Evidencing the Impact of Constructed Wetlands: Headstone Manor Park

River Crane Smarter Water Catchments Project

March 2023

Working in partnership

Thames Water

Crane Valley Partnership

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Author(s)	Azra Glover and Joe Pecorelli (Zoological Society London)		
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This document has been created for the purposes of Thames Water's Smarter Water Catchments initiative. Although Thames Water remain the primary client, this document will be made available to all partners associated with the project, in line with the true partnership ethos of the project. The work detailed in this report is based on the information available at the time. Any findings and/or recommendations will inform future phases of the project.

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- Richard Haine, Rob Gray, Citizen Crane
- Prof Lian Lundy, Middlesex University
- Dr Nathalie Gilbert, Thames 21
- John Waxman, Crane Valley Partnership

Contact: Joe Pecorelli, Programme Manager: marineandfreshwater@zsl.org

Executive Summary

This investigation was carried out as part of the Smarter Water Catchments (SWC) initiative for the Crane catchment. The aim of the study was to work collaboratively with local volunteers to assess and report on the water quality and biodiversity impact of the newly created Headstone Manor wetland. Data on the wetland was gathered using multiparameter sondes, water and sediment spot samples as well as biodiversity monitoring. Monitoring, with the assistance of citizen scientists, commenced in June 2022 and finished in January 2023. Conclusions and lessons learnt were used to make recommendations and inform continued monitoring and maintenance of the site. The data collected show the following,

- Water quality data, in particular dissolved oxygen, ammonium, nitrogen, phosphorus and heavy metal data indicate that high loads of pollutants are entering the wetland system from a range of sources upstream - likely a result of misconnections, cross connections, road runoff and urban runoff.
- A decreasing trend in Biological Oxygen Demand (BOD) between the inlet and the outlet was recorded, as well as an improvement in nitrogen and phosphorus concentrations, which is expected of a constructed wetland. However, the pollution loading during the summer sampling period created eutrophic conditions in the wetland that promoted algal blooms and a damaging spread of duck weed, causing the dissolved oxygen to drop to concentrations that caused a 'die-off'. This finding causes concern about the ability of wetlands, constructed as nature-based solutions, to cope with the pollution loads they may be subjected to in London. Ongoing monitoring is required to help disaggregate the relative impact of input pollution load, wetland maturity, wetland design, and the extreme weather conditions experienced during the summer monitoring. As the wetland matures it is anticipated that it will be able to process more nutrient pollutants, increasing its resilience to potential future 'die offs'.
- Invertebrate data corresponded with water quality data. Pre- 'die off' sampling found different taxa present at the inlet compared to the outlet, with the outlet containing more pollution sensitive taxa. These pollution sensitive taxa were not found in sampling that followed the decline in dissolved oxygen. This suggests that the biodiversity potential of the wetland is being compromised by the input water quality. Regular citizen science invertebrate sampling data (similar to the Riverfly Monitoring Initiative) will provide evidence on the ongoing wetland ecosystem health as well as evidence any future 'die offs;' should they recur.
- Sediment data indicated that although high concentrations of heavy metals are present (particularly copper, lead, zinc, nickel and cadmium), polycyclic aromatic hydrocarbons (PAHs) and petroleum hydrocarbons (PHCs) are entering the wetland system from upstream, the wetland is functioning successfully in storing these pollutants within sediments and preventing contaminants from being transported downstream.

Contents

1 Introduction

1.1 Background

Headstone Manor Park is in London Borough of Harrow in Northwest London (Figure 1.1). The wetlands were created as part of a wider programme of improvements in the park funded by London Borough of Harrow (LBH), National Lottery Heritage Fund (NLHF), Greater London Authority (GLA) and Thames Water via the Smarter Water Catchments Initiative (SWC). Construction of the wetlands started in July 2018 and was completed in December 2021. The site is of critical importance to the Crane Catchment as the historic moat that surrounds the Headstone Manor feeds water into the nascent Yeading Brook West.

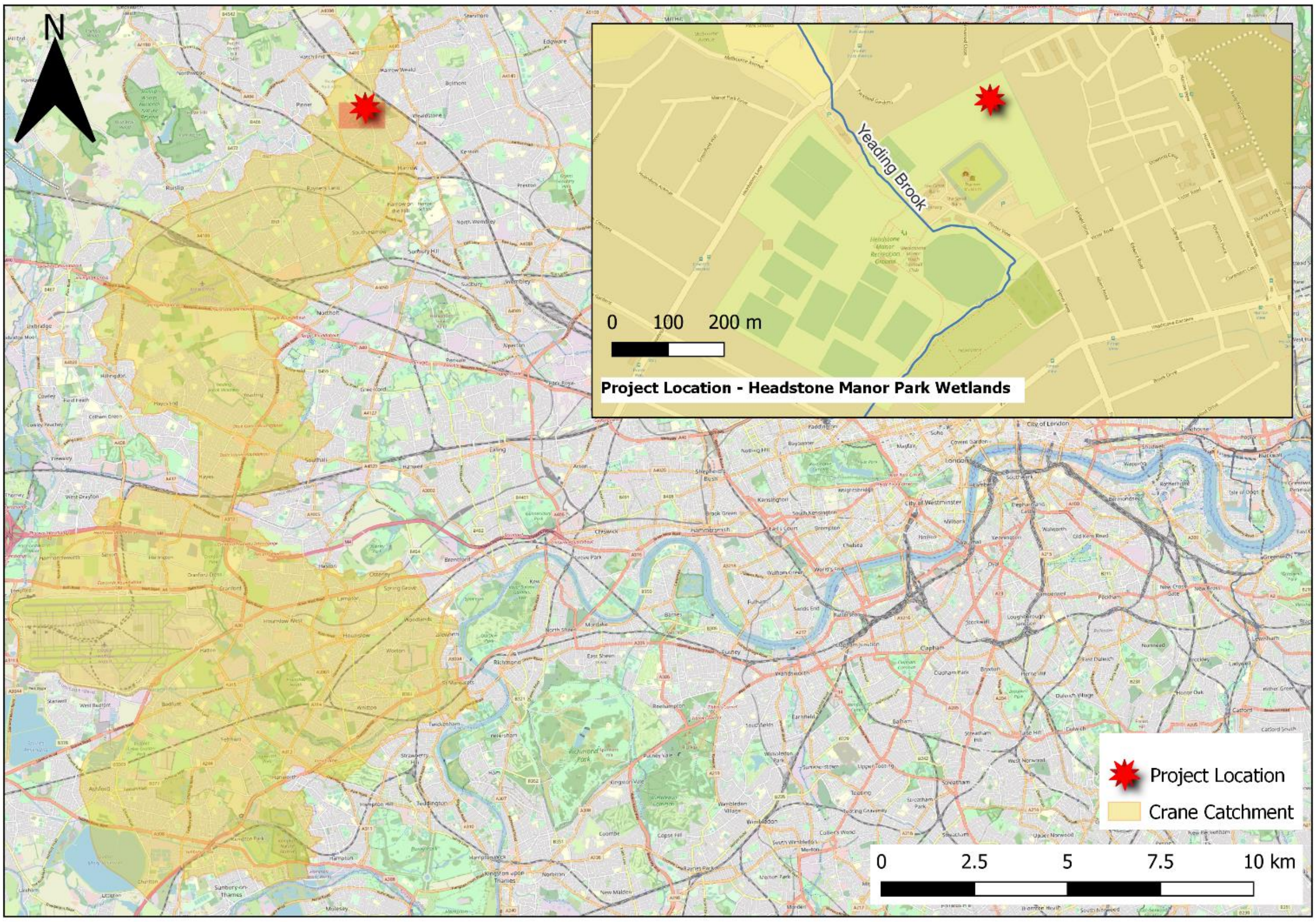

Figure 1.1: Map showing the location of the Headstone Manor Park Wetlands project within the context of the Crane Catchment.

This project is part of the Smarter Water Catchments (SWC) initiative for the Crane catchment. SWC is a five-to-ten-year, Thames Water funded programme of work, designed to enhance the community and environmental value of the Crane river system and its associated open spaces. This project investigated the impact and effectiveness of the Headstone Manor wetland system creation in relation to two key SWC themes, water quality and biodiversity. The intention is to learn lessons that can optimise the monitoring and operation of the wetlands and also be applied to other constructed wetlands proposed as part of the SWC programme.

1.1.1 The Headstone Manor Park Wetlands

Prior to the construction of the wetlands, the Headstone Manor moat was fed directly from a surface water sewer that drained a heavily urbanised catchment. The inflow was prone to poor water quality due to upstream sewage and polluted sediment inputs. This directly and indirectly contributed to poor water quality and large volumes of contaminated sediment and associated pollutants (including hydrocarbons) settling in the moat. The aim of the scheme was to construct a sedimentation pond and reed bed upstream to the northeast of the Manor, to improve the water quality within the medieval moat by intercepting and reducing sediment and pollutants from the upstream culverted catchment (see Figure 1.2). An overflow system at the inlet allows peak flows during rainfall events to bypass the wetland and be piped directly to the downstream moat.

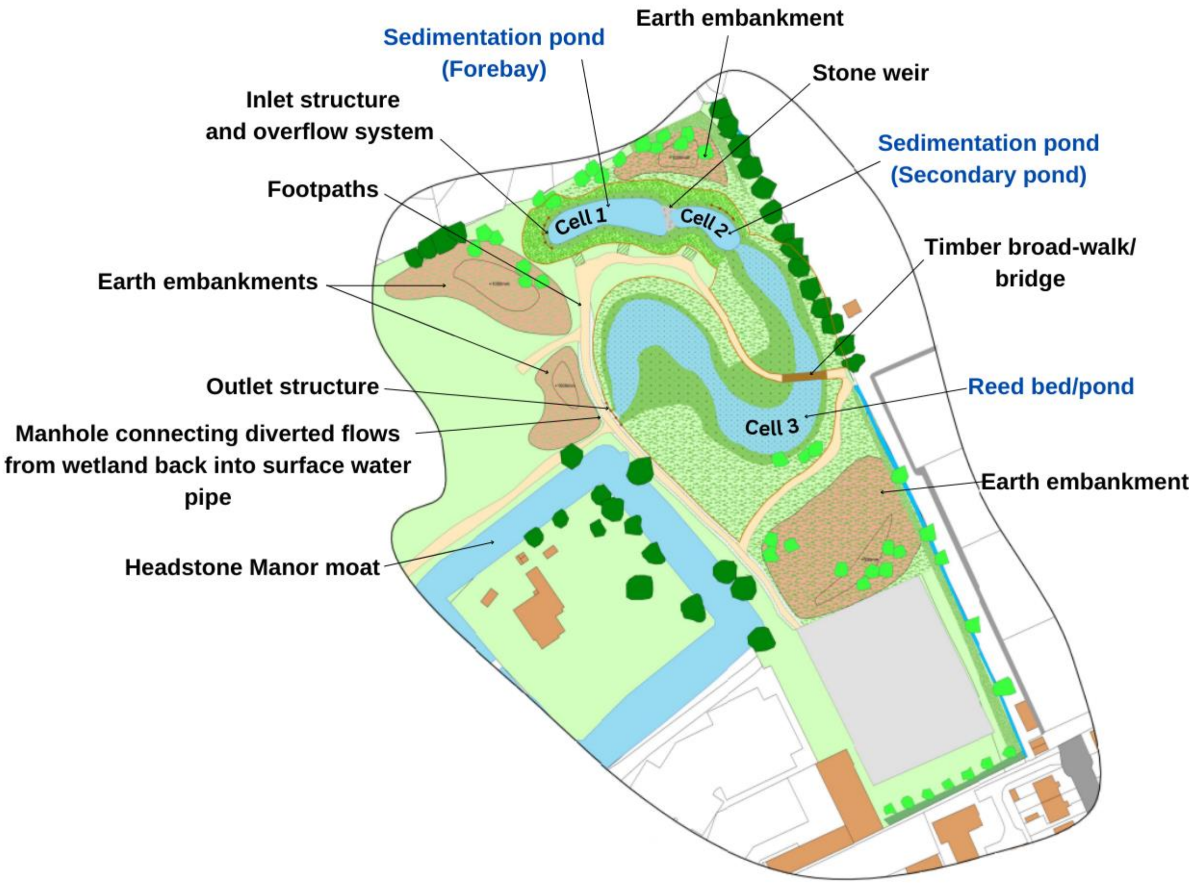

Figure 1.2: Headstone Manor Park site map.

In total, approximately 9,000 m^2 of wetlands were created. The wetland comprises of three main cells. A sediment pond, split into two cells (Cells 1 and 2); and a reedbed pond (Cell 3). The sediment pond is comprised of a sediment fore bay (Cell 1), which was designed to trap the majority of sediments[1]; and a secondary deeper pond (Cell 2) designed to capture the suspended sediments that are not captured within the fore bay (see Figure 1.2). A stone weir was built to split the two sediment ponds within the forebay (set at 500mm higher than the existing moat level) to attenuate water within the sediment forebay (Cell 1) until the top of the weir is breached, increasing retention time within the forebay particularly during smaller more frequent storm events which carry the majority of pollutant load.

The second cell transitions into the third cell, the reed bed/pond (Cell 3). This cell consists of a low flow channel, designed to always contain a minimum depth of 500mm of water. The shape of the reed bed and the varying slopes were designed to encourage pooling in some areas with varied velocities and overall, create a more natural watercourse. The design aimed to create two ecological environments a "dirty" pond at the inlet (Cell 1 and 2) and a "cleaner" pond at the outlet (Cell 3). Detailed design information is available in the AECOM (2014) Headstone Manor Sedimentation Pond and Reed Bed - Design Report (available upon request).

1.2. Aims

The aims of this investigation were to,

- Evaluate the function and impact of the wetlands on water quality, sediment and biodiversity through sampling and analysis of data in comparison to relevant standards (where available).
- Deliver the monitoring with the help of local volunteers with the objective of developing protocols for citizen science monitoring of other wetlands in the Crane Catchment as they come online.
- Work collaboratively with local, regional, and national organisations and experts to bring skills into the Crane Catchment.
- Feed the findings back to LB Harrow to inform continued monitoring and maintenance of the site and share lessons learnt more widely to inform future urban constructed wetland projects.

[1] The Headstone Manor Sedimentation Pond and Reed Bed - Design Report (AECOM, 2014) estimates that that during a 6.5mm/hr storm (which accounts for 99% of all UK storms) the peak flow within the sediment forebay is 0.0016m/s, which according to the Wentworth grain size chart, allows "Fine Silts" to settle within the pond (see AECOM, 2014; Appendix D for further information).

1.3 The Friends of Headstone Manor Park (FoHMP)

ZSL staff worked closely with The Friends of Headstone Manor Park (FoHMP), to investigate the impact and effectiveness of the newly created Headstone Manor Park wetland system in relation to water quality, biodiversity and community engagement. The FoHMP is a volunteer community group who aim to develop the use of Headstone Manor Park through events, activities and advocacy as well as deliver local environmental improvement.

The FoHMP currently have a well-established group of volunteers that, prior to this investigation, were already actively engaged in regular biodiversity/wildlife monitoring at the Headstone Manor Park. Initially 10 members of the friend's group were consulted through an online meeting (promoted via email and virtual flier) to introduce the SWC investigation into the social and environmental benefits of the wetland creation and better understand the practical conservation work that was already being carried out by FoHMP members.

These activities, include environmental monitoring activities such as wildlife surveys, nature walks and pollinator counts. This initial consultation was followed by a Q&A session in which a plan was established for how ZSL and FoHMP would work together to monitor the water quality and biodiversity of the Headstone Manor Park wetlands. To deliver the monitoring, FoHMP volunteers were trained by ZSL to assist in the collection of plant species data, water samples, invertebrate identification, and fixed-point photography. In addition, FoHMP volunteers ensured that water samples were transported to the laboratory each week for analysis and were responsible for sampling equipment storage and maintenance.

ZSL staff communicated regularly with volunteers and activity leaders through frequent face to face catchups as well as via email and through WhatsApp to provide support and guidance for monitoring the Headstone Manor Park Wetlands.

A project Padlet page was set up as a space for volunteers to communicate with ZSL staff, share news and updates, access resources such as live Google Doc activity sign-up sheets, risk assessments, monitoring protocols, as well as see any important reminders and share images (Figure 1.3). Volunteers were not required to sign-up using an email address.

Overall, eight volunteers were trained and subsequently involved in regular water sampling. Fifteen volunteers (including individuals from SWC partner organisations) attended a WaterBlitz sampling day, one volunteer provided monthly fixed point photography images and two volunteers worked with ZSL to collect plant data.

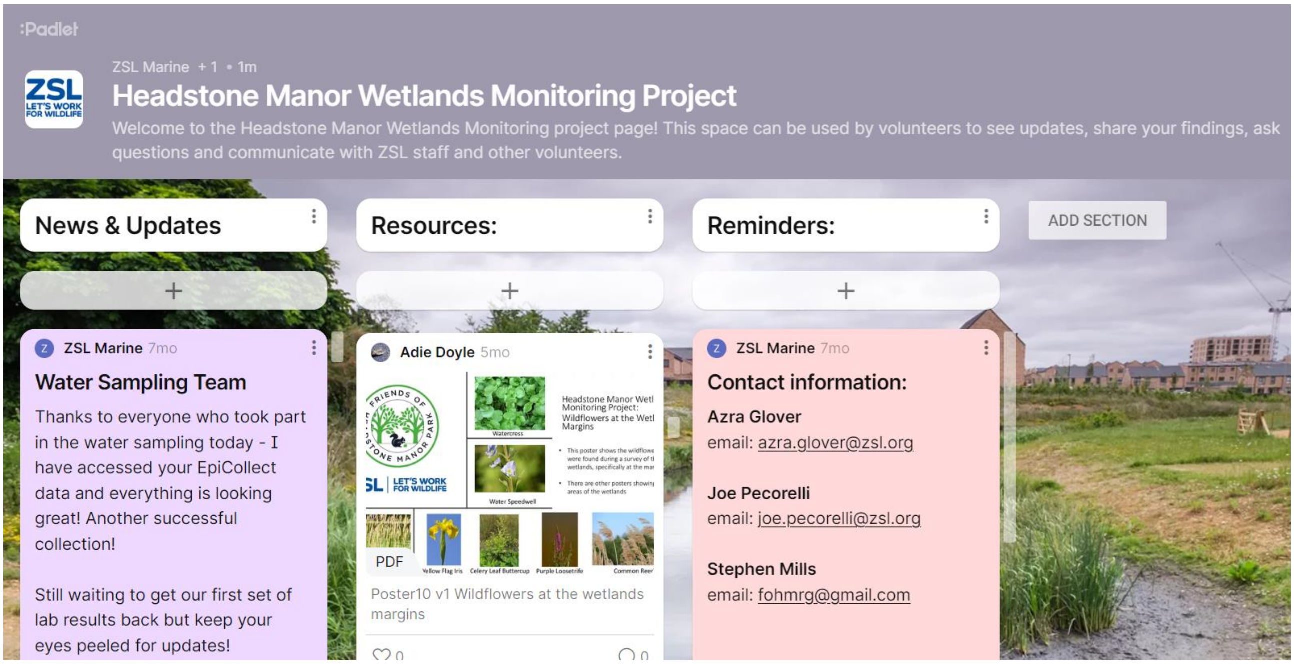

Figure 1.3: Screen shot of the Headstone Manor Park Wetlands Monitoring Project Padlet page created by ZSL.

1.4 Imperial College London's Investigation into Wetland Flow Gauging

Flow gauging of the Headstone Manor Park wetland was carried out by researchers at Imperial College London to support the water quality and biodiversity monitoring undertaken by investigation. The methods, results, conclusions and recommendations of this supporting study are presented in Appendix 6.

2 Methods

2.1 Water quality and sediment

2.1.1 Water Quality Sonde Data

Two ESNET portable systems with EXO multiparameter sondes were installed to record water quality parameters every 30 minutes for the duration of their deployment; one at the inlet to the wetland (TQ140898) and one at the outlet before water leaves the wetland and enters the moat (TQ141897) (Figure 1.2). These were installed for two one-month periods, see Table 2.1 below. Data were transmitted in real time. The sondes were programmed to measure: Temperature (°C), Conductivity (µS/cm), pH, Ammonium (mg/l), Turbidity (NTU) and Dissolved Oxygen (%).

Table 2.1: Summer and Winter sondes monitoring information.

	Summer Monitoring Period	Winter Monitoring Period
Timeframe	29/06/2022 to 10/08/2022	30/11/2022 to 2/01/2023
Total Days Deployed	42	33

Level sensors were also deployed alongside the sondes to measure water levels every 30 minutes at the inlet and outlet to the wetlands. One inlet sonde was deployed behind the metal grate where the culvert pipe enters the wetland. Water samples were taken from the area of water seen in Figure 2.1, just in front of the grate. The outlet sonde was deployed approximately 1m from the 10cm diameter outlet pipe that leads into a manhole that flows into the Headstone Manor moat. Water samples were also collected at this location.

Figure 2.1: (Top) Wetland inlet, with inlet sondes installed below metal grating. Credit: Adrian Butler, Imperial College London (Bottom left) Location of the wetland inlet spot samples. (Bottom right) Location of the wetland outlet sonde and spot samples.

2.1.2 Water Spot Sampling

A total of four water spot samples were taken during each sonde deployment period. 'Summer' samples were collected on 07/07/2022, 14/07/2022, 21/07/2022 and 28/07/2022. 'Winter' samples were collected on 1/12/2022, 07/12/2022, 15/12/2022, 05/01/2023 and an additional sample was collected on 06/10/2022. BOD was sampled as part of water sample collection on 06/10/2022 and 05/01/2023.

All samples were collected by groups of volunteers from the Friends of Headstone Manor Park who had been trained by ZSL staff. Two 300mL bottles and two 40mL vials of water were collected at each monitoring location (inlet and outlet) using an extendable sampling pole (see Figure 2.2). Sample bottles were labelled, stored in a chilled box, and sent directly to the i2 Analytical laboratory for analysis.

EpiCollect5 was used to record water sampling data and included the following information:

- Date
- Time
- Location (inlet or outlet)
- Weather conditions (approx. temperature and conditions)
- Photo of the sample location at the time of survey
- Video of the flow
- Additional notes

Figure 2.2: Citizen scientists collecting water samples at the Wetlands and entering data to EpiCollect5.

Parameters analysed by the laboratory included:

- General inorganics: total phosphate as P, total nitrogen (Kjeldahl), Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) (gravimetric method),
- Polycyclic Aromatic Hydrocarbons (PAHs),
- Petroleum Hydrocarbons (PHCs),
- Monoaromatics and oxygenates: Benzene, Toluene, Ethylbenzene, p & m-xylene, o-xylene and MTBE (Methyl Tertiary Butyl Ether),
- Dissolved heavy metals / metalloids: magnesium, potassium, cadmium, chromium, copper, lead, nickel and zinc,
- Biological Oxygen Demand (BOD).

2.1.3 Sediment Spot Sampling

Two replicate surface sediment samples were collected from both the inlet and outlet of the wetland by attaching a beaker to a pole which allowed safe access from the bankside on 03/08/2022. The sediment samples were transferred to sterile sample jars from the collection beaker and sent for analysis by i2 Analytical Laboratories.

Parameters analysed by the laboratory included:

- General inorganics: total phosphate as P, total nitrogen (Kjeldahl) and dry solids,
- Polycyclic Aromatic Hydrocarbons (PAHs),
- Petroleum Hydrocarbons (PHCs),
- Monoaromatics and oxygenates: Benzene, Toluene, Ethylbenzene, p & m-xylene, o-xylene and MTBE (Methyl Tertiary Butyl Ether),
- Heavy metals / metalloids (aqua regia extractable method): magnesium, potassium, cadmium, chromium, copper, lead, nickel and zinc.

2.2 Biodiversity Surveys

2.2.1 Aquatic invertebrates

Aquatic invertebrates were monitored twice over the course of this investigation by ZSL staff with volunteer assistance. The first set of invertebrate data was collected on 03/08/2022 and the second on 06/10/2022.

ZSL staff conducted two minutes of hand netting within the reed beds and vegetation at the perimeter of both the wetland inlet and outlet cells. Netted samples were dispensed into trays and invertebrates were identified and scored by ZSL staff and volunteers using the PSYM (Predictive System for Multimetrics) methodology (Environment Agency and Ponds Conservation Trust: Policy & Research, 2002). Any additional non-PSYM species, including fish were also identified and recorded (see Figure 2.3).

Figure 2.3: (Left) Hand netting of waters within marginal vegetation for invertebrates (Right) Identification and recording of invertebrates in the field.

2.2.2 Plants

A plant walkover survey was carried out on 12/08/2022 by FoHMP volunteers. The entire wetland perimeter was covered initially, following the main footpath (see Figure 1.2). Following this, two main interest areas were identified. An area near the wetland inlet which had been seeded during construction and an area of the wetland margin that had been planted. Species presence was recorded and compared to the list of planted grasses, reeds and wildflowers.

2.2.3 Birds

FoHMP volunteers have been recording bird data, at Headstone Manor Park using BirdTrack (Created through a partnership between the BTO, the RSPB, Birdwatch Ireland, the Scottish Ornithologists' Club and the Welsh Ornithological Society) on a weekly basis where possible since May 2022.

The BirdTrack methodology records all species seen and heard during a walkover survey. FoHMP also take part in the years Breeding Bird Survey, conducted annually in spring. The surveys involved two early-morning spring visits to an allocated 1km square, to count bird presence, through visual and audio detections, while walking two 1km lines across the set area. Records were made for any nest counts for colonial nesting birds in the area. One of the 1km transects used for this survey passes through the wetland area of Headstone Manor Park.

Figure 2.4: Egyptian Goose at the Headstone Manor Park wetlands. Credit: Adrian Butler, Imperial College London.

2.3 Fixed-Point Photography

Fixed point photography (FPP) images were taken on the same day each month ± 1 to 2 days, starting on July 8th, subject to volunteer photographer availability and weather conditions.

Photographs were uploaded at the highest resolution possible. Photographs were taken by the same volunteer each month, using the same camera at pre-defined locations:

- Inlet: TQ 1408 8984,
- Outlet: TQ 1411 8981,
- Facing West: TQ 1420 8979.

2.4 Sampling/Monitoring Locations

Monitoring and sample collection locations are illustrated below in Figure 2.5.

