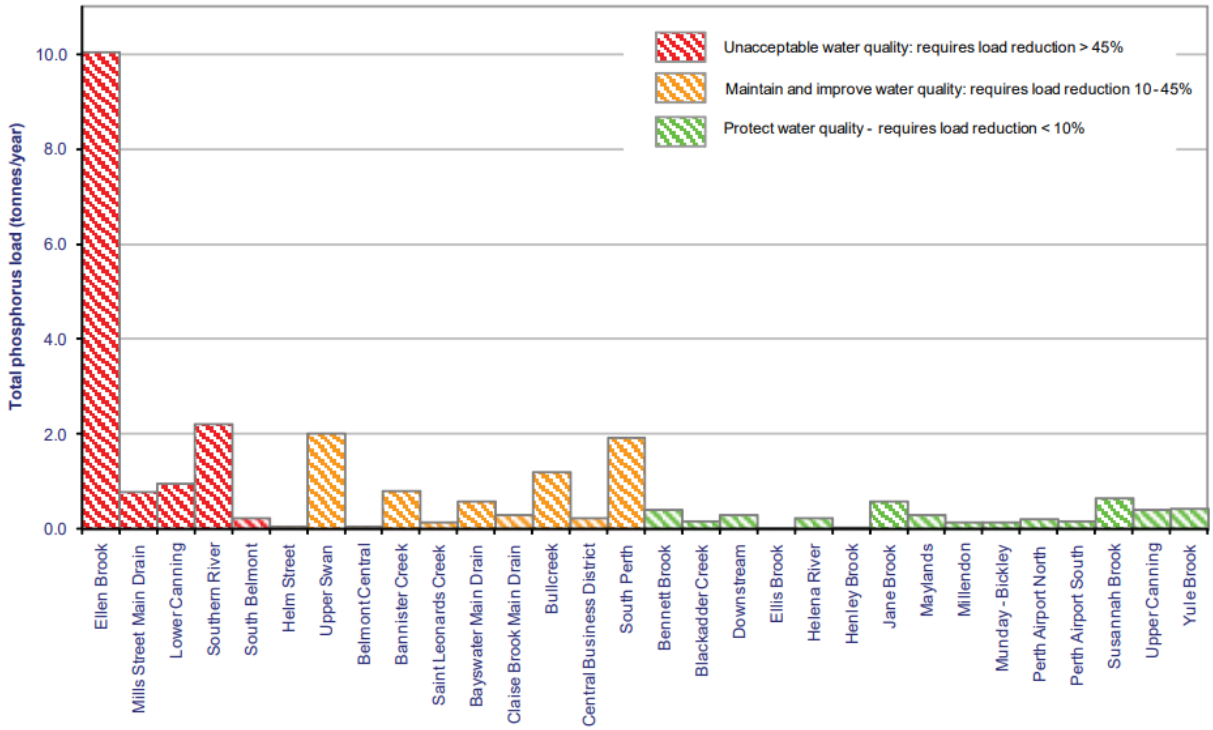

Figure 2: TP load by Swan Canning sub-catchments (Swan River Trust, 2009)

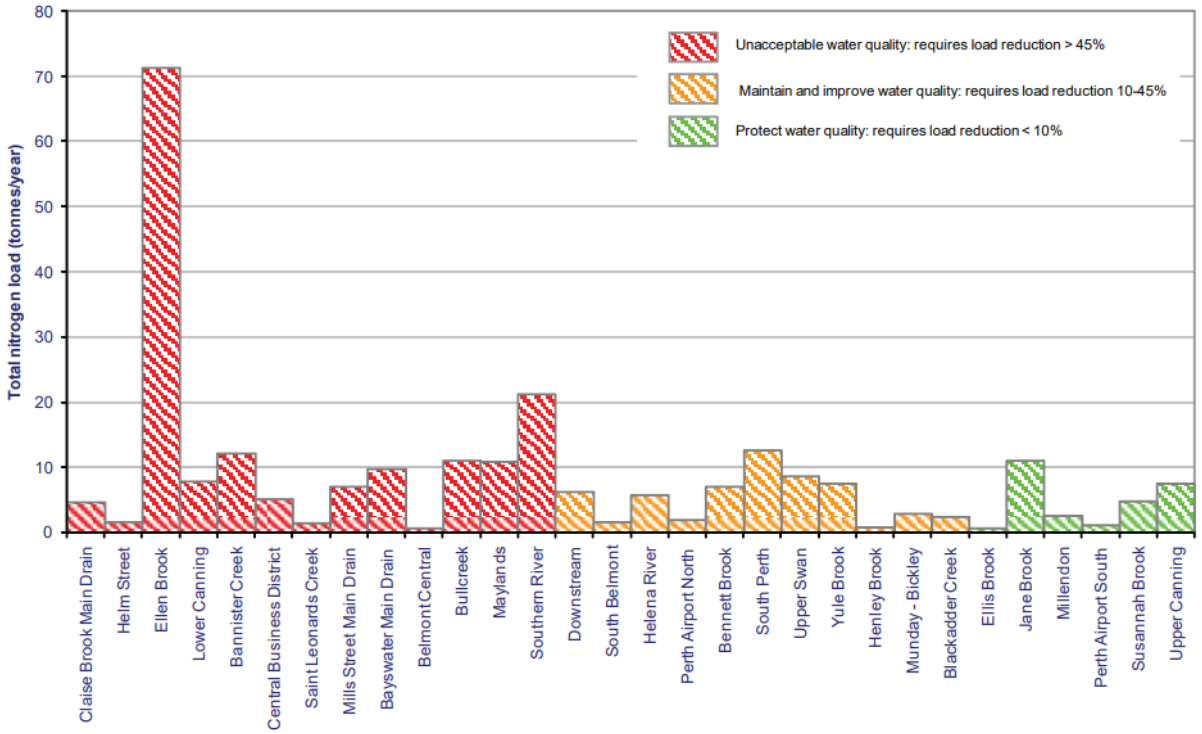

Figure 3: TN load by Swan Canning sub-catchments (Swan River Trust, 2009)

The Swan Canning Water Quality Improvement Plan was developed to reduce phosphorus (P) and nitrogen (N) loads into the SCRS (Swan River Trust, 2009). It identified the EBC as a first priority catchment in which reductions of 79% TP and 69% TN must be achieved to reach the recommended maximum acceptable discharge levels (Swan River Trust, 2009). The plan, developed in 2009, contained several actions which would assist in reaching such targets. This included soil amendment trials, farm nutrient mapping, revegetation of creek lines and construction of the Ellen Brook Wetland (EBW).

1.1.2. Ellen Brook Wetland

The EBW, located 1km upstream of the West Swan bridge crossing in Belhus, was commissioned in 2014 as the first of seven wetlands. The vertical flow constructed wetland was designed as a nutrient stripping system, planted with more than 50,000 (River Guardians, 2014) native seedlings which have now matured into a light vegetation cover (Figure 4). Circular in shape, it is 60m in diameter with a total surface area (SA) of approximately 2800m^2.

Figure 4: Vegetation of the Ellenbrook Wetland

1.1.2.1. Wetland Operation

Water is pumped[1] from the Ellen Brook and distributed through 18 slotted pipes on the surface of the wetland. The water penetrates vertically, by gravity, through a 500mm layer of filter media. The filter media is made up of 5% Iron-Man Gypsum (IMG) blended with Gingin quartz. IMG, a byproduct of mineral sands processing, contains high levels of gypsum and iron oxides which effectively retain phosphorus (Department of Water and Environmental Regulation, 2021). A collection system on the base of the EBW discharges the water into a basin. A bund separates the basin from a lower horizontal flow wetland which allows further polishing of the water (Department of Biodiversity Conservation & Attractions, 2018). The lower wetland discharges the treated effluent back into the Ellen Brook before it connects to the Swan River. An aerial image of the wetland is shown in Figure 5.

[1] Pump was operational between 8AM-4PM, Monday-Friday for the 2021 season

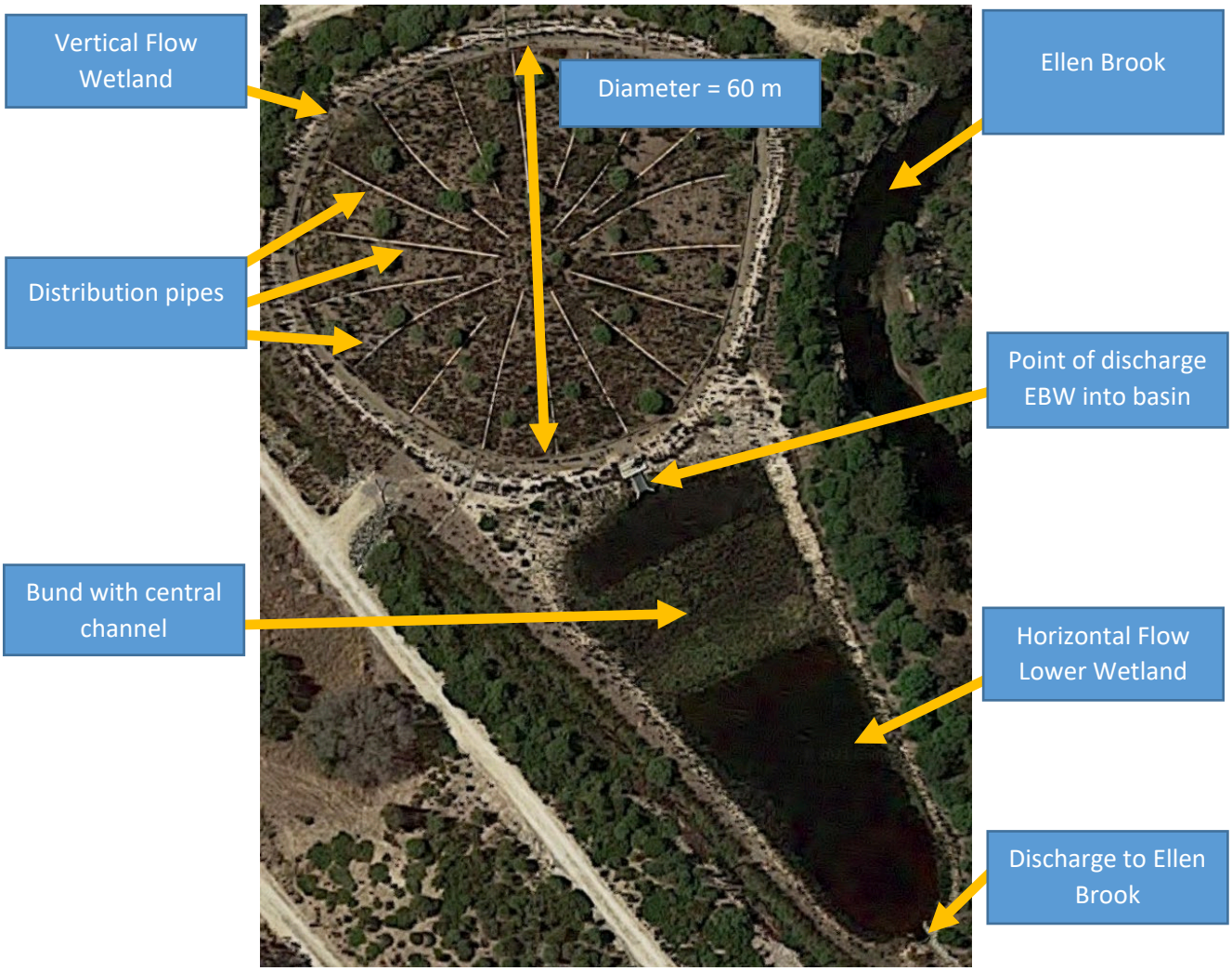

Figure 5: Ellen Brook Wetland

1.1.2.2. Modifications

Since initial construction, several operational changes and modifications to the wetland have been made. This includes:

- Loading: initial loading was continuous for four days (Monday to Thursday), followed by a three day drying period. This caused the wetland to fill and overflow, resulting in a less than expected volume of water treated. In 2020, eight hour loading and 16 hour resting periods were trialled, resulting in greater infiltration and therefore a larger volume of water was treated. As of 2021, the EBW has been operating at eight hours on, 16 hours off Monday to Friday with no loading on Saturday and Sunday.
- Bund: the bund between the basin and lower wetland was constructed to increase residence time in the basin. It was initially designed to be higher than the outlet pipes of the EBW, causing backpressure and subsequentially reduced the infiltration rate. A channel was created in the centre of the bund (Figure 6) and this resulted in increase in the infiltration rate. At the same time, a preferential flow path to the lower wetland resulted, thus reducing the efficiency of the system.

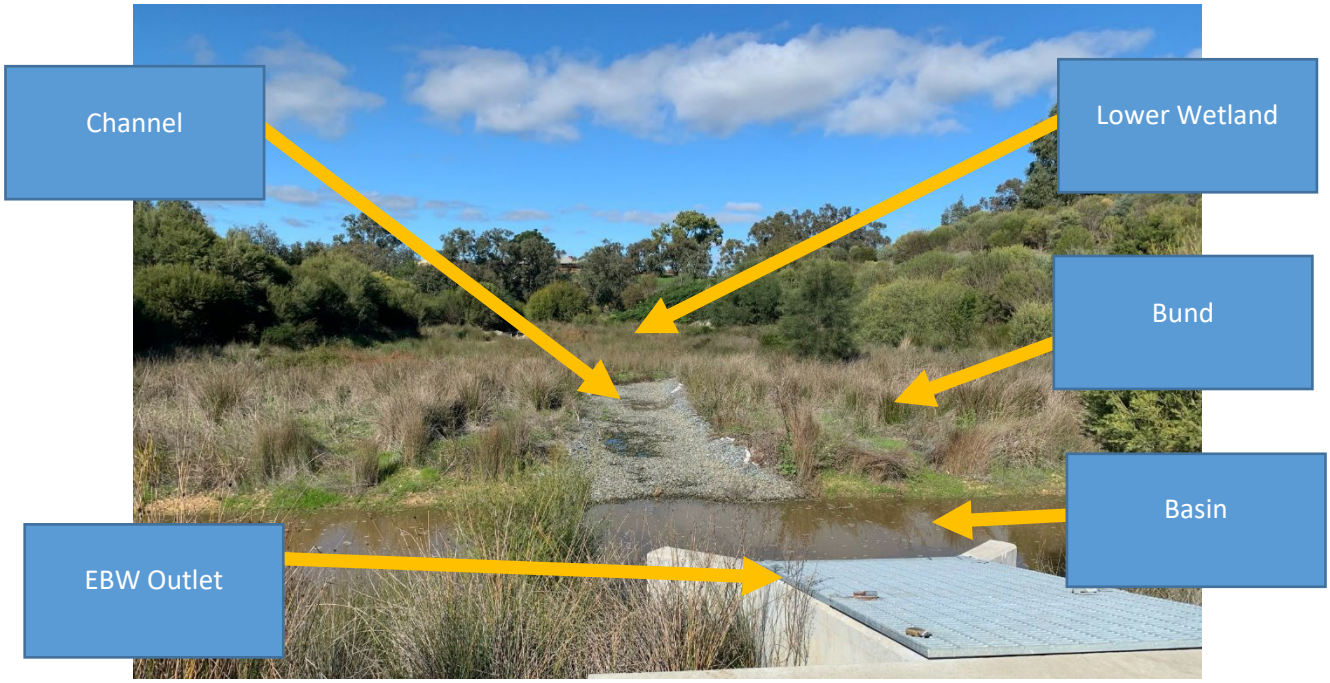

Figure 6: Channel in lower bund

1.1.2.3. Performance

The EBW was estimated to remove up to 270kg of TP and 330kg of TN every year (River Guardians, 2014). These targets have not been achieved and the performance of the EBW has significantly declined over the period of operation. This is evident through decreased infiltration rates, treatment capacity and nutrient removal efficiency. Historical removal of TN and TP are featured in Table 1.

Table 1: Historical TN and TP removal in the EBW[2]

	TN		**TP**	
	kg removed	% removed	kg removed	% removed
Estimated removal	330		270	
2016	50.9	15%	28.6	73%
2017	92.7	19%	50.2	53%
2018	156.6	23%	52.4	51%
2019	64.5	16%	15.5	33%
2020	43.5	17%	11.9	34%

[2] Data provided by DBCA

Over time, the filter media will saturate with phosphorus. It is estimated that this will need replacing before 2023. The research required to analyse the performance of filter media to replace the current filter media will be the key focus of this thesis topic:

Analysis of the nutrient recovery by filter media and their suitability to be implemented in a vertical flow constructed wetland in Ellenbrook, WA.

1.2. Aim and Objectives

The overall aim of this project was to conduct a pilot scale study to evaluate the treatment performance of several filter media. The objectives were as follows:

1. Identify potential filter media with high phosphorus sorption capacity and potential for repurposing.
2. Compare the treatment performance of several filter media to that of a) spent filter media from the EBW and b) fresh batch of the same filter media, under the same climatic conditions as the current large-scale project (EBW). The main performance indicators to be investigated include:
    - removal capacity of phosphorus and nitrogen,
    - infiltration rates and treatment volume, and
    - potential contaminant release.
3. Investigate the suitability of the filter media through comparison with relevant guidelines and literature values.
4. Compare the effect of aeration on treatment performance and capacity of two fresh IMG blends.

The research, data and information gathered from this thesis will contribute to the larger feasibility project, conducted by the Department of Biodiversity, Conservation and Attraction's (DBCA), to replace the filter media in the Ellenbrook wetland.

1.3. Thesis Structure

This thesis has been split into six chapters. A brief overview of each chapter is detailed below.

Chapter 1: Introduction provides a general overview of the EBW project and associated background information. The aims and objectives of the project itself are presented.

Chapter 2: Literature Review investigates the relevant background research for this thesis. This includes eutrophication and algal blooms, water quality parameters, constructed wetlands, phosphorus sorption by filter media, filter media guidelines, available filter media and an overview of previous studies.

Chapter 3: Materials and Methodology details the methodology required to conduct the experiment. This includes the selection of filter media, experimental design, operation and sampling.

Chapter 4: Results elaborates on the key results obtained during the experiment. This includes infiltration rates and nutrient removal.

Chapter 5: Discussion provides explanation and reasoning to the key results and links to relevant literature. Gaps in research and recommendations for future research are presented.

Chapter 6: Conclusion outlines the key findings presented in this thesis and provides a summary of recommendations.

2. Literature Review

The purpose of **Chapter 2: Literature Review** is to present the background research undertaken for this research. Themes that will be discussed include:

- Explain the causation of eutrophication and algal blooms associated with a deterioration in water quality
- Detail water quality parameters and relevant guidelines for trigger or investigation levels in the region and the subsequent determination of water quality
- Analyse the operation, effectiveness and factors affecting the performance of constructed wetlands treating nutrient rich waters
- Explain the role of filter media and the method of phosphorus sorption
- Detail relevant guidelines and properties for filter media in vertical flow constructed wetlands
- Provide an overview of research and experiments conducted to date on potential filter media for use in Ellen Brook Wetland
- Investigate the availability of filter media and their suitability in terms of removal capability, infiltration, reuse capacity and cost
- Summarise potential filter media to be considered for the pilot study

2.1. Eutrophication and Algal Blooms

2.1.1. Eutrophication

Eutrophication is the process in which a waterbody becomes overfertilised and enriched with nutrients, in particular N and P (Schindler and Vallentyne, 2008). Sources of nutrients can be from natural nutrient cycles (plant uptake, decomposition, sedimentation and oxidation) (Wong, 2006). Anthropogenic sources and activities provide excess nutrients and therefore, increase the rate of eutrophication (Gualtieri and Barsanti, 2006). Wong (2006) identifies the following as key sources of nutrients in waterbodies: soil erosion, cleared land, fertilisers, human waste, animal waste, fuel combustion, industrial and household chemicals, industrial processes and stormwater facilities. This is further exacerbated poorly by structured soils, prevalent on the Swan Coastal Plain, which have a low ability to retain nutrients. The influx of nutrients to the Ellen Brook and SCRS have been particularly influenced by soil erosion, land clearing and farming activities involving fertiliser application and animal wastes.

2.1.2. Algae and Algal Blooms

Algae, also known as phytoplankton, are naturally occurring photosynthetic organisms. Forming an integral part of the food chain through the production of organic matter, algae may also assist in the oxygenation of waterbodies (SRT, 2005). Algal growth depends on the availability of nutrients such as carbon, nitrogen and phosphorus (Wong, 2006). Unlike phosphorus, nitrogen and carbon are readily available and can be fixed from the atmosphere and this means that phosphorus is often regarded as the limiting nutrient in algal growth (Schindler and Vallentyne, 2008). When waterbodies become eutrophic, the influx of nutrients can be accompanied by a dense growth of algae. This is commonly known as an algal bloom. Some algal species can retain excess phosphorus in the form of phosphate. As a result, algal blooms can occur long after nutrient inputs have ceased (Schindler and Vallentyne, 2008). To reduce the occurrence and extent of algal blooms, eutrophication must be adequately

managed. Guidelines and parameters to assist in the preservation of water bodies have been developed and are elaborated in 2.2. Water Quality Parameters and Guidelines below.

2.2. Water Quality Parameters and Guidelines

The quality of a water body can be determined using digital water quality meters and/or laboratory analysis. This allows for analysis of a range of parameters, in particular:

- Dissolved Oxygen (DO)
- Salinity /Specific Conductance (SPC)
- Turbidity
- pH
- Water chemistry (concentration of P, N, metals, biological oxygen demand (BOD), chemical oxygen demand (COD) etc.)
- Total suspended solids (TSS)
- Organic Matter (OM)

Comparisons of these values with guidelines of interest is important to assess the health or the contamination of waterbodies. Guidelines used to assist in determining water quality in the EBW include the South-West Australia trigger values outlined by ANZECC and ARMCANZ (2000) (elaborated in Table 2 and Table 3). Short and long-term nutrient targets for the SCC have also been developed by Swan River Trust (2008) and are elaborated in Table 4.

Table 2: South-west Australia trigger values for physical and chemical stressors (adapted from ANZECC and ARMCANZ (2000)) [3]

Ecosystem type	TP	FRP	TN	NOx	$NH4^+$	DO (% Saturation)		pH	
	µg P/L	*µg P/L*	*µg N/L*	*µg N/L*	*µg N/L*	*Lower limit*	*Upper limit*	*Lower limit*	*Upper limit*
Lowland Rivers	65	40	1200	150	80	80	120	6.5	8

Table 3: South-West Australia trigger values for salinity and turbidity (adapted from ANZECC and ARMCANZ (2000))

Ecosystem Type	Salinity/SPC (uS/cm)		Turbidity (NTU)	
	Lower limit	*Upper limit*	*Lower limit*	*Upper limit*
Upland and lowland rivers	120	300	10	20

Table 4: Short and long-term nutrient targets for the SCC (adapted from Swan River Trust (2008))

Target	TN (mg/L)	TP (mg/L)
Short-Term	2.0	0.2
Long-Term	1.0	0.1

[3] Where FRP: filterable reactive phosphorus, NOx: nitrate and nitrite, $NH4^+$: ammonium

2.3. Constructed Wetlands

Constructed wetlands[4] (CW) are shallow basins filled with substrate and vegetation, operating as a low-cost, highly effective alternative to conventional water treatment (UN-Habitat, 2008). These engineered systems are designed to treat contaminated and polluted water (Stopher, Stecher, and Scholz, 2006) from a variety of sources including, but not limited to, industrial and municipal wastewater, stormwater, agricultural runoff and landfill leachate (Vymazal, 2016; Harrington, 2019). Using biological, chemical and physical processes similar to that of a natural wetland (Vymazal, 2016), CW's can effectively remove pollutants from the incoming wastewater. These robust systems require little operation, maintenance and external energy compared to that of conventional wastewater treatment systems (Dotro et al., 2017). Some design considerations of CW's include treatment capacity, influent concentration, removal requirements and land availability.

2.3.1. Types of Constructed Wetlands

Constructed wetlands can be defined according to their flow regime: surface flow (SF) (Figure 7) and subsurface flow (SSF). SSF CW's can be further defined by their flow path: horizontal flow (HF) (Figure 8) or vertical flow (VF) (Figure 9). These three types of CWs, along with their advantages and disadvantages, have been summarised in Table 5. Hybrid systems, such as VF followed by HF, are commonly adopted to overcome some of the issues associated with each and can result in a greater removal of target pollutants.

[4] Also referred to as artificial wetlands or treatment wetlands

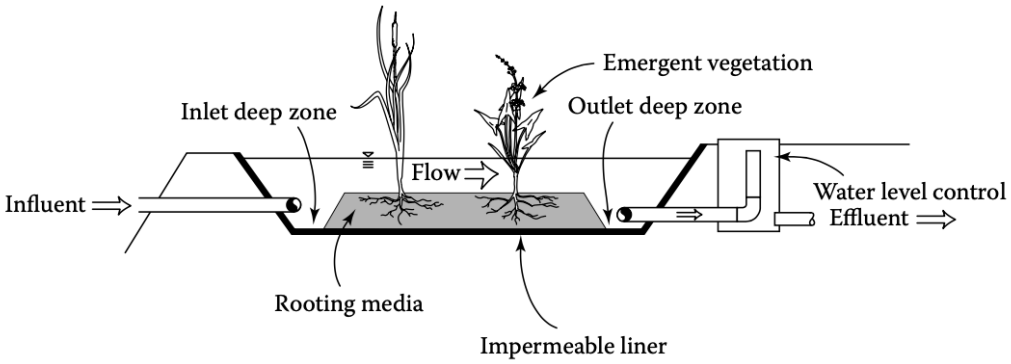

Figure 7: Surface flow CW (Kadlec and Wallace, 2009)

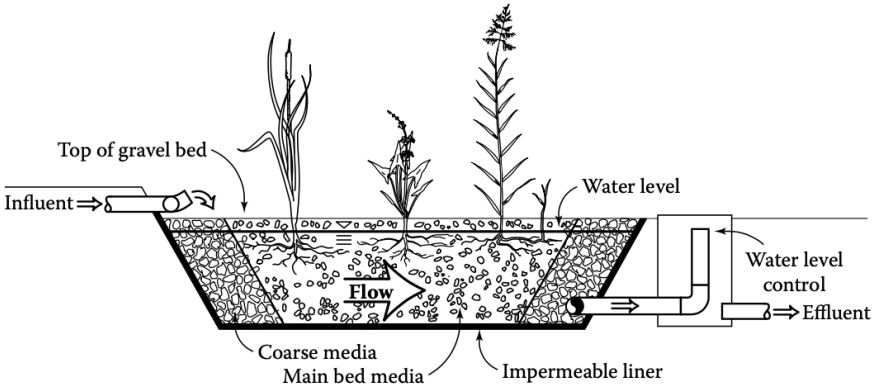

Figure 8: Horizontal flow CW (Kadlec and Wallace, 2009)

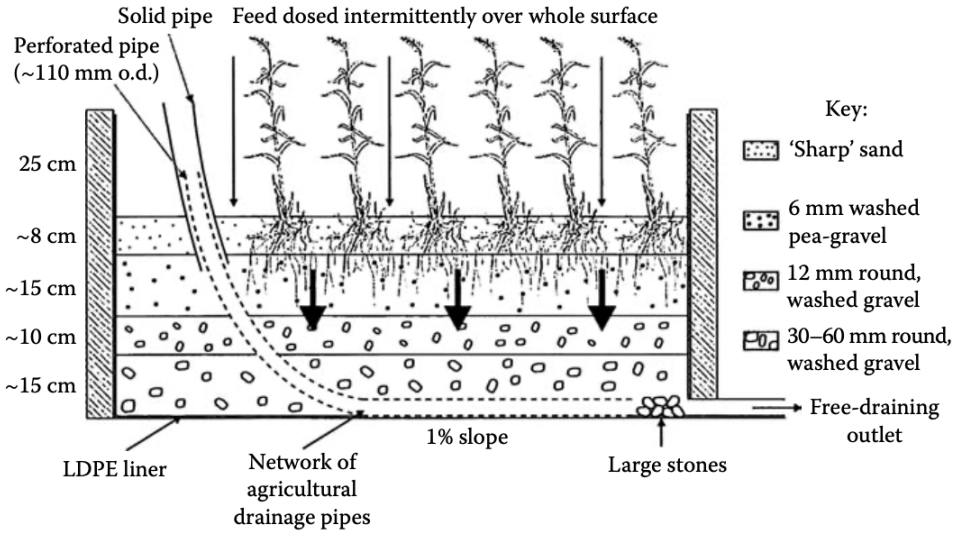

Figure 9: Vertical flow CW (Kadlec and Wallace, 2009)

Table 5: Overview, advantages and disadvantages of different types of constructed wetlands, adapted from Kadlec and Wallace (2009), Stefanakis, Akratos, and Tsihrintzis (2014) and UN-Habitat (2008).

Flow regime	Flow direction	Description/Operation	Advantages	Disadvantages
Surface Flow		• Open water, flowing horizontally above soils • Floating, submerged or emergent plants	• Lower construction and operating costs than SSF • Mimic natural wetlands and provide habitat • Effectively remove organics and SS	• Limited removal of P • Larger land area required than SSF
Subsurface Flow	Horizontal Flow	• Influent enters substrate and travels horizontally to the outlet • Porous media/sand or gravel bed	• Aerobic, anoxic and anaerobic zones • Effectively remove TSS, BOD, COD, OM	• Limited removal of nutrients (N and P) • Limited transfer of oxygen between atmosphere and substrate
	Vertical Flow	• Influent distributed over top, drains through media, collected at base • Porous media/sand or gravel bed • Intermittently loaded	• Intermittent loading allowing for re-aeration of substrate • Removal of BOD, COD, pathogens • Smaller land area demand than HF • Nitrification occurs	• Limited TSS removal • Easily clogged from solid accumulation • Denitrification does not occur

2.3.2. Constructed Wetland Hydraulics

The hydraulics of CW's are fundamental for the optimisation of treatment capacity and overall performance. Minor changes in the hydraulics can have major effects on the efficiency of a CW (Davis, 1995). A few key parameters are outlined below.

2.3.2.1. Hydraulic Loading Rate (HLR)

Hydraulic Loading Rate (HLR) is a function of the total volume of water being applied on a unit of area (Davis, 1995).

$$HLR = \frac{Volume\ (L)}{Area\ (m^2)}$$

2.3.2.2. Hydraulic Residence Time (HRT)

Hydraulic Residence Time (HRT) is the length of time that water is within the wetland, or the contact time of water with the substrate (Stefanakis, Akratos, and Tsihrintzis, 2014).

$$HRT = \frac{volume\ (L)}{outflow\ rate\ \left(\frac{L}{s}\right)}$$

Short circuiting due to preferential flow paths may reduce the HRT and reduce the treatment efficiency. Conversely, build-up of organic matter or retention of solids within the substrate may create stagnant zones, surface water flow, or pooling and increase HRT. An increased HRT will result in a decrease in the total volume treated (Davis, 1995).

2.3.2.3. Evapotranspiration (ET)

Evapotranspiration (ET) includes the water lost/consumed through evaporation and transpiration. This is influenced by surface area, vegetation and climate (Davis, 1995). The rate of evapotranspiration can affect the overall water balance.

2.3.2.4. Water Balance

Water balances are important to determine the input, output and internal storage/accumulation of water within a CW. Inputs include influent water and rainfall/precipitation and outputs include effluent, evaporative losses and in some cases, inputs to groundwater. A water balance may also allude to potential leaks in the system.

2.3.3. Vegetation

Vegetation within a CW is selected based on climate, soil type and loading regime (Melbourne Water, 2005). As explained by Stefanakis, Akratos, and Tsihrintzis (2014), several benefits of vegetation include:

- Root penetration into the substrate, increasing contact time between water and substrate,
- Facilitates and increases the growth of biofilm,
- Maintains aeration and oxygen transfer to lower depths of the wetland,
- Nutrient uptake, reducing nutrient concentration in the treated water,
- Provides a source of organic matter for microorganisms.

Research conducted by Abdelhakeem, Aboulroos, and Kamel (2016) showed that implementing vegetation within a CW showed an improved removal efficiency of COD, BOD, TSS, NH4 and TP by 46%, 47%, 33%, 6% and 5% respectively compared to that of CW's without vegetation. With this said, the uptake of P by plants only provides a temporary storage and may be counteracted by the release of P with decomposing organic matter (Reddy et al., 1999; Vymazal, 2010). If a CW is employed as a nutrient sink, vegetation will often be harvested on a regular basis to overcome and reduce this potential nutrient release.

2.3.4. Pollutant Removal

CW's can perform several physical, chemical, and biological processes to remove pollutants. A summary of such treatment processes and their target pollutants have been summarised in Table 6.

Table 6: Treatment processes occurring in CWs, adapted from Stefanakis, Akratos, and Tsihrintzis (2014)

Treatment process		Target Pollutants					
		Organic Matter	Suspended Solids	Nitrogen	Phosphorus	Pathogens	Heavy Metals
Physical	Filtration	X	X		X	X	
	Settling	X					X
	Sedimentation		X				
	Volatilization			X			
Chemical	Oxidation	X					
	Ion Exchange			X			
	Adsorption				X	X	X
	Precipitation				X		X
	UV-degradation					X	
Biological	Bacterial degradation	X					
	Microbial Consumption	X		X	X		
	Bacterial decomposition		X				
	Nitrification/ denitrification			X			
	Plant uptake			X	X		X
	Predation					X	
	Natural die-off					X	
	Biodegradation						X
	Phytodegradation						X
	Phytovolatilisation						X

The extent to which pollutants are removed from the wastewater will be influenced by several parameters. This includes the type of CW (SF, SSF, HF, VF), input/wastewater characteristics, climate (eg. temperature, rainfall) plant species and HRT (Stefanakis, Akratos, and Tsihrintzis, 2014). HRT is one of the most important factors as this directly reflects the time in which water is in contact with the CW and therefore the extent to which removal processes may occur. CW's can preserve waterbodies by removing, transforming and/or storing nutrients. This can have a significant impact on reducing or reversing the rate of eutrophication of receiving waters.

2.3.4.1. Phosphorus Removal

In water, phosphorus occurs in several dissolved and particulate, organic and inorganic forms. Transformations of P to organic P must occur before they are bioavailable (available for uptake by organisms). Removal of phosphorus in water can occur by precipitation/sorption to substrate, biomass storage/plant uptake, filtration or burial in CW's (Kadlec and Wallace, 2009). Filtration of phosphorus is only applicable for particulate forms. Figure 10 shows the different methods of transformation and uptake of phosphorus in CW's.

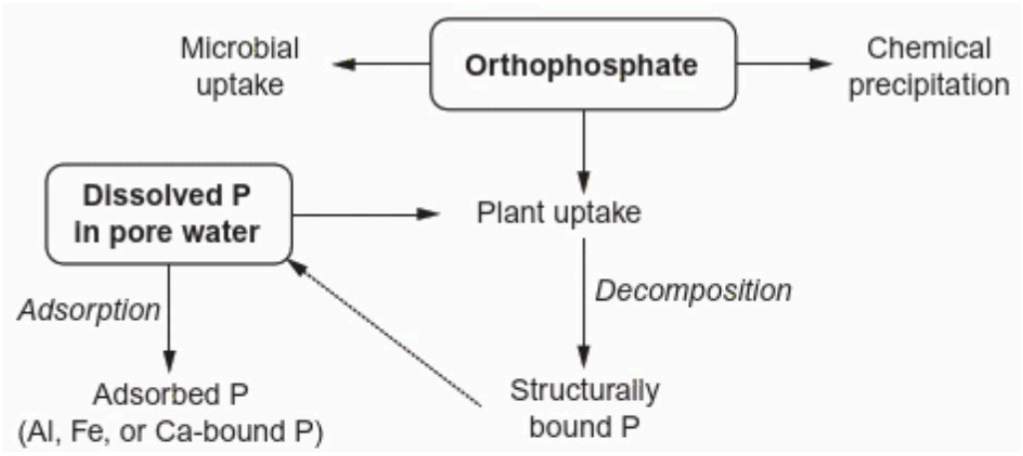

Figure 10: Phosphorus transformations and removal techniques in CW's (Stefanakis, Akratos, and Tsihrintzis, 2014)

Plants require phosphorus for growth and will uptake it through their root systems. This form of P removal is slow and harvesting of plants must occur to avoid release of P back into the system through decomposition (Reddy et al., 1999; Vymazal, 2010). Microbial uptake of P by bacteria and microorganisms may occur in systems with greater hydraulic residence time and is often limited in VFCW (Stefanakis, Akratos, and Tsihrintzis, 2014). It has been reported that in some areas, such as the Florida Everglades, constructed wetlands are the only economically feasible treatment method to remove phosphorus in waterbodies as a result of runoff (Kadlec and Wallace, 2009).

2.3.4.2. Nitrogen

Nitrogen in wastewater can be present in organic (urea, amino acids, uric acid, purine and pyrimidines) or inorganic (NH_3, NH_4^+, NO_3^-, NO_2^-, N_2O, N_2 and NO_2) forms (Stefanakis, Akratos, and Tsihrintzis, 2014). Within CW's, several transformation and removal reactions of nitrogen occur (Figure 11).

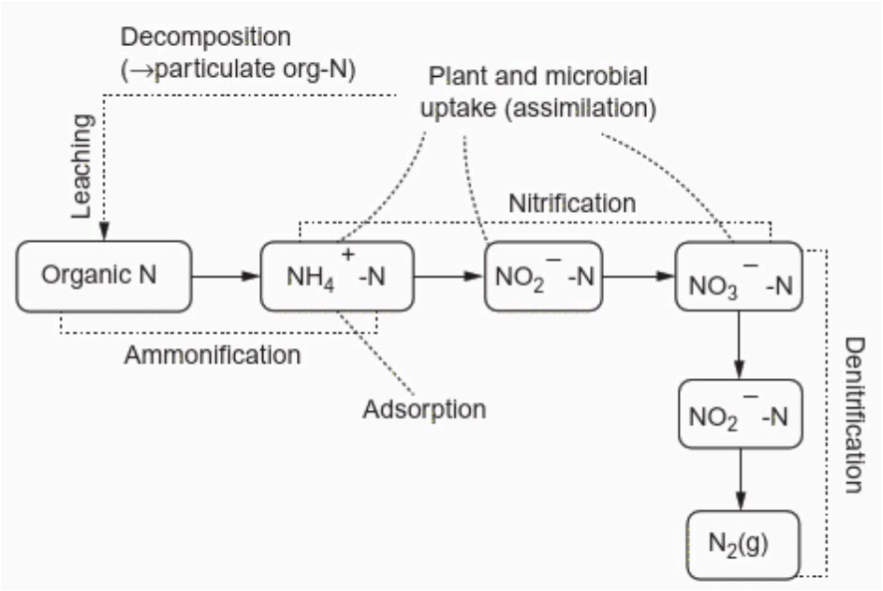

Figure 11: Nitrogen transformations and removal techniques in CW's (Stefanakis, Akratos, and Tsihrintzis, 2014).

Organic forms of nitrogen are converted to NH_4^+ by ammonification. This is influenced by temperature, pH, soil C/N ratio and texture (Reddy, Patrick, and Broadbent, 1984). NH_4^+ can be transformed by nitrification or removed through adsorption. Nitrification involves the oxidation of NH_4^+ to nitrite

(NO_2^-) and nitrate (NO_3^-) by nitrifying bacteria whereas adsorption to the substrate occurs through ion exchange. Adsorption usually accounts for minimal N removal as the ammonia adsorbed can oxidise to nitrate between loadings (drying phases) (Stefanakis, Akratos, and Tsihrintzis, 2014). Denitrification transforms NO_3^- to nitrogen gas ($N_{2(g)}$) by denitrifying bacteria under anaerobic or anoxic conditions. This is often limited in VFCW due to the aerobic nature of such systems (from fill and drain operation) (Vymazal, 2007; Stefanakis, Akratos, and Tsihrintzis, 2014).

2.3.5. Performance Indicators

Measuring the performance of a CW is important to ensure the specified design criteria is being met. Several indicators commonly used to measure the operation and performance of these systems include:

- Removal efficiency: the extent to which a target pollutant is removed from the wastewater

$$removal\ efficiency = \frac{input\ concentration - output\ concentration}{input\ concentration} * 100\%$$

- Mass removal rate
- Areal load reduction: mass removed per unit of area of CW

$$Areal\ load\ reduction = \frac{mass\ removed\ (kg)}{unit\ of\ area\ (m^2)}$$

- Hydraulic loading rate/volume treated
- Infiltration rate
- System response during periods of loading with high input volume and/or concentration of target pollutants (Davis, 1995; Kadlec, 2016).

The criteria for these indicators will vary based on the design and functionality of the CW.

2.4. Phosphorus Sorption by Filter Media in Constructed Wetlands

It has been widely acknowledged that the most effective method of phosphorus removal from wastewater in CW's is through sorption to a filter media[5] (Johansson Westholm, 2006; Arias and Brix, 2005; Brix, Arlas, and Del Bubba, 2001; Vohla et al., 2011; Sakadevan and Bavor, 1998; Stefanakis, Akratos, and Tsihrintzis, 2014; Kadlec and Wallace, 2009; Vymazal, 2010; Xu et al., 2006). Therefore, it is of utmost importance to carefully research, trial and select the substrate to be implemented as a filter media within a CW.

2.4.1. Mechanism of Phosphorus Sorption

Sorption is the process in which phosphate ions are removed from solution (Asomaning, 2020). This occurs in two distinct stages (Bhadha, Daroub, and Lang, 2012; Reddy et al., 1999). Firstly, P accumulates on the surface of the substrate and reacts with cations such as aluminium (Al), iron (Fe), calcium (Ca) and magnesium (Mg) to form precipitates (Stefanakis, Akratos, and Tsihrintzis, 2014; Bolland, Allen, and Barrow, 2003; Bhadha, Daroub, and Lang, 2012). This rapid process is followed by a slower secondary process in which the compounds penetrate into the particles of the substrate. Under certain conditions, the process of sorption is reversed (desorption) and can result in the release of P into solution (Bhadha, Daroub, and Lang, 2012; Reddy et al., 1999).

[5] Also known as substrate

2.4.2. Factors Affecting P Sorption

There are several factors that affect the ability and capacity of a substrate to sorb P. Several factors are detailed below.

Input concentration: higher input concentrations of P will result in a greater amount of P removed (Penn and Bowen, 2018). Penn and Bowen (2018) detail that some materials are unable to remove P at input concentrations below 0.2-0.3mg/L.

Metal content: increased concentration of metals within a substrate will result in increased sorption and precipitation of P (Stefanakis, Akratos, and Tsihrintzis, 2014). Metal oxides will coincide with a greater specific surface area (SSA) in which sorption can occur. Al oxides may absorb more than double that of Fe oxides (on a molarity basis) due to the larger SSA (Asomaning, 2020).

Particle size: finer particles have a larger SA (compared to that of coarser grained particles) in which sorption reactions take place. (Leader, Dunne, and Reddy, 2008; Stefanakis, Akratos, and Tsihrintzis, 2014). Studies conducted by Li et al. (2013) showed that P sorption was significantly influenced by presence of finer particles such as clay. At the same time, these finer particles may induce filter clogging, resulting in reduced infiltration rates and a decrease in the overall performance of a CW (Stefanakis, Akratos, and Tsihrintzis, 2014).

Hydraulic residence time (HRT): Increasing HRT will increase the contact time between the water and substrate and therefore increase P sorption. Conversely, decreasing the HRT will result in reduced removal of P but may prolong the lifespan of the substrate (Johansson Westholm, 2006).

Organic matter (OM): OM can inhibit metal oxide crystallisation and therefore reduce the ability for phosphate to be adsorbed (Borggaard et al., 1990). OM may also compete with phosphate sorption sites (Asomaning, 2020; Bai et al., 2017) or clog filter media (Xu et al., 2006).

Salinity: Negatively charged ions may compete with phosphate ions at binding sites (Bai et al., 2017), therefore an increase in salinity in the input water may result in decreased P removal.

The optimal conditions for phosphorus removal will vary in each CW. Research and analysis of these factors are essential when designing a CW and selecting an appropriate filter media.

2.4.3. Types of Substrates to be Used as Filter Media

Substrates are employed in CW's as a filter media. These filter media can be categorised into three types: natural, synthetic, and industrial and mining by-products.

Natural filter media include substrates such as minerals, rocks, soils or marine sediments that require no pre-treatment before use (Johansson Westholm, 2006). Chemical treatment, such as grinding or heating, may occur to optimise the P-sorption capacity (Johansson Westholm, 2006).

Synthetic filter media are factory-made products, often produced by exposing clays to high temperatures (Johansson Westholm, 2006). This results in highly porous, light weight ceramic aggregates. Synthetic media can be unfavourable due to their high embodied energy from manufacturing and cost.

Lastly, filter media can come in the form of industrial and mining by-products. This includes waste streams from steel, mining or coal industries (Johansson Westholm, 2006). Examples of such materials can include fly ash from coal combustion, red mud from alumina production or slag from steel production. These materials are often favourable due to their low cost, local availability and diversion from landfill.

Selection of filter media to be used in a CW is heavily influenced by the media's ability to retain P, predicted lifespan, potential to release contaminants, local availability of the material, cost and the ability to repurpose and/or reuse once the substrate is spent/saturated with phosphorus (Stefanakis, Akratos, and Tsihrintzis, 2014).

2.4.4. Adsorption Isotherms

Several models have been developed to describe sorption characteristics of a substrate. These models, known as adsorption isotherms, provide an indication as to how much P a substrate can retain or may predict the P removal efficiency of a substrate (Chung et al., 2015). Adsorption isotherms are typically represented as the P absorbed by the substrate against the concentration of P in solution (Reddy et al., 1999). Two commonly used isotherms are known as the Freundlich and Langmuir isotherms.

Numerous studies have indicated that P absorption is more accurately modelled by the Freundlich isotherm (Sakadevan and Bavor, 1998; Mead, 1981; Polyzopoulos, Keramidas, and Kiosse, 1985; Sanyal, De Datta, and Chan, 1993; Ratkowsky, 1986). It is suggested that this is due to the Freundlich isotherm assuming an exponential decrease in adsorption potential with an increased saturation whereas Langmuir assumes the adsorption potential remains constant (Sakadevan and Bavor, 1998).

2.4.5. Limitations of Sorption

Although P sorption to substrate proves to be the most effective method of P removal within a CW, there are a few limiting factors that must be considered. This includes:

- Saturation of filter media: As P is adsorbed, the ability to sorb more P is reduced and therefore rate of sorption decreases with time (Stefanakis, Akratos, and Tsihrintzis, 2014; Vohla et al., 2011). This means there is a finite capacity and once the media is saturated it may become a source rather than a sink of P (Ballantine and Tanner, 2010). A review conducted by Vohla et al. (2011) indicated that most filter media exhibit a significant decrease in their ability to retain P after 5 years.
- Uptake of other pollutants: Substrates may sorb other pollutants (such as heavy metals) present in the influent. This could have further negative effects if these pollutants are leached to the receiving water occurs. Ability to reuse the material once it has been saturated and removed from the CW may also be hindered (Johansson Westholm, 2006; Vohla et al., 2011)

- Scalability: Many substrates are trialled for their ability to sorb P under laboratory conditions (such as batch column experiments). These experiments are often temperature controlled and the hydraulic loading is closely monitored (Johansson Westholm, 2006). Furthermore, concentrations in artificially prepared wastewater samples are rarely a true representation of the fluctuating wastewater inputs to CW's (Johansson Westholm, 2006). Stefanakis, Akratos, and Tsihrintzis (2014) explain that media with high potential to sorb P under laboratory conditions may not be reflected by their performance under real operating conditions. This is elaborated by Vohla et al. (2011), who indicate the difficulty in extrapolating mesocosm tests to full-scale systems. Field trials in which experiments are subject to the same climatic and operational conditions are essential for more accurate representation of the performance of selected filter media in CW's.

2.4.6. Recommended Guidelines for Filter Media

Brix and Arias (2005) developed a number of guidelines for small-scale constructed wetlands in which have been successfully adhered to and implemented in many CW's around the world. The guidelines of interest are summarised in Table 7.

Table 7: Guidelines for filter media in VFCW (adapted from Brix and Arias (2005)

Factor	Guideline Value
d10	0.25-1.2mm
d60	1-4mm
C_u	<3.5
particles < 0.125mm	<0.5%

Where:

- d10: effective particle size: diameter in which 10% of particles are finer than this size
- d60: diameter in which 60% of particles are finer than this size
- C_u: Uniformity coefficient = d60/d10

Upon selecting a substrate to be used as a filter media, it is important to perform a characterisation survey to determine the constituents of the substrate itself. This allows analysis as to whether it may cause any ecological harm or danger to surrounding ecosystems. Guidelines of particular interest include:

- Assessment Levels for Soil, Sediment and Water Guidelines (Department of Environment and Conservation, 2010): provides investigation limits for certain metals, organic compounds, hydrocarbons etc.
- Investigation Levels for Soil and Groundwater (National Environment Protection Council, 2011): provides levels in which investigation is required in terms of site contamination. Particular limit of interest is health investigation level C (recreational)
- Landfill Waste Classification and Waste Definitions 1996 (amended 2019) (Department of Water and Environmental Regulation, 2019): criteria to determine the classification of waste for disposal.

These guidelines may also provide indication as to whether the filter media is able to be repurposed for an alternative use once it is spent. Investigation levels and/or threshold values for these guidelines can be found in Appendix A: Relevant Guidelines for Soil Characterisation.

2.5. Case Study: Ellen Brook Wetland Trials

The Ellen Brook Wetland was designed and commissioned in 2014 to reduce nutrient loads to the Swan River. Prior to commissioning, several experiments were conducted to identify a suitable substrate to use as a filter media which would effectively remove P. The purpose of this section is to summarise these experiments and their results/findings.

2.5.1. Laboratory Trials (2009)

11 Western-Australian industrial and mining by-products were evaluated in terms of their physical, mineralogical, chemical, radiological and toxicological properties (L. Wendling, Douglas, and Coleman, 2009). The aim of these laboratory trials was to identify materials that had the potential to act as soil or surface water amendments. Materials displayed promising properties included red mud, Neutralised Used Acid (NUA) and fly ash.

2.5.2. Column Trials (2010)

Column trials were conducted to assess the suitability and performance of different media and their removal of dissolved organic carbon (DOC), dissolved organic nitrogen and phosphorus (Wendling et al., 2010). Bassendean sand was mixed with three trial mixtures: NUA, NUA and Calcined Magnesia (MgO) and IMG and a steelmaking byproduct. The column trials were run for over 1 year and displayed significant P retention capacities. Conclusions from these column trials indicated that NUA was the most suitable for a large-scale system.