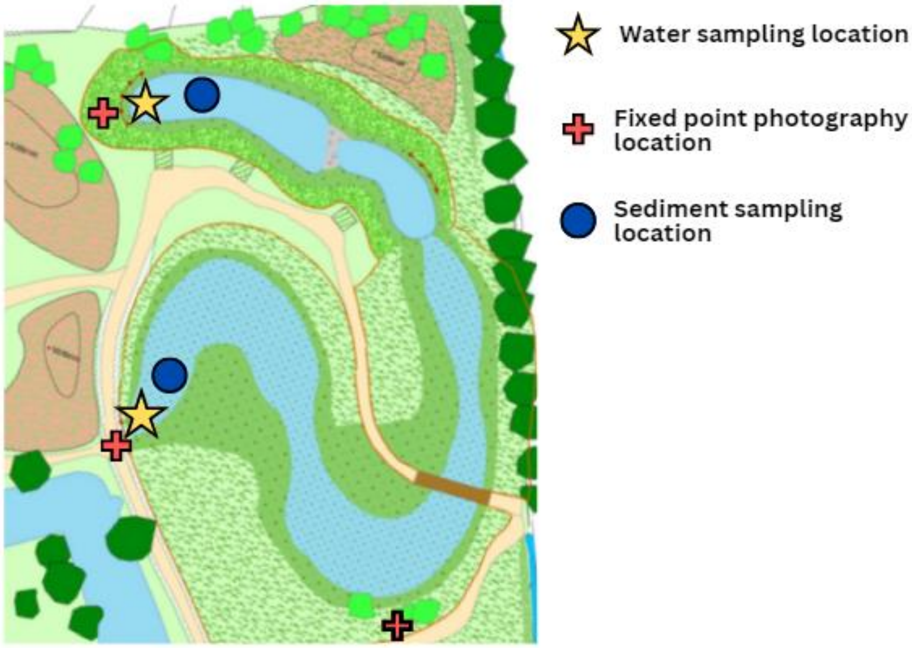

Figure 2.5: Map showing the locations of sampling activities. Water sampling locations indicate the locations for both water spot samples and sonde locations.

2.5 Data Processing

2.5.1 Sondes

Sonde data from the wetland inlet and outlet were uploaded in real time to the Meteor Data Cloud. Data were checked regularly by ZSL and Meteor staff to ensure that sensor readings were not drifting and that water levels were high enough for accurate reading to take place.

Figure 2.6: Image of the inlet sonde being installed for the summer monitoring period.

2.5.2 Comparison Standards/Guidelines

Water samples

The levels of heavy metals present in water samples were compared between sites, and against “UK Median” heavy metal concentrations derived from Johnson *et al.* (2018). The Water Framework Directive (Standards and Classification) Directions, (WFD, 2015) and the United Kingdom Technical Advisory Group Environmental Quality Standards (UKTAG, 2008), could not be compared due to results of this investigation being for metals in their dissolved form rather than their bioavailable form. No comparable standards were found for magnesium and potassium in freshwater systems.

Sediment samples

PAHs: Results were compared against the updated Canadian Interim Freshwater Sediment Quality Guidelines (ISQG) Threshold Effect Levels (TEL) and Probable Effect Level (PEL) guidelines where available (CCME, 2002). ISQG represents the concentration below which adverse biological effects are expected to occur rarely; PEL represents the level above which adverse biological effects are expected to occur frequently.

Heavy Metals: Results were compared against Dutch 'SedNet' Target and Intervention guidelines where available (Hin, Osté and Schmidt, 2010). Target guideline values indicate the level that has to be achieved to fully recover the functional properties of the sediment for humans, plant and animal life; intervention guideline values indicate when the functional properties of the sediment for humans, plant and animal life, are seriously impaired or threatened.

2.5.3 Data Analysis and Visualisation

The production of graphs/charts and data analysis has been carried out using MS Excel and R-Studio.

2.5.4 Weather Data

Precipitation and other weather data was obtained from the Northolt weather station (51.5485, -0.3678) via meteostat.net, approximately 5km away from the Headstone Manor Park wetland monitoring site.

3 Results

All data collected during this investigation can be found in the Report Appendices. Selected data, most pertinent to the aims of the project, are included here.

3.1 Water Quality

Monitoring periods as well as average air temperatures and total precipitation can be seen below in Table 3.1.

Table 3.1: General background information related to the two water quality monitoring periods in summer and winter.

	Summer Monitoring Period	Winter Monitoring Period
Timeframe	29/06/2022 to 10/08/2022	30/11/2022 to 2/1/2023
Average Air Temperature	20.3°C	4.7°C
Total Precipitation	8.2mm	55mm

3.1.1 Sondes Data

Dissolved Oxygen (DO)

Summer:

A strong diurnal pattern can be seen in DO concentrations at the outlet across the majority of the summer monitoring period. This diurnal pattern is not seen at the inlet (see Figure 3.1).

DO concentrations at the outlet fluctuate between supersaturation during the day (exceeding 100% and increasing to a maximum of 366% at 15:00 on 08/07/2022) and very low, often negative concentrations of dissolved oxygen during the night. Inlet DO concentrations remain consistently low over summer, only peaking to a maximum of ~55% following rainfall starting around the 18/07/22.

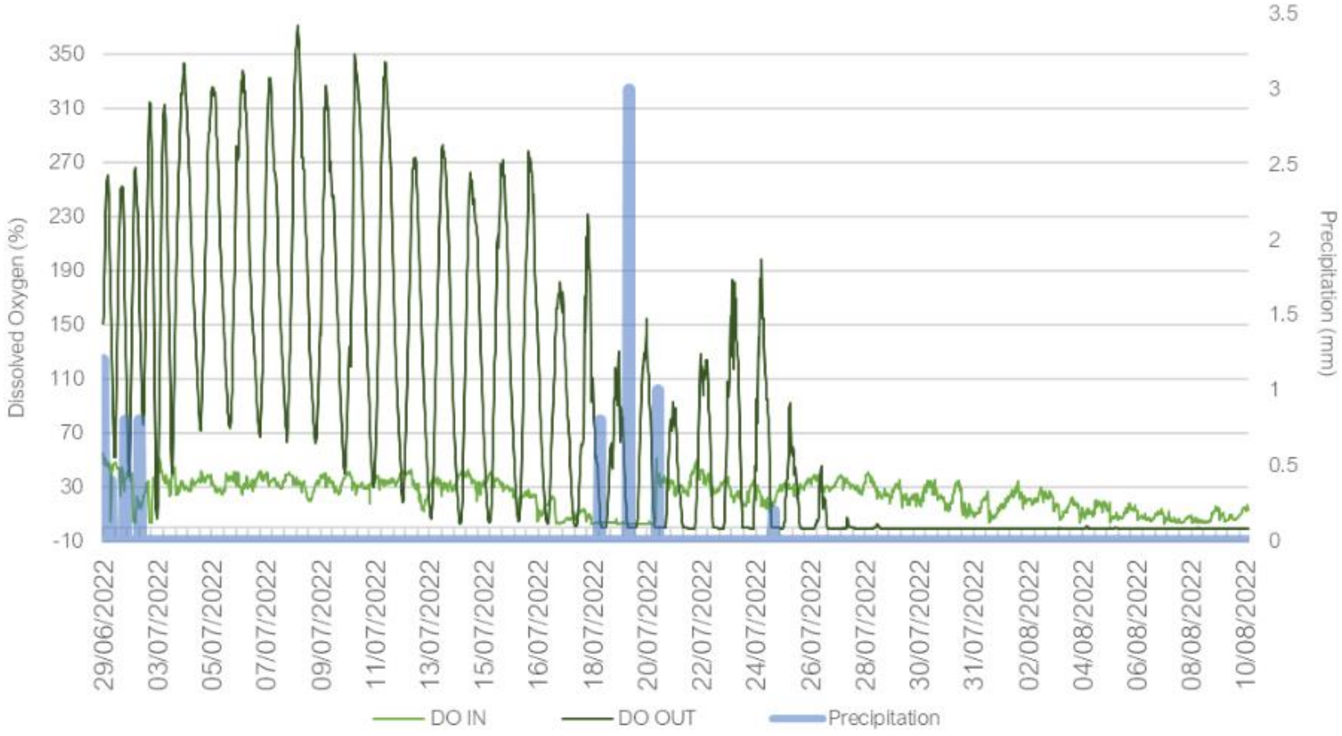

Figure 3.1: Dissolved oxygen concentrations (%) recorded at the inlet and outlet during the summer monitoring period displayed on the left axis with corresponding total daily precipitation displayed on the right axis.

Winter:

During the winter monitoring period, DO concentrations at the inlet generally remain consistently higher on average than those recorded at the outlet. During periods of no or light rainfall, the diurnal clear DO pattern can once again be seen at the outlet site with peaks at around 40% and troughs falling consistently below 20%. The inlet also demonstrates signs of a diurnal oxygen pattern during these times; however, peaks and troughs are not as pronounced with fluctuations occurring between.

From the 18/12/2022 onwards, during regular heavy rainfall conditions, DO peak concentrations at the inlet increase. Outlet concentrations lose their diurnal pattern and remain below 50% saturation but with troughs only declining to ~18% (see Figure 3.2).

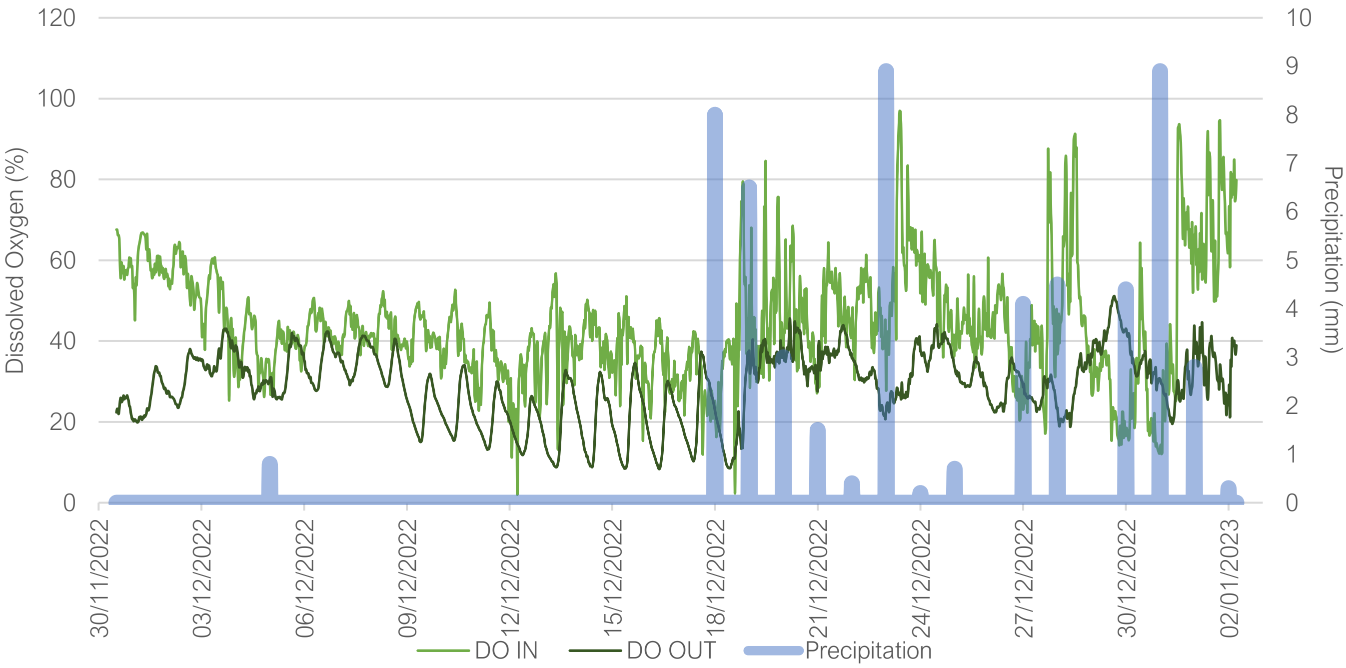

Figure 3.2: Dissolved oxygen concentrations (%) recorded at the inlet and outlet during the winter monitoring period displayed on the left axis with corresponding total daily precipitation displayed on the right axis.

Ammonium

Summer:

Ammonium spikes at the inlet can be seen to correlate with rainfall events. These spikes can also be seen at the outlet but with a lag time of approximately 2-3days. Following the rainfall recorded between 18/07/2022 and 20/07/2022, outlet ammonium concentrations increased, and became generally higher than inlet concentrations for the rest of the sondes summer monitoring period (see Figure 3.3). In the absence of precipitation, a daily double peak in ammonium concentration can be seen at the inlet (~1:30am and ~2:30pm ±1 hour).

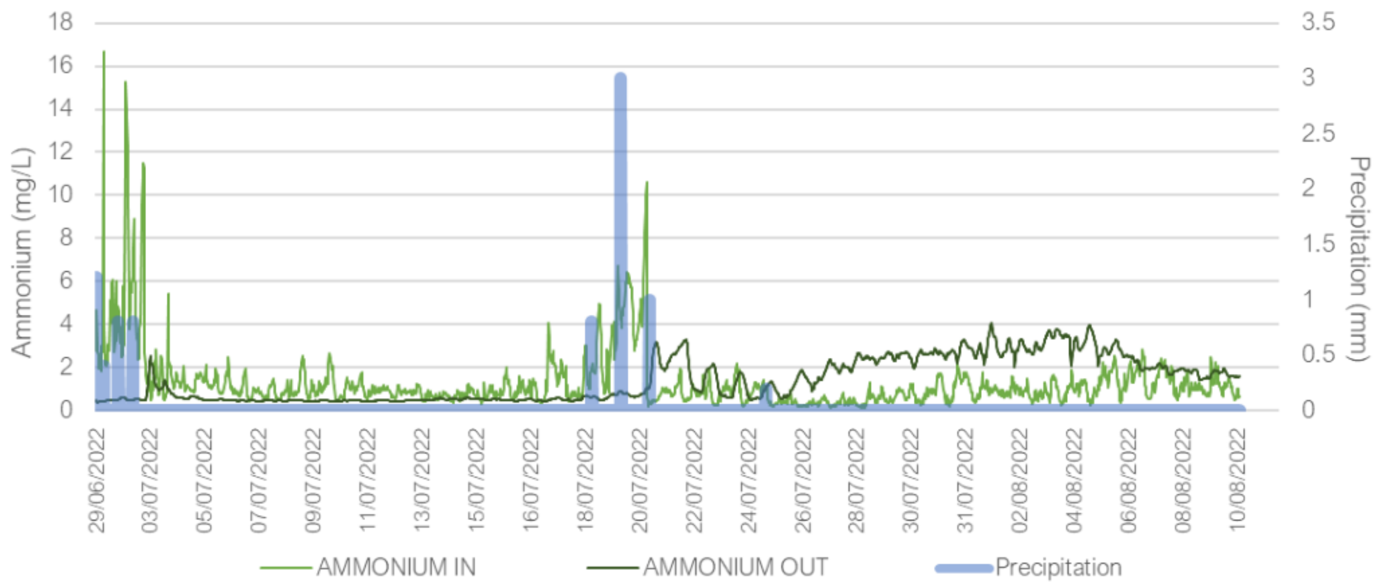

Figure 3.3: Ammonium concentrations (mg/L) recorded at the inlet and outlet during the summer monitoring period displayed on the left axis with corresponding total daily precipitation displayed on the right axis.

Winter:

Ammonium concentrations in winter are generally higher than those recorded in summer (see Figure 3.4 and Appendix Figure A1.4).

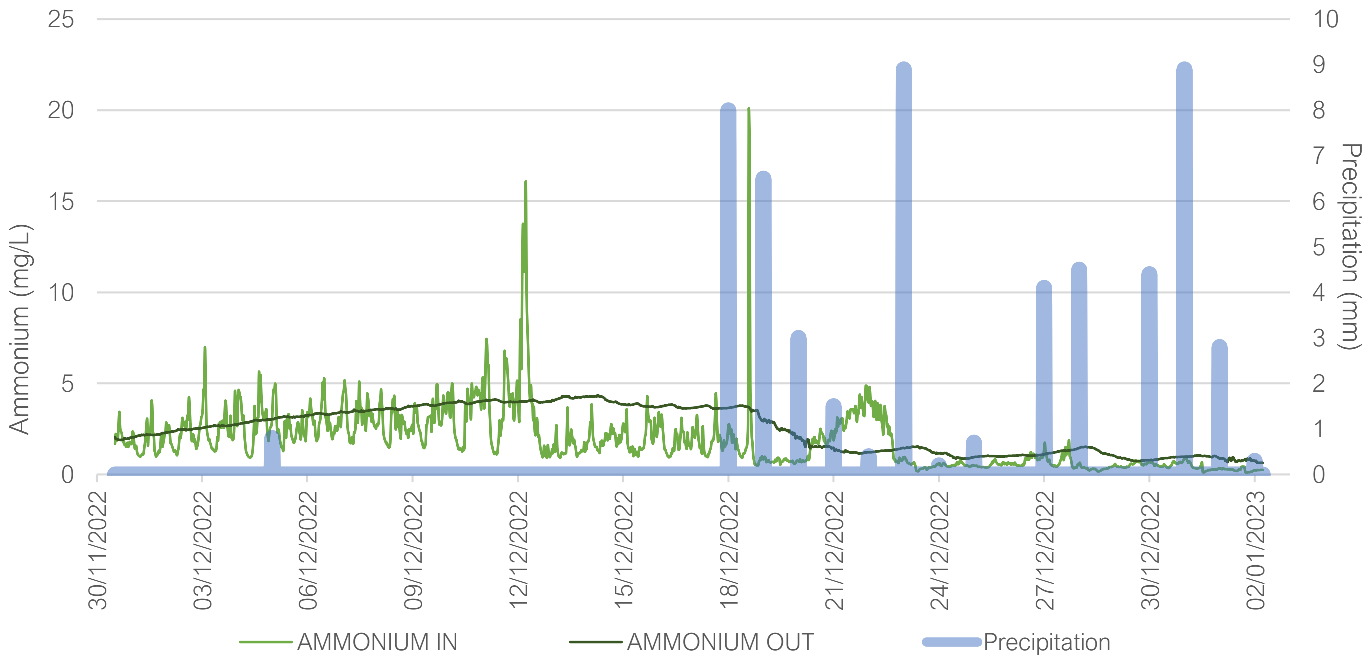

Figure 3.4: Ammonium concentrations (mg/L) recorded at the inlet and outlet during the winter monitoring period displayed on the left axis with corresponding total daily precipitation displayed on the right axis.

Following the first period of heavy rainfall recorded during the winter monitoring period, ammonium concentrations at the inlet spiked. However, following further rainfall, after the 23/12/2022, ammonium concentrations at the inlet fall consistently below <2 mg/L. Ammonium concentrations at the outlet can be seen to reduce from 18/12/2022, correlating with continued precipitation.

Turbidity:

Two raised periods of turbidity coupled with water temperature fluctuations can be seen during the summer monitoring period that are independent of precipitation (see Figure 3.5).

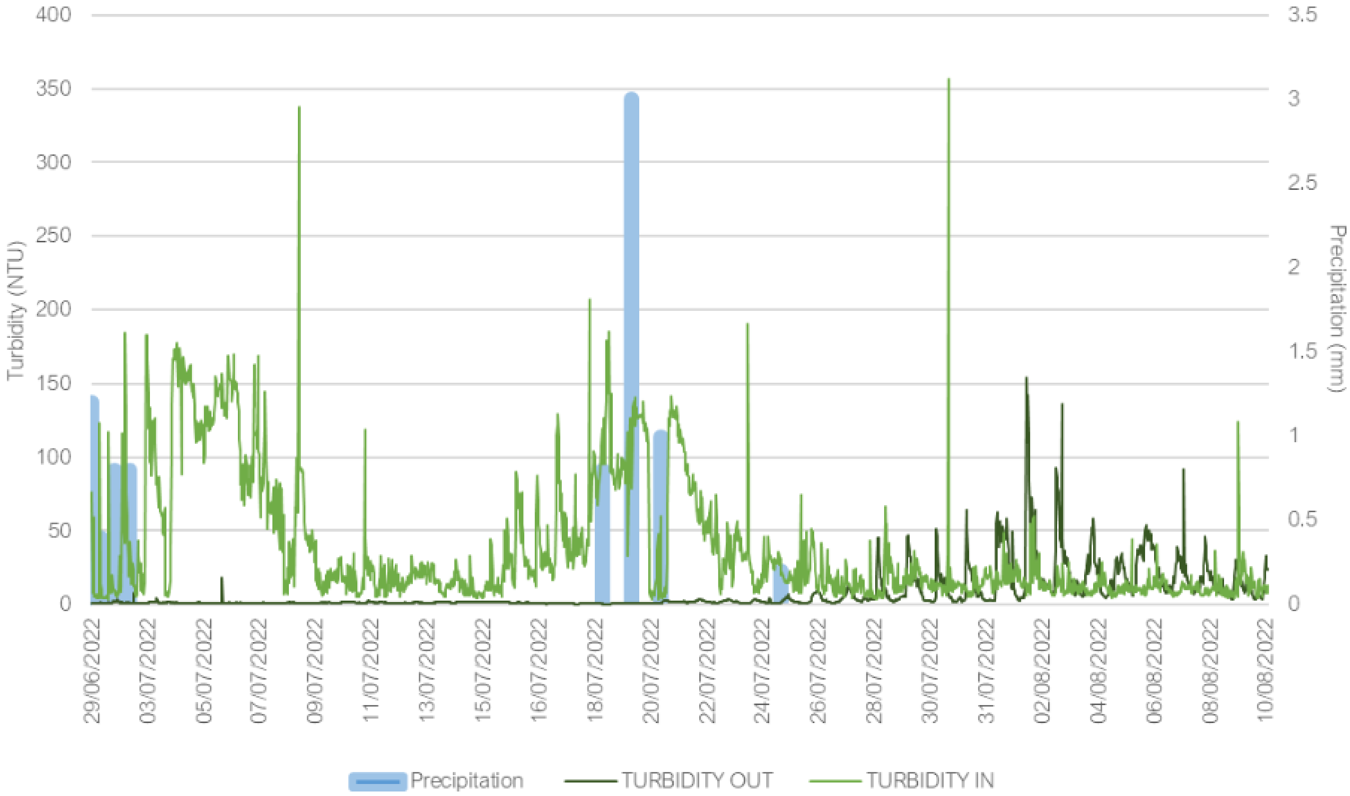

Figure 3.5: Turbidity (NTU) recorded at the inlet during the summer monitoring period displayed on the left axis with corresponding total daily precipitation (mm) and ammonium (mg/L) displayed on the right axis.

Temperature

During the summer monitoring period, temperatures at the outlet showed diurnal fluctuations reaching a maximum of ~26 °C while maximum inlet temperatures reached only ~21°C (Figure 3.6).

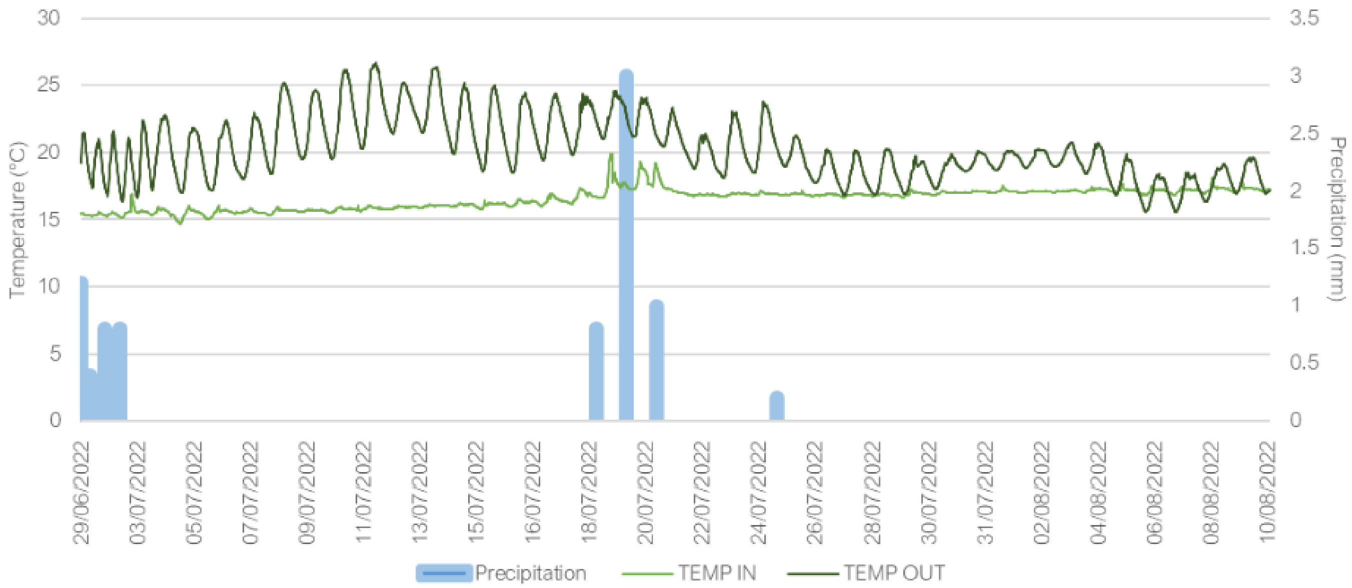

Figure 3.6: Temperature (°C) data recorded at the inlet and outlet during the summer monitoring period displayed on the left axis with corresponding total daily precipitation (mm) displayed on the right axis.

The opposite trend can be seen during the winter monitoring period, with average inlet temperatures exceeding those recorded at the outlet. In the absence of rainfall, diurnal fluctuations in temperature were seen in the outlet data (Figure 3.7).

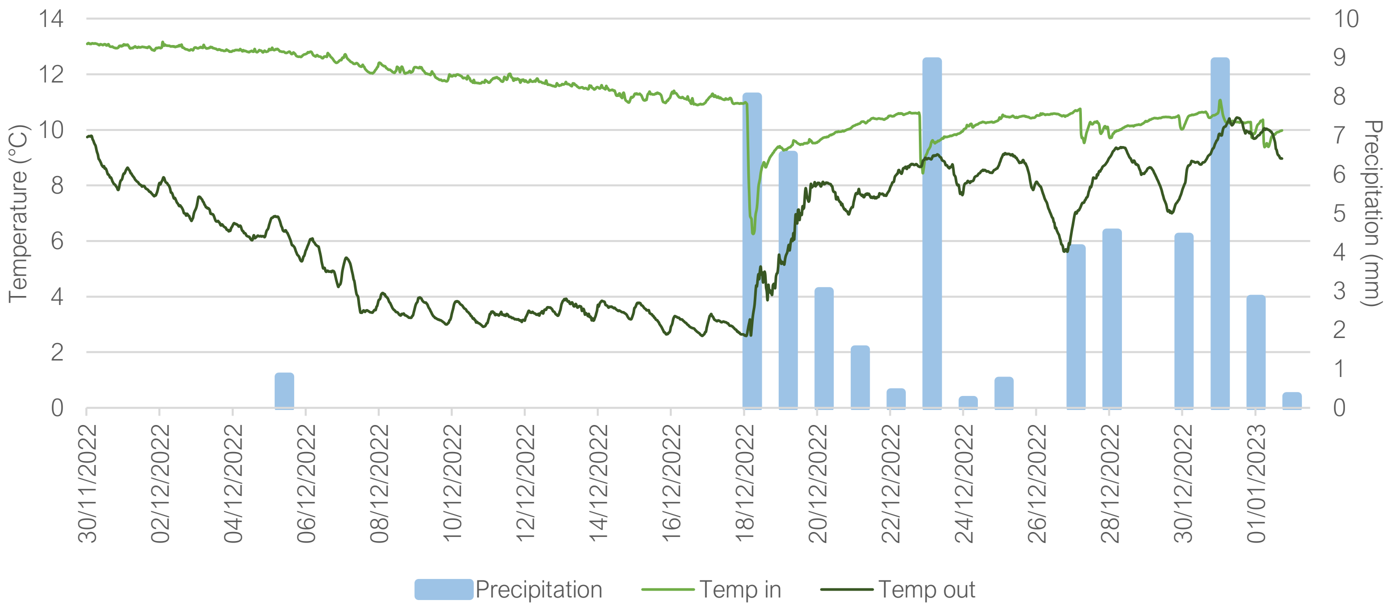

Figure 3.7: Temperature (°C) data recorded at the inlet and outlet during the winter monitoring period displayed on the left axis with corresponding total daily precipitation (mm) displayed on the right axis.