2.5.3. Field Trials (2012)

ChemCentre (2012) conducted a field study to determine the feasibility of using IMG at an end of catchment treatment system. 25% and 40% IMG blends were trialled both in active and

passive/gravity systems. Significant reduction in phosphorus, nitrogen and organic carbon was observed but hydraulic conductivity significantly decreased. Concluding remarks indicated that there was potential for large-scale use given the issues of hydraulic conductivity could be overcome.

2.5.4. NUA as a Soil Amendment

A Bullsbrook turf farm was subject to a 3.5 year trial using NUA as a soil amendment in a 5% by mass basis (Douglas et al., 2010). This resulted in an increase in the health and strength of turf growth and regeneration after harvesting. These benefits can be attributed to the nutrients and elements provided by NUA within the rooting zone.

2.5.5. Summary of Trials

The results from the laboratory, column and field trials were collated and assisted in determining the most suitable reactive filter media for P sorption to be implemented in the Ellen Brook Wetland.

2.6. Filter Media Desktop Study

This purpose of this section is to investigate the current availability and suitability of filter media to be considered for trialling. Consultation with DBCA identified several key parameters for consideration when choosing a suitable media. This includes (but is not limited to) availability, location, potential environmental impact, cost and ability to reuse and/or repurpose once saturated. Table 8 summarises the filter media and key points.

Table 8: Potential filter media

Product	Description	Advantages	Disadvantages
Filtralite: Nature P (Filtralite, n.d.)	Crushed expanded clay aggregates	• Highly porous • High concentration of metal oxides	• High pH (~12) • Pretreatment required before effluent can be distributed onto bed • Increased concentration of lime in effluent during start up period
Eclipse Soils: Phosphorus Retentive Filter Media (Eclipse Soils, 2019, 2020)	Super iron rich grit compounds	• Locally sourced, recycled materials • Local case studies to prevent phosphorus entering the Swan River • High permeability	• No known use/case studies in constructed wetlands
Lenntech: GEH-104 (Lenntech, 2012)	Granular ferric hydroxide	• Rich in iron • Targets a number of contaminents (such as As, V, Cu, Pb, U)	• Small PSD • Product should not dry out or be exposed to intense sunlight
Southern Spongolite Industries: Spongolite (Appendix B: Spongolite)	Stone formed from fossilised sponge	• Locally sourced • No known environmental impacts • High ion exchange capacity •	• Limited available research/data • Water retention
Iluka: Capel Iron-Man Gypsum (Iluka, 2018)	Byproduct from mineral sands processing	• Locally sourced • Repurposed waste material • High levels of Gypsum ($CaSO_4.2H_2O$) and CaO • Extensive research and development	• Potential infiltration issues • Blend required • Variations in product/batches
Eco-Filtration: Polonite (Polonite, 2021)	Natural material (Opoka)	• Based on natural material (opoka) • Large surface area • Potential to be repurposed	• Not locally available • High initial pH

2.7. Literature Review Summary

The long history of agricultural land use and fertiliser application in the Ellen Brook Catchment has resulted in extreme nutrient loads to the Swan-Canning River System (SCRS). The influx of nutrients to the SCRS is a catalyst for toxic algal blooms, resulting in a significant deterioration of water quality. Remediation measures thus far have included the construction and operation of the Ellen Brook Wetland.

In summary, this literature review has:

- explored the causes and results of nutrient loading in waterbodies and investigated the relationship between eutrophication and algal blooms,
- detailed guidelines and their parameters that are relevant in south-west WA for determination of water quality,
- explained the operation and treatment capability of constructed wetland for eutrophic waters,
- identified the major mechanisms, limitations and factors affecting the P sorption characteristics of substrates in constructed wetlands,
- explained guidelines of filter media applicable to vertical flow constructed wetlands
- summarised the trials that influenced the selection of substrate for P removal in the Ellen Brook Wetland,
- summarised available filter media.

3. Materials and Methodology

The purpose of **Chapter 3: Materials and Methodology** is to provide an overview of the experimental work conducted. This includes filter media selection, experimental design and set up, operation of the experiment and sampling procedure.

3.1. Filter Media Selection

Four substrates were selected to be used as filter media in this study. Details of each are provided in Table 9.

Table 9: Details of substrates selected to be used as filter media

Reference Code	Substrate Details
M1	New filter media (1)
M2 & M3	Fresh blend of 5% IMG with Gingin quartz
M4	New filter media (2)
M5	Spent filter media obtained directly from the larger EBW

The filter media of M5 was sourced directly from the EBW. An area from the wetland was selected at random and the filter media was removed (Figure 12). This was used as a control in the experiment. M2 and M3 were new batches of the same filter media used in the EBW. M1 and M4 were locally sourced filter media which have not been trialled in any previous studies for use in the EBW.

Figure 12: Filter media dug out from EBW

Once all filter medium were selected and obtained, a soil characterisation analysis by an external NATA accredited laboratory was conducted. This included particle size distribution (PSD), physical analysis and chemical analysis of the constituents of each filter media. The complete analysis can be found in Appendix B: Soil Characterisation Data.

3.1.1. Particle Size Distribution and Analysis

Particle size distribution (PSD) was conducted by wet sieving methods. Stones (particles >2mm), (refer Table 27) were removed prior to the analysis and therefore the PSD report only included the following size fractions: clay (<0.002mm), silt (0.002-0.02mm), sand (0.02-0.075mm, 0.075-0.106mm, 0.106-0.150mm, 0.150-0.180mm, 0.180-0.300mm, 0.300mm-0.600mm and 0.600-1.00mm). To include particles >2mm, the following calculation was performed:

$$size\ fraction = reported\ size\ fraction * \frac{\left(100 - stones(\%)\right)}{100}$$

The calculated size fractions have been summarised (alongside the recommended d10 and d60 values by Brix and Arias (2005)) in Figure 13.

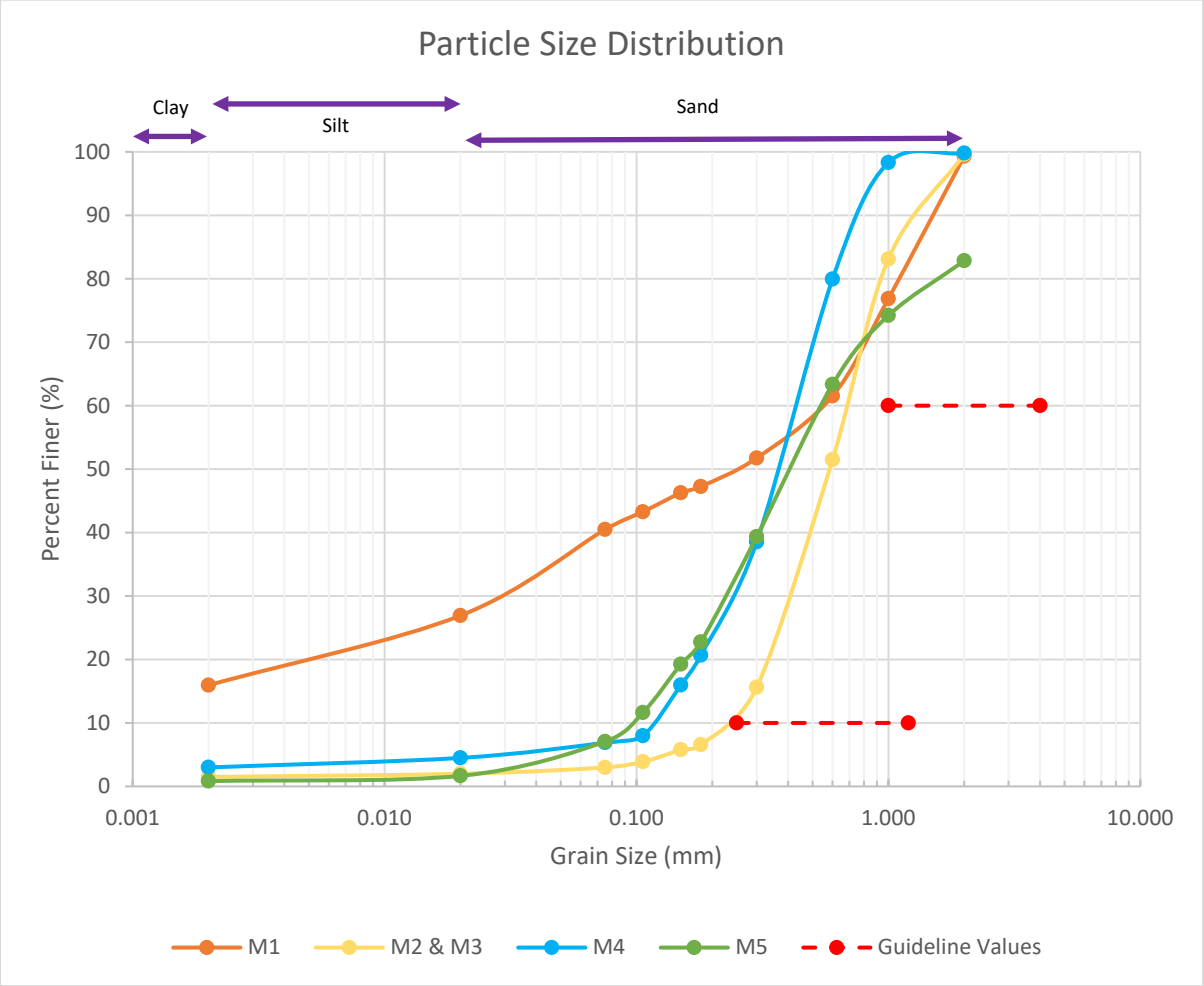

Figure 13: Particle size distribution plot of selected substrates

M1 had the greatest fraction of silt (<0.002mm) and clay (0.002-0.02mm) of all filter media. M4 and M5 both displayed similar characteristics for the smaller 40% size fractions, but M5 had a greater portion of stones (particles >2mm) than that of M4. M2 & M3 had slightly larger particles than the other media. d10 and d60 values of each filter media were estimated using the grain size distribution plot and are summarised in Table 10.

Table 10: d10, d60 and uniformity coefficient (Cu) for each reactive media and the recommended guidelines[6]

Filter media	d10 *mm*	d60 *mm*	C_u
M1	N/A	0.54	N/A
M2 & M3	0.25	0.70	2.80
M4	0.12	0.45	3.75
M5	0.10	0.55	5.50
Guidelines	0.25-1.2	1-4	< 3.5

d10 of M1 was unable to be determined from the data provided. M2 & M3 had the largest d10 and d60 values of all samples at 0.25 and 0.70mm respectively. A significant range of uniformity coefficients was calculated, with the lowest at 2.80 (M2 & M3) and the highest of 5.50 (M5).

[6] D10 and d60 values are estimations only based on the experimental data obtained

3.1.2. Physical Properties

Selected physical properties determined in the soil characterisation analysis of the filter media are summarised in Table 11 (refer Table 25 in Appendix B: Soil Characterisation for full analysis).

Table 11: Physical parameters of filter media used in experiment

Parameter	TOC *%*	pH	EC *mS/m*	PRI* *mL/g*	PBI	CEC *cmol(+)/kg*
M1	0.1	5.2	370	61	52.1	10
M2 & M3	0.025[7]	8.1	200	15	50.9	7
M4	0.77	7.7	14	88	165.6	4
M5	0.08	6.7	2	19	11.9	2

Total organic carbon (TOC) (by combustion) ranged from undetectable (M2 & M3) to 0.1% (M1). pH was determined through 0.01M $CaCl_2$ extraction and ranged from acidic (5.2 in M1) to slightly basic (8.1 in M2 & M3). pH between the fresh and spent IMG media differed by 1.4. Phosphorus retention index (PRI) and phosphorus buffering index (PBI) was greatest in M4. PRI in M5 was greater than M2 & M3 but PBI was significantly less. Cation exchange capacity (CEC) was greatest in M1 at 10 cmol(+)/kg.

[7] See 3.4.2.3. Limit of Reporting

3.1.3. Chemical Composition

The composition of each filter media was determined by several different laboratory analyses (refer Table 25 and Table 26 in Appendix B: Soil Characterisation for full analysis). Metal oxides determined by x-ray fluorescence (XRF) and acid digestible and extractable metals of interest are detailed in Table 12 and Table 13 respectively.

Table 12: Metal Oxides by XRF analysis in the filter media

	Metal Oxide (%)			
	Al_2O_3	Fe_2O_3	CaO	MgO
M1	9.02	7.67	0.06	0.37
M2 & M3	0.09	0.46	0.33	0.03
M4	4.54	1.14	0.38	0.04
M5	0.17	0.72	0.04	0.005

Table 13: Acid digestible and extractable metals in the filter media

	Acid digestible metals (mg/L DW)				Extractable metals in acidic or neutral soils (mg/L)			
	Al	Ca	Fe	Mg	Al	Ca	Fe	Mg
M1	19300	310	48000	1600	370	450	60	640
M2 & M3	270	2200	2500	120	28	3100	>550	130
M4	15000	2200	6100	120	>550	1300	180	37
M5	364	140	4700	110	48	160	420	47

M1 and M4 were dominated by aluminium and iron oxides (Al_2O_3 and Fe_2O_3) whereas M2 & M3 and M5 were dominated by calcium oxides (CaO). Similar trends were evident with acid digestible and extractable metals. In most cases, metal concentrations were much less in the extractable metals (with the exception of calcium (Ca) in M2 & M3). M5, filter media from the lower wetland, had a greater portion of acid digestible alumiunium (Al) and iron (Fe) than that of the fresh IMG blend (M2 & M3).

3.2. Experimental Design

3.2.1. Pilot Trial Wetlands

Five pilot trial wetlands (PTW) were constructed inside commercially available intermediate bulk containers (IBC) and assembled on the bunds of the lower wetland (Figure 14). This location was selected as it was easily accessible and had a large area of level ground.

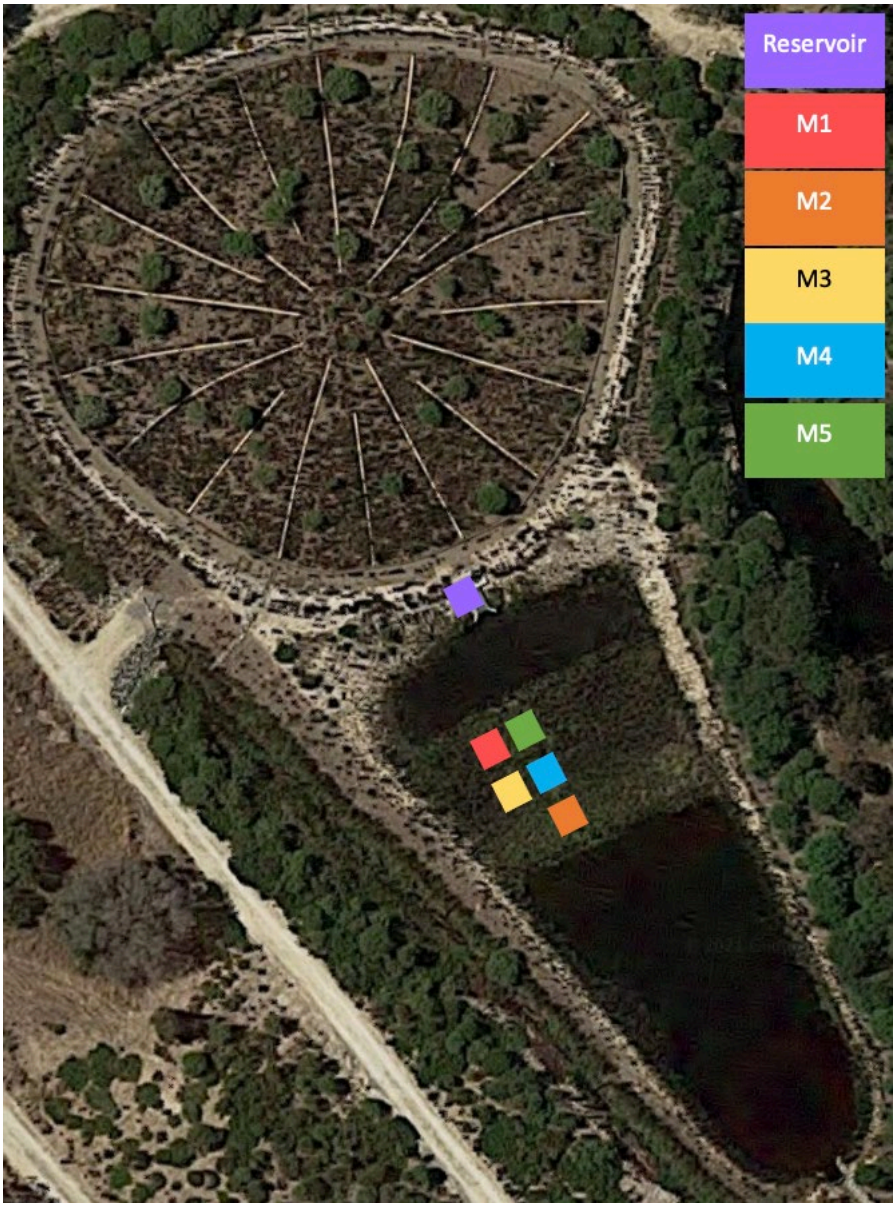

Figure 14: Location of PTW's and reservoir at the EBW

Each PTW was designed as a VFCW to mimic the EBW. Each PTW/IBC had dimensions of 1200mm L x 1000mm W x 1160mm H (surface area: 1.2m^2) and rated for 1000L (Figure 15). Exterior markings indicated 100L increments, up to 1000L. They were reinforced with a steel jacket with removable brackets on the top. The outlets had a diameter of 50mm and a valve which remained open during the entire experiment. The PTW's were modified by removing the top brackets, cutting off the top of the tank (for ease of access and observation), fitting an outflow tap to the outlet (for sampling) and additional increments of 50L were marked on the exterior.

Figure 15: Example of IBC used for the PTW's (prior to modifications) (Schutz, 2020)

A subsurface collection and drainage system, as shown in Figure 16, was installed at the base of each PTW and connected to the outlet. 50mm of PVC pipe (50mm diameter) was fitted into the outlet of each IBC. Connected to this was a 50:90mm reducer. A 90mm T piece connected the reducer to 50mm of 90mm PVC pipe. A 90mm elbow joined to 25mm of 90mm diameter pipe. This is connected to a 90:100mm M:F reducer and then 550mm of 100mm black corrugated, slotted drainage pipe (Vinidex Draincoil). On the other end of this was a 100:90mm F:M reducer. A 90mm 90◦ degree elbow was joined to a 1000mm long riser (diameter of 90mm). The risers were either capped with a 90mm cap or uncapped to provide aeration to the PTW (Figure 17).

Figure 16: Subsurface collection and drainage system

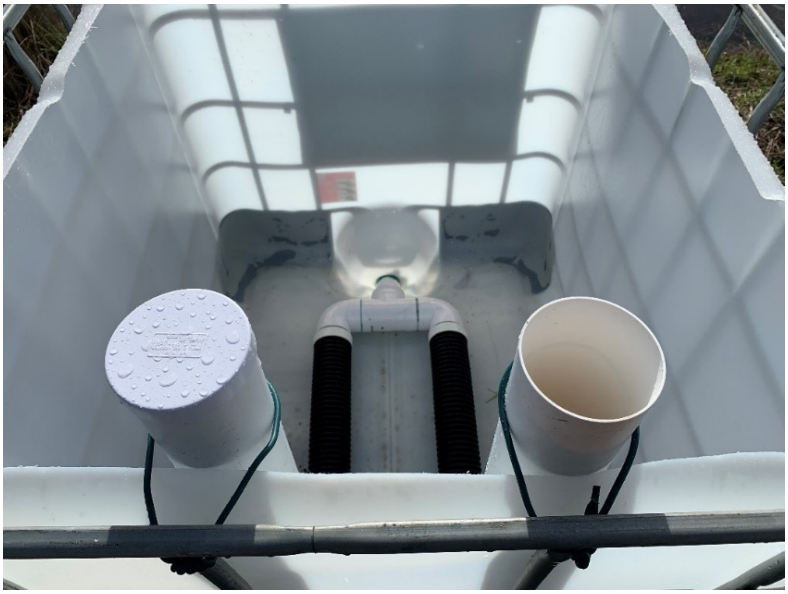

Figure 17: Capped aeration pipe (left) and uncapped (right)

Aeration (uncapped aeration pipe) was only provided to PTW M2 during this experiment but was installed in all PTW (capped) for potential future experiments and observation.

Once the collection system was installed, several layers were placed on top. Figure 18 depicts the layers within each PTW. This included:

- Drainage layer: 200mm of 14mm blue metal, a crushed aggregate rock, to stabilise the collection system.
- Transition layer: 100mm of Gingin Quartz to reduce potential losses of filter media flushing from system (Figure 19). This layer was not included in M5 as this PTW was replicating the EBW.
- Filter media layer: 500mm of filter media (as outlined earlier in Filter Media Selection).

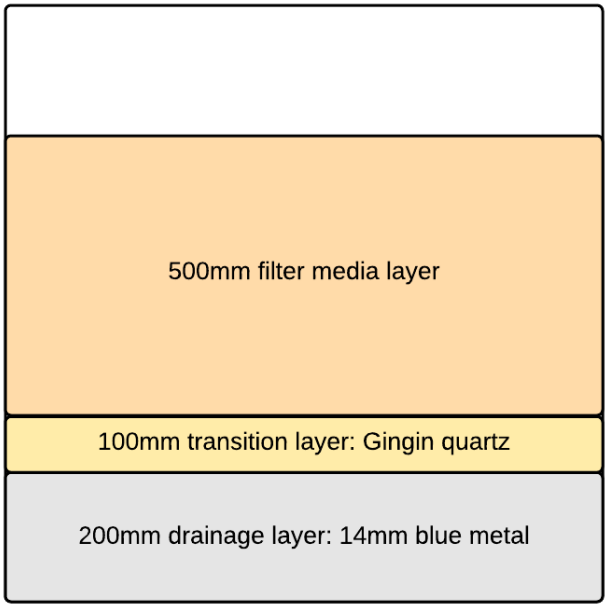

Figure 18: Cross sectional view of layers in each PTW

Figure 19: Gingin Quartz on top of 14mm blue gravel drainage layer

A sixth IBC was installed on top of the outlet structure next to the EBW (Figure 20). This was a reservoir tank which supplied the inlet water to each PTW.

Figure 20: Reservoir tank next to the EBW

Increments of 50L were clearly marked on the exterior of the reservoir tank to indicate the level of water within the reservoir and the volume of inlet water loaded onto each PTW during operation. 20m of polyethylene pipe (diameter of 40mm) was connected to the outlet of the reservoir tank and reached down along the basin to the PTW's as shown in Figure 21. On the end of this pipe was a valve which was secured to the steel jacket of M5. Connected to the valve was 5m of 40mm reinforced PVC hose (distribution line). During loading and operation, the distribution line was able to be directed to the surface of each PTW.

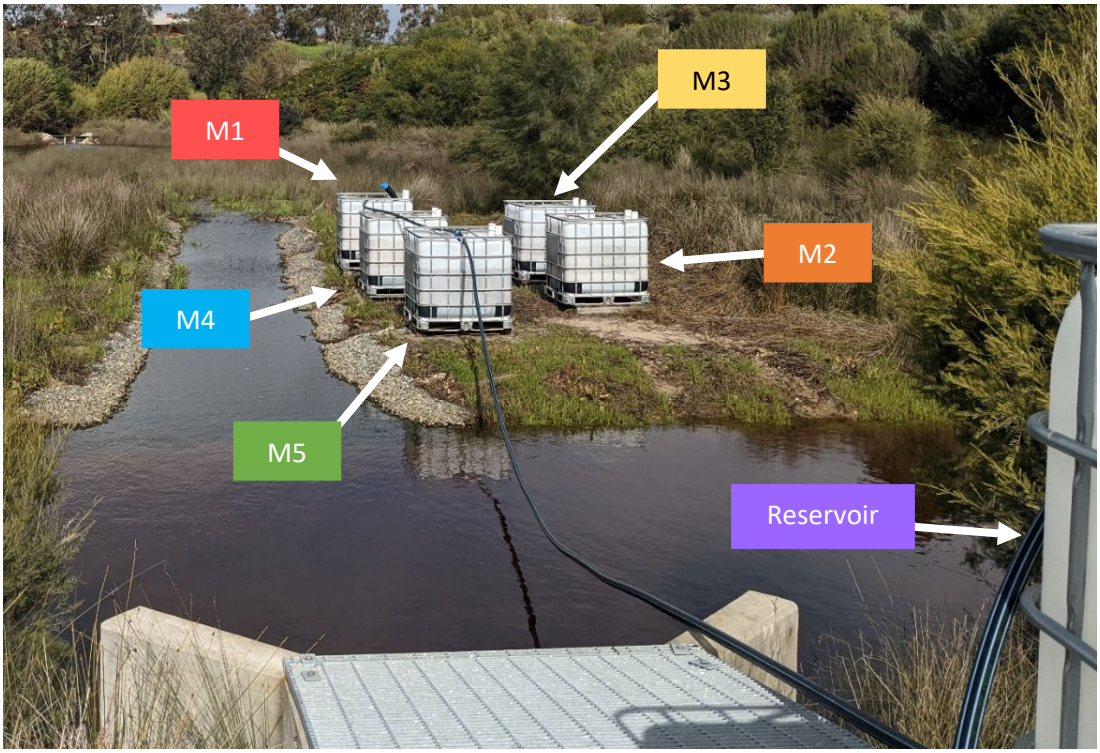

Figure 21: View of PTW's from the reservoir tank including distribution linw

A portable system (Figure 22) was designed to ensure even distribution of the influent water onto each PTW. A 120^{o} elbow was connected to 500mm of PVC pipe. A T piece joined this to the distribution piping which was made of four 720mm arms. Each arm had six, evenly spaced, 10mm orifices facing upwards. Each arm was evenly spaced, 190mm apart.