3.1.2 Water Spot Sampling Data

Phosphate and Nitrogen

High concentrations (fail to meet 'Good' being scored as either 'Moderate' or 'Poor' - discussed in detail in Section 4.2.2) of total phosphate as P were present in samples from both the outlet and inlet, with highest concentrations recorded during the summer monitoring period at the outlet, where it frequently exceeds 800µg/L (see Figure 3.8).

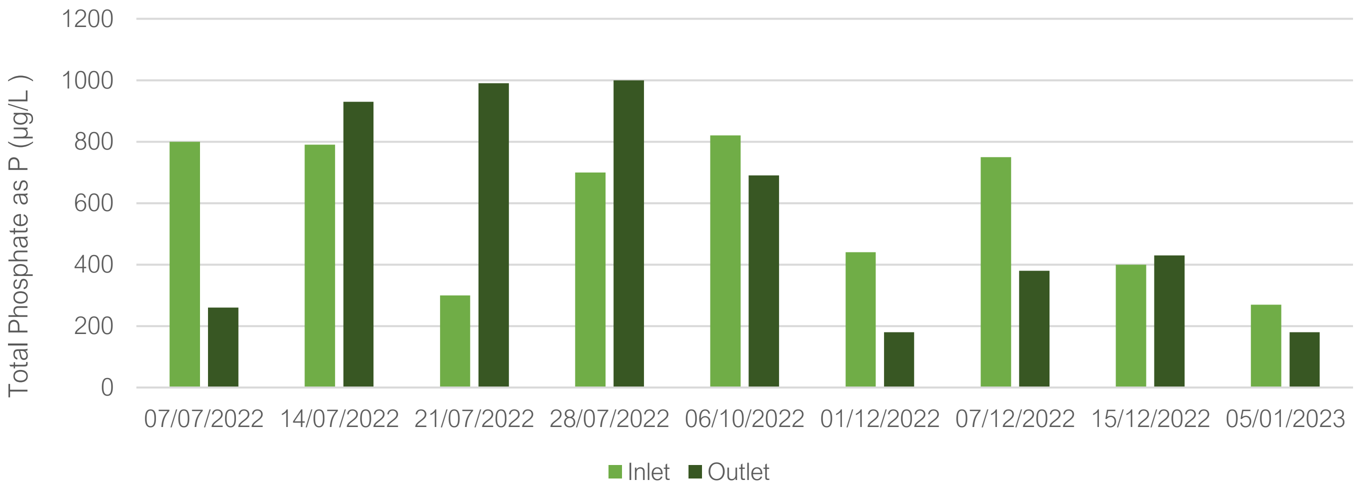

Figure 3.8: Water spot sample concentrations of total phosphate as P measured at the wetland inlet and outlet.

During the summer monitoring period, nitrogen concentrations were found to be initially higher at the inlet. This pattern switched over after the 21/07/2022, where higher nitrogen concentrations were subsequently being recorded at the outlet. On 06/10/2022 nitrogen concentrations increase at both the inlet and the outlet. Throughout the winter monitoring period, concentrations of nitrogen can be seen to fluctuate more than in summer (see Figure 3.9).

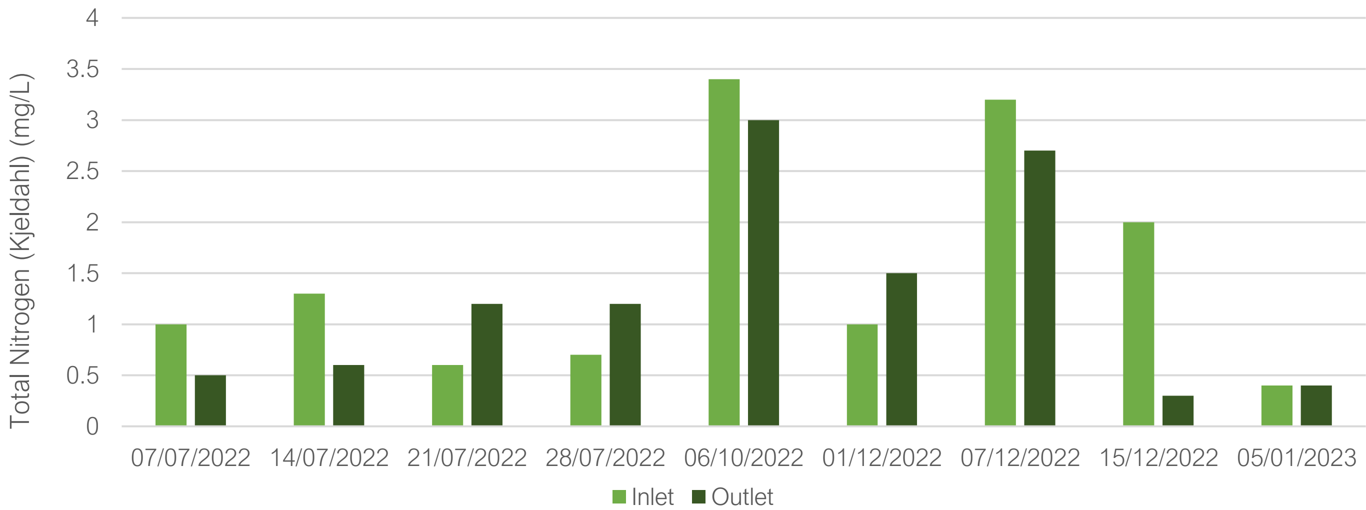

Figure 3.9: Water spot sample concentrations of total nitrogen measured at the wetland inlet and outlet.

Total Suspended Solids and Total Dissolved Solids

Total Suspended Solid concentrations fluctuate across the monitoring periods. Samples taken at the wetland inlet appear more consistent with less variation over time and are generally lower (other than on 07/07/2022 and 15/12/2022).

Outlet TSS concentrations are generally higher than those from the inlet samples with TSS concentration reaching 380mg/L in the outlet sample on 07/12/2022 (see Figure 3.10).

This general pattern in TSS concentration data does not correlate with sonde turbidity data, which showed no clear differences in overall turbidity and the inlet compared to the outlet (see Appendix Figure A1.5).

No meaningful differences were seen between inlet and outlet TDS concentrations recorded (see Appendix Figure A2.1).

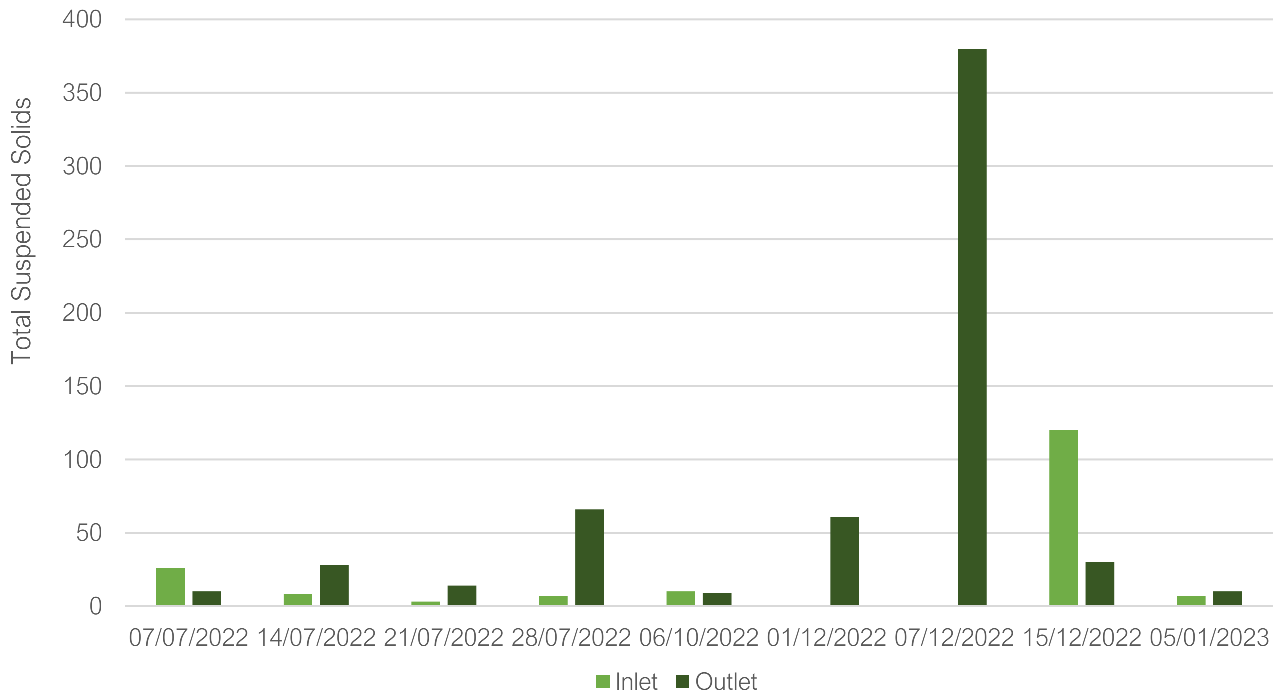

Figure 3.10: Water spot sample concentrations of Total Suspended Solids (TSS) measured at the wetland inlet and outlet.

Biological Oxygen Demand (BOD)

BOD levels at the inlet were higher than those at the outlet, with the highest concentration recorded at the inlet on 06/10/2022 (see Figure 3.11).

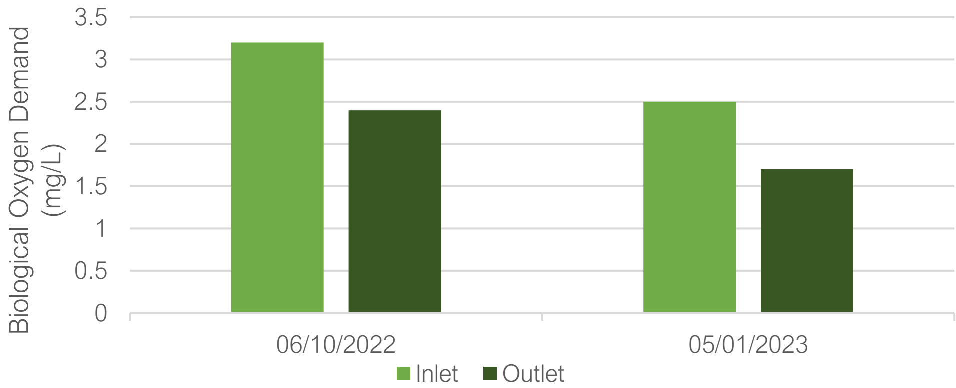

Figure 3.11: Biological Oxygen Demand (BOD5) (mg/L) comparison between the wetland inlet and outlet.

Heavy Metals

Results of individual dissolved heavy metal concentrations can be seen below in Table 3.2. For some samples at the inlet and outlet, concentrations for cadmium, chromium and lead were below detection limits.

Table 3.2: Concentrations of individual dissolved heavy metals (µg/l) within water samples collected at the inlet and outlet sampling sites.

		Magnesium	Potassium	Cadmium	Chromium	Copper	Lead	Nickel	Zinc
07/07/22	Inlet	16.00	6.40	0.06	< 0.20	25.00	< 0.20	2.90	18.00
	Outlet	15.00	4.00	0.07	0.30	40.00	< 0.20	3.30	4.00
14/07/22	Inlet	17.00	7.00	<0.00002	0.40	3.20	< 0.20	2.50	4.90
	Outlet	17.00	4.90	<0.00002	0.30	2.90	< 0.20	4.10	4.90
21/07/22	Inlet	17.00	6.70	0.03	0.60	6.80	< 0.20	3.10	20.00
	Outlet	17.00	8.10	0.04	0.50	7.30	< 0.20	4.70	9.70
28/07/22	Inlet	15.00	6.10	<0.00002	< 0.20	2.50	< 0.20	2.10	3.80
	Outlet	14.00	6.30	0.00003	< 0.20	1.60	< 0.20	3.20	5.20
06/10/22	Inlet	14.00	6.60	0.11	0.50	9.70	1.80	3.60	69.00
	Outlet	13.00	6.30	<0.00002	0.20	4.10	0.50	2.50	13.00
01/12/22	Inlet	20.00	5.50	<0.00002	0.40	5.70	0.30	3.10	28.00
	Outlet	17.00	5.30	<0.00002	< 0.20	2.70	< 0.20	3.00	11.00
07/12/22	Inlet	21.00	6.50	<0.00002	0.90	5.70	< 0.20	3.00	7.30
	Outlet	21.00	6.50	<0.00002	0.20	1.80	0.40	4.20	16.00
15/12/22	Inlet	19.00	6.80	<0.00002	< 0.20	3.30	1.00	3.50	25.00
	Outlet	16.00	5.50	<0.00002	< 0.20	2.40	< 0.20	2.30	6.60
05/01/23	Inlet	17.00	5.50	<0.00002	1.00	6.10	< 0.20	2.70	19.00
	Outlet	13.00	4.70	<0.00002	0.70	4.00	< 0.20	3.30	16.00

3.2 Sediment Quality

Nitrogen, Phosphate and Dry Solids

There were minimal differences between sediment results for water soluble phosphate concentrations at the inlet and outlet, with results showing sample concentrations <1mg/kg (see Figure 3.12a). Sediment sample total nitrogen and dry solid concentrations were higher in both outlet samples compared to the inlet (Figure 3.12b and Figure 3.12c).

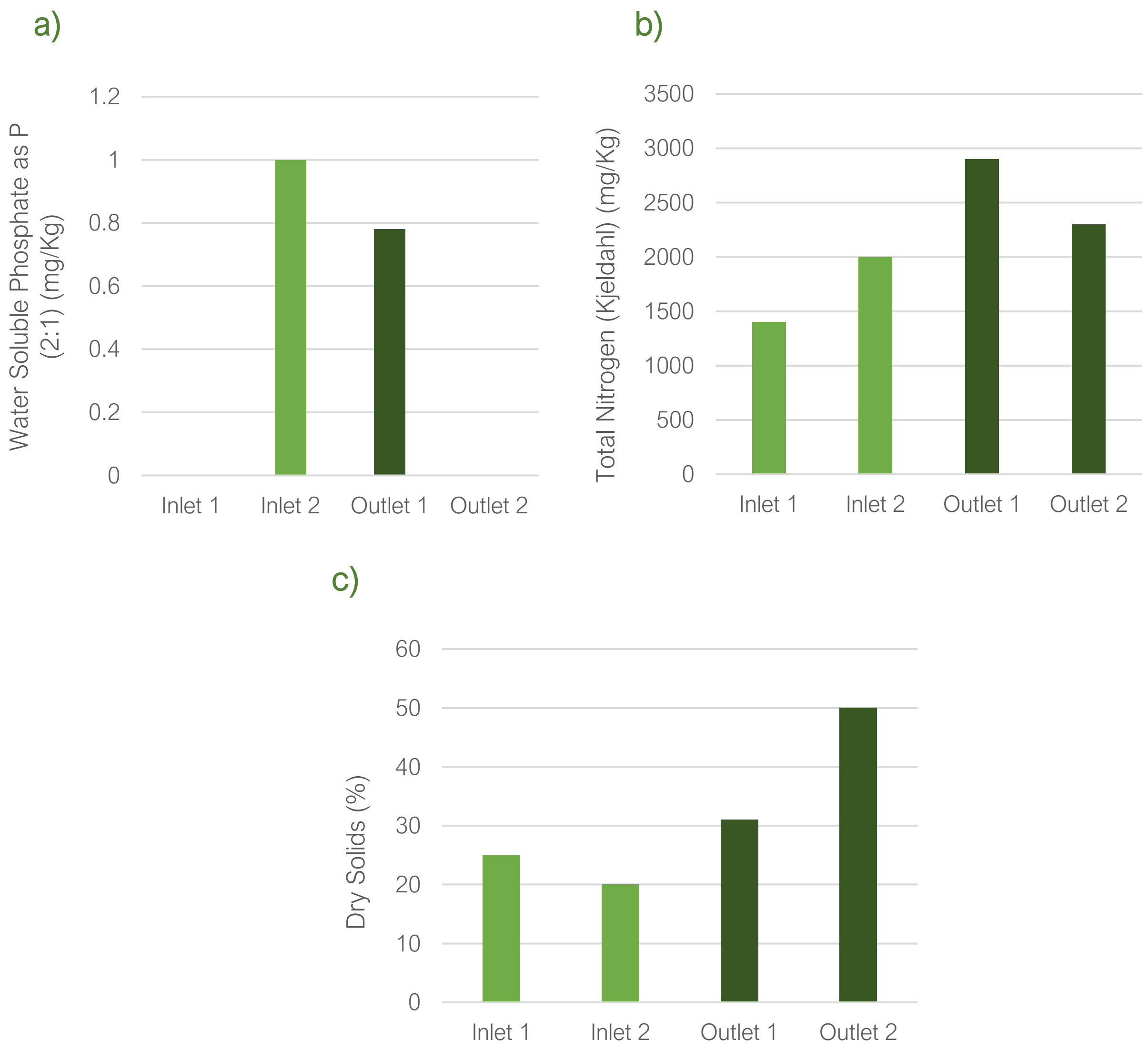

Figure 3.12: Overview of a) Water Soluble Phosphate as P (mg/kg), b) Total Nitrogen (Kjeldahl) (mg/kg) and c) Dry Solids (%) within sediment samples taken from the wetland inlet and outlet.

PHCs

Of the 8 Aliphatic Petroleum Hydrocarbons (PHCs) measured, 4 were detected in the inlet and 3 in the outlet samples. Of the 8 Aromatic PHCs measured, 5 were detected in the inlet and none in the outlet samples. See technical report for a breakdown of individual PHC results.

Where individual PHCs were detected in both the inlet and outlet samples, mean concentrations were consistently higher in the inlet samples than in outlet samples.

PAHs:

The concentration of Polycyclic Aromatic Hydrocarbons (PAHs) varied considerably between inlet and outlet sediment samples, with very high concentrations of several measured PAHs seen at the inlet (Figure 3.13) and much lower concentrations consistently seen within outlet samples.

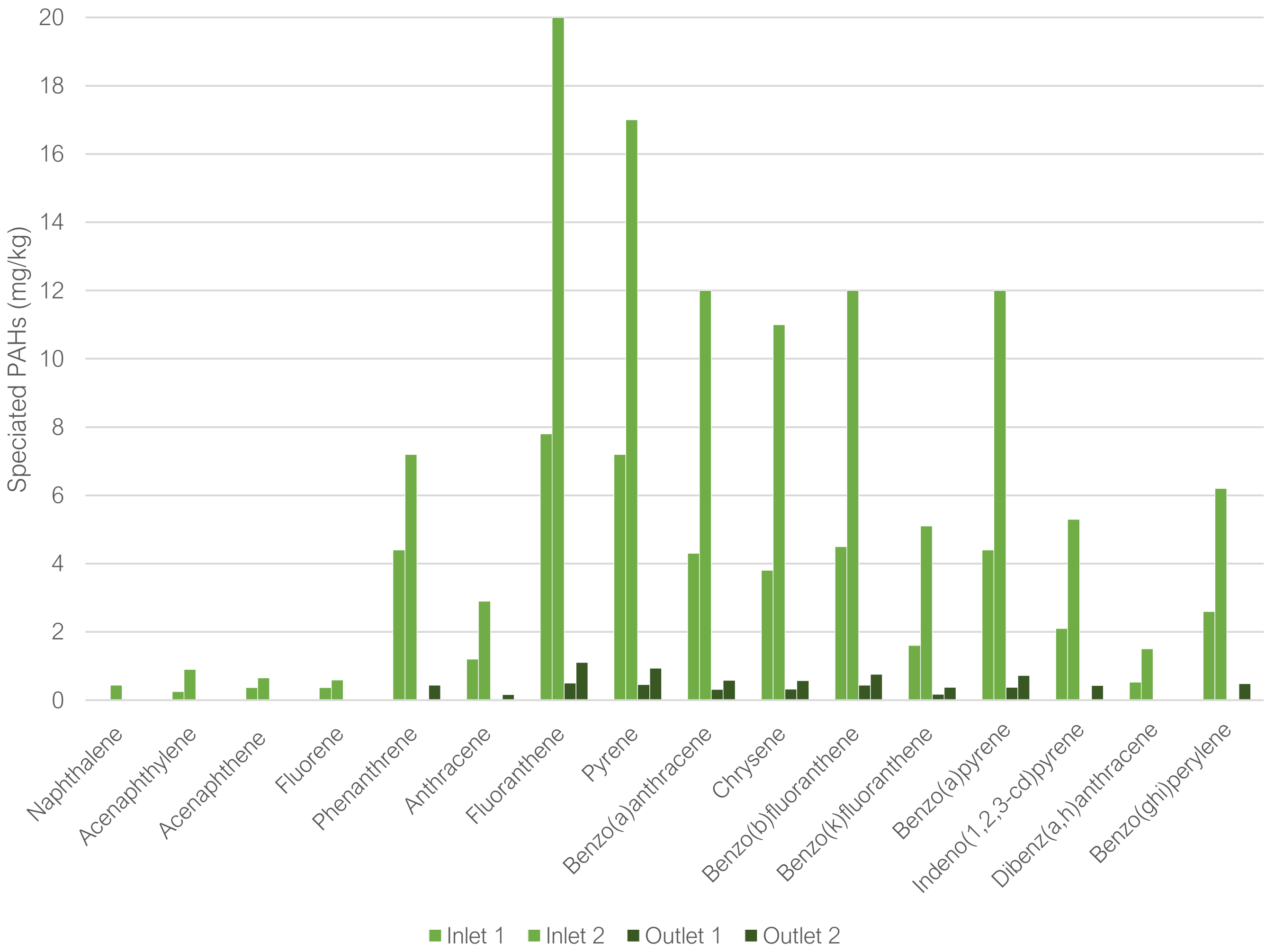

Figure 3.13: Sediment sample PAH concentrations at the inlet and outlet.

Speciated Total EPA-16 PAHs at the inlet were recorded at concentrations as high as 115 µg/l whereas the highest concentration at the outlet was 6.57 µg/l (see Table 3.3).

Table 3.3: Speciated Total EPA-16 Polycyclic Aromatic Hydrocarbons in sediment samples collected from the wetland inlet and outlet.

	Inlet 1	Inlet 2	Outlet 1	Outlet 2
Speciated Total EPA-16 PAHs (µg/l)	45.3	115	2.58	6.57

Monoaromatics & Oxygenates:

All pollutants were below detection level other than one reading for Toluene which has been discounted from analysis (see Appendix Table 3.2).

Heavy Metals:

Heavy metal concentrations can generally be seen to be higher within inlet samples than outlet samples, with mean inlet concentrations exceeding outlet concentrations for all heavy metals other than chromium (Table 3.4).

Table 3.4 Comparison of heavy metal concentrations (Left) Chromium, Copper, Lead, Nickel and Zinc, (Right) Cadmium, at the inlet and outlet with averages.

	Inlet			Outlet		
Pollutant (mg/kg)	Inlet 1	Inlet 2	Inlet Mean	Outlet 1	Outlet 2	Outlet Mean
Cadmium	0.9	1.1	**1**	0.6	0.5	**0.55**
Chromium	27	37	**32**	37	34	**35.5**
Copper	65	89	**77**	66	58	**62**
Lead	200	140	**170**	43	44	**43.5**
Nickel	340	21	**180.5**	26	26	**26**
Zinc	240	300	**270**	180	150	**165**

3.3 Level Sensor Data

The study carried out by Imperial College London identified that during the winter monitoring period, only ~16% of flows bypassed the wetlands, with 74% passing through the wetland before entering the moat downstream (further findings in Appendix 6). Please note that summer flows were particularly low due to extreme weather conditions and drought.

3.4 Biodiversity

3.4.1 Aquatic Invertebrates

Average scores per taxon (ASPT) were higher in outlet samples than in inlet samples (see Table 3.1). The overall highest ASPT was achieved within the outlet sample on 03/08/2022 and the poorest score was seen at the inlet sample taken on 03/08/2022 (Table 3.5).

Table 3.5: Comparison of average score per taxon (ASPT), and total number of PSYM and non-PSYM taxa at the wetland inlet and outlet.

	03/08/2022		06/10/2022	
	Inlet	Outlet	Inlet	Outlet
Average Score Per Taxon (ASPT)	3.6	4.5	4	4.4
Number of PSYM Taxa	8	14	5	5
Number of non-PSYM Taxa	4	4	2	3

On both the 03/08/2022 and 06/10/2022, samples taken from the outlet contained higher numbers of total taxa (PSYM and non-PSYM). On 03/08/2022, a total of 12 invertebrate taxa were found within the inlet sample and a total of 18 within the outlet sample. Both samples contained 4 non-PSYM scoring taxa. One fish (common stickleback) and a common newt eft (see Figure 3.14) were found in the August outlet sample.

Figure 3.14: Common newt eft found within the invertebrate kick sample on 03/08/2022.

On 06/10/2022, total taxa numbers declined compared to the previous survey results. The inlet and outlet samples contained 7 species each, 2 and 3 of which were non-PSYM scoring respectively (see Figure 3.15).

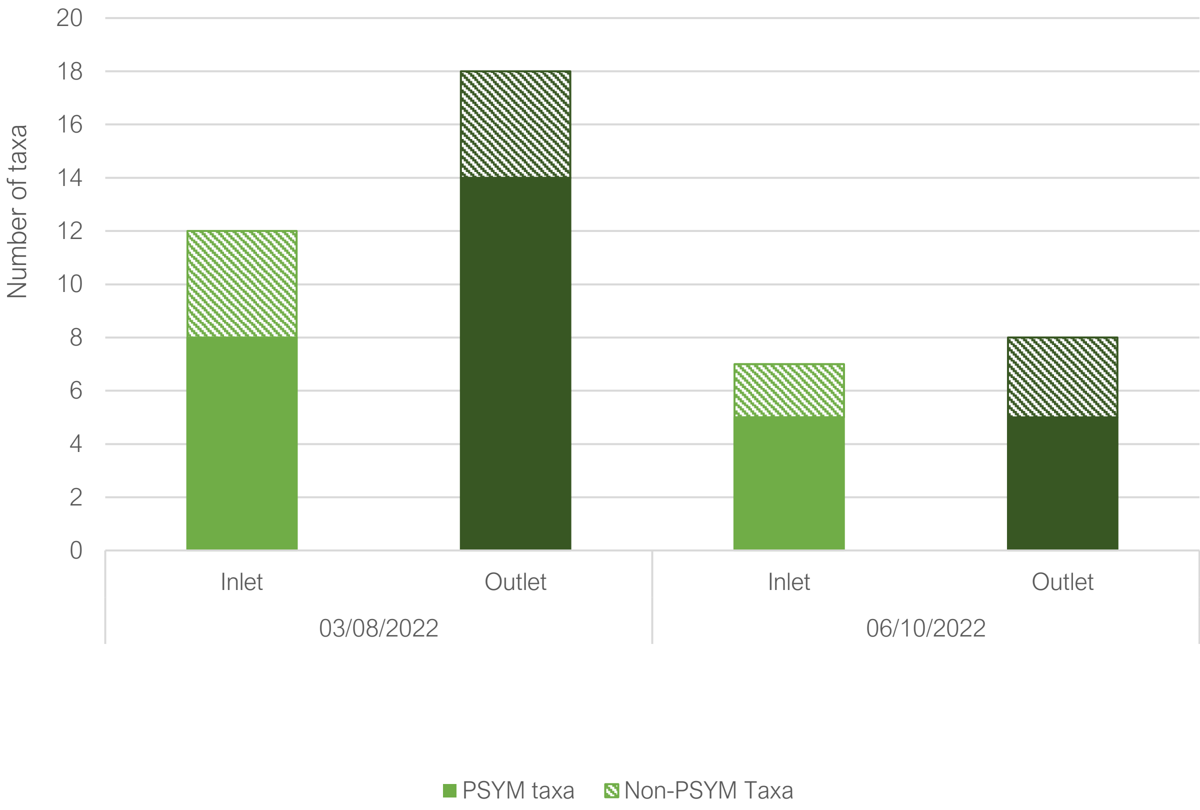

Figure 3.15: Comparison of PSYM and non- PSYM scoring species at the wetland inlet and outlet.

3.4.2 Plants

Based on the E10 Tussock seed mix, reed mix, and native shrub mix contents stated in the AECOM (2014) Headstone Manor Sedimentation Pond and Reed Bed Design Report, a total of 43 plant species were planted within the wetland area (excludes tree data).

Plant survey data carried out in August identified the presence of 46 species across the wetland area. Only 13 of these species identified were listed on the planted species list, with 30 of the species found having not been planted over the course of wetland construction. A breakdown of these results can be found in Appendix 4.2.

3.4.3 Birds

BirdTrack data gathered by volunteers and made available by the British Trust for Ornithology can be found in Appendix 4.3.

4 Discussion

4.1 Background Information and Site Conditions

During the summer monitoring period, starting in June 2022, the Crane catchment, and the United Kingdom as a whole experienced three heatwaves (three days in June, three days in July, six days in August). On the 19th of July 2022, record high temperatures of 40.2°C were recorded at Heathrow. These periods of drought and unusually hot weather were caused by rising high pressure from the European continent.

During the winter water quality monitoring period, starting at the end of November 2022, conditions throughout the second two weeks of December were particularly cold, bringing snow and ice across the catchment with temperatures falling to as low as -7°C (see Figure 4.1).

Therefore, both the summer and the winter monitoring periods were at, or towards, the extreme end of "normal" summer and winter conditions and this needs to be taken into consideration when reviewing the results.

Figure 4.1: Image taken of the Headstone wetland outlet cell (Cell 3) during the particularly cold period in December, showing frozen sections of the wetland. Credit: Adrian Butler, Imperial College London.

4.2 Water Quality and Sediments

4.2.1 Sonde data

<u>Dissolved Oxygen</u>

From analysis of dissolved oxygen concentrations and patterns recorded during the summer monitoring period (Figure 3.1), it can be seen the incoming water is generally of 40% DO or lower. This is a symptom of the high organic pollution load from sources in the upstream catchment, which is also evidenced by the Biological Oxygen Demand (BOD) data (Figure 3.11) which is higher at the inlet than the outlet.

The outlet (downstream) DO concentrations show a strong diurnal pattern of high concentrations during the day, reaching saturations of >300%, and low concentrations overnight, a pattern typical of a eutrophic waterbody, where the balance between photosynthesis and respiration causes extreme diurnal variations in dissolved oxygen concentrations. An example of this can be seen in sonde data from the 03/07/2022 to the 13/07/2022.

Following the rainfall event on 18/07/2022, an additional input of organic material can be seen to cause the already 'stressed' wetland system to become anoxic (oxygen deficient). While concentrations at the inlet remain very low between ~5% and ~30% outlet concentrations fall even lower, to a maximum of <2% after the 28/07/2022. These data, further supported by the invertebrate data in Section 3.1.1, indicate that DO concentrations are likely extremely low across the wetland cells. A die-off of pollution sensitive invertebrate taxa can be seen at both the inlet and outlet with only the more robust taxa remaining in samples taken after 18/07/2022.

Analysis of winter sonde data demonstrates a poor oxygen regime at both the inlet and outlet sampling locations. BOD data show that organic pollution loading remains relatively high in the system which is suppressing DO. Loss of the diurnal peaks at the outlet reflects macrophyte die back and limited photosynthesis taking place within the wetland in winter.

<u>Ammonium</u>

It should be noted that the ion selective sensors of the sonde devices used in this investigation are helpful in the identification of ammonium trends over long periods of time but do not consistently provide an accurate measure of ammonium concentration data as they are prone to interferences from other ions, namely potassium and sodium (Capella *et al.*, 2020). Therefore, these ammonium concentration data are to be used only as a guide.

Data recorded by the sondes during the summer monitoring period further confirm the "die-off" event seen in the DO and invertebrate results. Prior to rainfall on 18/07/2022 the wetland was functioning as expected, with lower ammonium concentrations at the outlet and higher concentrations at the inlet, indicating that ammonium is potentially being oxidised to nitrate via nitrification. It is probable that denitrification in the fine sediments of the wetland is also operating to remove nitrogen from the wetland system. Following rainfall on the 18/07/2022, outlet ammonium concentrations spike and concentrations exceed those recorded at the inlet, presumably a result of low oxygen conditions potentially preventing nitrification from occurring, resulting in ammonium not being converted to nitrate (pers comms. Prof Kate Heppell) and decomposition of organic material raising ammonium concentrations further (Farnsworth-Lee and Baker, 2000).

Due to the significant relationship between temperature and the activity of both macrophytes and microorganisms, it is expected that removal rates of ammonium would be reduced during the winter monitoring period (Zou *et al.*, 2016). This can be seen when comparing summer and winter sondes data, with average ammonium concentrations slightly higher in the winter period (see Appendix A1.4). Winter sondes data indicate that the wetland is buffering the spikes in ammonium entering the wetland system, with concentrations at the outlet still gradually increasing in the absence of rainfall, but without dramatic spikes and a smaller range in concentrations (Figure 3.4). A typical first flush response can be seen at the inlet with a spike in ammonium following rainfall which is not seen at the outlet, again indicating that the wetland is buffering these fluctuations and inputs of polluted water. Overall, prolonged, heavy rainfall can be seen to dilute ammonium concentrations within the wetland system.

During dry conditions in both summer and winter sondes data, daily double peaks in ammonium approximately 12-hours apart, in the absence of rainfall, are indicative of a point source impact linked to periods of greater domestic effluent releases in the morning and evening (Palmer-Felgate *et al.*, 2008) (see Figure 3.3). This pattern is typically seen as a direct result of point-source pollution from sewage treatment works inputs. However, as there are no sewage treatment works directly upstream of this site it could be assumed that this trend is a result of local misconnections.

Overall, it can be seen that ammonium concentrations within the Headstone Manor Park are at levels harmful to aquatic life, most likely predominantly derived from connections to the foul sewers and misconnections upstream. Visual signs of pollution, including floating coagulated fats and foamy scum, were regularly reported through the project by volunteers (see Figure 4.2). Similarly, turbidity increases can be seen to occur with and without rainfall, with inlet turbidity generally higher than outlet turbidity levels indicating an input of silt from upstream urban sources.

Figure 4.2: Examples of visual signs of pollution at the wetland inlet.

4.2.2 Spot samples

N & P processing in wetlands:

Both nitrogen and phosphorus are present in many forms within water bodies; particulate, dissolved, organic, inorganic. As wetlands slow the flow of water, they process and store nitrogen and phosphorus through a range of naturally occurring physical, chemical, and biological processes (see Figure 4.3).

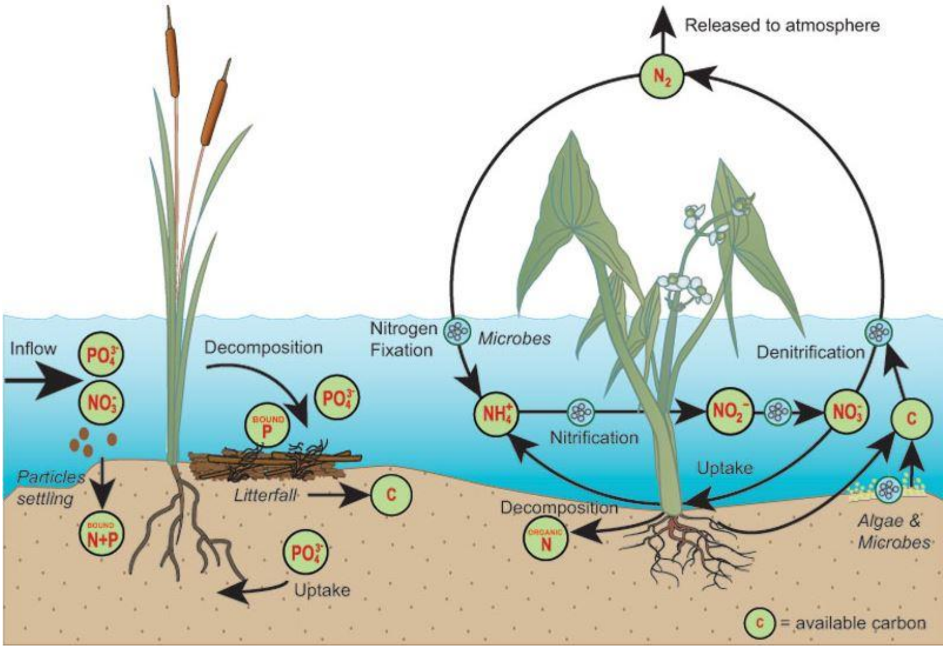

Figure 4.3: A simplified illustration of the nitrogen and phosphorus cycles in a wetland (IAN, University of Maryland; modified from Kadlec and Knight,1996).

The main physical processes driving nutrient storage/removal are sedimentation, volatilisation and sorption. Chemical processes include transformations and chemical precipitation in which solid compounds are formed from liquids through chemical reactions. Biological processes mainly consist of uptake/assimilation by plants, algae, and bacteria and transformation processes conducted by microbes. These processes occur throughout the different wetland compartments/cells, within water, plants, algae, bacteria, leaf litter, soils and sediments. The speed and efficiency of these removal and storage processes are heavily dependent on factors such as oxygen availability, light, temperature, water flow, nutrient loadings and the retention time of the wetland.

Examples of removal efficiencies can be seen within the Thames 21 report on processing nutrient pollution in the Firs Farm Wetlands, London. Water samples collected monthly for 8 months from the inflow and outflow at Firs Farm, similar to this investigation, with results indicating significant improvements in water quality after passage through the wetland. Phosphate was found to have been reduced by 78%, Ammonia by 92% and Total nitrogen (ammonia and nitrate) decreased by 58%. Further examples of wetland pollution removal efficiencies are discussed in The Urban Wetland Design Guide (Russell, 2021). Based on comparable studies, such as the Firs Farm study and knowledge of typical wetland function/nutrient processing, it would be assumed that N and P concentrations would be higher at the inlet than at the outlet. However, the water sample data collected does not appear to support this clearly.

Phosphate concentrations were converted to phosphorus concentrations so that data could be compared to guideline standards. Analysis of overall data (Figure 3.8) indicates signs of a slight improvement in phosphate concentrations between the wetland inlet and outlet when compared to UKTAG (2011) standards, with outlet phosphate concentrations meeting 'Good' standards on 1/12/2022 and 5/01/2023. All inlet samples fail to meet 'Good' standards throughout the monitoring periods, being scored as either 'Moderate' or 'Poor' (see Figure 4.4).

None of the samples taken from the inlet or outlet meet UKTAG (2011) 'High' standards. Overall, 56% of inlet samples were scored as 'Poor' and 44% were scored as 'Moderate'. An improvement can be seen in the comparison to outlet samples with 44% scoring 'Poor', 33% scoring 'Moderate' and 22% scoring 'Good' (see Figure 4.5). However, it should be noted that this overall positive observation was not consistent throughout the monitoring period. During the summer sampling period, between 14/07/2022 and 28/07/2022, the wetland was acting as a source of phosphate, with outlet concentrations exceeding those recorded at the inlet. The start of this monitoring period precedes the "die-off" event taking place on 18/07 (see Figure 4.4).

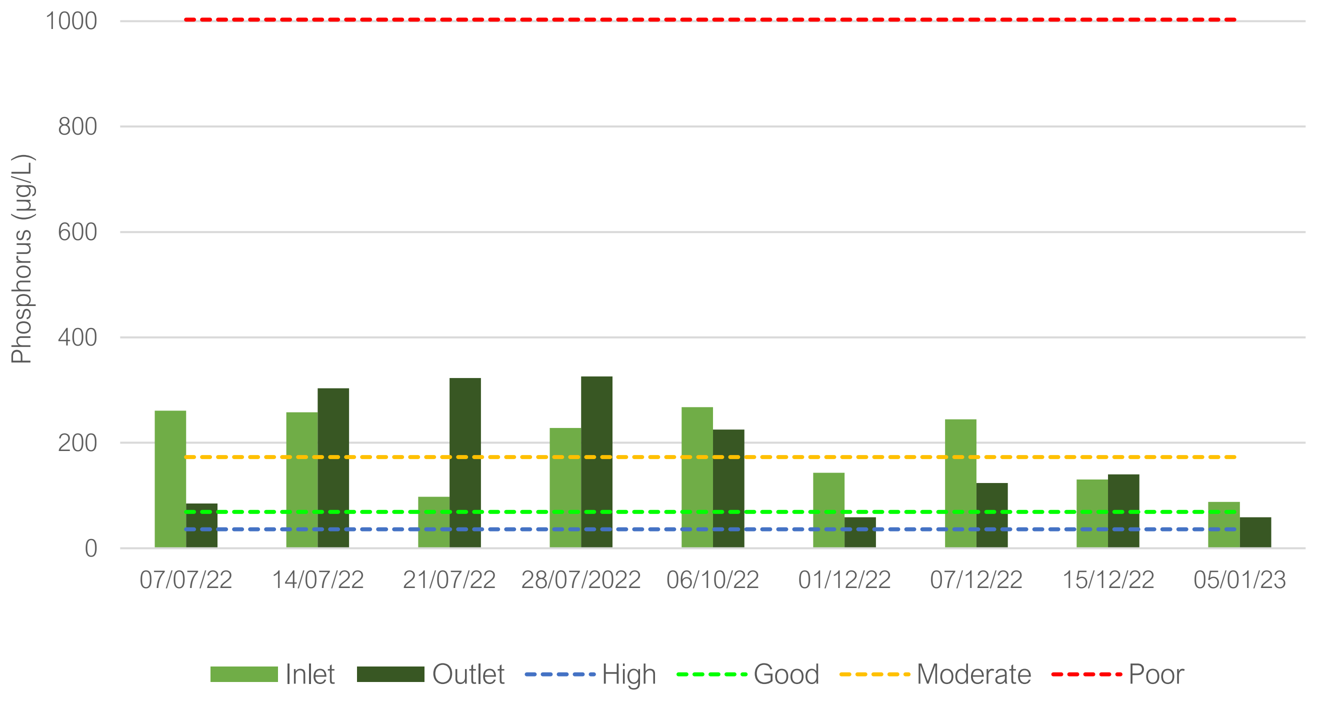

Figure 4.4: Comparison of Phosphorus* concentration data to UK TAG (2012) guidelines at the wetland inlet an outlet. Concentration meets the standard if below the following concentrations: High = 36µg, Good = >69µg/L, Moderate = 173µg/L and Poor = 1003µg/L. *PO4 data was converted to P for comparison to UKTAG standards.

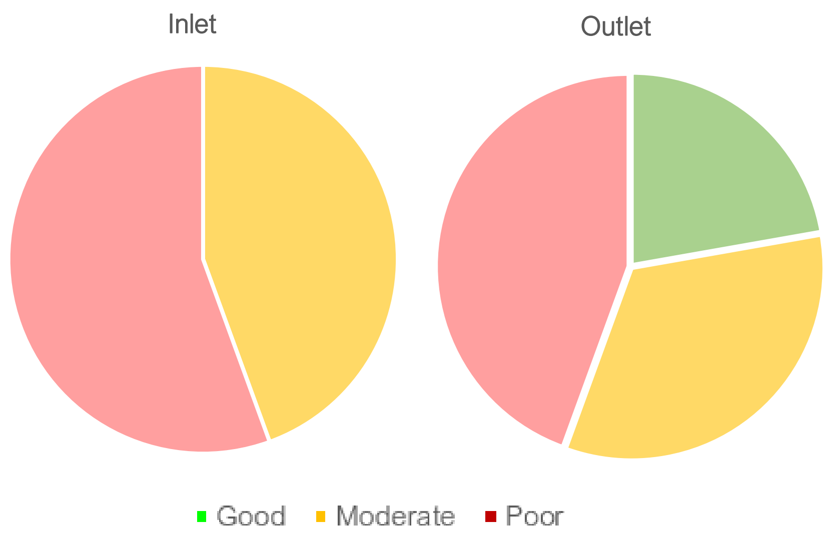

Figure 4.5: Comparison of the number of samples meeting UKTAG (2011) 'High', 'Good', 'Moderate' and 'Poor' standards for phosphorus at the wetland inlet and outlet.

A slight improvement in total nitrogen concentration data can be seen when comparing inlet and outlet samples to European Nitrogen Assessment standards (2011) (see Figure 4.6). Overall, 33% of inlet samples were scored as 'Poor' and 56% were scored as 'Moderate' and 11% were scored as 'Good'. As with phosphorus concentration data, a slight improvement can be seen when compared to outlet samples with 33% scoring 'Poor', 33% scoring 'Moderate' and 33% scoring 'Good' (see Figure 4.7).

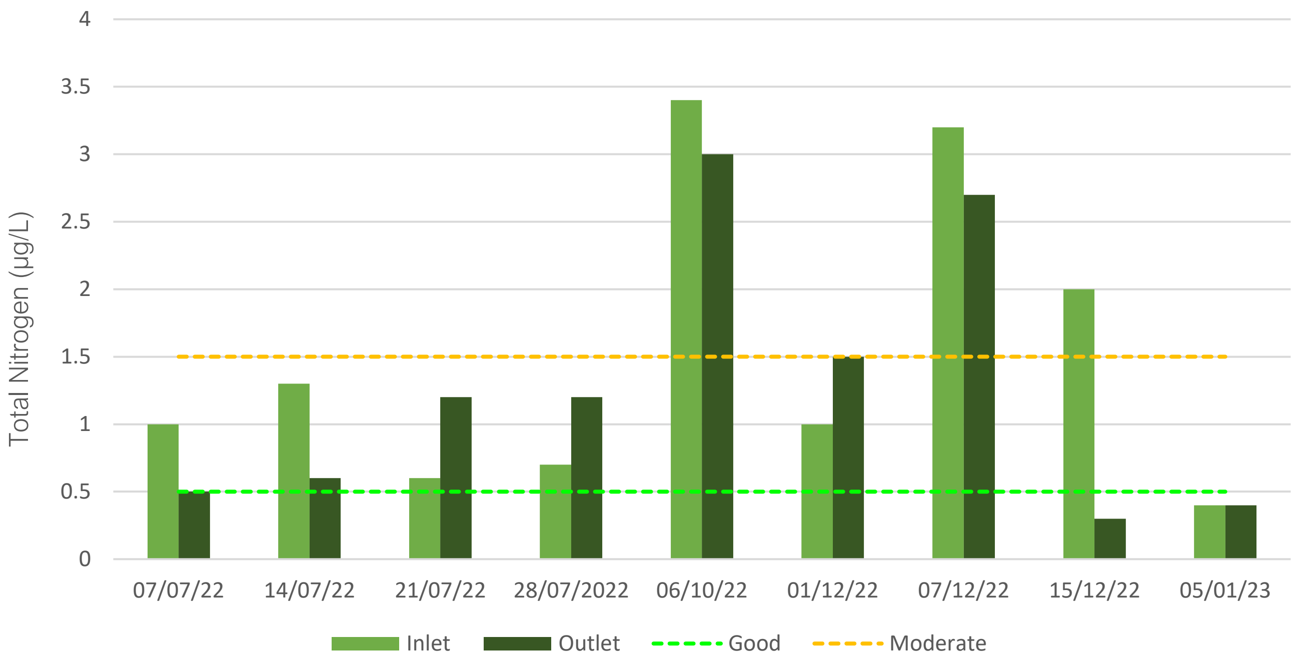

Figure 4.6: Comparison of total nitrogen concentration data to the European Nitrogen Assessment standards (2011) at the wetland inlet an outlet. Concentration meets the standard if within the following concentration ranges: Good = ≥0.5µg/L, Moderate = 0.6-1.5µg/L and Poor = >1.5µg/L.

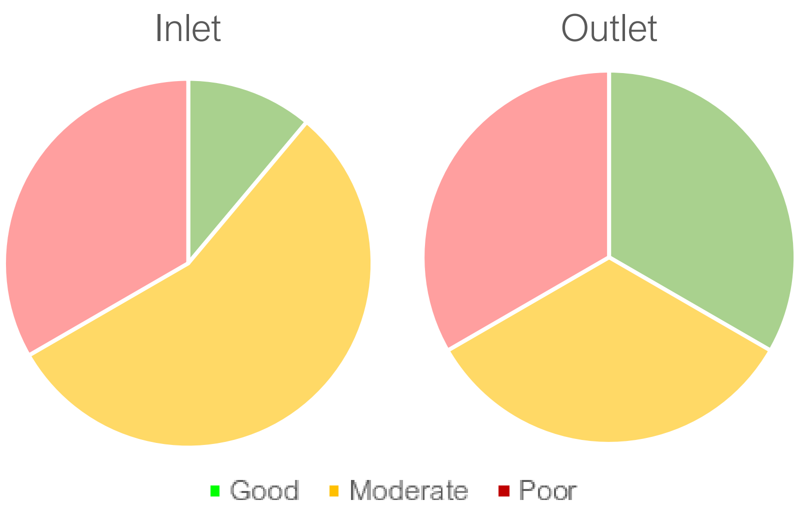

Figure 4.7: Comparison of the number of samples meeting the European Nitrogen Assessment Standards (2011) 'Good', 'Moderate' and 'Poor' standards for total nitrogen at the wetland inlet and outlet.

However, as with phosphate concentration data, concentrations of total nitrogen were also higher at the outlet than the inlet on 21/07/2022 and 28/07/2022 as well as on the 1/12/2022, indicating that at these sampling times, the wetland was acting as a source of total nitrogen rather than a sink (Figure 4.6). The Autumn and Winter data also show no clear pattern of total nitrogen reduction between the inlet and outlet.

This unexpected pattern in the nitrogen and phosphorus data is perhaps due to a number of factors including the extreme heatwave conditions which will have 'stressed' the wetland system (as temperatures increase, the concentration of dissolved oxygen in water decreases due to the inverse relationship between the two) as well as the sampling strategy, for example, too few samples taken and/or in locations that do not represent N and P concentration throughout the wetland system.

Furthermore, higher nitrogen and dry solid concentrations within outlet samples within several samples may also be a result of large amounts of nitrogen rich, "green" plant material being collected within water samples and algal/plant remains within sediments which could be impacting concentration data.

In addition, it should be noted that nitrogen compounds are generally easier to remove than phosphorus, and in some cases, concentrations of both nitrogen compounds and phosphorus have been seen to increase before and after constructed wetlands in their "start-up period". Wetland function is expected to become more efficient at removing these nutrients as vegetation matures and therefore, the lower-than-expected removal efficiencies seen at Headstone Manor Park Wetlands may improve with time (Folini, 2015 and Perales-Momparler *et al.*, 2013). Nevertheless, even when a wetland has matured, under anaerobic conditions it would be expected that the system would become a source of phosphorus.

Suspended Solids

Based on a general understanding of constructed wetland function and the process of sedimentation they support; it would be expected that higher suspended solids concentrations would be seen at the inlet compared to the outlet. However, analysis of water sample results does not support this. With ~66% of outlet samples showing higher Total Suspended Solid (TSS) concentrations than inlet samples.

Elevated TSS can be caused by a range of factors, including runoff, disruption to bottom sediments causing resuspension, untreated wastewater and much more. However, in this case, the gravimetric methodology used to calculate TSS (i.e. results determined by weight) means that results are likely impacted by algal material transported from the wetland due to the system being highly productive and eutrophic. Therefore, although the wetland may be trapping fine sediments, the increase in TSS concentrations at the outlet, is likely a result of the growth and suspension of algal material that is not seen in the inlet samples (see Figure 4.8).

Figure 4.8: Images of algal coverage and dense vegetation taken at the outlet sampling location on (Left) 14/07/2022 and (Right) 01/12/2022.

Biological Oxygen Demand (BOD)

BOD-5 (biological oxygen demand incubated over 5 days), measured as part of this investigation, is a proxy for the amount of organic pollution, such as sewage, in the water – evaluated from the oxygen consumption of microorganisms involved in its natural breakdown. Wetlands have been documented to reduce BOD successfully by processes of biological degradation and sedimentation. These processes involve wetland plants taking up dissolved organic nutrients into their roots and tissues, bacterial and microbial activity breaking down organic material and pollutants becoming buried and bound to sediments (Ellis, Shutes and Revitt, 2003 and Khanijo, 2002). Therefore, as a result of these processes taking place across wetland cells, lower BOD concentrations would be expected at the outlet.

Although limited to only two samples, analysis of BOD data from water samples taken as part of this investigation demonstrate this reduction, with BOD concentrations at the outlet 0.8mg/L lower in both samples. BOD is key metric for wetland function and therefore the collection of more BOD-5 samples during the spring/summer (when BOD concentrations are generally highest) would be useful in supporting the results seen from the samples already collected.