Figure 22: Distribution system

3.3. Experimental Operation and Loading

The pilot trial experiment commenced on Monday, 23 August 2021 and ceased on Tuesday, 28 September 2021. Loading occurred Monday to Thursday[8] with Friday to Sunday acting as a drying period, mimicking the original operation of the larger wetland (EBW). Water sampling for physical and chemical properties occurred on Tuesday and Thursdays. Table 14 summarises the frequency of loading and sampling.

Table 14: PTW experiment timetable

Week	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
1	23/8/21	24/8/21	25/8/21	26/8/21	27/8/21	28/8/21	29/8/21
2	30/8/21	31/8/21	1/9/21	2/9/21	3/9/21	4/9/21	5/9/21
3	6/9/21	7/9/21	8/9/21	9/9/21	10/9/21	11/9/21	12/9/21
4	13/9/21	14/9/21	15/9/21	16/9/21	17/9/21	18/9/21	19/9/21
5	20/9/21	21/9/21	22/9/21	23/9/21	24/9/21	25/9/21	26/9/21
6	27/9/21	28/9/21	29/9/21	30/9/21	1/10/21	2/10/21	3/10/21

Loading only

Loading and Sampling

No loading or sampling

Water was pumped from the Ellen Brook and distributed onto the surface of the EBW between 8AM-4PM each day (refer 1.1.2.1. Wetland Operation) . A Honda WX10T water transfer pump was placed next to the EBW. A PVC suction hose was installed into one of the distribution lines and transferred water to the pump. A second hose discharged the inlet water from the pump into the reservoir. During each day of operation, 1000L of water was transferred to the reservoir. Once full, the valve was completely opened and 200L of water was discharged, by gravity, directly into the channel of the bund. This was done to ensure any water remaining within the distribution piping from prior loading was flushed from the system.

[8] Exceptions to this include: week 3 in which loading occurred Tuesday to Thursday only, and week 5 when loading occurred Monday and Tuesday only.

The distribution system was manually placed on top of the filter media of the first PTW. The distribution hose was connected and the valve was fully opened. With a head difference of approximately 1m, water was gravity fed onto the surface of the PTW's. Once loading began, the influent penetrated vertically through the filter media and the effluent was collected via the collection system at the base of the IBC. This discharged via the outlet into the lower wetland.

Once 600L was loaded, the remaining 200L from the reservoir was drained to the lower wetland. The distribution system was removed, thoroughly rinsed, and installed on top of the next PTW. This process was repeated for the remaining PTW, with the reservoir only being filled to 800L, distributing 600L onto the PTW and discharging the remaining 200L. PTW's were loaded in the order: M5, M4, M3, M1 and M2. Each PTW was regularly levelled with a spirit level to ensure equal distribution of water on top of the filter media. The hydraulic loading rate (HLR) for each PTW was 500mm/day:

$$HLR = \frac{600L/day}{1.2m^2} = 500\frac{L/day}{m^2} = 500000\frac{m^3/day}{m^2} = 500\frac{mm}{day}$$

3.4. Sampling and Analysis

3.4.1. Flowrates

Every day, several measurements were taken to determine a number of flowrates elaborated below.

Inflow rate (Q_{in}): The rate of water into each PTW was determined by recording the water level (increments of 50-100L) on the reservoir tank and the time of each. The inflow rate (Q_{in}) was calculated using the following equation:

$$Q_{in}\ \left(\frac{L}{s}\right) = \frac{\Delta\ reservoir\ level\ (L)}{\Delta\ time\ (s)}$$

First flow (FF): A 9L bucket with 1L increments was placed under the outlet. The time in which continuous flow was first observed from the outlet pipe was recorded. Following this, the time to discharge 1L increments (until 8L) was also recorded.

Outflow rate (Q_{out}): After the first flow, the outlet flowrate was determined at regular intervals. Similar to measurements taken to determine of first flow, a bucket was placed under the outlet and the time it took to discharge a specific volume was recorded. From here, the outflow rate (Q_{out}) at the time of sample could be determined using the following equation:

$$Q_{out}\ \left(\frac{L}{s}\right) = \frac{Volume\ collected\ (L)}{time\ taken\ (s)}$$

This was conducted up to three times and an average taken:

$$Average\ Q_{out}\ \left(\frac{L}{s}\right) = \frac{Q_{out1} + Q_{out2} + Q_{out3}}{3}$$

Infiltration rate (IR): The rate in which water infiltrated the media was calculated using the following equation:

$$IR\left(\frac{mm}{h}\right) = Q_{out}\ \left(\frac{L}{s}\right) * \frac{m^3}{1000L} * \frac{1}{1.2m^2} * \frac{1000mm}{1m} * \frac{3600s}{1h}$$

3.4.2. Water Sampling

Every Tuesday and Thursday, water samples[9] were taken to analyse physical properties and water chemistry of the inlet water (EBW Inlet) from the Ellen Brook, as well as the effluent from each tank. The effluent samples were taken after approximately 300L had been discharged (50% of total daily volume loaded) from the outlet pipe. The time at which sampling was to take place was determined by the following equation:

$$Time\ of\ sample\ (mins) = Time\ taken\ to\ discharge\ FF\ (mins) + \frac{292L}{Average\ Q_{out}\ (L/min)}$$

When sampling, approximately 8L of the effluent was collected into a rinsed bucket. Aliquots were taken from the 8L sample to conduct physical analysis on site and then into rinsed sample bottles. The sample bottles were stored in a temperature-controlled box and delivered, on the same day of sampling, to an external, NATA accredited, laboratory for chemical analysis.

3.4.2.1. Physical Analysis

A handheld multiparameter digital water quality meter (YSI ProDSS) was used on site. The parameters analysed and their limit of reporting (LOR) have been summarised in Table 15.

[9] Samples were labelled, collected, prepared and analysed in accordance with the methods described in AS/NZS 5667.1.1998 (AS/NZS 1998).

Table 15: Physical parameters analysed

Parameter	Limit of Reporting (LOR)	Unit
Temperature	0.1	C
Dissolved Oxygen (DO)	0.1	%
	0.01	mg/L
Specific Conductance (SPC)	0.001	mS/cm
Salinity	0.01	ppt
pH	0.01	N/A
Oxidation-Reduction Potential (ORP)	0.1	Mv
Turbidity	0.01	NTU

Prior to each sampling event, the meter was calibrated for pH, SPC and DO. Turbidity and ORP were calibrated weekly.

3.4.2.2. Chemical Analysis

Initially, a full suite of parameters were analysed including (but not limited to) total and dissolved nutrients, total and dissolved metals, Iron (II) (Fe(II)), Chromium (VI) (Cr(VI)), Fluorine (F), Sulphates (SO_4), Sulphur (S), Alkalinity, Total Organic Carbon (TOC), Total Suspended Solids (TSS), Volatile Suspended Solids (VSS), Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Phosphorus was reported as total phosphorus (TP) and soluble reactive phosphorus (SRP). Nitrogen was reported as total nitrogen (TN), nitrate (NO_3^-), nitrite (NO_2^-) and ammonia (NH_3). NO_3^- and NO_2^- were added together and reported as NO_x. The difference between TN, NO_x and NH_3 was assumed to be dissolved organic nitrogen (DON). These parameters were reduced over the course of the trial as results identified significantly low or undetectable concentrations. As M2 & M3 consisted of the same media, sampling of M2 was reduced to four dates: 26 August, 31 August, 2 September and 21 September.

Samples were subject to several quality assurance and quality control (QA/QC) measures to ensure accuracy and precision of results. QA/QC, in the form of blind samples, were conducted in the field on one sampling occasion. This included field blanks (samples collected in the same manner using distilled water) and replicates (two samples from the same source. Internal QA/QC was also conducted by the laboratory itself. Reports were returned via email and subject to review by DBCA and the author. After review, several calculations were performed. These calculations are outlined below.

Removal efficiency of chemical parameters by each PTW was determined by the following calculation:

$$Removal\ efficiency = \frac{EBW\ inlet\ concentration - PTW\ concentration}{EBW\ inlet\ concentration} * 100\%$$

Daily nutrient removal during the experiment was determined by the following calculation:

$$Nutrient\ removal\ (g) = \frac{inlet\ concentration\ \left(\frac{mg}{L}\right) - outlet\ concentration\ \left(\frac{mg}{L}\right)}{volume\ loaded\ (600L)} * \frac{1g}{1000mg}$$

An average of the weekly concentrations was assumed for the days in which no sampling took place.

Maximum potential nutrient removal was determined by the following calculation:

$$Average\ nutrient\ removal\ \left(\frac{mg}{h}\right)$$
$$= IR\ \left(\frac{mm}{h}\right) * \frac{1m}{1000mm} * SA(1.2m^2) * \frac{1000L}{m^3} * concentration\ removed\ (\frac{mg}{L})$$

3.4.2.3. Limit of Reporting

For analytes that were reported as less-than the limit of reporting (LOR), half of the limit was accepted as the concentration of that analyte. These values are indicated in red. For example: The LOR for a certain analyte is 0.01mg/kg. The reported result was <0.01mg/kg, therefore the concentration would be changed to half the LOR and reported as 0.005mg/kg.

3.5. Limitations to Experiment

Lastly, there were several uncontrollable events and circumstances which hindered the experiment. The experiment was initially designed to operate for 12 weeks. With above average rainfall, the Ellen Brook overflowed and the EBW and surrounding areas turned into a floodplain. Due to this, the PTW's were inaccessible until the flooding subsided (Figure 23). Once the flooding subsided the main pump to the EBW stopped working. This meant that the PTW experiment could not take place as the EBW needed to be operational for the trials to run. Once the trials were underway, the project returned to normal operation. Essential equipment was stolen and therefore the experiment finished a week earlier than planned.

Figure 23: PTW's in flood waters

Limitations with sampling also arose. As the inlet water is from the Ellen Brook, only one sample is taken and assumed to be representative of the inlet water for that day. This means that any pulse inputs to the inlet are unaccounted for. Any discrepancies in this will be overcome by the number of data points in which abnormalities will be obvious. Secondly, the Pro-DSS probe used on site failed to display readings for some of the parameters during sampling events.

4. Results

Chapter 4: Results presents the results obtained during the PTW experiment. This includes infiltration rate, historical inlet nutrient concentration, nutrient removal and a summary of physical analysis. Further results can be found in Appendices.

4.1. Infiltration Rate

Figure 24 displays the maximum infiltration rate by each PTW, for each day of the experimental period.

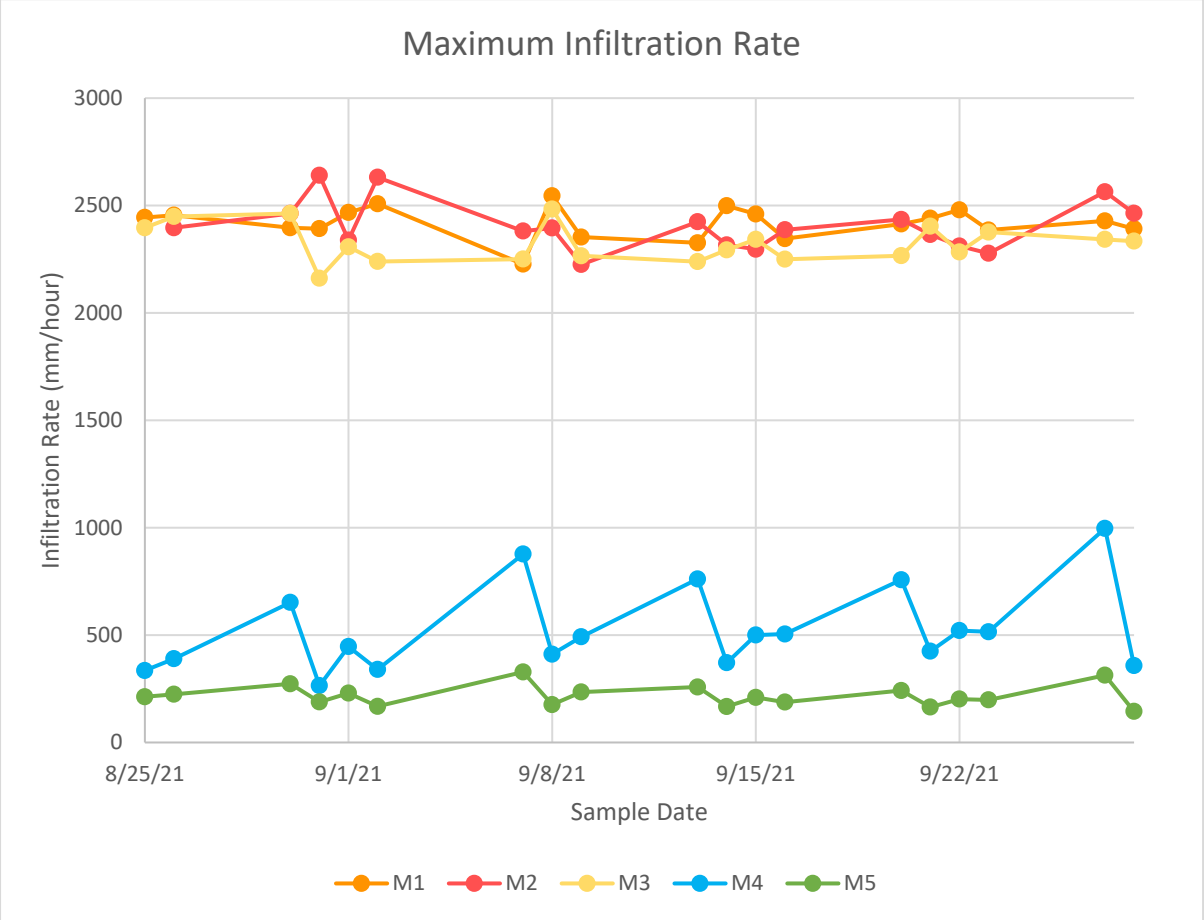

Figure 24: Maximum observed Infiltration rate per day

M1, M2 and M3 showed similar, steady maximum infiltration rates, almost 5 times that of M1 and more than 10 times M5. On average, M1 was only slightly greater than that of M2 and M3 (Table 16). Although the maximum infiltration rate of M4 was more than double that of M5, both PTW followed similar trends, with peaks evident on the first day of loading each week. M4 slightly increased over the experiment whereas the other PTW's remained relatively stable. No significant declining trends were observed.

Table 16: Mean maximum infiltration rate

Infiltration Rate (mm/h)	M1	M2	M3	M4	M5
Mean	2418.9	2406.3	2323.6	522.0	217.0
SE	17.0	27.1	20.0	45.6	11.4

4.2. Nutrient Analysis

The following section details phosphorus and nitrogen concentrations exhibited during the experiment. The complete data for phosphorus and nitrogen concentrations and removal efficiencies are in Appendix C: Nutrient Concentrations and Removal Efficiencies.

4.2.1. Phosphorus

4.2.1.1. Inlet Concentration

Figure 25 depicts the phosphorus concentrations observed in the Ellen Brook (inlet water for PTW's) over the course of the experiment.

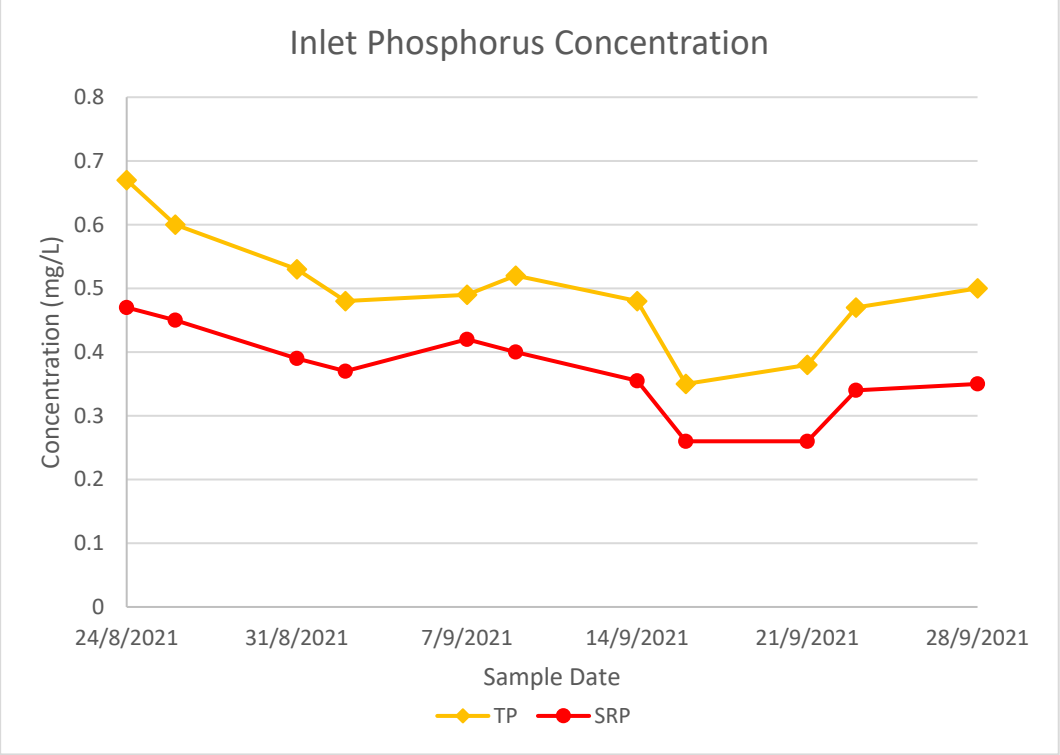

Figure 25: Inlet concentration of TP and SRP during the experimental period

As shown, TP and SRP concentrations in the EBW inlet have a similar declining trend with respect to time. On average, SRP was responsible for 75% of TP during the 2021 experimental period. The mean inlet concentration of TP was considerably higher than that of the historical data as shown in Figure 26.

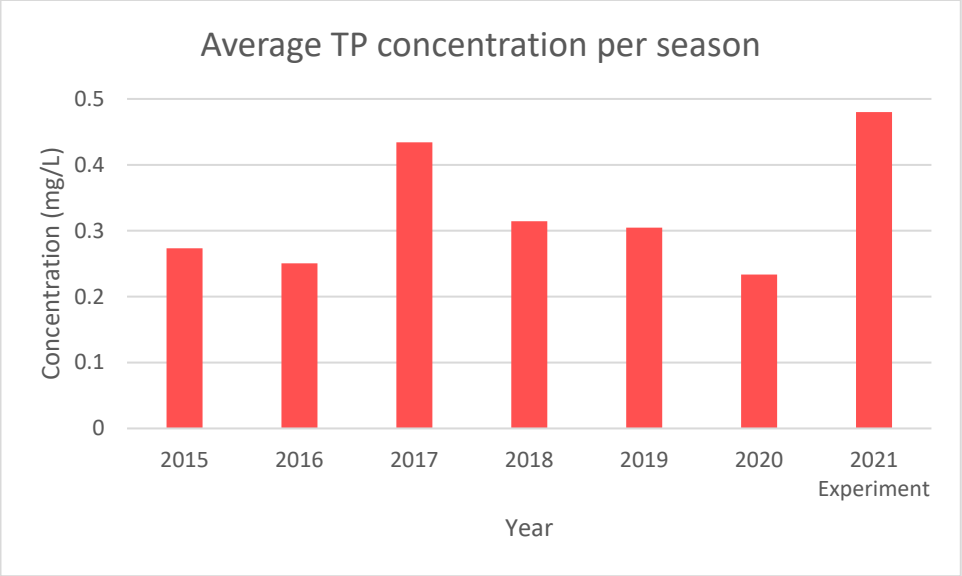

Figure 26: Historical Mean Inlet TP Concentration

On average, TP concentration in the Ellen Brook was approximately 0.3mg/L over the 2015-2020 period (min = 0.23mg/L, max = 0.43mg/L). Omitting the peak in average concentration observed in 2017 would reduce this figure to 0.28mg/L.

4.2.1.2. Removal Efficiency

The removal efficiency of TP by each PTW over the experimental period is shown in Figure 27.

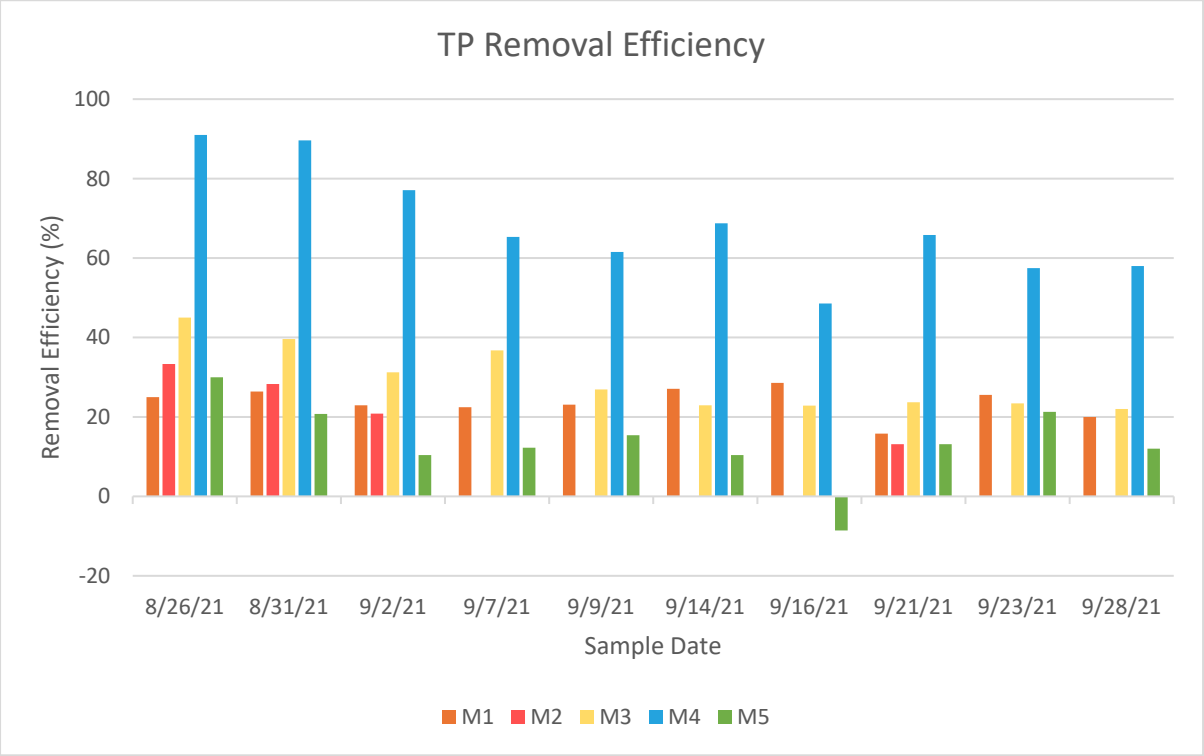

Figure 27: Removal efficiency of TP by PTW's

M4 showed the greatest TP removal, with an initial peak of 96.9% efficiency. This steadily declined for the remainder of the experiment and averaged 68.2% removal efficiency (Table 17). M1, M2 and M3 showed similar trends in removal efficiency, with M3 outperforming the others with a greater mean removal efficiency. M5 showed an increase in TP concentration as indicated by the negative value on 16/9/21. Omitting this data point would result in a mean removal efficiency of 16.18% compared to that of 13.71%.

Table 17: Average TP concentration and removal efficiency of EBW inlet, PTW's and EBW Outlet for sampling period

TP		M1	M2	M3	M4	M5
Removal Efficiency	Mean	23.7%	23.9%	29.4%	68.3%	13.7%
	SE	1.2%	4.4%	2.6%	4.4%	3.2%

4.2.2. Nitrogen

4.2.2.1. Inlet Concentration

Figure 28 depicts the nitrogen concentrations observed in the Ellen Brook (inlet water for PTW's) over the course of the experiment.