<u>Heavy Metals in Water</u>

Heavy metals are of significant concern in aquatic systems due to their persistence, toxicity, ability to enter food chains and are particularly problematic because they are not biodegradable (Zhuang and Gao, 2014). Aquatic organisms may absorb bioavailable heavy metals directly from water and indirectly through bioaccumulation resulting in the potential for a reduction in developmental growth and increases in developmental abnormalities in some cases extinction of entire populations of fish in polluted systems (Khayatzadeh and Abbasi, 2010; Singh and Kalamdhad, 2011 and Gilbert, 2020).

Main sources of diffuse heavy metal contaminants in urban wetlands include inputs from guttering and drain pipes, metal roofing materials, motor vehicle emissions, oil leaks/drips, vehicle tyre wear and asphalt road surfaces. During rainfall events, these contaminants are mobilised, being washed from roofs, roads and other surfaces into stormwater systems and discharged into surface waterways (Brown and Peake, 2006). Wetlands have been shown to effectively reduce and trap heavy metals (Gill *et al.*, 2017) through biological, chemical and physical processes including their accumulation within plant roots and tissues and becoming bound to sediments (Ellis, Shutes and Revitt, 2003, Gibbs *et al.*, 2014). As a result, it would be expected that inlet concentrations of heavy metals within water would be higher than concentrations within outlet water samples.

Analysis of water samples in this study were based on total concentrations of individual metals in their dissolved form, whereas UKTAG and EU Water Framework Directive standards for metals are stated in their bioavailable form. The fractions of bioavailable metal will be less than the dissolved concentration and therefore, a direct comparison cannot be made. Instead, results of this investigation were compared to UK median (dissolved) concentration data (see Table 4.1). Median values used for comparison were calculated by Johnson *et al.* (2018), based on chemical data collected from scientific literature (from 2000 onwards), and largely from the UK Environment Agency (2010 – 2012) monitoring data.

Table A4.1: Comparison of heavy metal concentrations at inlet and outlet sampling locations to Median UK concentrations (derived from Johnson *et al.*, 2018) where available. Grey box = no comparison standard available, Yellow Box = standard used for comparison, Red box = fails to fall below the standard, Green box = meets standard.

		Magnesium (µg/L)	Potassium (µg/L)	Cadmium (µg/L)	Chromium (µg/L)	Copper (µg/L)	Lead (µg/L)	Nickel (µg/L)	Zinc (µg/L)
	Median UK Concentration	N/A	N/A	0.5	0.25	1.66	1	1.69	6.5
07/07/22	Inlet	16.00	6.40	0.06	< 0.20	25.00	< 0.20	2.90	18.00
	Outlet	15.00	4.00	0.07	0.30	40.00	< 0.20	3.30	4.00
14/07/22	Inlet	17.00	7.00	<0.00002	0.40	3.20	< 0.20	2.50	4.90
	Outlet	17.00	4.90	<0.00002	0.30	2.90	< 0.20	4.10	4.90
21/07/22	Inlet	17.00	6.70	0.03	0.60	6.80	< 0.20	3.10	20.00
	Outlet	17.00	8.10	0.04	0.50	7.30	< 0.20	4.70	9.70
28/07/22	Inlet	15.00	6.10	<0.00002	< 0.20	2.50	< 0.20	2.10	3.80
	Outlet	14.00	6.30	0.00003	< 0.20	1.60	< 0.20	3.20	5.20
06/10/22	Inlet	14.00	6.60	0.11	0.50	9.70	1.80	3.60	69.00
	Outlet	13.00	6.30	<0.00002	0.20	4.10	0.50	2.50	13.00
01/12/22	Inlet	20.00	5.50	<0.00002	0.40	5.70	0.30	3.10	28.00
	Outlet	17.00	5.30	<0.00002	< 0.20	2.70	< 0.20	3.00	11.00
07/12/22	Inlet	21.00	6.50	<0.00002	0.90	5.70	< 0.20	3.00	7.30
	Outlet	21.00	6.50	<0.00002	0.20	1.80	0.40	4.20	16.00
15/12/22	Inlet	19.00	6.80	<0.00002	< 0.20	3.30	1.00	3.50	25.00
	Outlet	16.00	5.50	<0.00002	< 0.20	2.40	< 0.20	2.30	6.60
05/01/23	Inlet	17.00	5.50	<0.00002	1.00	6.10	< 0.20	2.70	19.00
	Outlet	13.00	4.70	<0.00002	0.70	4.00	< 0.20	3.30	16.00

When compared to median UK concentrations copper and nickel exceed averages consistently across all samples. Over half of the samples exceed median concentrations of chromium and ~72% of samples exceed median zinc concentrations (see Table 4.1). Dissolved copper concentrations were higher in ~77% of inlet samples. Only two spot samples, on 07/07/2022 and 21/07/2022 contained higher outlet dissolved copper concentrations and these data may therefore indicate a high concentration of this contaminant entering the wetland from upstream sources. Copper is known to make its way into urban aquatic systems from sources such as wear and tear of vehicle parts, break wear, roofing materials and engine wear/fluid leakages (Bruen *et al.* 2006; Sansalone *et al.* 1996). Copper concentrations were particularly high within the first water sample collected on 07/07/2022 particularly at the outlet. The cause of this is unknown, however it is possible that this spike could be linked to a pollution event (see Figure 4.9).

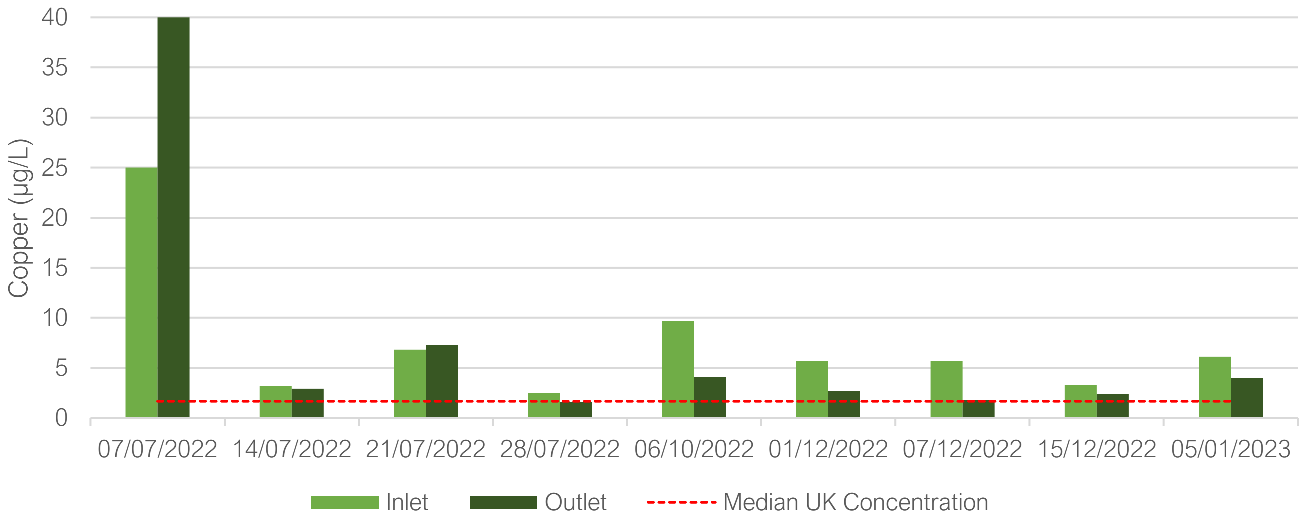

Figure 4.9: Comparison of dissolved copper concentrations (µg/L) at the wetland inlet and outlet to UK median concentrations.

As with the analysis of copper and nickel concentration data, it can be seen that dissolved zinc concentrations frequently exceeded UK median concentrations (see Figure 4.10). Primary sources of zinc which include run-off from guttering and drainpipes, car parks, roofing materials, vehicle tyre and brake wear and tear (Bookter, 2017). Comparison of samples taken from the inlet and the outlet show that concentrations of dissolved zinc were higher at the inlet in 66% of samples, with zinc concentrations seen to be particularly high on the 6/10/2022, reaching 69 µg/L. This is indicative of a heavy metal pollution problem upstream of the wetland system likely originating from a combination of the sources described.

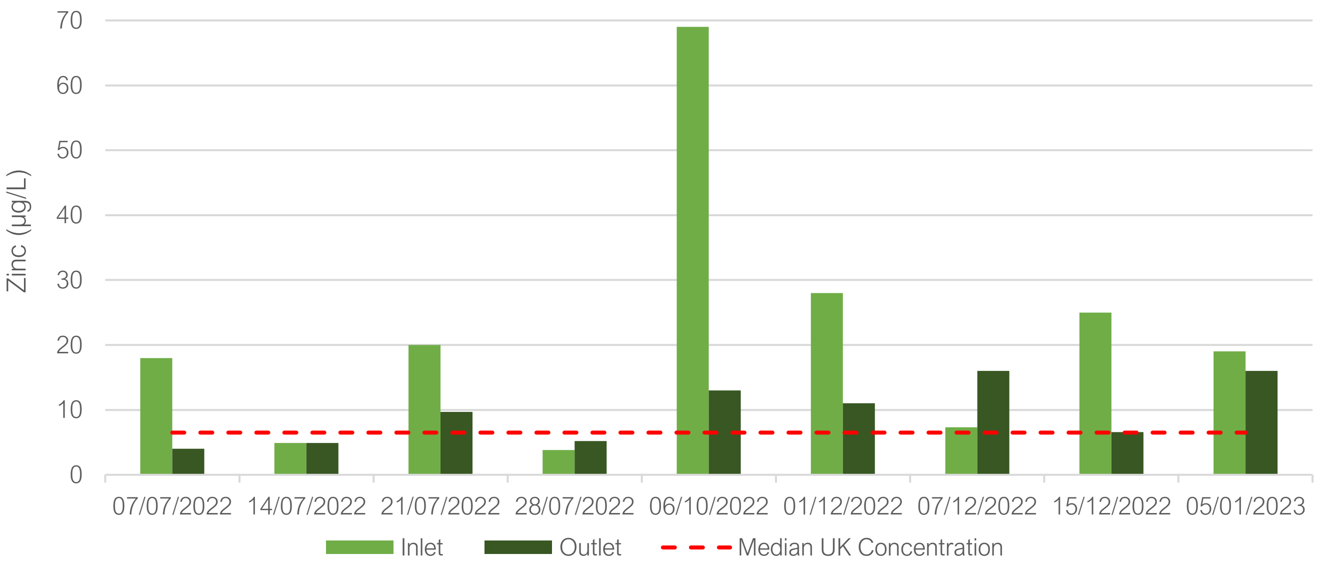

Figure 4.10: Comparison of dissolved zinc concentrations (µg/L) at the wetland inlet and outlet to UK median concentrations.

Although all nickel samples exceeded median UK concentrations, in contrast to results of copper data and zinc, highest concentrations were recorded in outlet samples. Nickel concentrations were consistently higher at the outlet during the summer monitoring period and no clear trends were seen during the winter monitoring (see Figure 4.11).

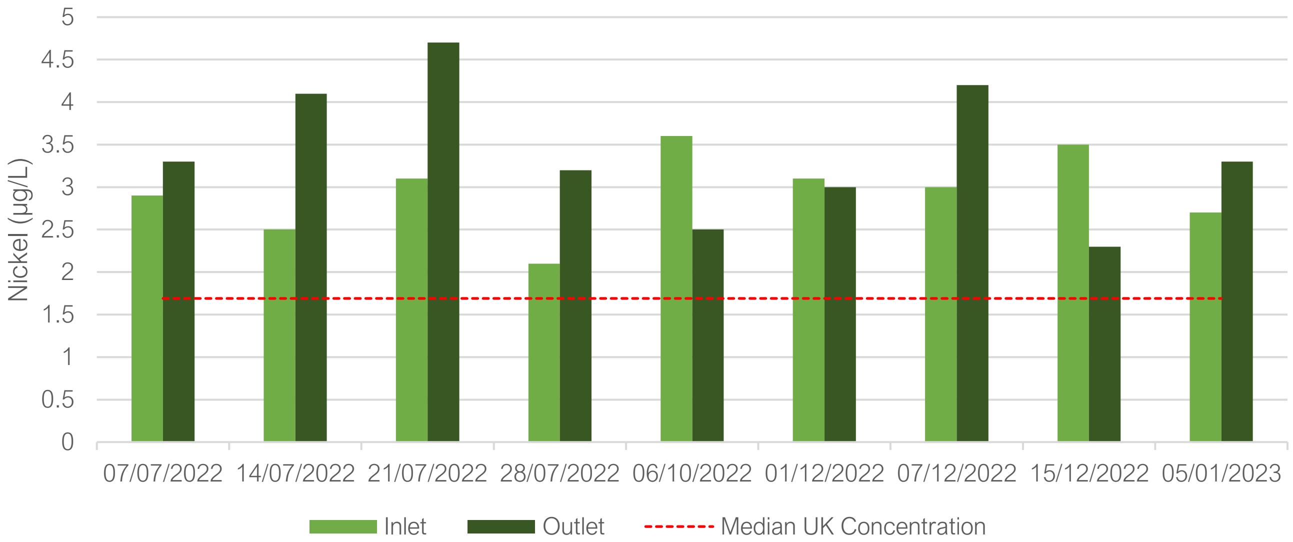

Figure 4.11: Comparison of dissolved nickel concentrations (µg/L) at the wetland inlet and outlet to UK median concentrations.

It should be noted that although a number of individual heavy metal concentrations have been found to exceed UK median concentrations, this does not necessarily mean that they are present in concentrations high enough to act as a risk to aquatic life as we have not determined bioavailability.

Targeted sampling of wet weather, and in particular "first flush" events could not be captured within this investigation. However, it would be useful in order to better understand the signs of serious pollution indicated by results of this investigation so far and in particular the response of the wetland to heavy metal transportation following extended dry periods when metals have built up in higher concentrations on road surfaces. Metals tend to settle out of water samples very quickly, and so to assess the true concentrations of these in their bio-available form (i.e., most toxic form) sampling during first-flush, wet weather events can effectively capture this information.

Heavy Metals in Sediments

Depending on the physiochemical characteristics of individual metals, these contaminants may become associated with suspended particulate matter and then deposited into sediments. As a result, sediments represent a more stable medium for tracing metal sources compared to water and provide a better representation of pollutant trends over longer periods of time (Lundy *et al.*, 2017). Through sedimentation these individual metals become sequestered in constructed wetlands, preventing them from entering the downstream river system and harming wildlife - provided they stay locked up in the sediments. Harrow Council's intention is to periodically remove the polluted sediment from the forebay of the wetland. If a wetland is poorly designed however there is the potential for metals to become re-released into the water, acting as a 'secondary source' of heavy metal pollution (Cui *et al.*, 2019).

As with water sample heavy metal concentrations, it would be expected that if functioning effectively, the wetland inlet concentrations of sediment heavy metals would be higher than concentrations within outlet samples. When data from this investigation were compared with compared to Dutch SedNet guidelines, 75% of inlet sediment samples failed 'Target' heavy metal guidelines. One of the sediment samples taken at the inlet contained concentrations of nickel (340 mg/L) that failed to fall below the Intervention guideline level (Figure 4.12).

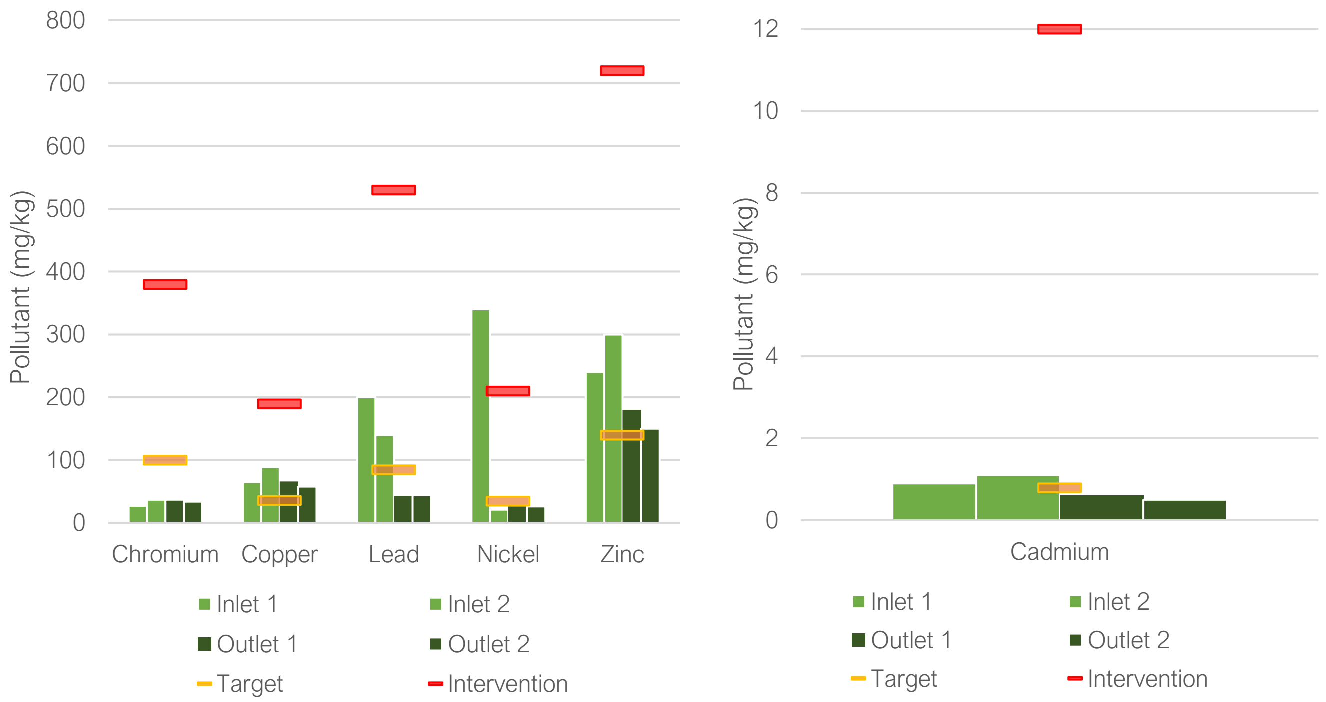

Figure 4.12: Comparison of heavy metal concentrations (Left) Chromium, Copper, Lead, Nickel and Zinc, (Right) Cadmium, at the inlet and outlet to Dutch SedNet Target and Intervention Guidelines.

The failure of copper, lead, zinc and cadmium concentrations to meet 'Target' guidelines and the failure of nickel concentrations to meet 'Intervention' guidelines align with the findings of water sample heavy metal data in the indication that there are serious, chronic heavy metal pollution inputs to the wetland system.

In contrast to water heavy metal results however, a clearer difference between inlet and outlet sediment heavy metal concentrations can be seen, with the inlet samples generally containing higher concentrations of lead, zinc and cadmium. Approximately 67% of outlet sediment samples met the 'Target' guidelines and none of the metal concentrations within outlet samples exceeded 'Intervention' guidelines (see Figure 4.6).

This could indicate that, at the time of monitoring, heavy metals were largely being transported into the wetland by sediments with the wetland depositing these in low velocity areas at the forebay/secondary cells, successfully reducing their transportation to the outlet/reed pond cell and transportation into the Headstone moat.

PAHs

Polycyclic aromatic hydrocarbons (PAHs) refer to a group of compounds that are products of the incomplete combustion of oils and fuels. PAHs are known to persist in the environment and accumulate in biota and food chains with the potential to have adverse effects on aquatic life and humans. These compounds are carcinogenic and are classed as priority hazardous substances and ubiquitous persistent, bioaccumulative and toxic (uPBT) compounds under the Water Framework Directive (WFD) in the related Environmental Quality Standards Directive (EQSD) (Environment Agency, 2019). PAHs have been identified as the major toxicants in road runoff contaminated sediments. PAHs can enter surface waters directly from the air with dust and precipitation but also as particles washed from road surfaces. PAHs in road runoff are primarily derived from used crankcase oil, lubricating oils, and fuels (Bruen *et al.* 2006).

These compounds often concentrate in sediments while also being slow to degrade in the environment and thereby, sediments can act as both sink and source for PAH contamination (Zhao *et al.*, 2017). PAHs and some of their degradation products are known to bioaccumulate in lipid tissues of organisms, generate toxic, carcinogenic, or mutagenic effects in aquatic organisms and are of particular concern in the study of water system health (Neff *et al.*, 2005), meaning that their removal from the aquatic environment is of high importance.

Constructed wetlands have been shown to effectively remove PAHs from polluted waters and therefore, their concentrations would be expected to be lower in outlet samples following removal/storage by the wetland through process such as root and sediment absorption as well as microbial and bacterial degradation (Zhao *et al.*, 2017, Environment Agency, 2019).

Where comparable guidelines were available (Canadian Interim Freshwater Sediment Quality Guidelines (ISQG)/Threshold Effect Levels (TEL) and Probable Effect Level (PEL) standards), a meaningful difference can be seen between the inlet and outlet samples. Approximately 96% of inlet samples failed to fall below both ISQG/TEL and PEL guidelines. In contrast, only approximately 58% of outlet sediment samples failed to fall below the ISQG/TEL guidelines and ~13% failed to fall below PEL standards (see Figure 4.13 for comparison of sediment samples at the inlet and outlet as well as to PEL standards).

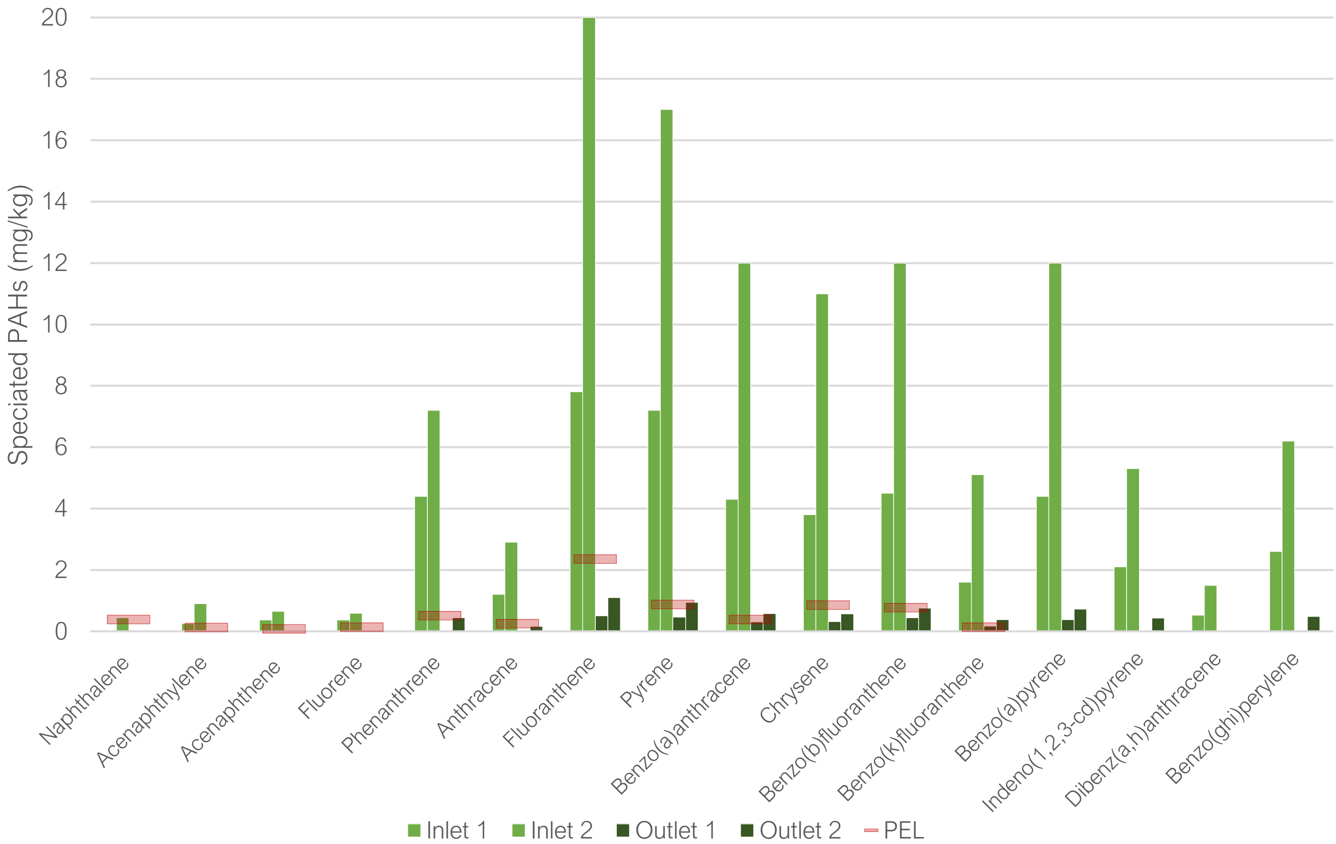

Figure 4.13: Comparison of sediment sample PAH concentrations at the inlet and outlet to Canadian Probable Effect Level (PEL) guidelines (where available).

These results are indicative of elevated, and likely harmful concentrations of PAHs entering the wetland system, with the inlet consistently reaching concentrations much higher than those at the outlet at concentrations high enough that biological effects are expected to occur frequently (see Figure 4.13). The success of the wetland in trapping these high PAHs concentration sediments, appears to be preventing large concentrations of contaminants being transported downstream. PAHs stored in wetland sediments can be removed mechanically by Harrow Council, in turn reducing adverse effects to water quality and biodiversity lower down the catchment Yeading Brook and the Crane.

PHCs

Petroleum hydrocarbons (PHCs) are a group of compounds derived from crude oil that vary considerably in their chemical properties and characteristics. These variations influence their transport, bioavailability and toxicity within aquatic environments. Petroleum hydrocarbons with lower molecular weight are typically partly soluble in water (including benzene, toluene, ethylbenzene and xylene), while higher molecular weight hydrocarbons, are usually less mobile, and associated with sediments or organic matter. Primary PHC pollutant pathways are linked to fuel leaks and spills, vehicle emissions and tyre wear (Schueler and Youngk, 2015) and therefore main sources of petroleum hydrocarbons in urban areas are linked to vehicles and areas with high traffic volumes such as motorways, main roads, car parks and residential streets.

Results from this investigation showed that all measured concentrations for both Aliphatic and Aromatic PHCs within sediments were higher in inlet samples than outlet samples. Consistently higher concentrations of these pollutants in the inlet indicates that they are being washed into the system but are being successfully stored within sediments in the inlet/forebay cell. As with heavy metal and PAH concentration results, lower concentrations of PHCs within outlet samples suggest that at the time of monitoring, the inlet/forebay cell is successfully trapping contaminants in sediments and reducing the concentrations of PHCs transported through the system towards the wetland outlet and downstream catchment.