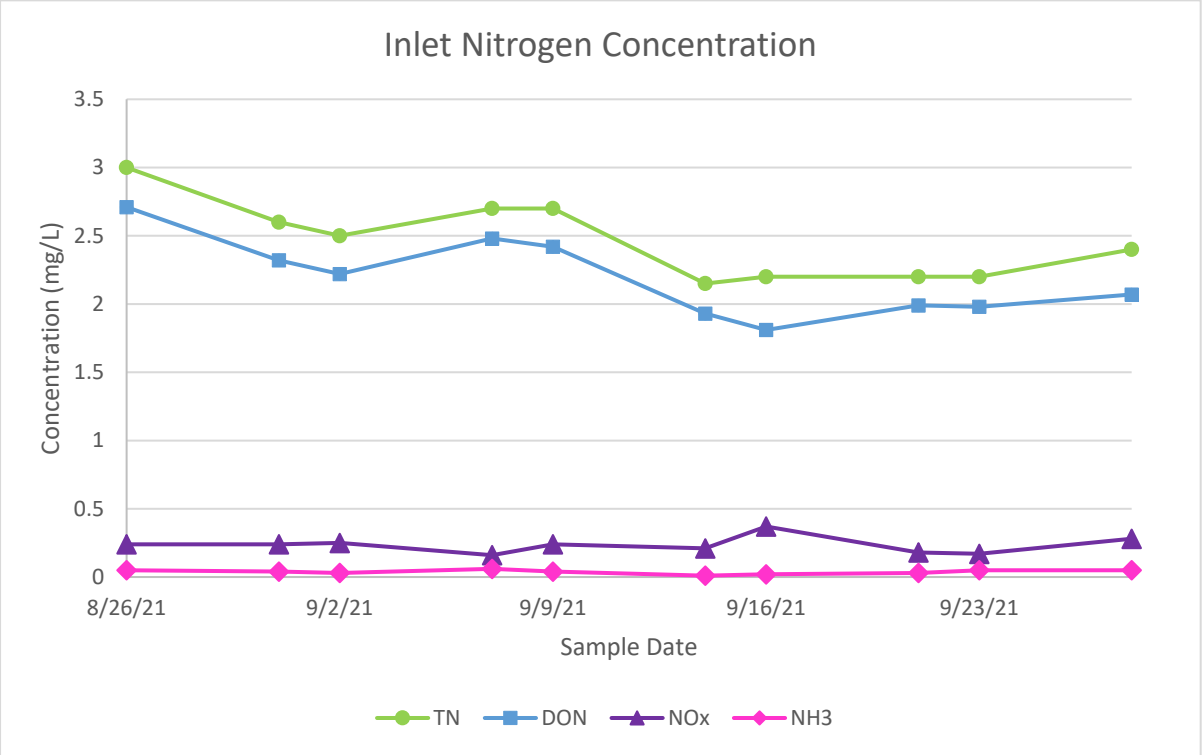

Figure 28: Inlet concentration of TN, DON, NO_x, NH_3 during the experimental period

Overall, nitrogen concentration steadily declined over the sampling period. On average, DON, NOx and NH3 were responsible for 89.0%, 9.5% and 1.5% of the inlet TN during the 2021 experimental period respectively. The inlet concentration of TN was slightly higher but comparable with that of the historical data as shown in Figure 29.

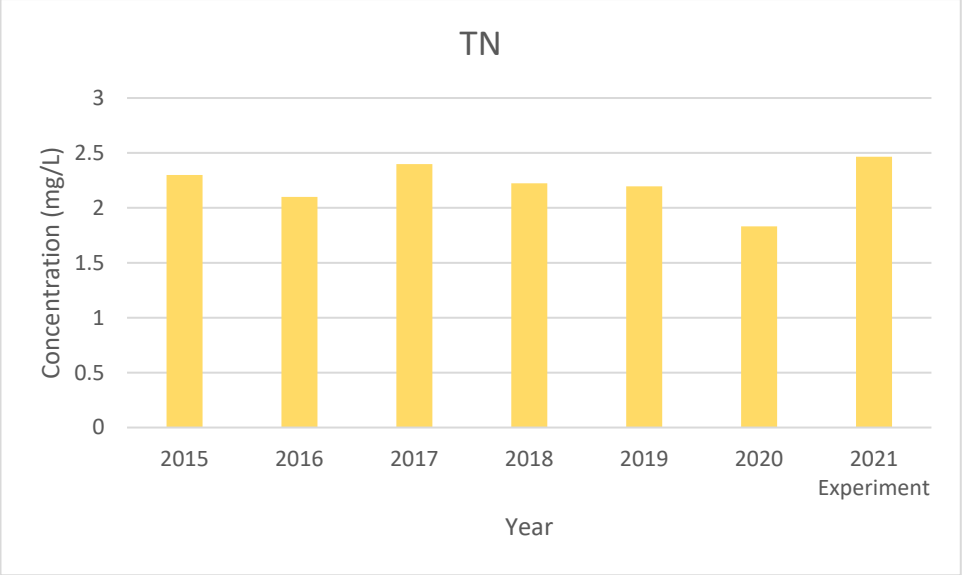

Figure 29: Historical mean TN concentration

The concentration of TN in the Ellen Brook remained stable, with a mean concentration of 2.18mg/L over the 2015-2020 period (min = 1.83mg/L, max = 2.40mg/L).

4.2.2.2. Removal Efficiency

The removal efficiency of TN by each PTW over the experimental period is shown in Figure 30.

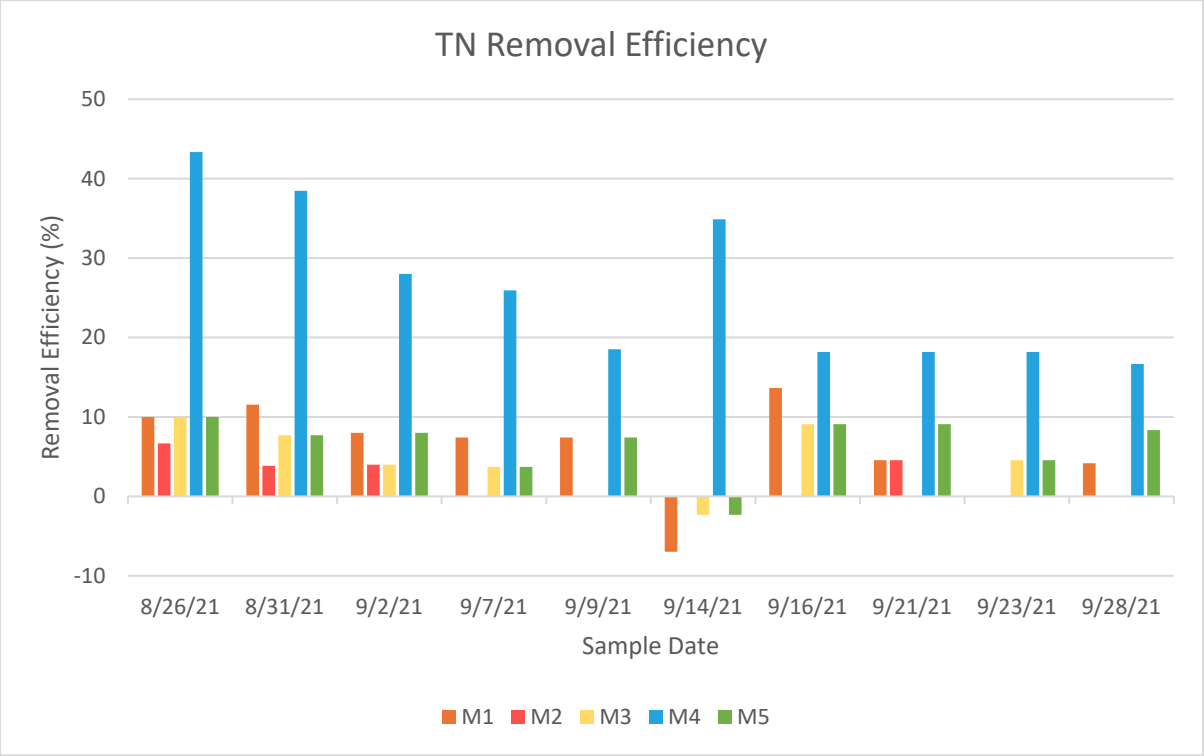

Figure 30: Removal efficiency of TN by PTW's

M4 displayed the greatest removal efficiency of TN. The significant declining trend saw a decrease by more than half that of the initial value. TN removal in remaining PTW (M1, M2, M3 and M5) was limited, averaging less than 7% removal efficiency (Table 18). The negative values on 14/9/21 was indicative of an increase in TN concentration between the inlet and outlets of M1, M3 and M5 (no data for M2 on this date). This was coupled with an unusual spike in TN removal by M4 on the same date.

Table 18: Mean TN concentration and removal efficiencies of each PTW

TN		M1	M2	M3	M4	M5
Removal Efficiency	Mean	6.0%	4.8%	3.7%	26.0%	6.6%
	SE	1.9%	0.7%	1.4%	3.1%	1.2%

4.2.3. Nutrient Removal

4.2.3.1. Nutrient Removal During Experiment

The total mass of TP and TN removed during the experimental period is shown in Figure 31.

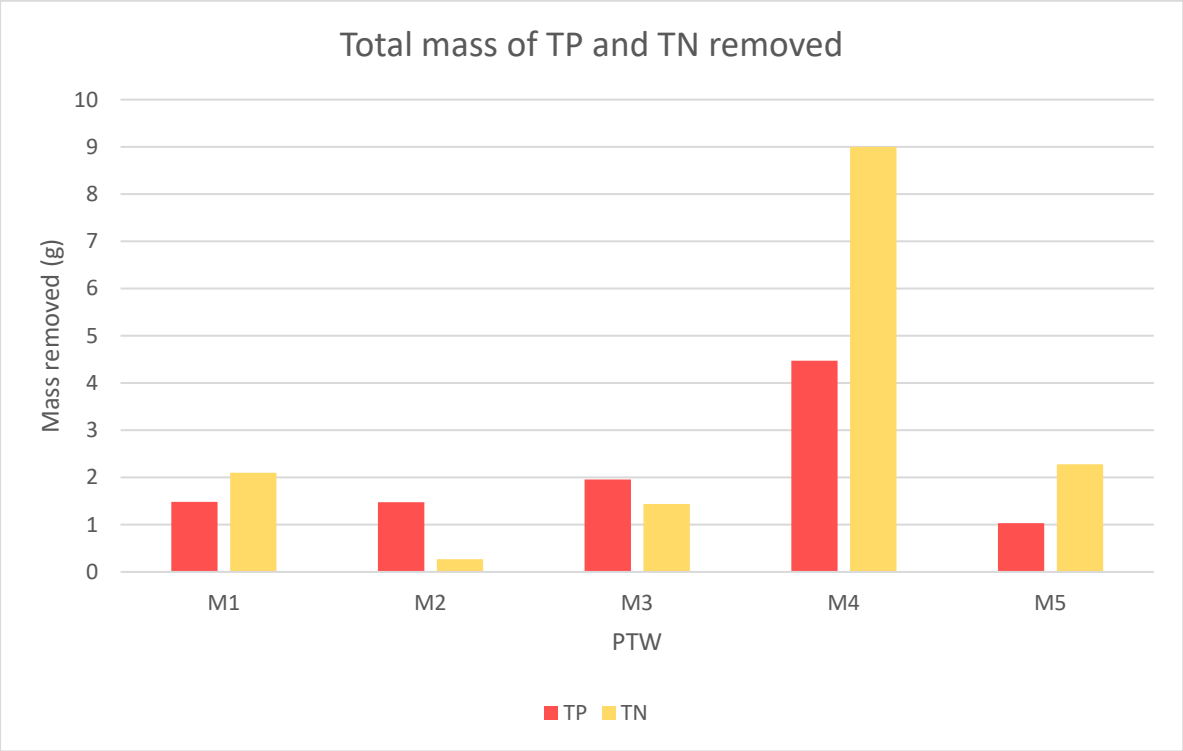

Figure 31: Mass of TP and TN removed during experiment

M4 removed the largest amount of TP and TN of all PTW at 4.5g and 9.0g respectively. Removal of TP in PTW M1 and M2 was equal (1.5g) and the mass of TN removed in M1 and M5 was comparable (2.1g compared to 2.3g). M3 removed slightly more TP than M2, but more than 5 times TN.

4.2.3.2. Maximum Potential Nutrient Removal

The maximum potential TP and TN removal on an hourly basis was calculated using the maximum infiltration rate observed and the average removal efficiency by each PTW. The results are summarised in Figure 32.

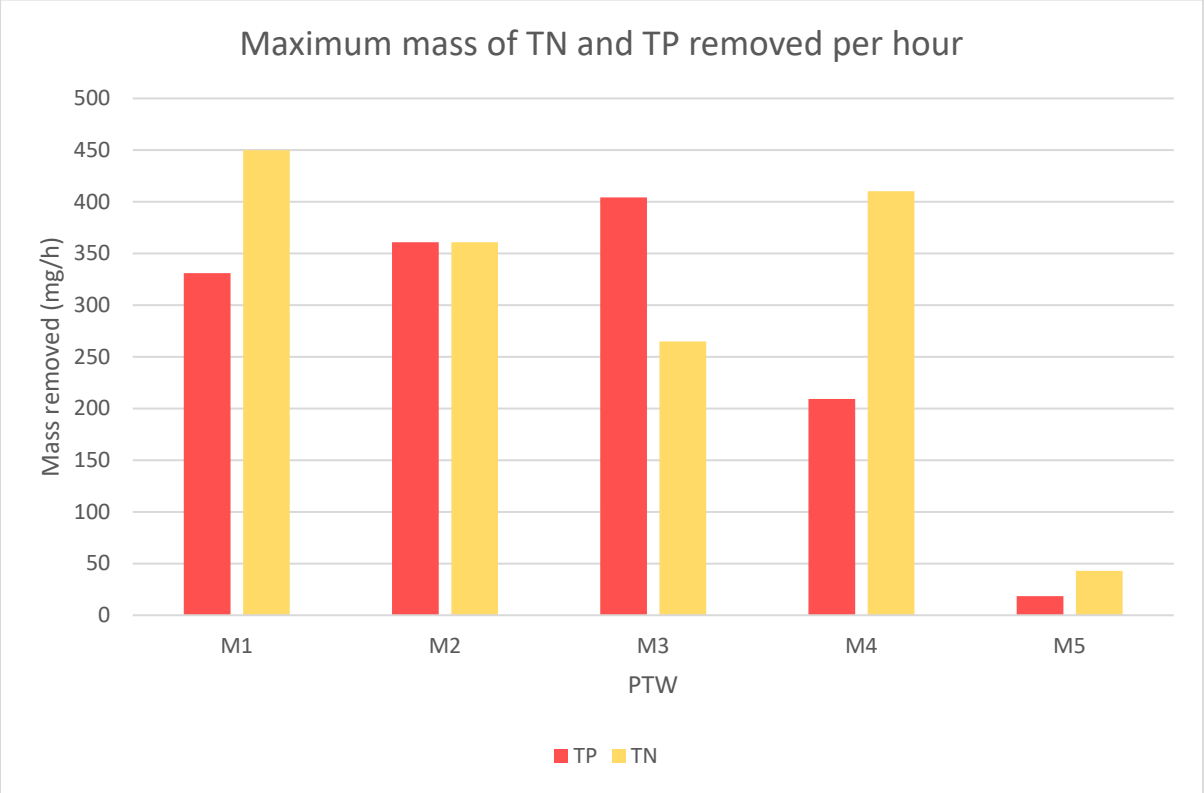

Figure 32: Maximum hourly removal of TP and TN on a mass basis

TP removal was estimated to be maximised in M3 (404mg/h). This is followed by M2 and M1 (361mg/h and 331mg/h respectively). M1 showed the greatest potential to remove TN at 450mg/h. This is comparable with M4 at 410mg/h. M2 showed equal removal of both TN and TP on an hourly basis (361mg/h). Removal of both TP and TN in M5 is significantly reduced in comparison to the other PTW's.

4.3. Physical Parameters

All physical parameters analysed over the course of the experiment can be found in Appendix F: Physical Analysis. The mean value of each parameter over the experimental period is displayed in Table 19.

A significant increase in DO was observed in all PTW. Specific conductance (SPC) was almost equal between the inlet and M5 but increased in all remaining PTW. The increase in SPC ranged between 0.011mS/cm (M1) and 0.097mS/cm (M2). A decline in pH was observed only in M1 and all other PTW increased pH. Decreases in oxidation reduction potential (ORP) were observed in all PTW whereas turbidity increased.

Table 19: Mean values of physical parameters over the experimental period

	Temp (°C)		DO (mg/L)		SPC (mS/cm)		pH		ORP (Mv)		Turbidity (NTU)	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Inlet	15.78	0.35	6.89	0.14	1.290	0.025	7.22	0.04	179.1	15.4	9.71	1.07
M1	19.04	0.78	9.35	0.08	1.301	0.020	7.05	0.03	167.9	10.5	23.09	3.52
M2	19.01	0.68	9.35	0.10	1.387	0.023	7.50	0.08	163.9	10.6	24.71	1.69
M3	18.88	0.73	9.48	0.07	1.339	0.084	7.66	0.03	160.5	11.2	31.00	2.24
M4	19.34	0.78	9.40	0.10	1.319	0.015	7.60	0.03	169.0	10.3	38.01	6.87
M5	18.00	0.55	9.55	0.08	1.291	0.016	7.33	0.03	172.1	11.7	12.72	0.86

5. Discussion

5.1. Phosphorus Removal

The extent to which phosphorus was removed in each PTW varied significantly. The relationship between phosphorus removal and inlet concentration, infiltration rate, soil constituents and aeration have been explored below.

5.1.1. Inlet Concentration

A correlation between inlet concentration and removal efficiency of phosphorus was observed in most PTW's. M4 exhibited this behaviour significantly, with efficiency peaking when inlet concentration was greater than 0.5mg/L. A minimum in inlet TP concentration was observed on 16 September and as a response, removal efficiency in M3, M4 and M5 declined[10] (in which the concentration of TP in the outlet of M5 was greater than that of the inlet concentration). This is supported by research conducted by Penn and Bowen (2018), who explain that phosphorus sorption by substrates is limited at lower input concentrations. As the 2021 experimental period exhibited significantly higher inlet phosphorus concentrations (likely due to increased rainfall and flooding) than that of previous years (refer Figure 26), further research into the system response at lower input concentrations is recommended.

[10] No data for M2 on this date

5.1.2. Infiltration Rate and Hydraulic Residence Time

A strong relationship between infiltration rate and removal efficiency of phosphorus in each PTW was observed. High infiltration rates of M1, M2 and M3 corresponded with a lower removal efficiency of P. This is expected due to the reduced HRT and, therefore, time for sorption to take place. M4 had a much greater HRT than that of the other PTW's and removed more P. The increased infiltration of M1, M2 and M3 would result in treatment of a larger volume of water than that of M4 and M5. As shown by the maximum potential nutrient removal per hour (refer Figure 32), this resulted in a greater mass removal on a time basis. Further research is required into the lifespan of each media, as Johansson Westholm (2006) describe that the amount of water passing through a filter media will affect the rate of saturation of the substrate, and therefore influence the lifespan of the filter media.

Peaks in infiltration observed in M4 and M5 corresponded with the first day of loading each week. This is likely to be attributed to the drying period where water retained within the media is released. M1, M2 and M3 did not display these characteristics which may indicate that these PTW's did not fully saturate. This is further supported by observation in which no ponding of inlet water above the filter media. M1, M2 and M3 were not impacted by the drying period and, therefore, are likely able to operate over a longer period without significant change to their infiltration rate.

Infiltration rates of M2 and M3 remained relatively stable. This did not correspond to prior research where a declining trend in infiltration of IMG based medias was evident (ChemCentre, 2012). This may be explained by different ratios of IMG to Gingin quartz or length of experimental period to that of previous studies.

The steady increase in the infiltration rate of M4 may be explained by finer particles flushing from the system. This was evident as the effluent from M4 was seen to rapidly change over the course of the experiment (Figure 33). This was also supported by an increase in TSS and turbidity exhibited in the midstream samples (refer Appendix E: Chemical Analysis, Figure 40 and Appendix F: Physical Analysis, Table 38).

Figure 33: First flow from M4 on 26 August (left) and 16 September (right)

5.1.3. Soil Constituents

It is difficult to establish a trend between the presence of metal elements and oxides within the filter media and the capacity for the filter media to remove P from incoming wastewater. For example, M1 had a significantly greater portion of metal oxides and concentration of most metals than that of the other PTW's (refer Table 12 and Table 13) but did not outperform them on a removal efficiency basis. As explained by Stefanakis, Akratos, and Tsihrintzis (2014), sorption of P is significantly influenced by the presence of Al, Fe and Ca oxides. It is likely that those substrates with greater concentration of these metal and metal oxides will be able to either remove a greater amount of P and/or have a longer lifespan. The discrepancy between literature and experimental data is likely due to increased infiltration rates (as previously discussed).

5.1.4. Aeration

There is limited data available to compare the effect of aeration on the performance of filter media. The aerated PTW (M2) displayed a slight increase in infiltration rate compared to that of the non-aerated PTW (M3). Air pockets observed in the outlet of M3 could indicate that the lack of external aeration created a suction within this PTW and therefore air was entering via the outlet pipe, resulting in a decrease in outflow rate. TP concentration in the outlet was, on average, only 0.03mg/L less in M3 than M2. Due to the limited data points of M2 (4 compared to 10 of M3), no conclusions can be drawn on the effect of aeration on phosphorus removal without further investigation. The effect of aeration on infiltration rate and overall performance may increase when implemented on a larger scale.

5.2. Nitrogen Removal

Nitrogen removal was limited in all PTW except M4. Concentration of NO_x was almost unchanged in all cases (refer Figure 36), indicating that minimal nitrification took place. This is to be expected as the bacteria responsible for nitrogen removal require a longer period than the experimental timeframe to establish. M5, containing spent media from the existing wetland, showed an increase in concentration of NO_x. It is likely that over the seven-year period of operation and loading, nitrifying bacteria have become well established within this filter media. The increasing removal efficiency observed towards the end of the experiment within the other PTW's (M1, M2, M3 and M4) could allude to this community being formed. A longer experimental period would likely provide more information as to how biofilm grow within each filter media. Due to this, it is assumed that most of the reduction of NH_3 concentration is through adsorption to the filter media.

The cation exchange capacity (refer Table 11) suggests that N removal by sorption would be favoured in M1. This was not the case as M4 had the greatest NH_3 removal, indicating that nitrogen removal and transformation reactions are also time dependant and therefore significantly influenced by HRT. The transformation of DON to NH_3 through ammonification was greatest in M4. No external or environmental factors were found to influence this result and is, therefore, inconclusive.

Due to the limited extent of nitrification observed in each PTW, the maximum nitrogen removal per hour (refer Figure 32) is likely to change once biofilm has adequately developed. Further investigation into the growth of biofilm within each media is required to understand the potential for each PTW to successfully remove nitrogen. It is expected that filter media with larger SA and, therefore, more biofilm, will show a greater removal of nitrogen.

5.3. Leaching and Contaminant Release

Although most PTW showed promising results in terms of nutrient removal, it is important to evaluate any contaminant release observed. The release of contaminants in each PTW are detailed below.

5.3.1. M1

Laboratory analysis indicated that TSS from the effluent of M1 was significantly greater than that of the influent and effluent of other PTW's (refer Figure 40). Upon analysis, increases in the concentration of several analytes were evident, particularly Al, Fe and Pb. PSD analysis determined that M1 had the highest portion of clay than that of the other PTW which are likely to flush from the system and cause the increase in TSS.

5.3.2. M2 & M3

Early in the experiment, significant quantities of Ca and S were released from M2 & M3. The difference in Ca and S concentrations within the filter media of M2 & M3 (Ca: 2200mg/kg, S: >250mg/kg) and M5 (Ca: 140mg/L, S: 2mg/L) indicate that this flushing likely occurred in the initial operation of the EBW. Concentration of both Ca and S in the outlet of M5 was similar to that of the inlet, suggesting that leaching is no longer occurring.

5.3.3. M4

Although M4 removed a significant portion of P and N from the incoming wastewater, M4 displayed a release of Al, Fe, Cr and Pb during the experiment (refer Appendix D: Chemical Analysis). The loss of from the filter media may impact communities downstream and reduce the lifespan of the filter media.

5.3.4. M5

M5, containing filter media sourced directly from the EBW, displayed a decrease in the concentration of multiple analytes compared to that of other PTW. This is most likely due to the greater HRT. The total uranium detected in the effluent was significantly greater than other PTW's and more than five times that of the influent.

The releases of contaminants each PTW have displayed are likely to result in issues during the commissioning of a larger scale treatment system. Further research into the extent and length of such leaching is recommended in order to determine the potential impact this could have on the environment.

5.4. Guidelines and Trigger Values

5.4.1. Nutrients

On average, M4 was the only PTW which achieved the short term targets for the SCC (Swan River Trust, 2008) for both TN and TP concentrations (2.0mg/L and 0.2mg/L respectively). With this said, the high inlet concentration of TP (refer Figure 26) may play a factor in achieving this and again, further investigation into the treatment performance at lower inlet concentrations is required. The remaining PTW did not achieve these targets. No PTW met the nutrient targets outlined by ANZECC and ARMCANZ (2000).

5.4.2. Dissolved Oxygen

Although it appears that all PTW's met the DO limits outlined by ANZECC and ARMCANZ (2000), this has been influenced by a number of external factors. Significant increases in DO of all effluent samples (see Appendix E: Physical Analysis) are likely due to several areas of unavoidable agitation and turbulence during the trials. This includes:

- Pumping of water from river to EBW
- Pumping of water from EBW distribution line to reservoir
- Loading water onto PTW
- Collection of water into sampling bucket

If these sources of agitation and turbulence were removed, no major change in DO between the inlet and outlets would be expected.

5.4.3. pH

pH of the effluent was slightly increased in all PTW's with exception of M1 in which a slight decrease was observed (see Appendix E: Physical Analysis). These changes in pH were minor and all effluent samples remained within the ANZECC and ARMCANZ (2000) trigger values of 6.5-8.

5.4.4. Specific Conductance and Salinity

SPC and salinity remained relatively stable between the inlet water and effluent from PTW M1, M4 and M5. M2 and M3 both increased SPC, but was reduced over the experimental period. SPC in both the inlet and outlet water exceeded the limits of 120-300 uS/cm (0.12-0.3 mS/cm) outlined by ANZECC and ARMCANZ (2000).

5.4.5. Particle Size Distribution

The particle size distribution (refer Figure 13) indicated that none of the filter media were within all recommended guidelines as set out by Brix and Arias (2005). M2 & M3 met some of these values: d10 was equal to the lower limit and C_u was within the guidelines (2.80 compared to guideline of <3.5). As all filter media were less than the lower bounds, it is likely that there will be less available pore spaces within the media and, therefore, reduced infiltration rate and volume of water treated may be observed over a longer period. Filter clogging may be observed over time.

The results from the PSD were quite unexpected when compared with field observations. These observations indicated that the filter media were likely have a greater portion of larger particles (M1 in particular). At the time of writing, a secondary PSD analysis is underway to confirm these results. It is recommended that the results from this secondary analysis are compared with the initial PSD and guidelines previously discussed to assess their suitability to be implemented as filter media within the EBW.

5.4.6. Soil Characterisation Investigation Limits

Comparison of the soil characterisation survey with various guidelines indicated that M2 & M3 and M4 met all variables. Those instances in which guideline limits were exceeded have been summarised in Table 20.

Table 20: Filter media exceeding soil characterisation investigation/guideline values

PTW	Guideline	Parameter	Limit	Level detected
M1	Ecological Investigation Level (Department of Environment and Conservation, 2010)	As	20 mg/kg	30 mg/kg
M1		V	50 mg/kg	76 mg/kg
M5		Mn	500 mg/kg	580 mg/kg

Although M1 and M5 exceeded the ecological investigation levels (Department of Environment and Conservation, 2010), no net release of these contaminants were detected in the outflow water during the experiment. It is recommended that these analytes are monitored closely. Values for sulphur in M1 and M2 & M3 were at the upper limit of detection (>250mg/kg) and no conclusions can be made as to whether these fall within the Department of Environment and Conservation (2010) trigger value of 600mg/L. Further test work to determine the actual concentration of S within these filter media is required.

6. Conclusion

The Ellenbrook wetland has been removing contaminants from the Ellen Brook since 2014. Saturation of the current filter media indicates it has approximately two years until it requires replacement. The aim of this thesis was to analyse the performance of different filter media in a vertical flow constructed wetland arrangement under the same climatic conditions and controls as that of the Ellenbrook wetland. Five pilot trial vertical flow constructed wetlands (M1, M2, M3, M4 and M5) containing four different filter medium, selected based on availability, cost, location and potential to repurpose, were constructed inside intermediate bulk containers. Each pilot trial wetland was loaded with a total of 12.6kL of water from the Ellen Brook over a six-week period. Sampling of physical and chemical parameters occurred twice a week. Key performance indicators that were analysed included: infiltration rate, phosphorus removal, nitrogen removal, contaminant leaching and comparison with guideline values.

Phosphorus removal was greatest in M4 with an average TP removal efficiency of 68.2%. These values were significantly influenced by the inlet concentration and infiltration rate. Maximum potential removal of phosphorus was calculated as a function of infiltration rate and was estimated to be greatest in M3 at 404mg/h. It was assumed that nitrogen removal was limited due to the length of the experimental period in which biofilm could not effectively establish. Removal efficiency ranged between 26% (M4) and 3.7% (M3) and maximum mass removal was estimated to range between 450mg/h (M1) and 43mg/h (M5). The effect of aeration on wetland performance appeared to be minimal and limited comments can be made due to the number of data points. Significant releases of several contaminants were detected in the outlet of all PTW. This included Al, Ca, Fe, Pb, S, U and Cr (refer Appendix E: Chemical Analysis). None of the filter media analysed conformed to all guideline and literature recommendations. This could result in reduced infiltration rates overtime and difficulty

to repurpose the filter media once saturated. Upon analysis of these results, several recommendations for future research have been made. This includes:

- Analysis of system response at reduced inlet concentrations
- Further investigation into the effect of aeration at a larger scale
- Investigation into the development of biofilm in each filter media
- Conduct and compare a secondary particle size distribution with the recommended guideline values
- Secondary soil characterisation survey to assess what remains within the media and what may have been leached from the system.

The Ellenbrook catchment was identified as a high priority catchment due to its large nutrient input into the Swan River. To preserve the health of the Swan River, eutrophication must be managed through essential remediation measures. The results and recommendations from this study will assist in the process of replacing the current filter media in the Ellenbrook wetland. This, in turn, could have a long lasting and significant impact on the water quality and health of the Swan River and surrounding ecosystems.

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Appendices

Appendix A: Relevant Guidelines for Soil Characterisation

Table 21: Assessment levels for soils, sediment and water (Department of Environment and Conservation, 2010)

	Ecological Investigation Levels	Health Investigation Levels			
		A[1]	D	E	F
	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
Metals/Metalloids					
Antimony, Sb	-	**31**[12]	-	-	**410**[12]
Arsenic, As	20[8]	100[8]	400[8]	200[8]	500[8]
Barium, Ba	**300**[8]	**15,000**[12]	-	-	**190,000**[12]
Beryllium, Be	-	20[8]	80[8]	40[8]	100[8]
Cadmium, Cd	3[8]	20[8]	80[8]	40[8]	100[8]
Chromium[2] (Cr III)	**400**[8]	**120,000**[8]	**480,000**[8]	**240,000**[8]	**600,000**[8]
Chromium[2] (Cr VI)	**1**[8]	100[8]	400[8]	200[8]	500[8]
Cobalt, Co	50[9]	100[8]	400[8]	200[8]	500[8]
Copper, Cu	**100**[8]	1,000[8]	4,000[8]	2,000[8]	5,000[8]
Lead, Pb	**600**[8]	300[8]	1,200[8]	600[8]	1,500[8]
Manganese, Mn	500[8]	1,500[8]	6,000[8]	3,000[8]	7,500[8]
Methyl mercury[3]	-	10[8]	40[8]	20[8]	50[8]
Mercury (inorganic), Hg	1[8]	15[8]	60[8]	30[8]	75[8]
Molybdenum, Mo	40[9]	390[12]	-	-	**5100**[12]
Nickel, Ni	60[8]	600[8]	2,400[8]	600[8]	3,000[8]
Tin, Sn	50[10]	**47,000**[12]	-	-	**610,000**[12]
Vanadium, V	50[8]	**550**[12]	-	-	**7,200**[12]
Zinc, Zn	200[8]	7,000[8]	28,000[8]	14,000[8]	35,000[8]
Other Inorganics					
Boron, B	-	3,000[8]	12,000[8]	6,000[8]	15,000[8]
Cyanides (complexed)[4], CN	50[9]	500[8]	2,000[8]	1,000[8]	2,500[8]
Cyanides (free)[4], CN	10[9]	250[8]	1,000[8]	500[8]	1,250[8]
Phosphorus, P	2,000[8]	-	-	-	-
Sulfur, S	600[8]	-	-	-	-
Sulfate[5], SO_4	2,000[8]	-	-	-	-
ORGANIC COMPOUNDS					
Methyl tertiary butyl ether, MTBE	-	**0.5**[13]	**0.5**[13]	**0.5**[13]	**0.5**[13]
Total Petroleum Hydrocarbons (TPH)					
C_6-C_9	100[7]	-	-	-	-
C_{10}-C_{14}	500[7]	-	-	-	-
C_{15}-C_{18}	1,000[7]	-	-	-	-
>C_{16}-C_{35} (aromatics)	-	90[8]	360[8]	180[8]	450[8]
>C_{16}-C_{35} (aliphatics)	-	5,600[8]	22,400[8]	11,200[8]	28,800[8]

	Ecological Investigation Levels	Health Investigation Levels			
		A[1]	D	E	F
	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
>C_{35} (aliphatics)	-	56,000[8]	224,000[8]	112,000[8]	280,000[8]
Monocyclic Aromatic Hydrocarbons					
Benzene	1[10]	**1.1[12]**	-	-	**5.6[12]**
Toluene	3[9]	520[11]	-	-	**5200[11]**
Ethylbenzene	5[9]	230[11]	-	-	230[11]
Xylenes	5[9]	**600[12]**	-	-	**2600[12]**
Polycyclic Aromatic Hydrocarbons (PAHs)					
Total PAHs[14]	-	20[8]	80[8]	40[8]	100[8]
Anthracene	10[9]	**17,000[12]**	-	-	**170,000[12]**
Benzo[a]pyrene	1[9]	1[8]	4[8]	2[8]	5[8]
Fluoranthene	10[9]	**2,300[12]**	-	-	**22,000[12]**
Naphthalene	5[9]	60[11]	-	-	190[11]
Phenanthrene	10[9]	-	-	-	-
Pyrene	10[9]	**1,700[12]**	-	-	**17,000[12]**
Phenols					
Phenol[6]	-	8,500[8]	34,000[8]	17,000[8]	42,500[8]
2-methylphenol	-	**3,100[12]**	-	-	**31000[12]**
3-methylphenol	-	**3,100[12]**	-	-	**31000[12]**
4-methylphenol	-	**310[12]**	-	-	**3,100[12]**
Total phenols	1[9]	-	-	-	-
Polychlorinated Biphenyls (PCBs)					
total PCBs	1[10]	10[8]	40[8]	20[8]	50[8]
OC & OP Pesticides					
Individual organochloride pesticides	0.5[9]	-	-	-	-
Total organochloride pesticides	1[9]	-	-	-	-
Total non-chlorinated pesticides	2[9]	-	-	-	-
Individual non-chlorinated pesticides	1[9]	-	-	-	-
Aldrin plus dieldrin	-	10[8]	40[8]	20[8]	50[8]
Dieldrin	0.2[10]	-	-	-	-
Chlordane	0.5[9]	50[8]	200[8]	100[8]	250[8]
DDT + DDD + DDE	1[9]	200[8]	800[8]	400[8]	1,000[8]
Heptachlor (including its epoxide)	0.5[9]	-	-	-	-
Heptachlor	-	10[8]	40[8]	20[8]	50[8]

BOLD indicates a change from the previous version of this guideline

Key to source of assessment levels:

VIC EPA[7]	NEPM[8]	"Dutch B"[9]	ANZECC B[10]
DoH[11]	USEPA RSLs[12]		DEC/DoH[13]

Table 22: Health based investigation levels for soil contaminants (National Environment Protection Council, 2011)

Chemical	Health-based investigation levels (mg/kg)			
	Residential A	Residential B	Recreational[1] C	Commercial/ industrial D
Metals and Inorganics				
arsenic[2]	100	500	300	3000
beryllium	70	100	100	500
boron	5000	40000	20000	300000
Cadmium	20	140	100	800
chromium (VI)	100	500	240	3000
Cobalt	100	600	300	4000
Copper	7000	30000	20000	250000
lead[3]	300	1200	600	1500
manganese	3000	8000	9000	40000
methyl mercury[4]	7	30	10	200
mercury (inorganic)	200	600	400	4000
Nickel	400	900	800	4000
Selenium	200	1500	700	10000
Zinc	8000	60000	30000	400000
cyanide (free)	250	400	350	2000
Polycyclic Aromatic Hydrocarbons (PAHs)				
benzo(a)pyreneTEQ	3	4	4	40
PAHs	300	400	400	4000
Phenols				
Phenol	3000	50000	45000	250000
pentachlorophenol	100	150	140	700
Cresols	400	5500	4700	27000
Organochlorine Pesticides				
DDT+DDE+DDD	260	700	400	4000
aldrin and dieldrin	7	10	9	50
chlordane	50	100	80	560
endosulfan	300	460	400	2000
Endrin	10	20	20	100
heptachlor	7	10	9	50
HCB	10	20	15	85
methoxychlor	400	550	500	2700
Mirex	10	20	20	100
toxaphene	20	35	30	170
Phenoxyacetic Acid Herbicides				
2,4,5-T	700	1000	900	5000
2,4-D	1000	2000	1400	9500
MCPA	700	1000	900	5000
MCPB	700	1000	900	5000
mecoprop	700	1000	900	5000
Picloram	5000	8000	6500	37000
Other Pesticides				
Atrazine	360	550	500	3000
chlorpyrifos	170	400	300	2000
Bifenthrin	600	900	750	4000
Other Organics				
PCBs	1	2	2	8
PBDE Flame Retardants (Br1-Br9)	1	2	2	10

Table 23: Landfill Waste Classification (Department of Water and Environmental Regulation, 2019)

Table 3 Contaminant threshold (CT) values for waste not requiring a leach test

Contaminant[1]	Maximum values of total concentration for classification without the requirements to assess leachability[2,3]			
	CT1 (mg/kg) Class I	CT2 (mg/kg) Class II	CT3 (mg/kg) Class III	CT4 (mg/kg) Class IV
Metals and metalloids				
Arsenic	14	14	140	1,400
Beryllium	2	2	20	200
Cadmium	0.4	0.4	4	40
Chromium (Hexavalent)	10	10	100	1,000
Lead	2	2	20	200
Mercury	0.2	0.2	2	20
Molybdenum	10	10	100	1,000
Nickel	4	4	40	400
Selenium	2	2	20	200
Silver	20	20	200	2,000
Other Inorganic Species				
Cyanide (amenable)[4]	7	7	70	700
Cyanide (total)	16	16	160	1,600
Fluoride	300	300	3,000	30,000
Non-Chlorinated Organics				
Benzene	0.2	0.2	2	20
Cresols (total)	400	400	4,000	40,000
2,4-D	0.02	0.02	0.2	2
Ethylbenzene	60	60	600	6,000
Petroleum hydrocarbons	N/A	N/A	N/A	N/A
Phenol (total, non-halogenated)	28.8	28.8	288	2,880
Polycyclic aromatic hydrocarbons (total)	N/A	N/A	N/A	N/A
Styrene (vinyl benzene)	6	6	60	600
Toluene	160	160	1,600	16,000
Xylenes (total)	120	120	1,200	12,000
Chlorinated Organics[5]				
Organochlorine pesticides, polychlorinated biphenyls etc.	N/A	N/A	N/A	N/A
Other metals[6]	% by weight	% by weight	% by weight	% by weight
Aluminium , barium, boron, cobalt, copper, manganese, vanadium and zinc	5	5	10	20

Appendix B: Spongolite

Phosrox – a new technology to purify waterways

The pollution of waterways by phosphates and nitrates of agricultural origin is a major environmental problem, causing eutrophication, algal blooms and environmental degradation. In WA a number of products have been trialled to improve this situation, including soil ameliorants to increase nutrient binding, and by directly treating water bodies. Although there have been successes, the treatment costs are typically very high.

Southern Spongolite Industries has been working with Bioscience to develop a cost-effective way of removing phosphates and nitrates from waterways. Spongolite is a lightweight and very porous mineral traditionally used as an absorbent of oil and chemical spills, and is considered a benign, natural mineral. The new patented technology is based on physical and chemical modification of spongolite into Phosrox.

Phosrox is made up of solid, porous rocks, so it can be recovered easily from waterways for subsequent beneficial use.

Studies have shown that Phosrox develops an extraordinarily high capacity to bind anions like phosphate and nitrate after specialized treatment and processing.

Phosrox blends can be made available in different processed forms that can achieve a phosphorus retention index (PRI) ranging from 1200 to 2600, and a phosphate sorbance ranging from 5mg/g to 12mg/g. In addition, with an alternative process a nitrate retention index of 500 with a nitrate sorbance of 3mg/g can be achieved.

Phosrox blends can be made available to suit a wide range of different requirements, from a soil amendment, to intensive agriculture to waterbodies. For example, by placing gabions containing Phosrox to form permeable weirs in waterways, phosphates and nitrates are removed. When Phosrox becomes fully loaded (about 0.5- 1.2% dry weight) it can be easily recovered and replaced with fresh material.

The P and N-loaded material can be then dried and crushed to a gravel size for a valuable soil amendment that can both improve water holding capacity and act as a slow release fertilizer.

It is possible to tailor make Phosrox blends specifically suited to individual waterways, considering the pH and the levels of phosphates, nitrates and salts present.

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8th October 2020

Figure 34: Phosrox fact sheet

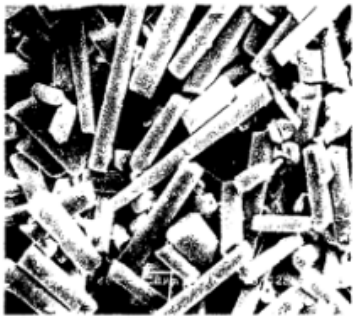
Southern Spongolite Industries
PO Box 99, Nth Fremantle
WA 6159

Spongolite

What is Spongolite?

Spongolite is a stone formed from fossilised sponges. A number of significant deposits exist in south-western Australia.

The spongolite deposits were formed millions of years ago when a shallow sea occupied the south coast of Western Australia.



Spongolite consists of millions of tiny hollow tubes of amorphous silica known as spicules that originally formed the skeleton of the sponges. This unique structure means that Spongolite has very specialised properties including:

- A low specific gravity and bulk density
- The ability to absorb and retain a significant about of water and other liquids
- A high ion exchange capacity which allows to capture and retain contaminants and nutrients such as phosphorous.

Physical and Chemical Properties

Spongolite is a rigid solid that can be cut into blocks but is a relatively soft material

Typically spongolite is cream in colour but the colour can vary significantly depending in the depth of occurrence in the deposit. Material from the Kendenup deposit mined by Southern Spongolite can be grey, red, orange or even purple depending in trace contaminants.

The following key properties have been established:

Property	Value
Specific Gravity	1.4 -1.5
Bulk density	0.7 - 0.8
Saturated Bulk Density	0.94 - 1.04
Cation Exchange Capacity	15 - 20 eEq/ 100g
pH	5.5 - 7
Water Retention (% W/W)	35 - 42%
Phosphorous Retention (% W/W)	4 - 8 %

As Spongolite is composed of amorphous silica rather than crystalline silica and does not represent a respirable dust hazard. Normal dust controls can be applied during handling.

Uses for Spongolite

Historically Spongolite has been used as building material but its physical strength and tendency to wear have limited this use.

Its major current uses are

- As an absorbent in products like kitty litter or industrial spill kits
- As a filter medium for the aquarium industry
- In landscaping soil mixes because of its moisture and nutrient retention properties
- In architectural landscaping for producing light weight soils for use in situations where weight is critical (such as planters on suspended slabs)
- It is used either alone or in conjunction with other materials to trap nutrients (particularly phosphorous) in stormwater systems and in effluent treatment systems.

Southern Spongolite has an ongoing research program to widen the range of applications for the material

Figure 35: Spongolite fact sheet

Appendix C: Soil Characterisation

Table 24: Soil Characterisation Data

Parameter	Method Code	LOR	Units	M1	M2 & M3	M4	M5/EBW
LOI_550C	LOI	0.1	%	8.4	0.5	3.3	0.3
TIC	(combs)	0.05	%	0.025	0.025	0.05	0.025
TOC	(combs)	0.05	%	0.1	0.025	0.77	0.08
Ag	iMET2SAMS	0.05	mg/kg	0.025	0.025	0.025	0.025
Al	iMET2SAICP	10	mg/kg	19300	270	15000	364
As	iMET2SAMS	0.2	mg/kg	30	0.7	8	0.8
B	iMET2SAICP	5	mg/kg	24	2.5	2.5	2.5
Ba	iMET2SAICP	0.1	mg/kg	47	0.7	11	10
Be	iMET2SAMS	0.05	mg/kg	0.21	0.025	0.15	0.025
Ca	iMET2SAICP	10	mg/kg	310	2200	2200	140
Cd	iMET2SAMS	0.05	mg/kg	0.025	0.025	0.025	0.025
Co	iMET2SAMS	0.5	mg/kg	2	43	20	40
Cr	iMET2SAICP	0.05	mg/kg	54	2.5	24	2.6
CrVI	iCRS1STCO	0.5	mg/kg	0.25	0.25	0.25	0.25
Cu	iMET2SAMS	0.5	mg/kg	6	0.25	1	0.7
Fe	iMET2SAICP	5	mg/kg	48000	2500	6100	4700
H2O	(105C)	0.1	%ar	11.1	5.5	10.6	6.7
K	iMET2SAICP	5	mg/kg	1800	11	190	59
La	iMET2SAICP	0.1	mg/kg	8.7	1.7	7	2.2
Li	iMET2SAICP	0.2	mg/kg	7	0.1	3.7	0.2
Mg	iMET2SAICP	5	mg/kg	1600	120	120	110
Mn	iMET2SAICP	0.2	mg/kg	8	460	26	580
Mo	iMET2SAMS	0.05	mg/kg	1.1	0.08	0.28	0.18
N_NOx	iNTA1SFIA	0.05	mg/kg	2.3	0.18	0.13	0.8
N_TK	iAMMS1CODA	50	mg/kg	55	25	140	25
N_total	iAMMS1CALC	50	mg/kg	57	25	140	25
Na	iMET2SAICP	10	mg/kg	3800	5	73	19
Ni	iMET2SAMS	0.1	mg/kg	3.8	1.4	2	2.2
P	iMET2SAICP	5	mg/kg	69	8	170	62
Pb	iMET2SAMS	0.5	mg/kg	9.4	1.9	2.9	1.8
pHfox	iCRS	0.1		3.6	8.8	6.8	6.5
pHfoxr	iCRS	0		X	XXX	X	XX
Sb	iMET2SAMS	0.05	mg/kg	0.1	0.025	0.06	0.025
Se	iMET2SAMS	0.05	mg/kg	1.7	0.025	0.1	0.025
Sn	iMET2SAMS	0.5	mg/kg	1	0.25	0.25	0.25
Stones	(>2mm)	0.1	%	0.3	0.6	0.2	17
Th	iMET2SAMS	0.5	mg/kg	15	3.5	3.8	3.6
U	iMET2SAMS	0.01	mg/kg	0.59	0.21	0.23	0.36
V	iMET2SAICP	0.2	mg/kg	76	1.3	11	3
Zn	iMET2SAMS	0.25	mg/kg	8.9	1.3	2	3.6
EC	(1:5)	1	mS/m	370	200	14	2

pH	(CaCl2)	0.1		5.2	8.1	7.7	6.7
OrgC	(W/B)	0.05	%	0.12	0.025	0.59	0.1
C	(combs)	0.05	%	0.1	0.025	0.82	0.09
NH4-N	NO3-NH4	1	mg/kg	2	0.5	0.5	0.5
NO3-N	NO3-NH4	1	mg/kg	2	0.5	0.5	0.5
K	(HCO3)	10	mg/kg	350	5	19	12
P	(HCO3)	2	mg/kg	1	3	5	17
P	PRI	-20	mL/g	61	12	83	1.6
PRI*	PRI	-1000	mL/g	61	15	88	19
PBI	PBI	0.1		52.1	50.9	165.6	11.9
CEC	(NH4Cl)	1	cmol(+)/kg	10	7	4	2
Ca	(exch)	0.02	cmol(+)/kg	1.3	7.2	1.3	0.75
K	(exch)	0.02	cmol(+)/kg	0.51	0.01	0.06	0.01
Mg	(exch)	0.02	cmol(+)/kg	2.9	0.21	0.01	0.25
Na	(exch)	0.02	cmol(+)/kg	3.2	0.01	0.16	0.01
Al	(M3)	1	mg/kg	370	28	>550	48
B	(M3)	0.1	mg/kg	1.5	0.05	0.2	0.1
Ca	(M3)	10	mg/kg	450	3100	1300	160
Cd	(M3)	0.01	mg/kg	0.03	0.06	0.08	<0.10
Co	(M3)	0.01	mg/kg	0.02	1.5	0.02	0.49
Cu	(M3)	0.1	mg/kg	0.05	0.5	0.2	0.05
Fe	(M3)	1	mg/kg	60	>550	180	420
K	(M3)	1	mg/kg	330	2	18	4
Mg	(M3)	10	mg/kg	640	130	37	47
Mn	(M3)	0.05	mg/kg	1.5	160	7.8	43
Mo	(M3)	0.01	mg/kg	0.02	0.01	0.02	0.005
Na	(M3)	1	mg/kg	>1000	3	31	0.5
Ni	(M3)	0.1	mg/kg	0.05	1	0.05	0.3
P	(M3)	1	mg/kg	0.5	3	11	26
S	(M3)	1	mg/kg	>250	>250	47	2
Zn	(M3)	0.1	mg/kg	0.5	0.5	0.4	0.05
As	(M3)	0.1	mg/kg	0.05	0.05	0.2	0.05
Pb	(M3)	0.1	mg/kg	0.2	0.6	0.5	0.4
Se	(M3)	0.1	mg/kg	0.05	0.05	0.05	0.05

Table 25: Metal oxide content by XRF analysis

Metal Oxide (%)	M1	M2 & M3	M4	M5
Al2O3	9.02	0.09	4.54	0.17
BaO	0.02	0.005	0.03	0.005
CaO	0.06	0.33	0.38	0.04
Cr2O3	0.01	0.01	0.005	0.005
Fe2O3	7.67	0.46	1.14	0.72
K2O	0.67	0.005	1.03	0.03
MgO	0.37	0.03	0.04	0.005
MnO	0.005	0.07	0.005	0.08
Na2O	0.69	0.005	0.09	0.005
P2O5	0.022	0.003	0.048	0.019
SO3	0.23	0.41	0.12	0.01
SiO2	75.3	97.96	89.5	98.06
TiO2	0.57	0.24	0.28	0.42