4.3 Biodiversity

4.3.1 Aquatic Invertebrates

Aquatic invertebrates are powerful indicators of the condition of waterbodies and have commonly been used to monitor the health of aquatic ecosystems for many years. Aquatic invertebrates respond to disturbance in reasonably predictable ways, are easy to identify to family level and, unlike fish, their mobility is limited, meaning that they cannot escape pollution events. For these reasons, their abundance and diversity can give us an indication of the biological condition of a waterbody. In general, waterbodies with high diversity that support an abundance of pollution sensitive species can be assumed to be in healthy condition. In contrast, those with low abundance and/or those containing only pollution tolerant species, may be indicative of poor biological health. Establishing the biological health of a system can in turn help indicate other conditions within a waterbody. When the biology is shown to be healthy, then often the chemical and physical components of the waterbody are also in good condition (Carter *et al.*, 2017 and USEPA, 2022).

As the Headstone wetlands are designed to improve water quality and sediments across the different cells, with the inlet/forebay designed as the ‘dirty’ cell and the outlet reed bed cell designed as the ‘clean’ bed, it would be expected that different invertebrate communities would be present in these cells. Dominance of pollution tolerant species would therefore be expected at the inlet, with the outlet more likely to contain pollution sensitive species and show greater invertebrate abundance and diversity.

Results of invertebrate data from this investigation initially support this and indicate significantly different invertebrate communities being present at the inlet compared to the outlet. Summer data demonstrate that the outlet contained communities of good abundance with high diversity of pollution sensitive taxa such as *Aeshnidae* (dragonfly larvae) and *Coenagrionidae* (damselfly larvae). These summer outlet samples also contained small vertebrate taxa such as fish and newts. The lower diversity and greater abundance of pollution tolerant species (also linked to the lower ASTP score) in the summer inlet sample was likely caused by poor quality, polluted water entering the system and resulting in poor biological health within the inlet/forebay.

Following this, when the wetland was sampled again in October, both the abundance and diversity of species found at both the inlet and the outlet was seen to decline, with the pollution sensitive taxa at the outlet disappearing. The significant decline in the previously abundant pollution sensitive invertebrate species at the outlet align with the water quality sondes results discussed earlier in this report (see Section 4.2.1). The dramatic declines in dissolved oxygen, to anoxic levels, likely resulted in the die-off of large numbers and entire groups of invertebrates that had previously be living within the wetland outlet cell. These data suggest that although under some conditions, areas of the Headstone Manor Park wetlands are able to support healthy and diverse communities, the structure of these communities can change rapidly with die-off events linked to poor water quality and/or extreme weather events.

4.3.2 Plants

While terrestrial plant data show a good diversity of wildflower, grass and reed species, aquatic vegetation and algal species were not surveyed as part of this investigation. Based on quick visual observations, there is a noticeable lack of aquatic macrophyte diversity growing within the system. Diverse macrophyte communities of native emergent, submersed, and floating species have a range of functions that have been highlighted throughout this report, trapping nutrients and sediments, slowing flows and reducing the risk of resuspension, but they also provide habitat and food for aquatic wildlife. Furthermore, as reeds and aquatic plants mature, they help to reduce or eliminate the possibility of weed growth, with dense algal and phytoplankton populations commonly associated with sparse submerged aquatic macrophytes or none at all (Kaldec *et al.*, 2000 and Phillips *et al.*, 1978). A professional macrophyte survey would be useful in determining the abundance and diversity of aquatic plant species present within the wetland as this may provide further insight into wetland function.

Furthermore, events such as blooms of filamentous algae and duck weed persisted for long periods of time throughout the monitoring periods (Figure 4.14). These are likely to have had a significant effect on water quality during this investigation but, were only documented visually through observations made while sampling and through fixed point photography (see Section 4.4 below). It is likely that the eutrophic conditions within the wetland, particularly at the outlet, drive the growth of algae, duck weed and blanket weed. Dense covers of duckweed are known to inhibit oxygen entering surface waters though diffusion and limit the photosynthetic production of oxygen by phytoplankton because of poor light penetration (Vymazal, 2008). As a result, and, as seen in water quality data from this investigation, the water is at risk of becoming anoxic. Excessive duckweed growth can accumulate large amounts of mineral nutrients (N and P) in their tissues. Monitoring and control of duckweed is therefore essential in order to maintain healthy growth rates and nutrient uptake. However, if duckweed is not removed from wetlands/surface waters then the nutrients accumulated can be very rapidly released from decomposing detritus back into the water which in turn adds to the eutrophication issues (Vymazal, 2008 and Szabó,*et al.*, 2000).

Figure 4.14: (Left) Image of Wetland outlet cell with extensive cover of duckweed. (Right) FoHMP volunteer documenting the presence of dense algal biomass and blanked weed at outlet cell adjacent to outlet sonde during a water spot sample collection.

If frequently occurring, this growth of extensive covers of such weed and subsequent decomposition will likely shorten the ‘life-time’ of the wetlands, increasing the speed at which the system will start acting as a source of nutrients and other pollutants rather than a sink.

4.3.3 Birds

Methods currently being used by FOHMP volunteers to gather bird data are limited to providing bird species presence over the Headstone Manor Park site as a whole. British Trust for Ornithology methods used by FOHMP volunteers splits the entire Headstone Manor Park into two transects across 10km squares (the Headstone Manor and the Headstone Manor Park).

Although the wetland falls within one of these sampling squares, and is intersected by the corresponding sampling transect, the lack of GPS data makes it difficult to isolate the wetland itself from other potential bird habitats such as the moat. Therefore, these data do not allow for specific analysis of potential impacts that the wetland construction alone has had on bird population trends over time. Volunteers that regularly carry out bird surveys across the site have highlighted that the majority of birds use both the moat and the wetlands interchangeably, however by combining species data with accurate location data, better insight into this observation, and in turn trends over time, could be gathered and analysed more effectively. The use of the BirdTrack mobile application would help facilitate this, as a live GPS grid reference location can be submitted with each individual bird sighting that is logged on the application.

Figure 4.15: Images of birds that have been seen using both the Headstone Manor Park moat and wetlands in 2022. Top left to bottom right: Lesser black-backed gull, little egret, black headed gull, Egyptian geese, greylag goose, grey wagtail. Credit: Peter Elton (FoHMP).

4.4 Fixed-Point Photography

Fixed-Point Photography (FPP) was used to observe and visually demonstrate wetland benefits to non-technical audiences. FPP was also used as a method to monitor habitat changes/development over time (the course of one year) and accompanied plant diversity survey data. Key events in the monitoring timeline can be seen more clearly from the FPP images (see Figure 4.16). For example, the first signs of duckweed, blanket weed and other algal and vegetation growth at the outlet cell in July. By August, the entire outlet cell can be seen to be covered in algae/vegetation, aligning with, and supporting the data gathered through spot sampling and sonde measurements. In October, algae/vegetation can be seen to have cleared (died-off) almost completely, while macrophyte and reed coverage at the outlet remains dense. The FPP also evidences conditions such as drought and heavy rainfall, with water levels and wetland size being seen to vary significantly throughout the monitoring period. For example, in the images taken in September and November, water levels can be seen to be higher than in other months, with water colour and clarity looking quite turbid, which can be a useful indicator of not only precipitation but also potential pollution. Furthermore, these images help to track changes in the diversity of flowering terrestrial plants and wildflowers.

Figure 4.16: Fixed-Point Photography images of the outlet from July to October 2022. Credit: Peter Elton (FoHMP).

5 Conclusions

5.1 Citizen Science

Citizen Scientists were successful in collecting meaningful data that supported sonde measurements and data collected by ZSL staff and partners. Working with an existing group of volunteers with a passion for improving Headstone Manor Park led to good engagement numbers with volunteers willing to participate in a range of monitoring activities. Secure on-site facilities meant that equipment could be stored safely, and samples could easily be processed and sent to the laboratory for analysis. The FoHMP are happy to continue collecting data and be trained in new methodologies for monitoring the wetlands.

5.2 Biodiversity

Consistent biodiversity data is already being collected by volunteers. However, the shift of data collection to application-based data entry would improve the comparability of species data, particularly for birds. By recording using the BirdTrack app rather than by submitting monthly recordings via email, data can be viewed, accessed, and downloaded more easily, with the additional benefit of geo-located entries.

Initial invertebrate data indicated significantly different taxa present at the inlet compared to the outlet, with the outlet containing communities of good abundance and several pollution sensitive taxa. Following the decline of dissolved oxygen concentrations at the outlet to anoxic levels over summer, the presence of these communities significantly declined and, in some cases, completely died-off. This implies that although the wetlands can at times support healthy, diverse invertebrate taxa, they are not resilient to the conditions that have been observed. These conditions include (a) the wetland being at an immature stage of development with the flora and fauna not fully established; (b) weather conditions being particularly testing, including an extreme hot weather event over the summer and (c) inputs of high concentrations of nutrient and other pollutants typical of urban conditions, leading to the development of eutrophic conditions.

5.3 Water Quality and Sediment Conclusions

Based on the data gathered through this investigation and initial interpretations, it is currently difficult to disaggregate the relative impact of input pollution load, wetland maturity, wetland size and shape, and meteorology with high certainty. This being said, a number of key conclusions can be drawn from this investigation relating to the function and impact of the wetlands on water quality, sediment and biodiversity which will help to inform future monitoring and management.

Overall, the range of pollutants that have been highlighted within this report that are present within sediments and water indicate that poor quality water is entering the system through a number of pathways, likely through local misconnections, cross connections, road run off and urban runoff.

5.3.1 Water Quality

Dissolved Oxygen

A consistently poor oxygen regime was identified at the inlet and outlet over the course of monitoring and is likely a result of the high organic pollution load from sources in the upstream catchment. The outlet showed a strong diurnal dissolved oxygen pattern, a typical symptom of eutrophication. Following additional organic material input linked to rainfall during the summer monitoring period, the wetland became anoxic.

Ammonium

Ammonium concentrations are frequently reaching levels that are harmful to aquatic life and ammonium data are indicative of point and non-point source pollution to the wetland system. This was clearly demonstrated by high ammonium concentration inputs entering the system during/following rainfall events, but also through regular spikes of ammonium being recorded in the absence of precipitation. Inlet sonde data show signs of a daily double peak of contaminant rich water entering the wetland system linked to periods of greater domestic effluent discharge in the morning and evening.

Nitrogen and Phosphate

Nitrogen and phosphate data indicate that the wetland system is subject to high loads of contaminated water entering from the upstream catchment. Eutrophic conditions at the outlet were likely caused by inputs of nitrogen and phosphorus rich waters promoting algal blooms and vegetation growth, followed by their decomposition (exacerbated by drought conditions).

A first flush event on the 18th of June tipped the system over the edge with the wetland outlet becoming a source of nitrogen and phosphorus which was then reflected in the die-off of invertebrates. This was most probably not a one-off event and is likely to occur frequently within the wetland due to a consistent input of poor quality of water. This has the potential to limit wetland functionality, however the degree to which the system is vulnerable to this is not yet known.

Overall, although some positive indicators of wetland function are seen initially in the improvement of nitrogen and phosphorus concentrations in comparison to UKTAG-EQS and European Nitrogen Assessment standards, the results of this investigation, in particular the incidences of the wetland becoming a source of nutrients rather than a sink, indicates that inputs of organic pollution are too high at present for the wetland to operate effectively in providing consistent improvements in water quality. This, in turn, limits benefits to biodiversity and the ability of the wetland to function as a multi-benefit system.

Heavy Metals

Although direct comparisons to standards for certain metals cannot be made due to bioavailable metal concentrations being lower than the measure dissolved concentrations, initial conclusions can still be drawn. The pollutants of greatest concern at the wetland appear to be copper, nickel and zinc. Copper and zinc were more frequently found at higher concentrations in inlet samples than in outlet samples, indicating that these are being washed into the system from a range of upstream pollution sources. However, nickel concentrations were more frequently higher in outlet samples. Wet-weather event/storm sampling would be effective in gaining a better understanding of wetland function in relation to the reduction of water-bound heavy metal pollutants passing through the wetland and entering the moat.

BOD

Unlike other water quality data, BOD results show a clear trend of reduction in BOD between the inlet and the outlet, supporting the assumption that wetlands can effectively reduce the concentration of BOD as water passes through different cells. However, it should be noted that these results are only based on two samples.

5.3.2 Sediment Quality

Heavy Metals

Inlet samples consistently contained higher concentrations of individual heavy metals indicating successful wetland function. The failure of copper, lead, zinc, nickel and cadmium to meet SedNet guidelines support the findings of water sample data, indicating that there are serious, chronic heavy metal pollution inputs to the wetland system.

PAHs and PHCs

Inlet samples consistently contained higher concentrations of individual PAHs and consistently failed to meet guideline standards. Initial PAH results look promising, with data so far indicating that the wetland is successfully trapping high PAHs inputs and preventing these contaminants from being transported downstream.

Sediment concentrations for individual Aliphatic and Aromatic PHCs were higher in inlet samples than within outlet samples. This indicated that although these pollutants are entering the system at the inlet, they are being successfully stored within sediments in the inlet/forebay cell.

However, the system is still young and additional data on sediment transport downstream in the event of heavy rainfall would need to be monitored to confirm these initial conclusions.

6. Next Steps & Recommendations

The final aim of this investigation was to use findings to help inform future monitoring and maintenance of the Headstone Manor wetlands site and share lessons learnt more widely to advise upcoming wetland projects within the catchment. Based on the findings of this investigation, the following recommendations and next steps are proposed.

6.1 Next Steps for ZSL

ZSL will work with FoHMP and Harrow Council to support long-term monitoring of the wetland. This will encompass the following activities:

Continued citizen science monitoring

Invertebrate sampling as part of this investigation was useful in identifying a period of change within the wetland, aligning well with the findings of the water quality data. It is unknown if the shift from aerobic to largely anaerobic conditions (the 'die off') will happen again or if it was a function of the extreme heat experienced in the summer of 2022 and high pollution loading into a maturing wetland.

It is important we continue to routinely monitor the wetland to check it is functioning as a predominantly aerobic system. To do this, ZSL will develop a citizen science invertebrate monitoring method, adapted from the PSYM methodology and the Riverfly (RMI) Monitoring Methodology (used widely across the rivers of the Crane catchment). A trigger level could be set that would be indicative of a pollution/die-off event, at which point Harrow Council and the Citizen Crane team could be alerted and further investigation could be carried out to identify and remedy the problem. Invertebrate sampling could be combined with the collection of water quality data through the use of Nitrogen, Phosphorus and Ammonium strip tests (as used during the WaterBlitz sampling day) to record chemistry at the time of sampling.

Future monitoring and reporting

This investigation, and the monitoring data gathered to support it, was carried out shortly after construction and prior to the complete maturation of the wetlands (usually estimated at approximately 3-4 years). Therefore, to understand the full potential of wetland function, it is important to periodically revisit sampling the Headstone Manor Park wetlands to collect data that can be compared to the data presented in this report.

Key future monitoring activities to be carried out by ZSL within the SWC programme include nutrient water spot sample monitoring (N, P and BOD) and sediment monitoring (organics, heavy metals, PAHs and PHCs). Based on maturation times and wetland lifetime estimates (time taken before large-scale sediment removal is required to prevent the wetland becoming a source rather than a sink), it is recommended that this data collection and subsequent reporting takes place after Year 3 (2025) and Year 5 (2027) subject to SWC funding.

Comparison to long-term Citizen Crane data in Yeading Brook West

The Citizen Crane Programme began in 2014, produces an annual progress report, that summarises long-term RMI and water quality data from up to 16 sites across the Crane catchment. One of the sites regularly monitored within The Citizen Crane programme is located at Headstone Manor Park, on the Yeading Brook downstream of the wetlands.

In future Citizen Crane Reports, it would be useful to highlight any impacts of the wetlands on the downstream RMI data. This will provide useful context to whether or not downstream conditions have improved since the construction of the wetland and what future trends may look like.

Work with FoHMP to support them in the collection of biodiversity data

The Crane Valley Partnership, supported by SWC, have plans to improve biodiversity monitoring, with a particular focus on standardising data collection of bat populations within the Crane catchment. The Headstone Wetlands would be a suitable site to be used as a pilot for this, as not only do wetlands have the potential to provide suitable habitat for bats, but also, previous bat records are available from this site that could be used for comparison.

It is recommended that ZSL work with FoHMP volunteers to map existing data, identify survey gaps and work with citizen scientists to systematically record and monitor bat communities using Anabat detectors.

6.2 General Recommendations

6.2.1 Monitoring

In addition to the monitoring activities recommended to be continued by Citizen Scientists and ZSL, it would be useful for the following monitoring and maintenance activities to take place and the results fed into follow-up reporting:

Wet-weather/Storm-event sampling:

The Guidance Manual for Constructed Wetlands (Ellis, Shutes and Revitt, 2003) recommends that one storm event during each season should also be sampled to provide information on short-term wet weather event performance as well as help to determine residence times.

This data will allow for the evaluation of the capacity of the wetland to provide treatment for substances such as those associated with road runoff pollution, which is suggested to be a key source of pollution into the Headstone Manor Park wetlands, based on findings from this investigation. We were unable to capture wet weather performance data due to logistical restrictions as well as the extreme weather conditions. Wet-weather data will also help to ground-truth ammonium spike concentration data, which, as highlighted in this report, are not consistently and accurately recorded by the ion selective sonde sensors. This will enable ammonium concentration data to be compared to WFD guidelines more reliably.

Develop a better understanding of wetland flow, pollution loadings and bypass structure usage:

Further studies on the flow through the wetland and the bypass are recommended. Flow in combination with concentration data for key water quality parameters will allow the calculation of load. Calculating pollutant loadings entering the wetland will allow us to track the impact of remediation work by Thames Water and any new pollution source control measures in the upstream catchment over time. In addition, measuring the frequency and proportion of flow that bypasses the wetland is important in understanding the overall impact of the wetland on the river downstream and will be helpful in defining maintenance protocols and if necessary, any adjustments to the current design. The flow investigation carried out by Imperial College London researchers, as part of the CAMELLIA Project, alongside ZSL have provided a rudimentary understanding of the hydraulic workings of the wetland. Due to several limitations, accurately modelling flow with the available level sensor data was not possible. However, data was successfully used to calculate approximate values. Further detailed recommendations specific to investigation wetland flows are provided in Appendix 6.

6.2.2 Maintenance and pollution removal

<u>Remove pollution at the source - Thames Water Surface Water Outfall Programme</u>

During regular observations carried out as part of the volunteer water sample data collection, as well as during staff sampling and site visits, the Headstone Manor wetland inlet was recorded to frequently display signs of visual pollution impacts across the forebay cell (>10m) as well as strong smells, discolouration, visible foam/scum, large coverage of grey fungus and/or litter being consistently present. If scored using the Outfall Safari methodology (ZSL, 2019) for locating, assessing the impact of, and reporting polluted surface water outfalls (PSWOs), the headstone outlet would regularly score >10, which would indicate a pollution problem that requires urgent attention. It is therefore recommended that Thames Water's Surface Water Outfall Programme team investigate the upstream catchment (see Figure 6.1) to locate and resolve sources of pollution.

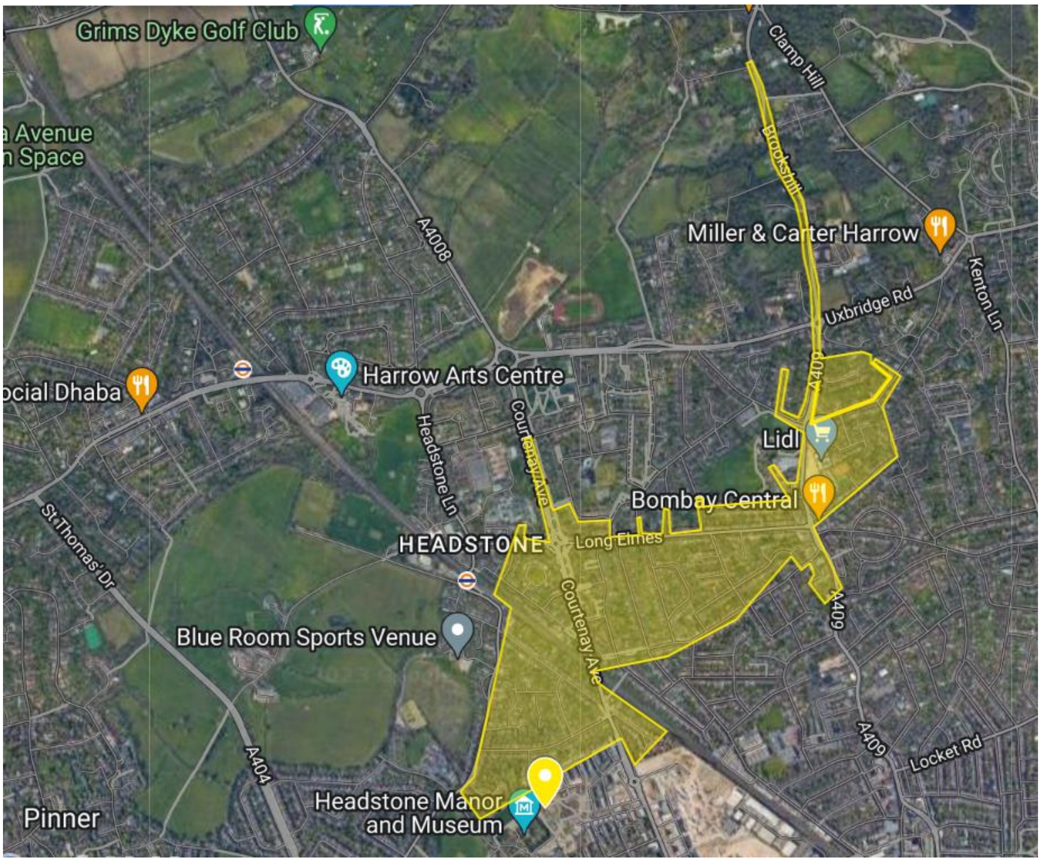

Figure 6.1: Map showing the area of land within the upstream drainage catchment (Credit: Thames Water) of the Headstone Manor Park Wetlands (highlighted in yellow). Map created using Google (n.d.). *Please note that this is a rough representation of upstream catchment area to only be used as a guideline.*

Vegetation management

Monitoring aquatic plant growth as well as Invasive Non-Native Species (INNS) monitoring, through the commissioning of periodic professional surveys, would not only help to inform management practices, such as vegetation clearing and weed control, but also advise potential future planting practices, to maximise wetland function and prevent future bloom events like those seen during this investigation.

Algal blooms and their subsequent die-off are negatively impacting the wetland health and are a function of high nutrient inputs to the wetland. Regular and extensive blooms of algae and duckweed can also build-up and clog outflow pipes, interfering with wetland flows and water levels and therefore their control and management should be considered following the results of this study. Although vegetation management takes place regularly on site, these activities do not directly target algal bloom events and blankets of duckweed forming at the outlet cell in particular. There are number of options for control and/or removal of this vegetation that could be considered (Ellis, Shutes and Revitt, 2003) and Kaldec and Wallace (2009), however, reducing nutrient inputs at source would likely be the most effective method of control.

If future monitoring shows continued summer die-offs due to low dissolved oxygen, then options for an aeration system that can be activated by low DO concentrations can be investigated.

Public perception surveys

Over the course of this investigation, local community members and volunteers working with ZSL were keen to share and discuss their opinions of how construction of the wetland had changed their perception of the area and impacted the way in which they used and interacted with the Headstone Manor Park site. We suggest that an assessment of the social impacts of the wetlands through public perception surveys, similar to those carried out in the Lower Crane Restoration Pilot Project Report (ZSL, 2023), would be useful in evaluating community feedback in order to gain a better understanding of the wetlands function as a multi-benefit system, providing not only water quality and biodiversity benefits but also benefits from a communities and engagement perspective.

Sediment accumulation and removal rates

Once the wetland has matured, the AECOM Design Report recommends the removal of sediments from the forebay every 2-3 years and the removal of sediments from the secondary pond/reed pond every 2-10 years (or as required).

Future investigation into the silt/sediment accumulation rates of the wetland would help to inform wetland management and maintenance activities and more accurately forecast timings for desilting. This could in turn reduce the risk of the wetland becoming a source of pollutants rather than a sink in the coming years. It may also be useful to investigation the silt accretion in the moat over the next few years and compare this to wetland rates.

Although analysis of data gathered through this investigation suggests that ~90% of PAHs are being stored, the presence of high concentrations of pollutants such as Benzo-a-pyrene will usually tip waste sediment from non-hazardous to hazardous (pers comms. Richard Haines). Therefore, the control of these sediments will need to be carefully managed as the implications of the presence of these pollutants will have implications on the way spoil/sediments are treated.

<u>Share data to further the study of urban constructed wetlands used as nature-based solutions</u>

It is recommended that the data gathered through this investigation are made available for others who are studying constructed wetland function. Integrating Headstone wetland data within wider reporting, such as peer reviewed papers, would help to establish how this system is functioning in comparison to other constructed wetlands in urban areas. This will develop understandings of the capacity and limitations of wetlands to process pollutants found in urban surface water runoff and refine how wetlands as nature-based solutions are designed and manged for maximum water quality and biodiversity benefit.

Furthermore, the potential to co-work with partner SWC organisations and academic institutions or/researchers would benefit the continued monitoring and reporting on the Headstone Manor Park wetlands.

7 Limitations

The majority of limitations to this investigation have already been discussed throughout the report, however, key factors that restricted monitoring, analysis and interpretation of results included (but are not limited to) the following:

- **The age of the system:** The Headstone Manor Park Wetlands were sampled shortly after their construction and therefore still need time to mature before their maximum potential can be assessed.
- **Time, funding and resources:**
    - Limited timeframes for reporting meant that a full year of data could not be collected and therefore a complete assessment of seasonal impacts on the wetlands could not be achieved. Ideally, more samples would have been collected, particularly for BOD and the wetland would have been monitored under more 'normal' conditions, with abnormally hot and cold periods having potentially influenced the results of this investigation and in turn the conclusion drawn about wetland function.

- The high costs of using sondes restricted their use for two ~1-month periods at a time. Water sample and sediment collections were also limited. Results of this investigation, particularly during the summer monitoring period showed that the outlet cell (Cell 3) was almost functioning as a separate system, with algal blooms and duckweed significantly impacting results. Ideally an additional sampling point would have been added to help better distinguish functionality between cells (Cells 1 and 2).
- Furthermore, due to the design of the wetland, it was difficult to gather sediment samples from areas that may have provided a better insight into sedimentation and pollution storage however steep drop-offs in depths meant that sampling locations were constrained due to access and safety. The use of monitoring equipment such as grab samplers could therefore assist in more targeted sediment sampling.

- Comparison of results to standards and other wetlands:
  - Relatively little information if available for comparison of data such as water and sediment quality, to other urban (and more specifically London) wetlands systems that could have helped better interpret findings of this investigation.
  - Many of the recommended standards for comparison are based on the bioavailable concentrations of pollutants which could not be recorded as part of this investigation and so, meaningful comparisons to official guidance standards could not be made.

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9 Appendices

Appendix 1: Sonde Data

The results of summer and winter sondes data for Temperature (°C), Conductivity (µs/cm), pH, Ammonium (mg/l), Turbidity (NTU) and Dissolved Oxygen (%) are presented below as box plots.

A1.1 Temperature

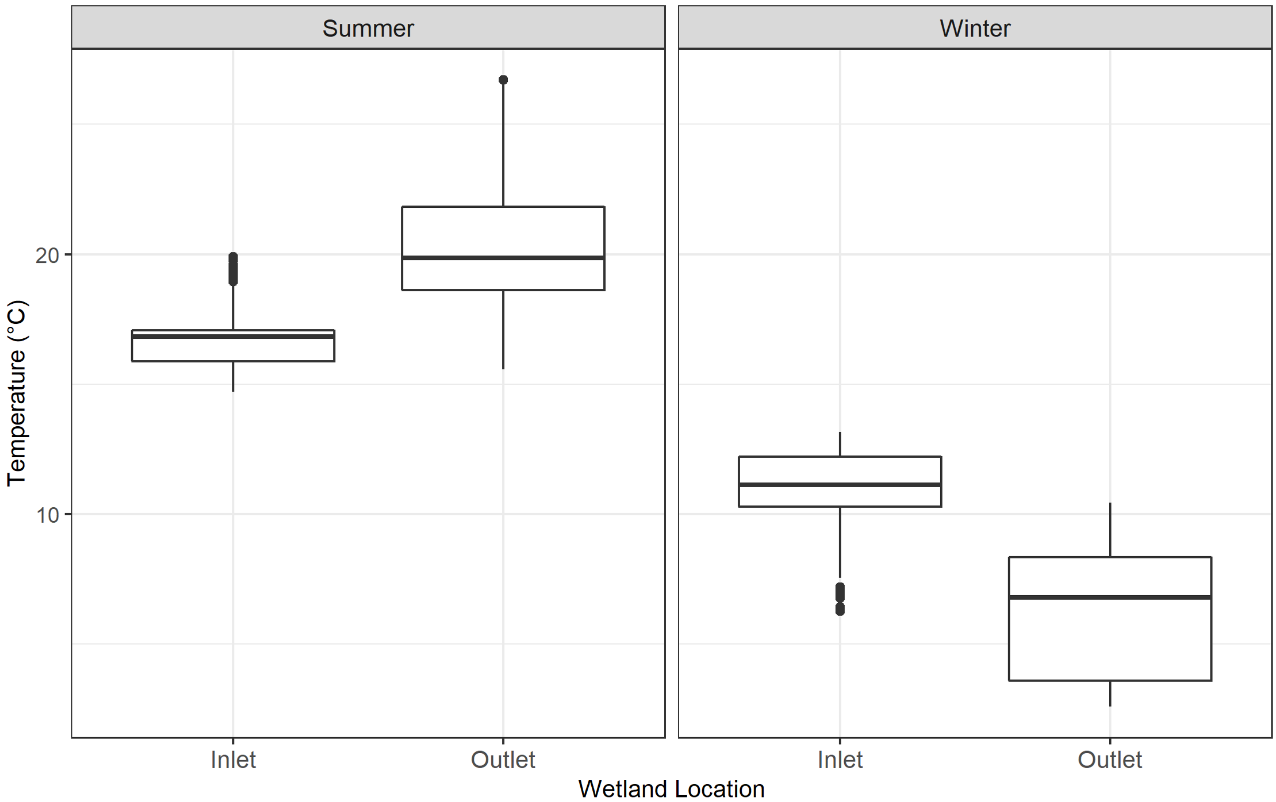

Figure A1.1: Comparison of Temperature data at the wetland inlet and outlet during summer and winter sondes deployment periods.

A1.2 Conductivity

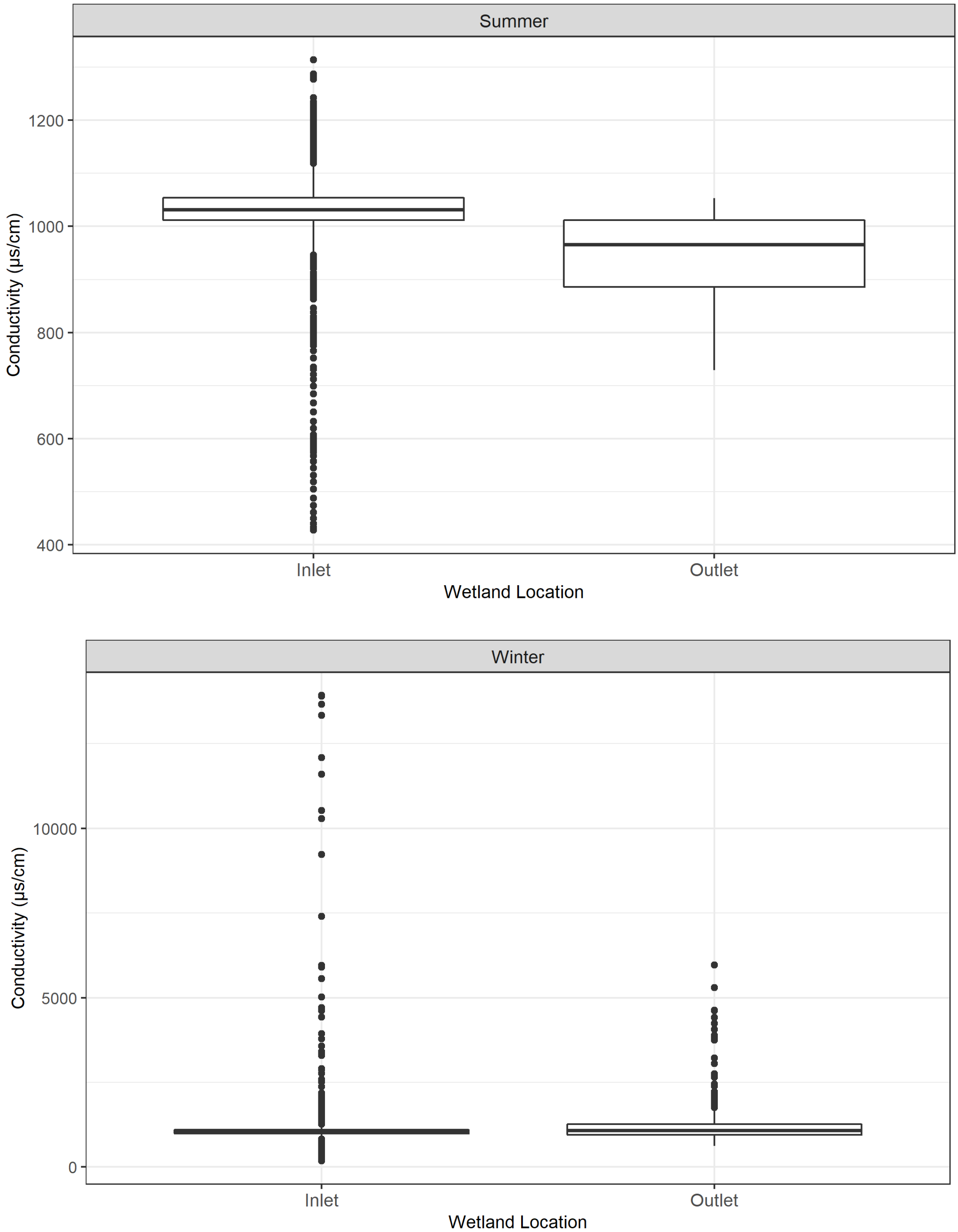

Figure A1.2: Comparison of Conductivity (µs/cm) data at the wetland inlet and outlet during summer and winter sondes deployment periods. Summer and winter data have been split for better visualisation.

A1.3 pH

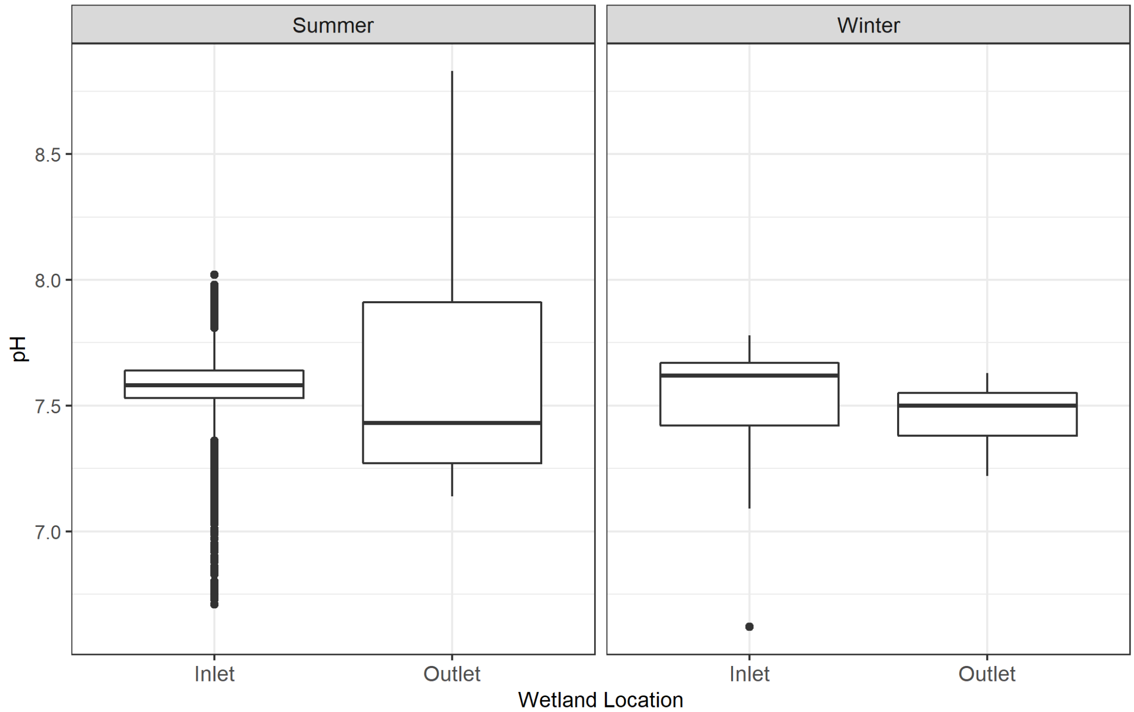

Figure A1.3: Comparison of pH data at the wetland inlet and outlet during summer and winter sondes deployment periods.

1.4 Ammonium

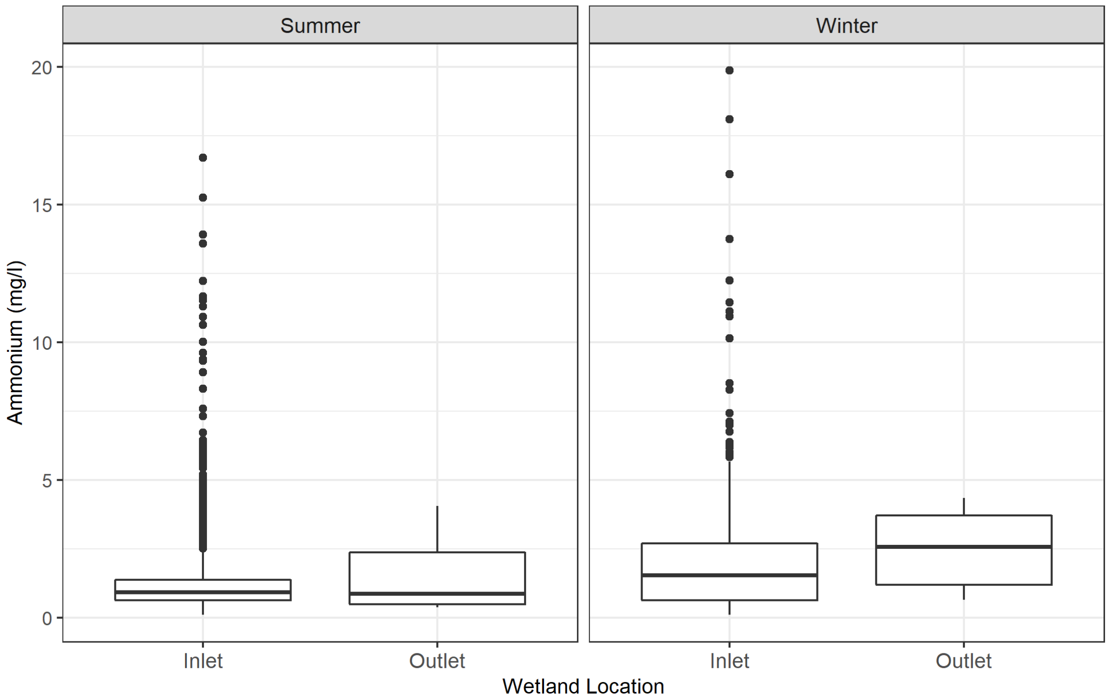

Figure A1.4: Comparison of Ammonium (mg/L) data at the wetland inlet and outlet during summer and winter sondes deployment periods.

A1.5 Turbidity

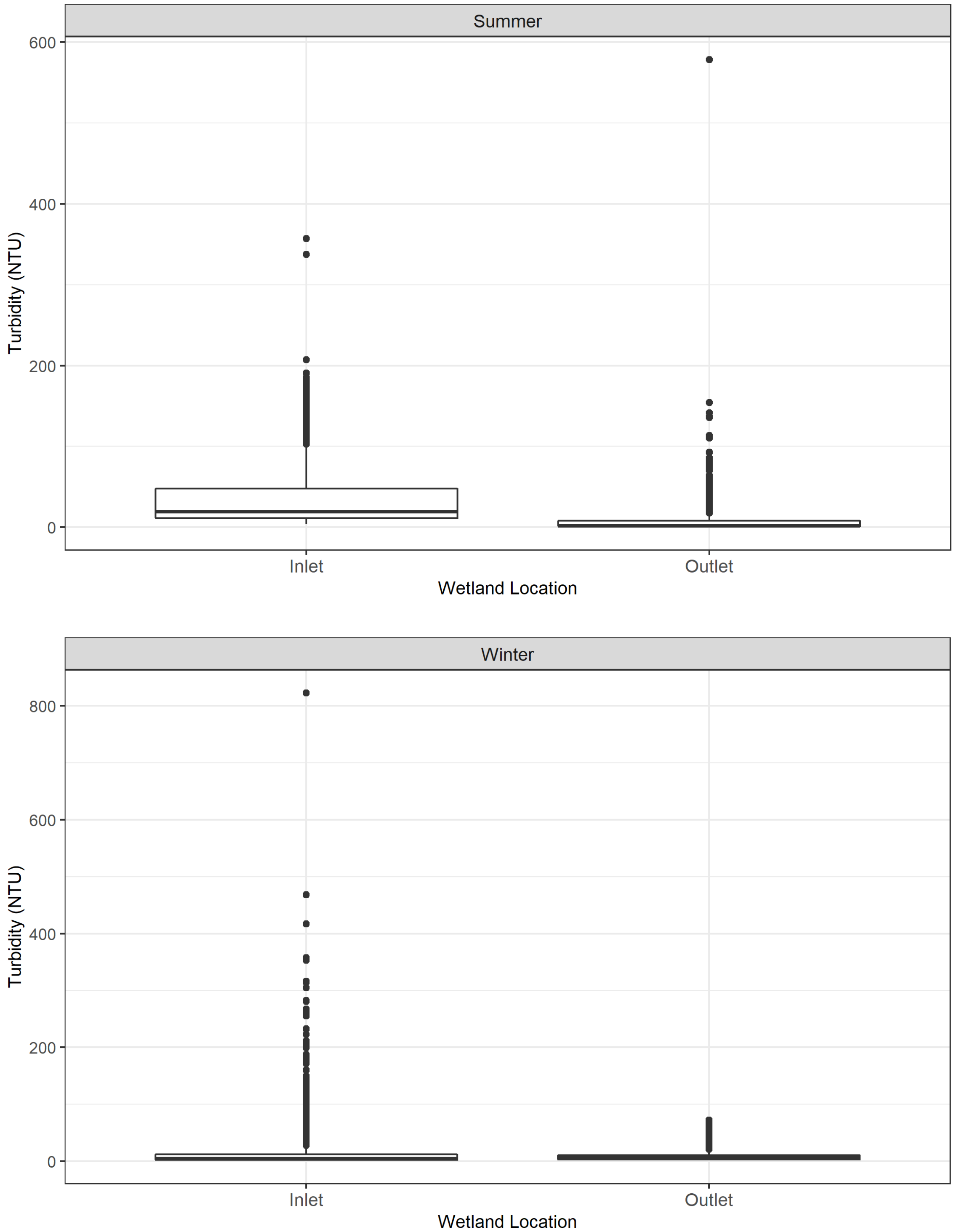

Figure A1.5: Comparison of Turbidity (NTU) data at the wetland inlet and outlet during summer and winter sondes deployment periods. Summer and winter data have been split for better visualisation.

A1.6. Dissolved Oxygen

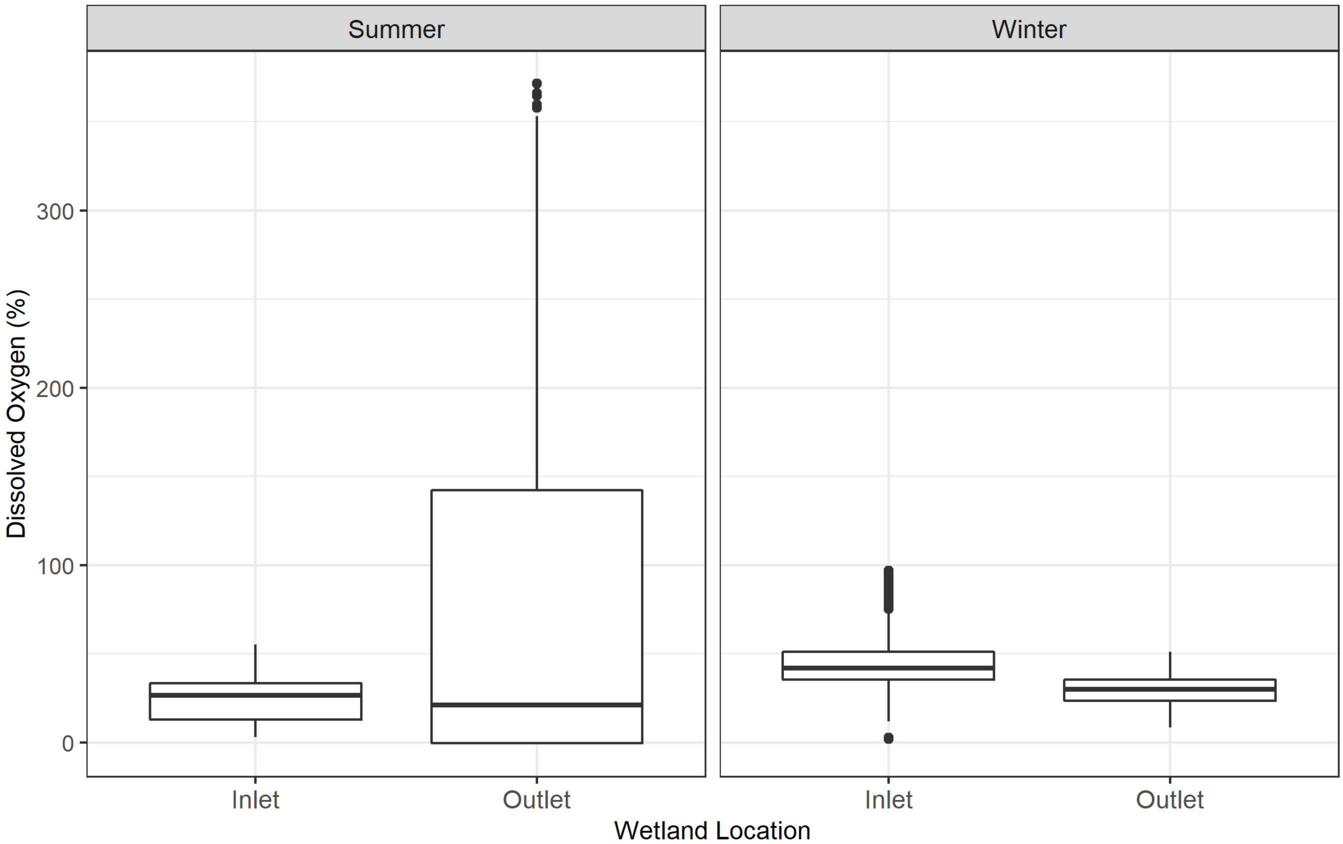

Figure A1.6: Comparison of Dissolved Oxygen (%) data at the wetland inlet and outlet during summer and winter sondes deployment periods.

Appendix 2: Water Spot Sample Data

Results of water spot sample data for 'General Inorganics' (Total Phosphate as P (µg/L), Total Nitrogen (Kjeldahl) (mg/L), Total Suspended Solids (mg/L) and Total Dissolved Solids (Gravimetric) (mg/L)) can be seen in Table A2.1.

Table A2.1: Comparison of water spot sample data across sampling dates and between the inlet and outlet sampling locations.

	Total Phosphate as P (µg/L)		Total Nitrogen (Kjeldahl) (mg/L)		Total Suspended Solids (mg/L)		Total Dissolved Solids (Gravimetric) (mg/L)	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
07/07/2022	800	260	1	0.5	26	10	620	490
14/07/2022	790	930	1.3	0.6	8	28	560	590
21/07/2022	300	990	0.6	1.2	3	14	550	590
28/07/2022	700	1000	0.7	1.2	7	66	560	510
06/10/2022	820	690	3.4	3	10	9	630	610
01/12/2022	440	180	1	1.5	0	61	600	500
07/12/2022	750	380	3.2	2.7	0	380	670	690
15/12/2022	400	430	2	0.3	120	30	850	620
05/01/2023	270	180	0.4	0.4	7	10	600	520

Visual representation of data in Table 2.1 can be found in the main report, other than results for Total Dissolved Solids, which can be seen below in Figure 2.5.

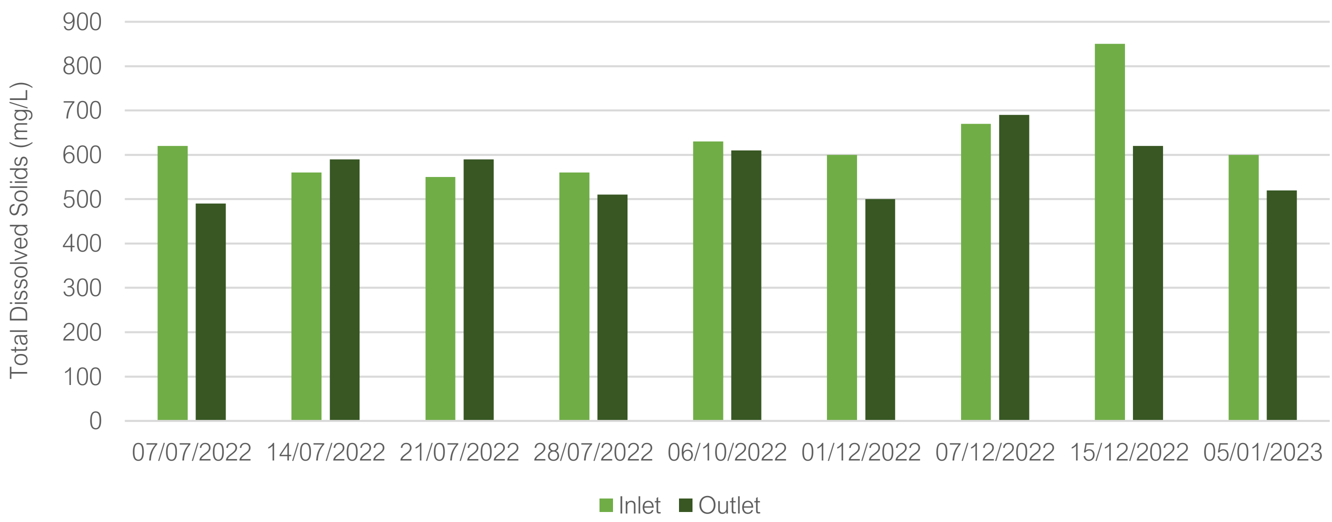

Figure A2.1: Comparison of water spot sample concentrations of Total Dissolved Solids (TDS) measured at the wetland inlet and outlet.

Appendix 3: Sediment Data

A3.1 Parameters analysed by i2 Laboratories

Parameters analysed by i2 Laboratories in the sediment samples included the following:

- Water Soluble Phosphate as P (2:1)
- Total Nitrogen (Kjeldahl)
- Dry solids @ 105ºC using gravimetric analysis
- Total Petroleum Hydrocarbon (TPH): Criteria Working Group (CWG) including BTEX (benzene, toluene, ethylbenzene and xylene) & MTBE (methyl tertiary butyl ether) using GC/MS and gas chromatography with flame-ionization detection analysis (GC-FID)
- Polycyclic aromatic hydrocarbon (PAH) – Speciated (Environmental protection agency -16) using GC/MS analysis: Napthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benzo(a)anthracene, Chrysene, Benzo(b)fluoranthene, Benzo(k)fluoranthene, Benzo(a)pyrene, Indeno(1,2,3-cd) pyrene, Di-benzo(a,h)anthracene, Benzo(ghi)perylene.
- Cadmium using ICP-OES analysis
- Chromium using ICP-OES analysis
- Copper using ICP-OES analysis
- Lead using ICP-OES analysis
- Nickel using ICP-OES analysis
- Zinc using ICP-OES analysis
- Magnesium ICP-OES analysis
- Potassium ICP-OES analysis

A3.2 General Inorganics

Table A3.1: Comparison of phosphate, total nitrogen and dry solid concentrations at the inlet and outlet samples with mean values shown as averages. Where readings were below detection limit, they were rounded down to zero to give a representative mean result.

			Inlet			Outlet		
	Units	Detection Level	Inlet 1	Inlet 2	Average	Outlet 1	Outlet 2	Average
Water Soluble Phosphate as P (2:1)	mg/kg	0.1	< 0.1	1	0.5	0.78	< 0.1	0.39
Total Nitrogen (Kjeldahl)	mg/kg	5	1400	2000	1700	2900	2300	2600
Dry solids	%	0.1	25	20	22.5	31	50	40.5

A3.3 Monoaromatics & Oxygenates

Table A3.2: Comparison of individual monoaromatics and oxygenates concentrations at the inlet and outlet.

	Inlet		Outlet	
Pollutant (µg/kg)	Inlet 1	Inlet 2	Outlet 1	Outlet 2
Benzene	< 1.0	< 1.0	< 1.0	< 1.0
Toluene	2400*	< 1.0	< 1.0	< 1.0
Ethylbenzene	< 1.0	< 1.0	< 1.0	< 1.0
p & m-xylene	< 1.0	< 1.0	< 1.0	< 1.0
o-xylene	< 1.0	< 1.0	< 1.0	< 1.0
MTBE (Methyl Tertiary Butyl Ether)	< 1.0	< 1.0	< 1.0	< 1.0

*Likely a false result – needs further investigation.