Table 26: Soil texture and particle size distribution data

Parameter	Method Code	LOR	Units	M1	M2 & M3	M4	M5
Sand.	fraction	0.5	%	73	98	95.5	98
Silt.	fraction	0.5	%	11	0.5	1.5	1
Clay.	fraction	0.5	%	16	1.5	3	1
>1.00mm	Sieve	0.01	%	22.5	16.6	1.5	10.4
>0.600mm	Sieve	0.01	%	15.4	31.8	18.4	13.1
>0.300mm	Sieve	0.01	%	9.8	36.1	41.5	28.9
>0.180mm	Sieve	0.01	%	4.5	9.1	17.9	20
>0.150mm	Sieve	0.01	%	1	0.8	4.7	4.2
>0.106mm	Sieve	0.01	%	3	1.9	8	9.2
>0.075mm	Sieve	0.01	%	2.8	0.9	1.1	5.5
<0.075mm	Sieve	0.1	%	13.6	1	2.4	6.5

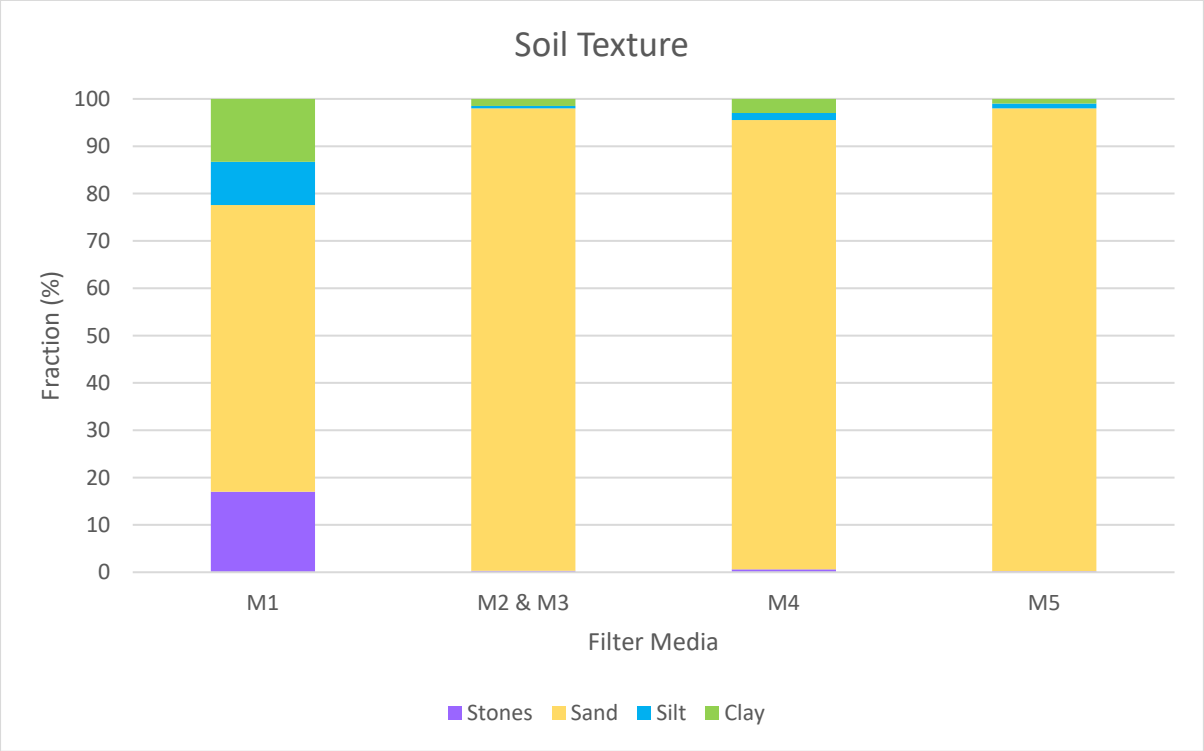


Figure 36: Soil texture of filter media

Appendix D: Nutrient Concentrations and Removal Efficiencies

Table 27: TP Concentrations of inlet and PTW's

TP (mg/L)	Inlet	M1	M2	M3	M4	M5
26/8/21	0.6	0.45	0.4	0.33	0.054	0.42
31/8/21	0.53	0.39	0.38	0.32	0.055	0.42
2/9/21	0.48	0.37	0.38	0.33	0.11	0.43
7/9/21	0.49	0.38		0.31	0.17	0.43
9/9/21	0.52	0.4		0.38	0.2	0.44
14/9/21	0.48	0.35		0.37	0.15	0.43
16/9/21	0.35	0.25		0.27	0.18	0.38
21/9/21	0.38	0.32	0.33	0.29	0.13	0.33
23/9/21	0.47	0.35		0.36	0.2	0.37
28/9/21	0.5	0.4		0.39	0.21	0.44
Average	0.48	0.37	0.37	0.34	0.15	0.41
SE	0.0226	0.0171	0.0149	0.0125	0.0182	0.0116

Table 28: SRP Concentrations

SRP (mg/L)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	0.45	0.32	0.29	0.2	0.02	0.31
31/8/21	0.39	0.28	0.26	0.24	0.04	0.34
2/9/21	0.37	0.26	0.28	0.23	0.05	0.37
7/9/21	0.42	0.26		0.21	0.06	0.36
9/9/21	0.4	0.29		0.27	0.09	0.35
14/9/21	0.36	0.24		0.23	0.05	0.36
16/9/21	0.26	0.16		0.18	0.08	0.35
21/9/21	0.26	0.21	0.25	0.22	0.09	0.28
23/9/21	0.34	0.23		0.24	0.09	0.34
28/9/21	0.35	0.27		0.27	0.1	0.36
Average	0.36	0.25	0.27	0.23	0.07	0.34
SE	0.0197	0.0142	0.0091	0.0090	0.0084	0.0087

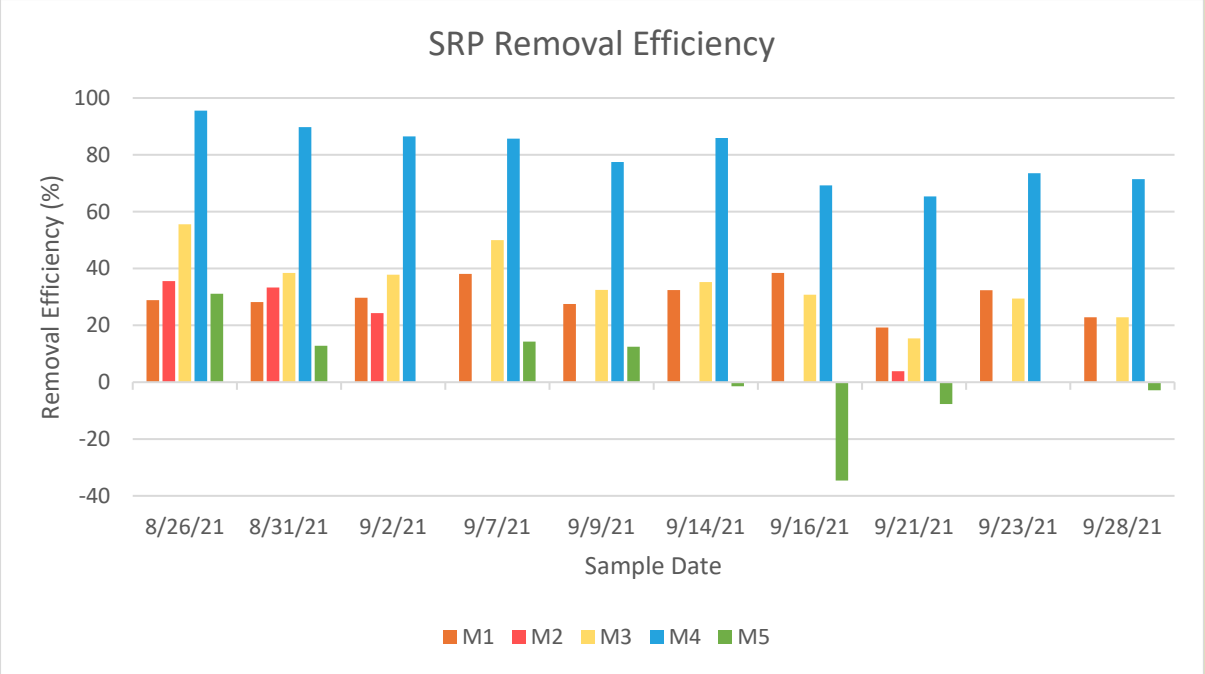


Figure 37: Soluble reactive phosphorus removal efficiency

Table 29: TN Concentrations

TN (mg/L)	Inlet	M1	M2	M3	M4	M5
26/8/21	3	2.7	2.8	2.7	1.7	2.7
31/8/21	2.6	2.3	2.5	2.4	1.6	2.4
2/9/21	2.5	2.3	2.4	2.4	1.8	2.3
7/9/21	2.7	2.5		2.6	2	2.6
9/9/21	2.7	2.5		2.7	2.2	2.5
14/9/21	2.15	2.3		2.2	1.4	2.2
16/9/21	2.2	1.9		2	1.8	2
21/9/21	2.2	2.1	2.1	2.2	1.8	2
23/9/21	2.2	2.2		2.1	1.8	2.1
28/9/21	2.4	2.3		2.4	2	2.2
Average	2.47	2.31	2.45	2.37	1.81	2.30
SE	0.0901	0.0706	0.1443	0.0775	0.0706	0.0775

Table 30: NH_3 Concentrations

NH3 (mg/L)	Inlet	M1	M2	M3	M4	M5
26/8/21	0.05	0.06	0.04	0.04	0.005	0.04
31/8/21	0.04	0.06	0.02	0.03	0.005	0.02
2/9/21	0.03	0.06	0.03	0.03	0.005	0.005
7/9/21	0.06	0.09		0.03	0.005	0.02
9/9/21	0.04	0.04		0.03	0.005	0.01
14/9/21	0.01	0.01		0.02	0.005	0.01
16/9/21	0.02	0.05		0.005	0.02	0.01
21/9/21	0.03	0.04	0.03	0.04	0.03	0.02
23/9/21	0.05	0.05		0.03	0.01	0.03
28/9/21	0.05	0.05		0.06	0.03	0.04
Average	0.04	0.05	0.03	0.03	0.01	0.02
SE	0.0049	0.0064	0.0041	0.0045	0.0033	0.0040

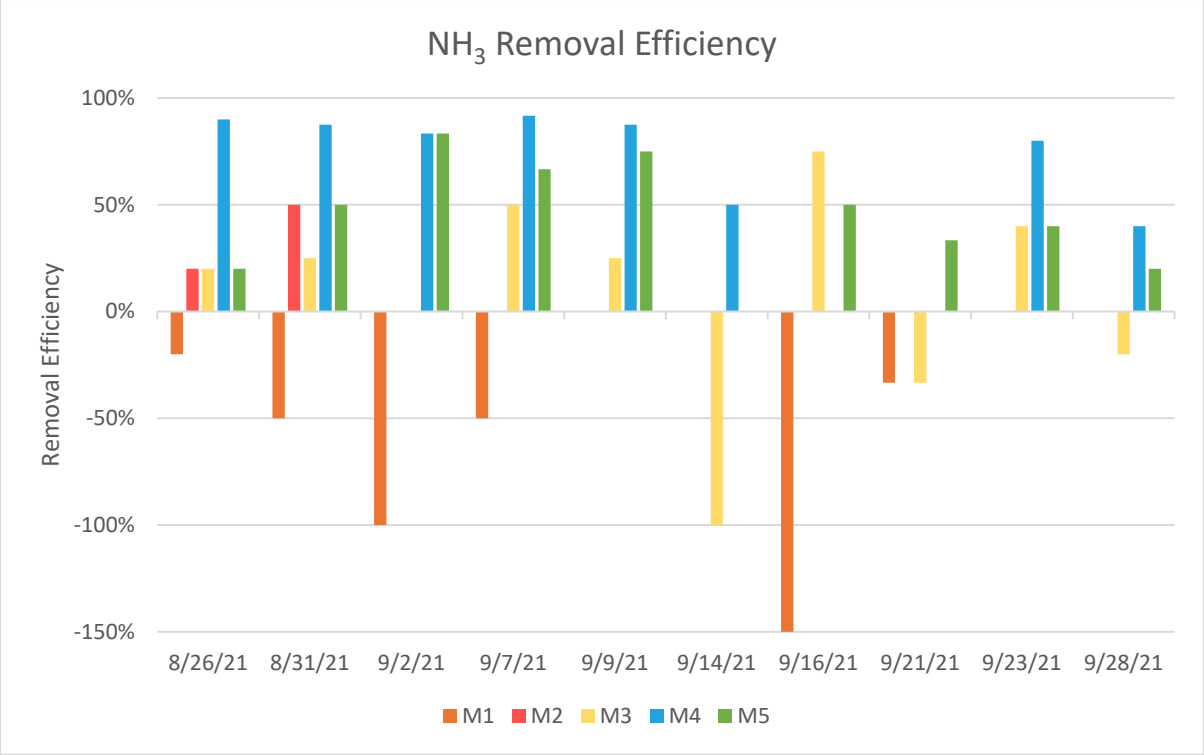


Figure 38: NH_3 removal efficiency

Table 31: NO_2 Concentrations

NO2 (mg/L)	Inlet	M1	M2	M3	M4	M5
24/8/21	0.01	0.005	0.01	0.005	0.005	0.005
26/8/21	0.01	0.01	0.01	0.01	0.005	0.005
31/8/21	0.005	0.005	0.01	0.005	0.005	0.005
2/9/21	0.005	0.005	0.005	0.005	0.005	0.005
7/9/21	0.005	0.005		0.005	0.005	0.005
9/9/21	0.005	0.005		0.005	0.005	0.005
14/9/21	0.005	0.005		0.005	0.005	0.005
16/9/21	0.005	0.005		0.005	0.005	0.005
21/9/21	0.005	0.005	0.005	0.005	0.005	0.005
23/9/21	0.005	0.005		0.005	0.005	0.005
28/9/21	0.005	0.005		0.005	0.005	0.005
Average	0.01	0.01	0.01	0.01	0.01	0.01
SE	0.0005	0.0005	0.0014	0.0005	0.0000	0.0000

Table 32: NO_3 Concentrations

NO3 (mg/L)	Inlet	M1	M2	M3	M4	M5
24/8/21	0.25	0.25	0.22	0.26	0.25	0.27
26/8/21	0.23	0.23	0.23	0.21	0.29	0.26
31/8/21	0.24	0.25	0.24	0.25	0.27	0.28
2/9/21	0.25	0.24	0.23	0.23	0.25	0.24
7/9/21	0.16	0.24		0.19	0.19	0.2
9/9/21	0.24	0.22		0.23	0.22	0.21
14/9/21	0.21	0.2		0.19	0.19	0.22
16/9/21	0.37	0.37		0.35	0.34	0.36
21/9/21	0.18	0.17	0.15	0.15	0.15	0.15
23/9/21	0.17	0.18		0.17	0.16	0.17
28/9/21	0.28	0.29		0.26	0.23	0.26
Average	0.23	0.24	0.21	0.22	0.23	0.24
SE	0.0194	0.0183	0.0210	0.0179	0.0189	0.0190

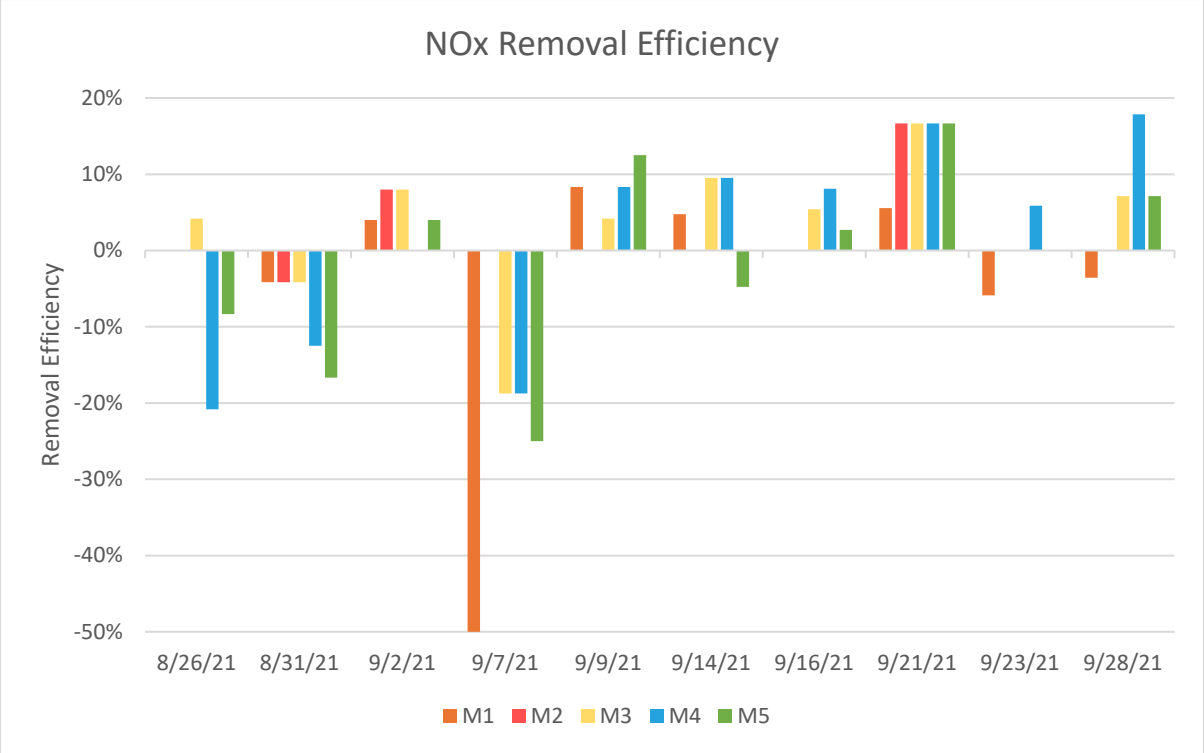


Figure 39: NO_x removal efficiency

Appendix E: Chemical Analysis

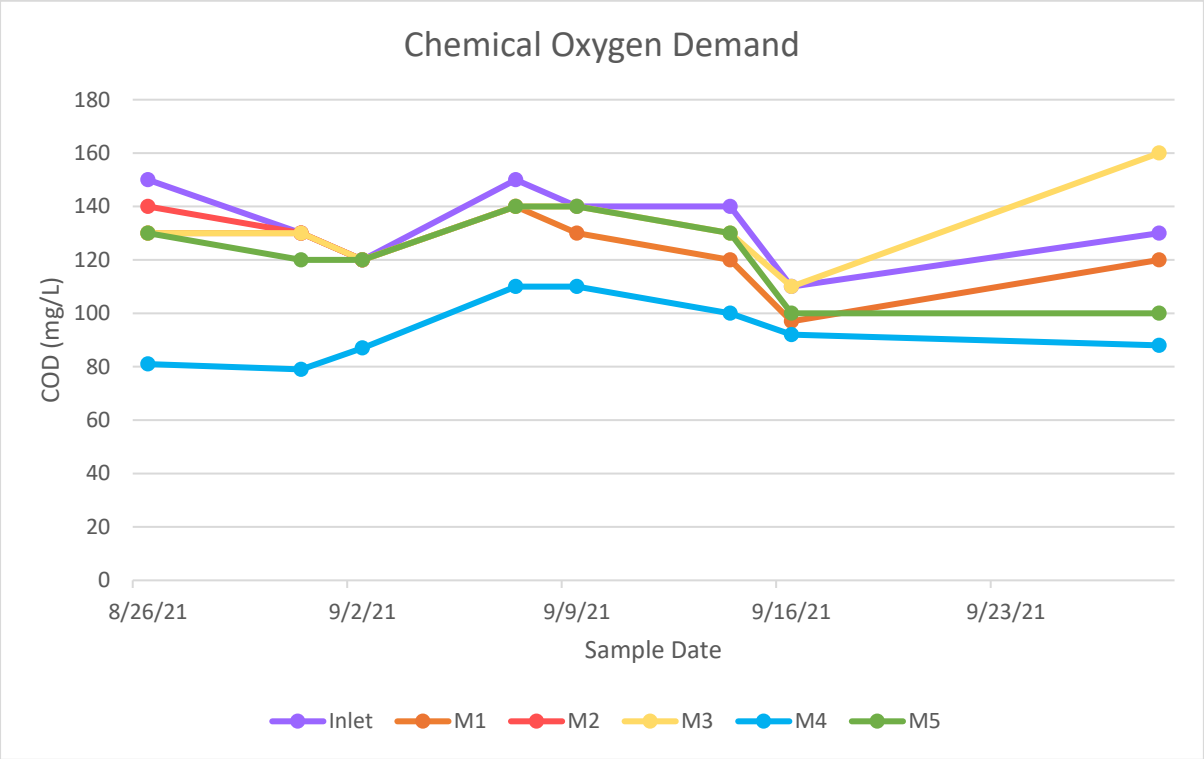


Figure 40: Organic matter concentration (expressed as COD) of inlet and PTW outlets

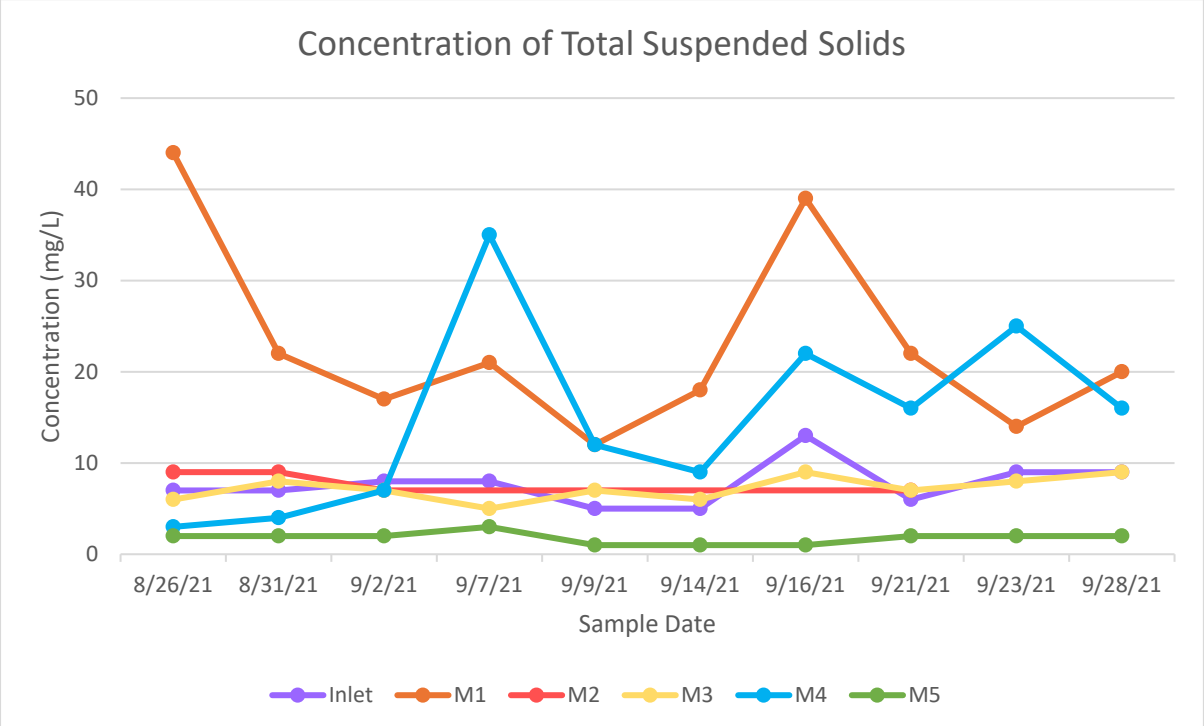


Figure 41: Total suspended solids concentration of inlet and PTW outlets

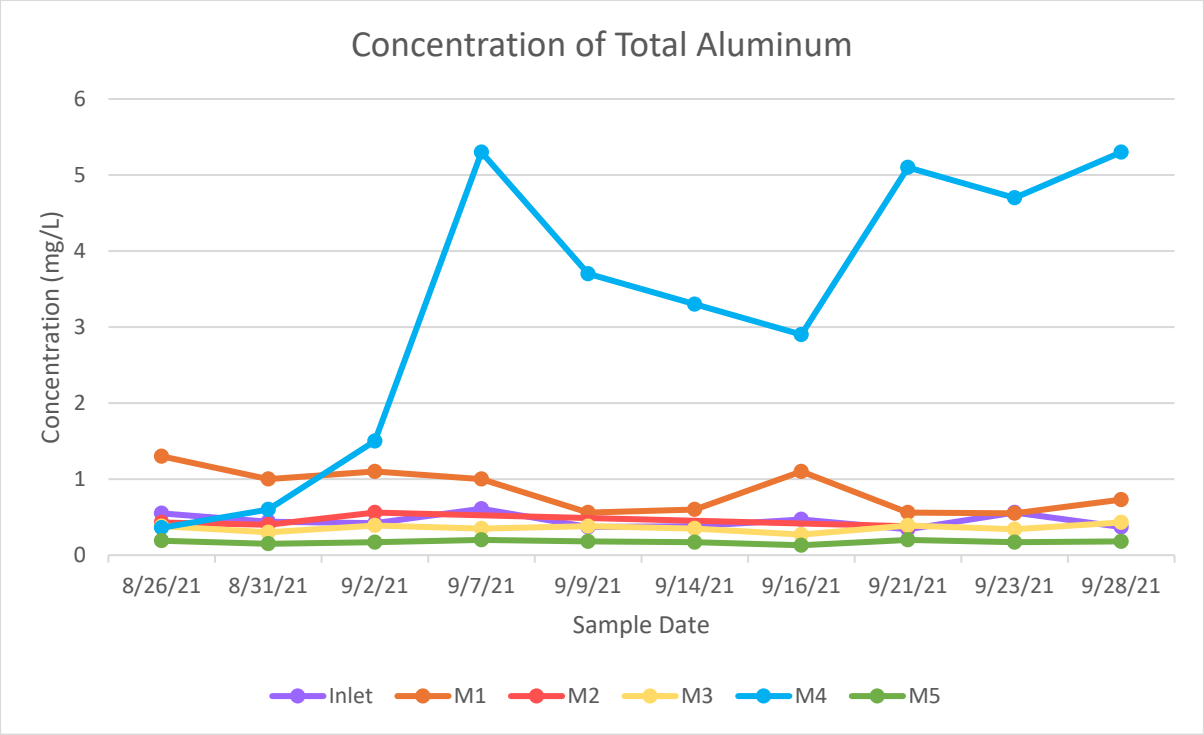


Figure 42: Total aluminium concentration of inlet and PTW outlets

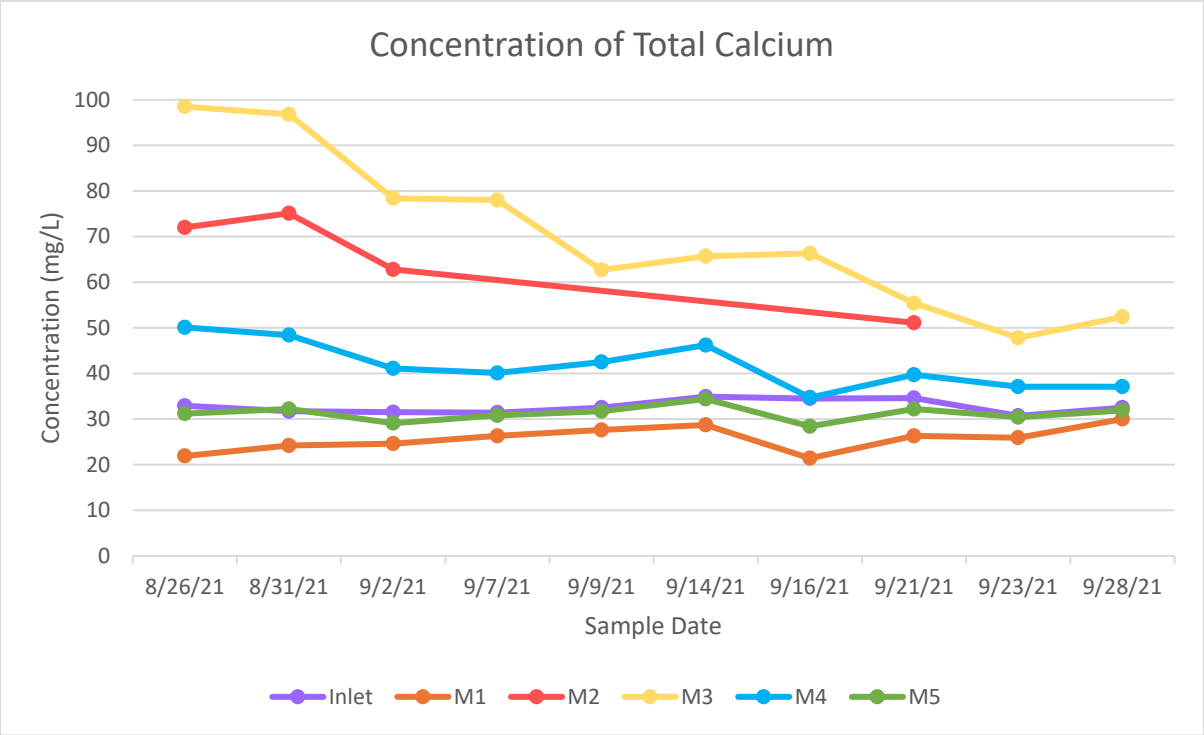


Figure 43: Total calcium concentration of inlet and PTW outlets

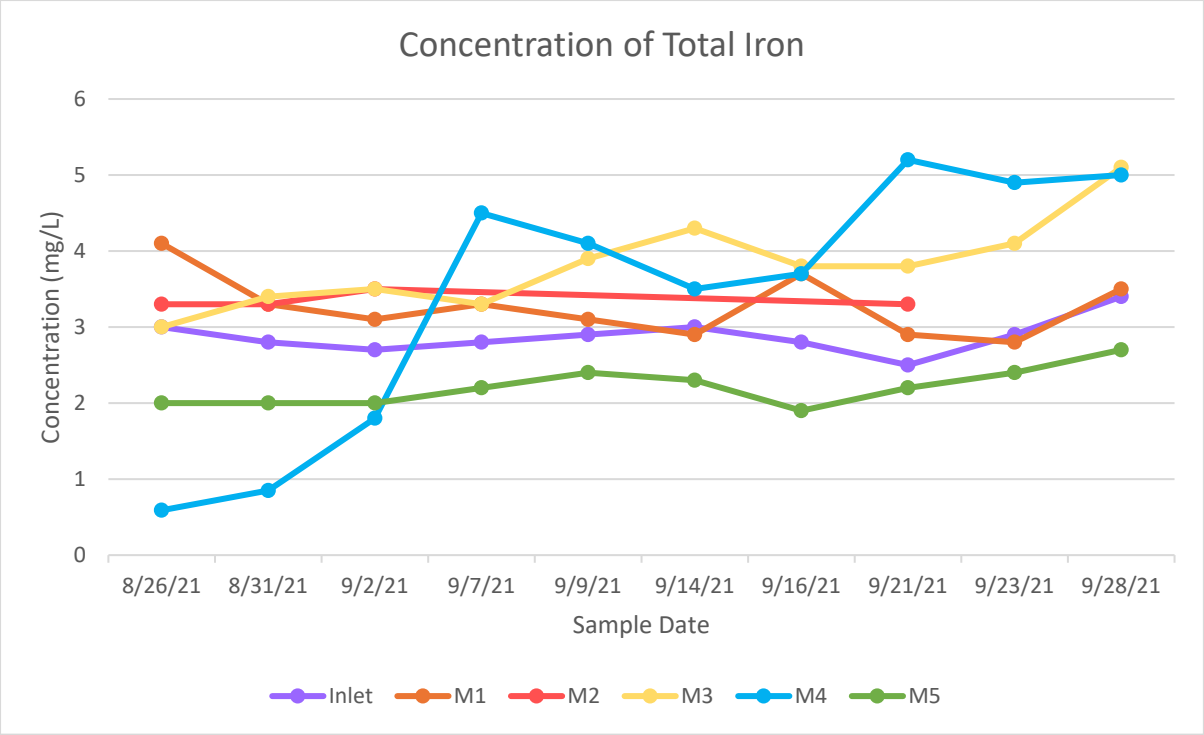


Figure 44: Total Iron concentration of inlet and PTW outlets

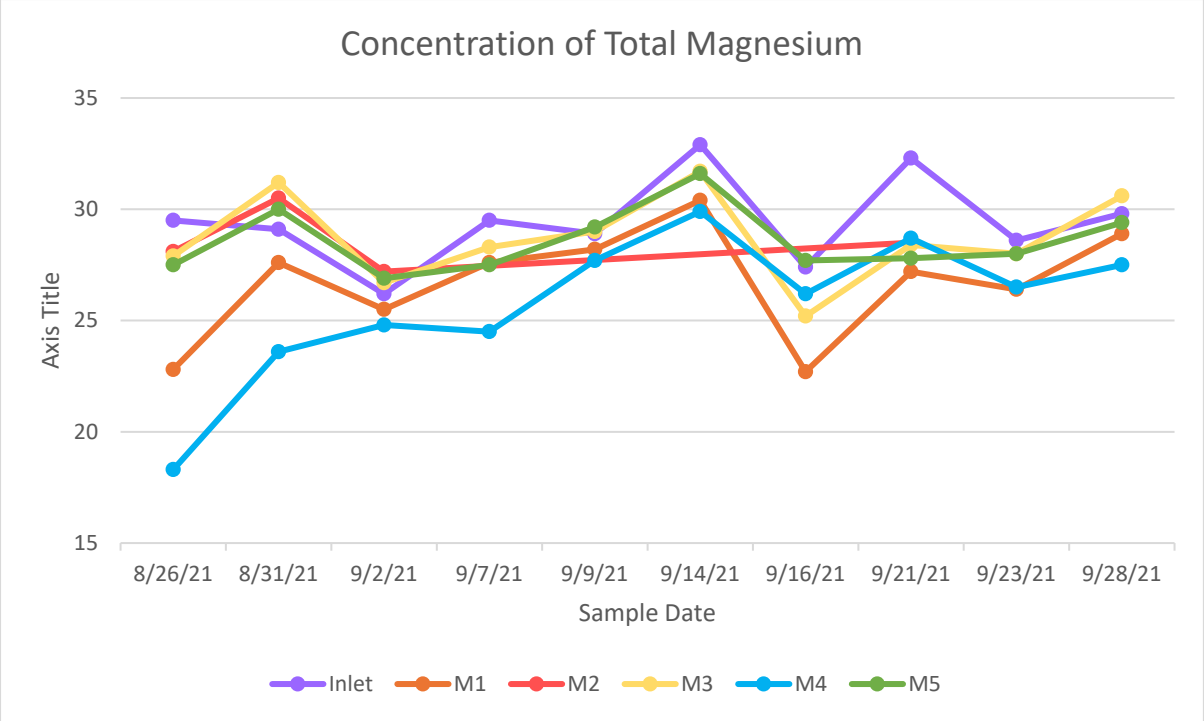


Figure 45: Total magnesium concentration of inlet and PTW outlets

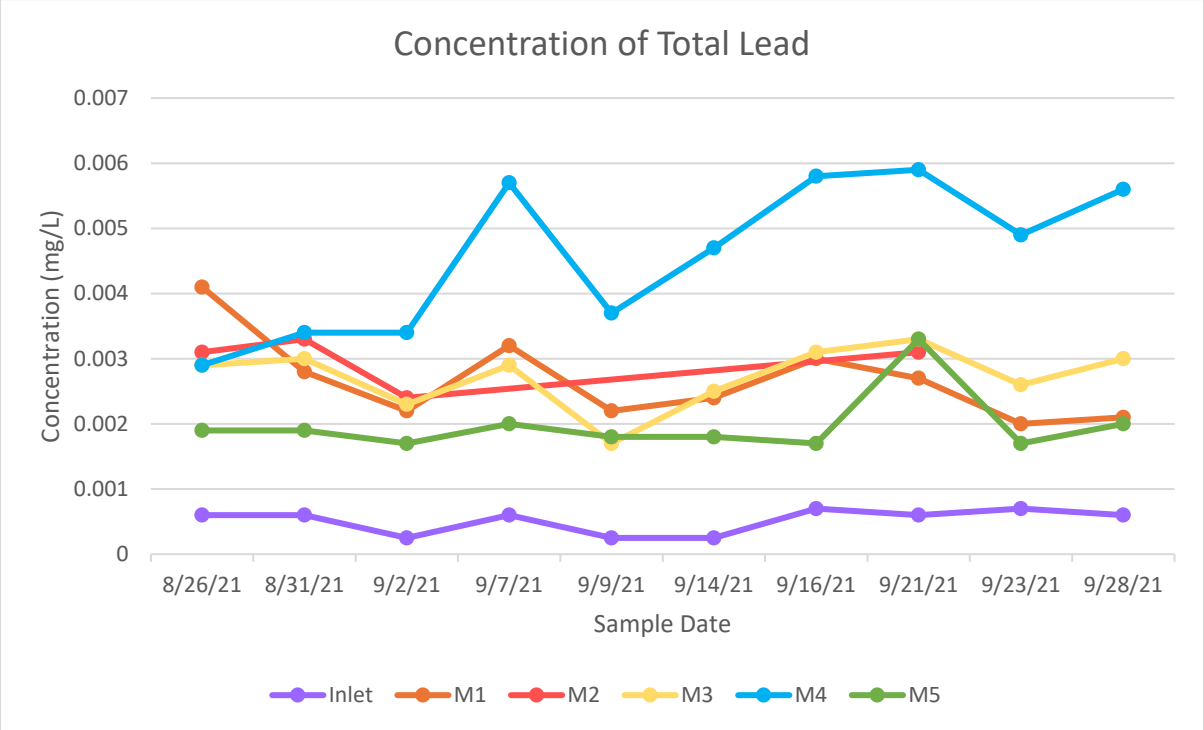


Figure 46: Total lead concentration of inlet and PTW outlets

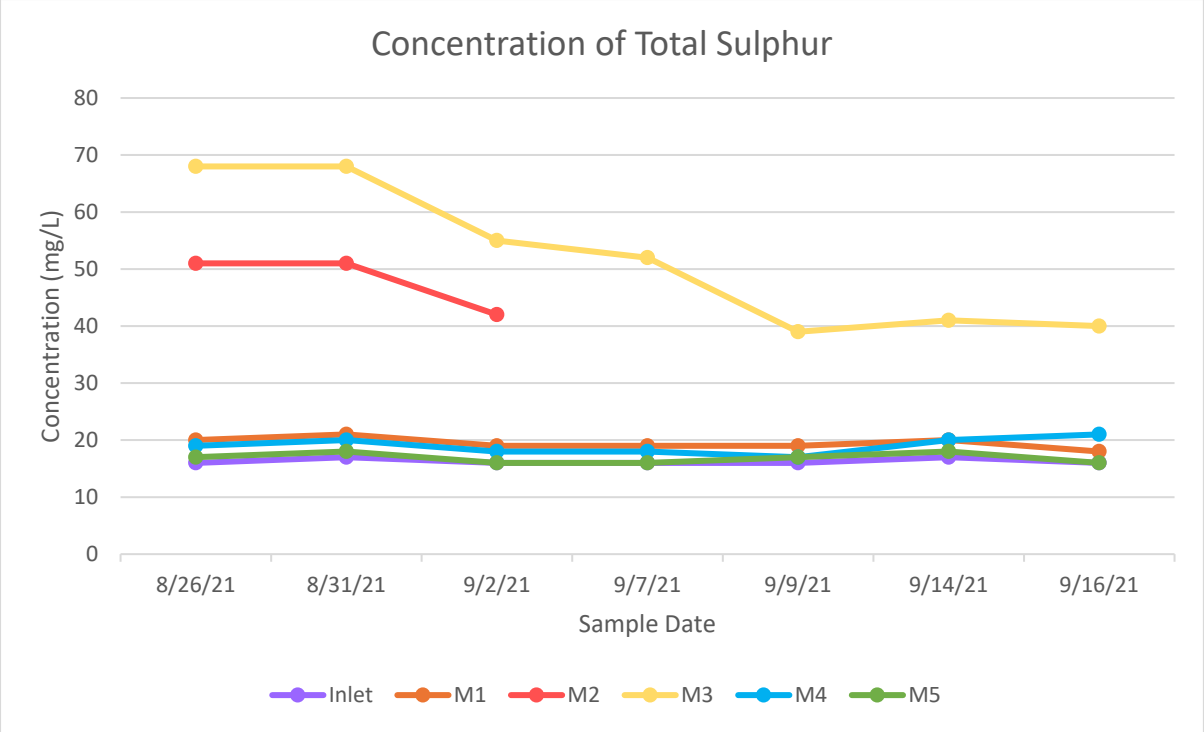


Figure 47: Total sulphur concentration of inlet and PTW outlets

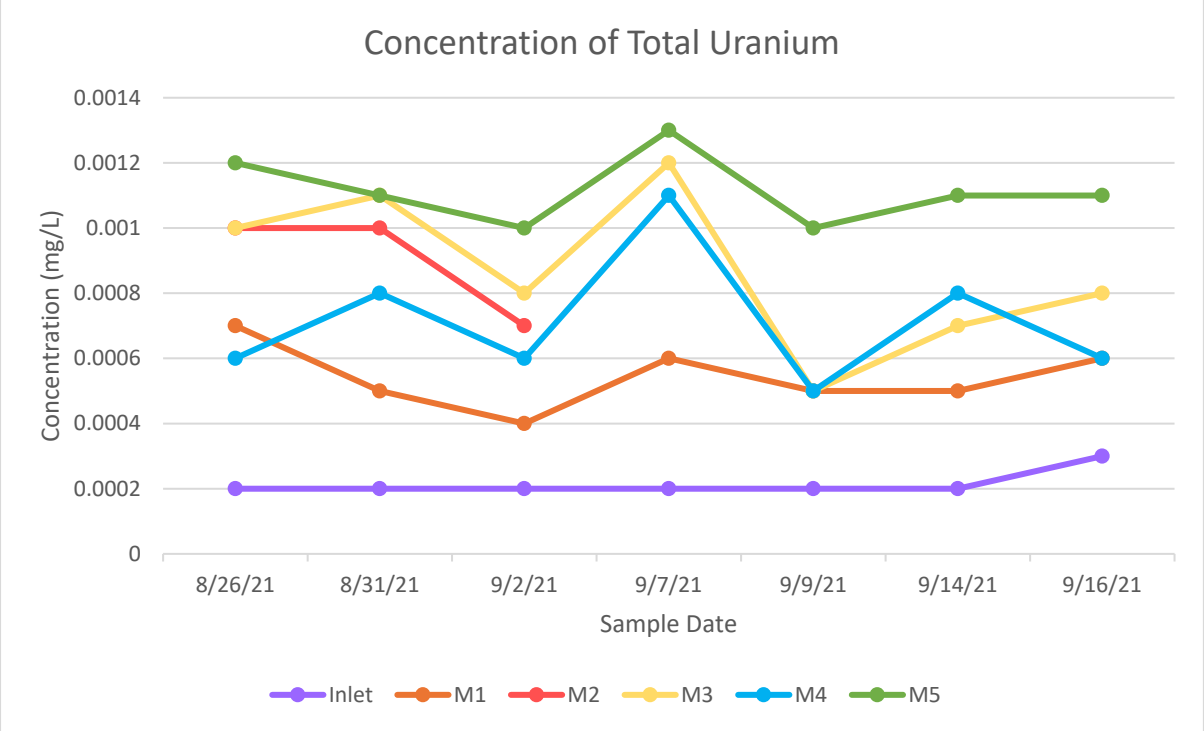


Figure 48: Total uranium concentration of inlet and PTW outlets

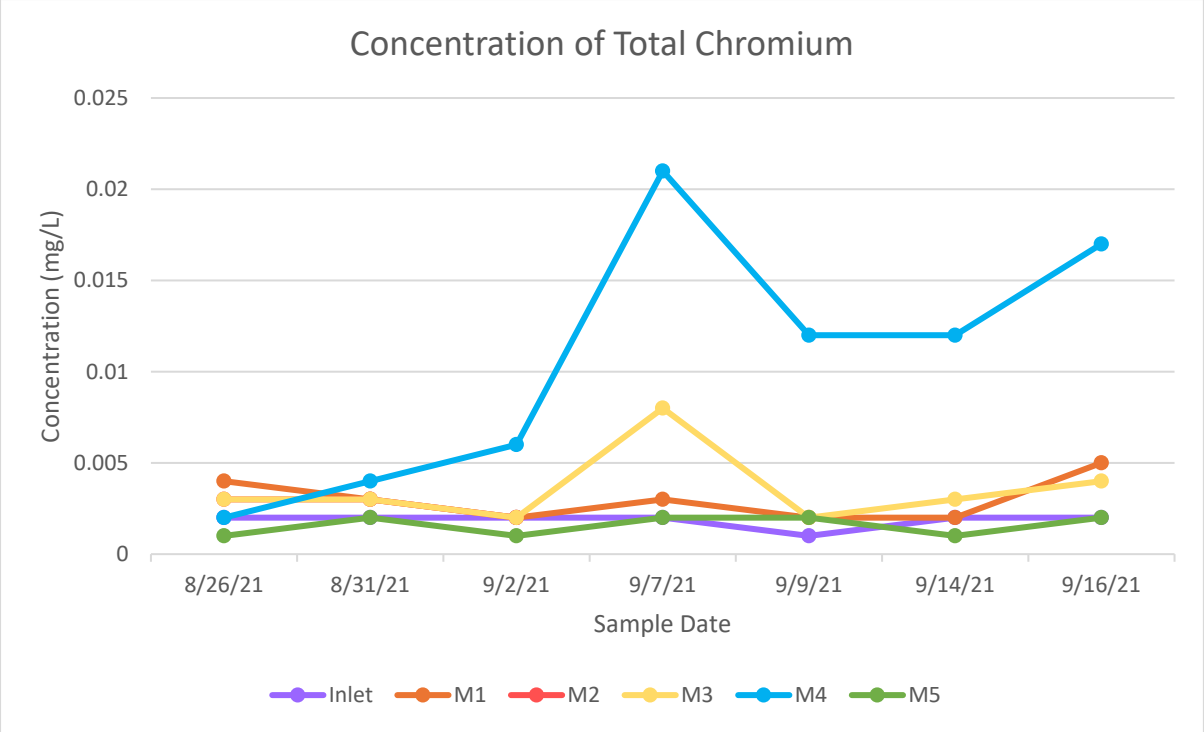


Figure 49: Total chromium concentration of inlet and PTW outlets

Appendix F: Physical Analysis

Table 33: Temperature

Temperature (°C)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	15.0	16.8	17.7	17.7	17.8	17.1
31/8/21	15.5	19.6	19.7	19.2	19.7	17.9
2/9/21	14.9	15.7	15.7	15.7	16.7	15.9
7/9/21	15.9	21.8	20.4	20.5	21.3	19
9/9/21	17.0	16.2	16.6	16.7	16.5	16.3
14/9/21	14.2	19.9	20	19.8	20.8	19
16/9/21	15.1	16.7	16.7	16.03	15.8	15.8
21/9/21	15.9	22.2	22.2	22.9	23.1	21
23/9/21	18	20.5	20.6	19.9	20.3	18.1
28/9/21	16.3	21	20.5	20.4	21.4	19.9

Table 34: Dissolved oxygen

Dissolved Oxygen (mg/L)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	6.90	9.62	9.59	9.67	9.46	9.56
31/8/21	6.84	9.34	9.34	9.57	9.26	9.50
2/9/21	7.25				9.97	10.10
7/9/21	7.25	9.26	9.36	9.41	9.46	9.63
9/9/21	6.09	9.74	9.78	9.73	9.70	9.58
14/9/21	7.30	9.39		9.56	9.38	9.55
16/9/21						
21/9/21	7.26	9.20	9.14	9.42	9.24	9.47
23/9/21	6.52	9.14	9.08	9.24	9.15	9.36
28/9/21	6.61	9.12	9.13	9.22	8.99	9.22

Table 35: Specific conductance

SPC (mS/cm)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	1.385	1.394	1.608	1.681	1.421	0.714
31/8/21	1.312	1.349	1.508	1.567	1.373	1.327
2/9/21	1.247	1.292	1.426	1.489	1.327	1.306
7/9/21	1.249	1.266	1.371	0.707	1.305	1.256
9/9/21	1.317		1.387	1.410	1.315	1.321
14/9/21	1.333	1.353	1.459	1.468	1.376	1.343
16/9/21	1.453	1.340	1.381	1.451	1.358	1.345
21/9/21	1.211	1.236	1.323	1.332	1.270	1.242
23/9/21	1.225	1.211	1.283	1.287	1.244	1.209
28/9/21	1.267	1.271	1.345	1.343	1.300	1.271

Table 36: pH

pH	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	7.14	7.15	7.52	7.56	7.45	7.26
31/8/21	7.27	6.91	7.66	7.63	7.56	7.41
2/9/21	7.17	7.01	7.50	7.66	7.66	7.35
7/9/21	7.48	7.18	6.87	7.69	7.70	7.42
9/9/21	7.11	6.99	7.54	7.55	7.49	7.18
14/9/21	7.20	7.17	7.52	7.66	7.50	7.31
16/9/21	7.38	7.07	7.77	7.84	7.81	7.52
21/9/21	7.15	6.93	7.58	7.68	7.59	7.31
23/9/21	7.15	7.00	7.50	7.65	7.58	7.30
28/9/21	7.15	7.08	7.55	7.69	7.61	7.28

Table 37: Oxygen reduction potential

ORP (Mv)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	163.8	189.3	179.4	182.9	180.5	197.8
31/8/21	165.6	162.8	139.9	158.7	158.0	166.0
2/9/21	186.3	197.7	200.8	201.5	204.6	216.6
7/9/21	198.2	190.6	198.2	147.2	154.5	162.9
9/9/21	224.2	201.4	184.6	198.9	210.3	225.0
14/9/21	225.9	181.2	186.3	186.9	200.9	167.0
21/9/21	106.0	138.8	134.5	113.4	132.7	116.4
23/9/21	113.8	113.8	122.1	126.2	147.5	150.1
28/9/21	227.7	135.7	129.2	128.5	132.0	147.4

Table 38: Turbidity

Turbidity (NTU)	EBW Inlet	M1	M2	M3	M4	M5
26/8/21	8.63	34.88	22.90	21.27	7.67	10.25
31/8/21	8.84	21.00	22.89	22.01	9.25	9.97
2/9/21		21.64	28.83	32.36	23.05	11.65
7/9/21	10.20	25.01	23.44	27.55	59.41	15.21
9/9/21	10.82	3.32	25.48	28.68	41.83	13.26
14/9/21	9.14	21.88	29.71	33.25	39.10	12.62
16/9/21	14.87	39.74	13.39	39.76	46.95	13.39
21/9/21	11.09	25.50	29.82	39.40	65.09	17.81
28/9/21	4.07	14.82	25.96	34.70	49.75	10.35