A3.4 PAHs

Table A3.3: Speciated PAH totals at inlet and outlet monitoring sites.

	Unit	Inlet	Outlet
Speciated Total EPA-16 PAHs	mg/kg	115	4.575

Table A3.4: Comparison of Speciated PAH concentrations (mg/kg) concentrations at the inlet and outlet monitoring sites to Canadian Guideline values for Interim Sediment Quality (ISQG/TEL) and Probable Effect Level (PEL) concentrations. Grey box = standard used for comparison, Red box = fails ISQG/TEL standard, Red text = fails PEL standard.

	Canadian Guidelines		Inlet		Outlet	
Speciated PAHs (mg/kg)	ISQG/TEL	PEL	Sample 1	Sample 2	Sample 1	Sample 2
Naphthalene	0.0346	0.391	< 0.05	0.44	< 0.05	< 0.05
Acenaphthylene	0.00587	0.128	0.25	0.9	< 0.05	< 0.05
Acenaphthene	0.00671	0.0889	0.37	0.65	< 0.05	< 0.05
Fluorene	0.0212	0.144	0.37	0.59	< 0.05	< 0.05
Phenanthrene	0.0419	0.515	4.4	7.2	< 0.05	0.44
Anthracene	0.0469	0.245	1.2	2.9	< 0.05	0.16
Fluoranthene	0.111	2.355	7.8	20	0.5	1.1
Pyrene	0.053	0.875	7.2	17	0.46	0.94
Benzo(a)anthracene	0.0317	0.385	4.3	12	0.31	0.58
Chrysene	0.0571	0.862	3.8	11	0.32	0.57
Benzo(b)fluoranthene	0.0319	0.782	4.5	12	0.44	0.76
Benzo(k)fluoranthene	0.00622	0.135	1.6	5.1	0.17	0.38
Benzo(a)pyrene	n/a	n/a	4.4	12	0.38	0.72
Indeno(1,2,3-cd)pyrene	n/a	n/a	2.1	5.3	< 0.05	0.43
Dibenz(a,h)anthracene	n/a	n/a	0.53	1.5	< 0.05	< 0.05
Benzo(ghi)perylene	n/a	n/a	2.6	6.2	< 0.05	0.48

A3.5 Heavy Metals

Table A3.5: Comparison of sediment heavy metal concentrations (mg/kg) at inlet and outlet monitoring sites to SedNet Guideline values for Target and Intervention standards.

	Dutch (SedNet) Guidelines		Inlet		Outlet	
Pollutant (mg/kg) aqua regia extractable	Target	Intervention	Inlet 1	Inlet 2	Outlet 1	Outlet 2
Cadmium	0.8	12	0.9	1.1	0.6	0.5
Chromium	100	380	27	37	37	34
Copper	36	190	65	89	66	58
Lead	85	530	200	140	43	44
Nickel	35	210	340	21	26	26
Zinc	140	720	240	300	180	150

A3.6 PHCs

Table A3.6: Comparison of individual PHC concentrations at the inlet and outlet with averages. Grey box = value was below detection level.

Petroleum Hydrocarbons (mg/kg)	Detection Level	Inlet			Outlet		
		Inlet 1	Inlet 2	Inlet Mean	Outlet 1	Outlet 2	Outlet Mean
TPH-CWG - Aliphatic >EC5 - EC6 HS_1D_AL	0.001	< 0.001	< 0.001	0	< 0.001	< 0.001	0
TPH-CWG - Aliphatic >EC6 - EC8 HS_1D_AL	0.001	< 0.001	< 0.001	0	< 0.001	< 0.001	0
TPH-CWG - Aliphatic >EC8 - EC10 HS_1D_AL	0.001	< 0.001	< 0.001	0	< 0.001	< 0.001	0
TPH-CWG - Aliphatic >EC10 - EC12 EH_CU_1D_AL	1	< 1	< 1	0	< 1	< 1	0
TPH-CWG - Aliphatic >EC12 - EC16 EH_CU_1D_AL	2	12	12	12	< 2	< 2	0
TPH-CWG - Aliphatic >EC16 - EC21 EH_CU_1D_AL	8	32	47	39.5	21	27	24
TPH-CWG - Aliphatic >EC21 - EC35 EH_CU_1D_AL	8	250	360	305	160	170	165
TPH-CWG - Aliphatic (EC5 - EC35) EH_CU+HS_1D_AL	10	290	420	355	180	190	185
TPH-CWG - Aromatic >EC5 - EC7 HS_1D_AR	0.001	< 0.001	< 0.001	0	< 0.001	< 0.001	0
TPH-CWG - Aromatic >EC7 - EC8 HS_1D_AR	0.001	2.4	< 0.001	1.2	< 0.001	< 0.001	0
TPH-CWG - Aromatic >EC8 - EC10 HS_1D_AR	0.001	< 0.001	< 0.001	0	< 0.001	< 0.001	0
TPH-CWG - Aromatic >EC10 - EC12 EH_CU_1D_AR	1	< 1	< 1	0	< 1	< 1	0
TPH-CWG - Aromatic >EC12 - EC16 EH_CU_1D_AR	2	< 2	11	5.5	< 2	< 2	0
TPH-CWG - Aromatic >EC16 - EC21 EH_CU_1D_AR	10	30	52	41	< 10	< 10	0
TPH-CWG - Aromatic >EC21 - EC35 EH_CU_1D_AR	10	150	170	160	< 10	< 10	0
TPH-CWG - Aromatic (EC5 - EC35) EH_CU+HS_1D_AR	10	190	240	215	< 10	< 10	0

Appendix 4: Biodiversity Data

A4.1 Aquatic Invertebrates

Table A4.1: Comparison of invertebrate sampling results between the inlet and outlet monitoring sites.

PSYM Scoring Invertebrates					
Taxa	BMWP Score	03/08/2022		06/10/2022	
		Inlet	Outlet	Inlet	Outlet
Aeshnidae	8	-	✓	-	-
Asellidae	3	✓	✓	✓	✓
Baetidae	4	✓	✓	✓	-
Chironomidae	2	✓	✓	✓	-
Coenagrionidae	6	-	✓	-	-
Corixidae	5	✓	✓	✓	✓
Erpodellidae	3	✓	✓	-	-
Gammeridae	6	✓	✓	✓	✓
Gerridae	5	-	✓	-	-
Glossiphoniidae	3	-	✓	-	✓
Lymnaeidae	3	-	✓	-	-
Physidae	3	✓	✓	-	-
Planorbidae	3	✓	✓	-	-
Trichoptera sp.	8	-	✓	-	-
Notonectidae	5	-	-	-	✓
Total no. of listed PSYM taxa		8	14	5	5
ASPT Score		3.6	4.5	4	4.4
Non-PSYM Taxa					
Invertebrate Taxa		03/08/2022		06/10/2022	
		Inlet	Outlet	Inlet	Outlet
Chaoboridae		✓	-	-	-
Culicidae		✓	-	-	-
Dugsiidae		-	✓	✓	✓
Hydrachnidia		-	✓	-	-
Oligochaeta		✓	-	-	-
Syrphidae		✓	-	-	-
Bithyniidae		-	-	✓	✓
Planorbis		-	-	-	✓
Vertebrate Taxa		Inlet	Outlet	Inlet	Outlet
Stickleback		-	✓	-	-
Common newt eft		-	✓	-	-
Total no. of PSYM and non-PSYM taxa		12	18	7	8

A4.2 Plants

Table A4.2: Plant survey data comparing species planted to species observed during survey.

a) Wildflowers/Flowering plants and Shrubs:

Common Name	Latin Name	Planted	Recorded	Planted & recorded
Agrimony	*Agrimonia eupatoria*	✓		
Bird's-foot trefoil	*Lotus corniculatus*		✓	
Black medick	*Medicago lupulina*		✓	
Black mustard	*Brassica nigra*		✓	
Blackthorn	*Prunus spinosa*	✓		
Bladder campion	*Silene vulgaris*	✓		
Bramble	*Rubus fruticosus*	✓	✓	
Broad-leaved everlasting pea	*Lathyrus latifolius*		✓	
Broad-leaved willowherb	*Epilobium montanum*		✓	
Buddleja	*Buddleja davidii*		✓	
Clustered dock	*Rumex conglomeratus*		✓	
Common evening primrose	*Oenothera biennis*		✓	
Common fleabane	*Pulicaria dysenterica*		✓	
Common knapweed	*Centaurea nigra*	✓	✓	✓
Common mallow	*Malva sylvestris*		✓	
Common sorrel	*Rumex acetosa*	✓		
Cornflower	*Centaurea cyanus*		✓	
Creeping buttercup	*Ranunculus repens*		✓	
Creeping thistle	*Cirsium arvense*		✓	
Crosswort	*Cruciata laevipes*	✓		
Curled dock	*Rumex crispus*		✓	
Dogwood	*Comus sanguineum*	✓		
Goats rue	*Galega officinalis*		✓	
Goat's-beard	*Tragopogon pratensis*	✓		
Great mullein	*Verbascum thapsus*	✓		
Great willowherb	*Epilobium hirsutum*		✓	
Greater knapweed	*Centaurea scabiosa*	✓	✓	✓
Greater plantain	*Plantago major*		✓	
Hedge bedstraw	*Galium album (Galium mollugo)*	✓		
Hedge bindweed	*Calystegia sepium*		✓	
Hedge woundwort	*Stachys sylvatica*		✓	
Lady's bedstraw	*Galium verum*	✓	✓	✓
Lesser burdock	*Arctium minus*	✓		
Marsh thistle	*Cirsium palustre*		✓	
Meadow cranesbill	*Geranium pratense*	✓		
Meadowsweet	*Filipendula ulmaria*	✓		
Melilot	*Melilotus spp*		✓	
Musk Mallow	*Malva moschata*	✓		

Oxeye daisy	*Leucanthemum vulgare*			
Pepper Saxifrage	*Silaum silaus*			
Pineappleweed	*Matricaria discoidea*			
Purple loosestrife	*Lythrum salicaria*			
Ragged robin	*Lychnis flos-cuculi*			
Red campion	*Silene dioica*			
Redleg	*Persicaria maculosa*			
Ribwort plaintain	*Plantago lanceolata*			
Rough chervil	*Chaerophyllum temulum*			
Scentless mayweed	*Tripleurospermum inodorum*			
Selfheal	*Prunella vulgaris*			
Spear thistle	*Cirsium vulgare*			
Tansy	*Tanacetum vulgare*			
Tuften vetch	*Vicia cracca*			
Upright hedge-parsley	*Torilis japonica*			
Weld	*Reseda luteola*			
White clover	*Trifolium repens*			
Wild angelica	*Angelica sylvestris*			
Wild carrot	*Daucus carota*			
Wild teasel	*Dipsacus fullonum*			
Yarrow	*Achillea millefolium*			
	Total:	30	37	8

b) Grasses:

Common Name	Latin Name	Planted	Recorded	Planted & Recorded
Cocksfoot	*Dactylis glomerata*			
Common bent	*Agrostis capillaris*			
Common wheat	*Triticum aestivum*			
Crested dog's- tail	*Cynosurus cristatus*			
Meadow fescue	*Festuca pratensis*			
Meadow foxtail	*Alopecurus pratensis*			
Perennial ryegrass	*Lolium perenne*			
Quacking grass	*Briza media*			
Red fescue	*Festuca rubra*			
Sweet vernal-grass	*Anthoxanthum odoratum*			
Tall fescue	*Festuca arundinacea*			
Timothy	*Phleum pratense*			
Tufted hair-grass	*Deschampsia cespitosa*			
Yorkshire fog	*Holcus lanatus*			
	Total	11	7	3

c) Reeds

Common Name	Latin Name	Planted	Recorded	Planted & Recorded
Common mace	*Typha latifoli*			
Common reed	*Phragmites australis*			
	Total	2	2	2

A4.3 Birds

Table A4.3: Bird species sightings recorded for 2021 and 2022. Please not these are not standardised for effort. Data collected by FoHMP volunteers and recorded using BirdTrack. BirdTrack is organised by the BTO for the BTO, RSPB, BirdWatch Ireland, SOC and WOS.

Common name	Species	2021	2022
Blackbird	*Turdus merula*	✓	✓
Blackcap	*Sylvia atricapilla*	✓	✓
Black-headed Gull	*Chroicocephalus ridibundus*	✓	✓
Blue Tit	*Cyanistes caeruleus*	✓	✓
Canada Goose	*Branta canadensis*	✓	✓
Carrion Crow	*Corvus corone*	✓	✓
Chaffinch	*Fringilla coelebs*	✓	✓
Chiffchaff	*Phylloscopus collybita*	✓	✓
Coal Tit	*Periparus ater*		✓
Collared Dove	*Streptopelia decaocto*	✓	✓
Common Gull	*Larus canus*	✓	✓
Coot	*Fulica atra*	✓	✓
Cormorant	*Phalacrocorax carbo*	✓	
Dunnock	*Prunella modularis*	✓	✓
Egyptian Goose	*Alopochen aegyptiaca*		✓
Feral Pigeon	*Columba livia f. domestica*	✓	✓
Goldcrest	*Regulus regulus*		✓
Goldfinch	*Carduelis carduelis*	✓	✓
Great Spotted Woodpecker	*Dendrocopos major*	✓	✓
Great Tit	*Parus major*	✓	✓
Green Woodpecker	*Picus viridis*		✓
Greenfinch	*Chloris chloris*	✓	✓
Grey Heron	*Ardea cinerea*	✓	✓
Grey Wagtail	*Motacilla cinerea*	✓	✓
Greylag Goose	*Anser anser*		✓
Herring Gull	*Larus argentatus*	✓	✓
House Sparrow	*Passer domesticus*	✓	✓
Jackdaw	*Coloeus monedula*	✓	✓
Jay	*Garrulus glandarius*	✓	✓
Kestrel	*Falco tinnunculus*	✓	
Kingfisher	*Alcedo atthis*	✓	✓
Lesser Black-backed Gull	*Larus fuscus*	✓	✓
Linnet	*Linaria cannabina*		✓
Little Egret	*Egretta garzetta*	✓	✓
Long-tailed Tit	*Aegithalos caudatus*		✓
Magpie	*Pica pica*	✓	✓
Mallard	*Anas platyrhynchos*	✓	✓
Meadow Pipit	*Anthus pratensis*	✓	
Mistle Thrush	*Turdus viscivorus*		✓

Moorhen	*Gallinula chloropus*	✓	✓
Mute Swan	*Cygnus olor*	✓	✓
Nuthatch	*Sitta europaea*	✓	✓
Peregrine	*Falco peregrinus*		✓
Pied Wagtail (yarrellii)	*Motacilla alba yarrellii*	✓	✓
Red Kite	*Milvus milvus*	✓	✓
Redwing	*Turdus iliacus*	✓	✓
Ring-necked Parakeet	*Psittacula krameri*	✓	✓
Robin	*Erithacus rubecula*	✓	✓
Song Thrush	*Turdus philomelos*	✓	✓
Starling	*Sturnus vulgaris*	✓	✓
Stock Dove	*Columba oenas*	✓	✓
Swallow	*Hirundo rustica*		✓
Swift	*Apus apus*	✓	✓
Tufted Duck	*Aythya fuligula*	✓	✓
Woodpigeon	*Columba palumbus*	✓	✓
Wren	*Troglodytes troglodytes*	✓	✓

Appendix 5: Fixed-Point Photography

Fixed Point Photography images from the wetland inlet and outlet (Credit: Peter Elton, FoHMP).

June Inlet:

June Outlet:

July Inlet:

July Outlet:

August Inlet:

August Outlet:

September Inlet:

September Outlet:

October Inlet:

October Outlet:

November Inlet:

November Outlet:

December Inlet:

December Outlet:

Appendix 6: Imperial College London's Investigation into Wetland Flow Gauging

Dr Thomas Rowan and Prof Adrian Butler (Imperial College London)

A6.1 Introduction

Flow gauging of the wetland at Headstone Manor Park was carried out by researchers at Imperial College London in the Summer 2022 and Winter 2023 to support the water quality and biodiversity work conducted as part of the "Evidencing the Impact of Constructed Wetland: Headstone Manor Park River Crane Smarter Water Catchments Project."

It is essential to understand the discharge (or volume of flow) to calculate the contaminant fluxes and pollution loads. Although the scope of the flow gauging was limited, the design of the wetland and the characteristics of the flow control structures made it possible to use simple calculations to obtain flows from the level sensor data.

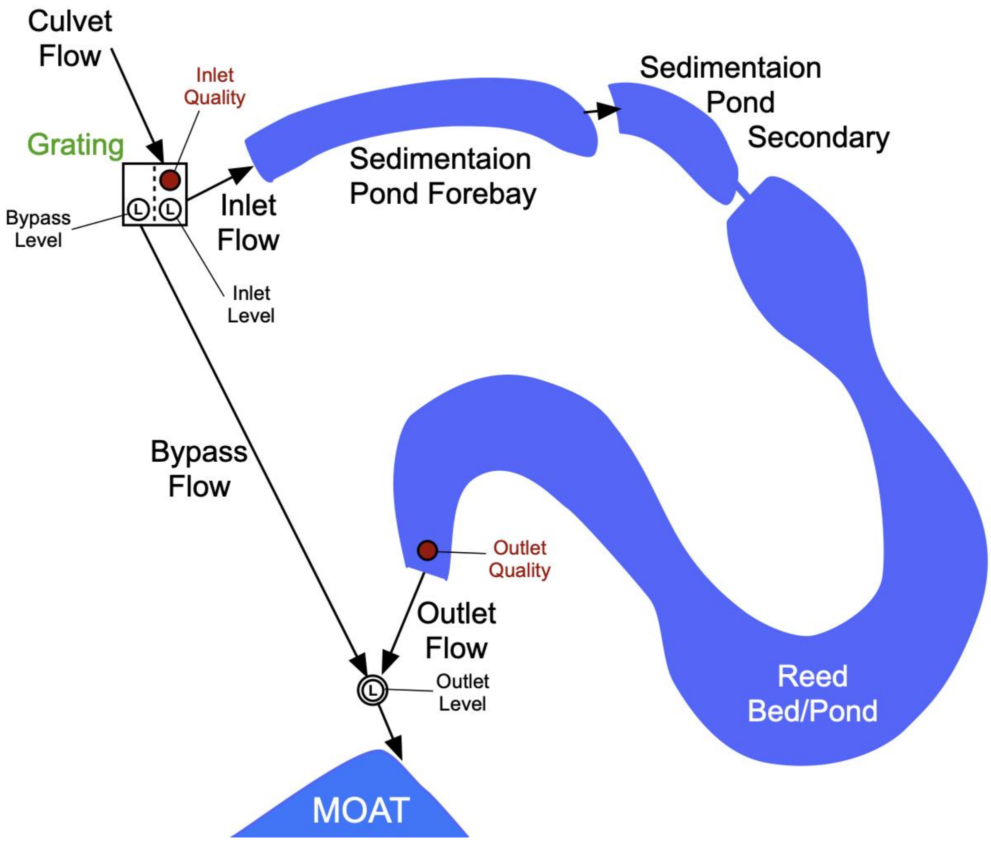

Figure A6.1: Diagram of the wetland detailing the positions of the level sensors on each of the three Level sensors 'L' (Inlet, Bypass and Outlet) and the Inlet and Outlet Quality sensors shown in red.

As shown in Figure A6.1, the wetland comprises three cells, with a flow restriction at the outlet and a height restriction at the inlet, making it ideal for non-contact level gauging to determine the flow regime through the wetland. The confluence of the wetland outlet flow and the bypass flow can be accessed via a manhole, providing an excellent location for flow gauging. Access for any other kind of flow gauging is limited.

A6.2 Theory

The wetland, designed by AECOM and evaluated by Metis, is designed to reduce surge flows by storing up to 1500m^3 of runoff during surge events, while also preserving a minimum flow rate at all other times.

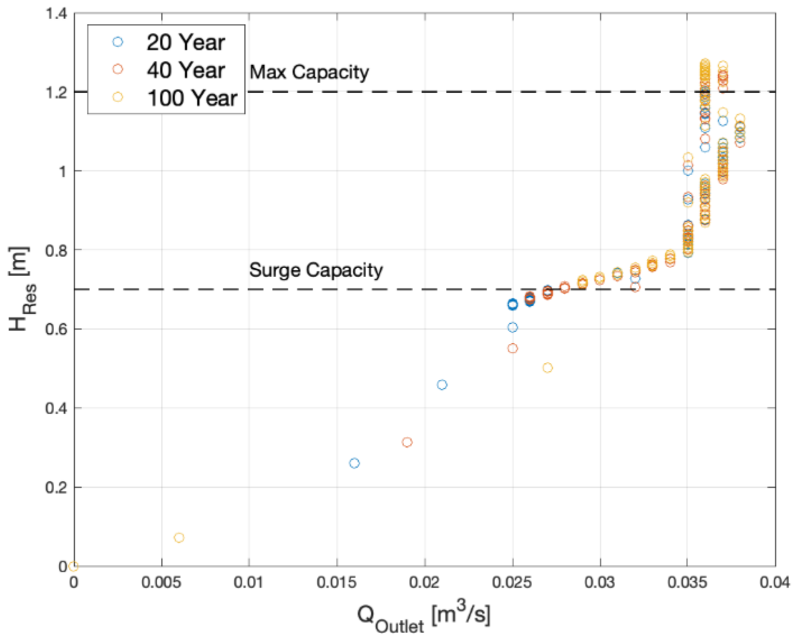

Figure A6.2: Outlet flow relations as calculated by Metis, for a 20, 40 and 100 year flood event.

Four key control structures were installed on the wetland to achieve this:

- **Sluice gate** on the wetland's inlet, which when set to a winter height of 225mm limits the inlet flow to 600l/s. For a submerged sluice gate the discharge can be approximated using:

$$Q = \mu ab\sqrt{2g(h_{up} - h_{down})}, \quad (1)$$

  where Q is the flow rate, μ is the discharge coefficient, a is the height of aperture of the sluice gate, b is the width, g is the acceleration due to gravity, h_{up} is the upstream flow height and h_{down} is the downstream flow height. We combine this with the modelling from Metis to create the crude relation shown in (3).
- **Bypass weir**, which can also be configured. During the period of data collection, it was set to a height of 370mm, above which it will divert flow to the bypass channel. We use a condition on the bypass flow Q_{bypass} that if $H_{inlet} < 0.370$ then the bypass flow is 0.
- **Outlet Pipe**, which restricts the outlet of the water to a maximum of 38l/s. From the Metis data, shown in Figure 2, is possible to infer the following relations shown in (4).
- **The Culvert pipe** of the bypass has a constant radius and known hydraulic characteristics and can be computed using the Manning Equation.

$$Q = \frac{A}{n}R^{\frac{2}{3}}S^{\frac{1}{2}}, \quad (2)$$

  where A is the area of the flow, R is hydraulic radius S is the slope of the pipe and n is the roughness coefficient.

A6.3 Flow Model

Accurately modelling flow is not possible with the available data, so an approximate bucket model has been developed. To create this model, a few assumptions had to be made.

- It was assumed that the wetland contains 8000m^3 of water when the water level is 52.5m AoD and a minimum through flow of 2l/s was set.
- Secondary inflow from the upstream development to the northeast of the wetland was not taken into consideration, as it was not possible to gauge this small input.
- The three cells of the wetland were amalgamated into one bucket in the model. Losses, leaks and blockages (even though they are evident in some cases in the structures) were neglected.
- The weir height of the inlet control structure was assumed to be 0.37m.
- The bypass pipe was assumed to have a Manning's coefficient of 0.013 (that of an unfinished concrete pipe) and a slope of 0.002.
- It was assumed that concentrations are uniform (i.e. perfect mixing is assumed).

Given these assumptions, the simple model is depicted in Figure 3 was created and provides a basic initial calculation that gives insights into the functioning of the wetland.

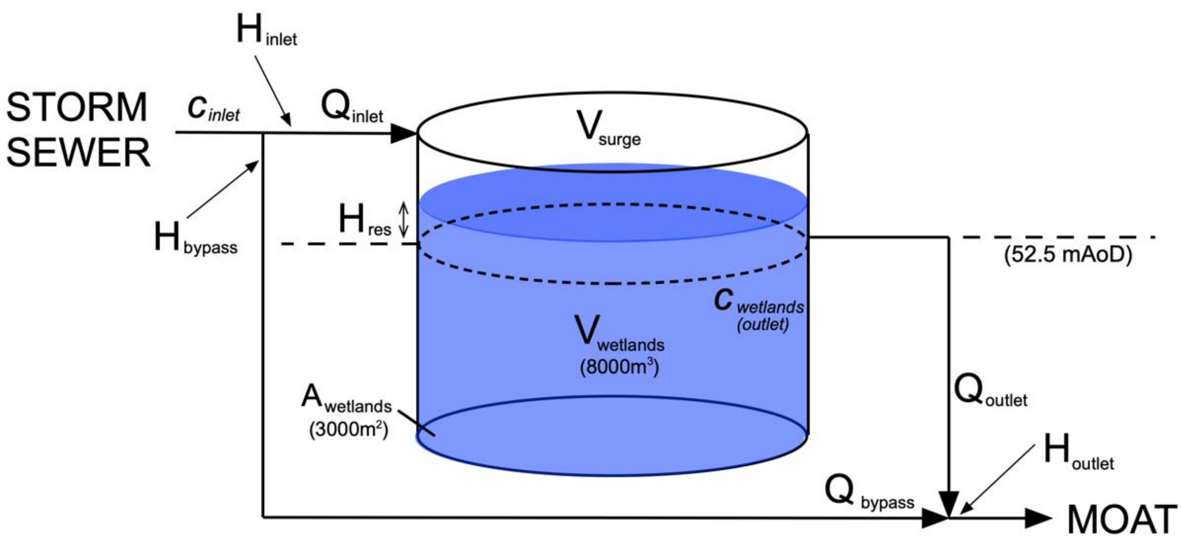

Figure A6.3: A simple diagram of the Flow model, showing: Q_{inlet}, Q_{bypass} & Q_{outlet} and H_{inlet}, H_{bypass} & H_{outlet} which are the volumetric flow rates and heights of the inlet bypass and outlet respectively. The wetlands is split into two volumes $V_{wetlands}$ the fixed volume and the surge volume V_{surge}. H_{res} is the height of the surge volume above the surface of the fixed volume (52.5mAoD). The concentration of a contaminant of the inlet and bypass flows is c_{inlet} and c_{oultet} is the concentration of the wetland volumes and outlet flow.

The model has three relations governing the three flows:

$$Q_{inlet} = \begin{cases} 0.002\ \mathrm{m^3}/s, & \text{if } H_{inlet} = H_{res}\,, \\ 0.051 \times \sqrt{2g(H_{inlet} - H_{res})}\ \ \mathrm{m^3}/s, & \text{elseif } H_{inlet} - H_{res} < 0.6\mathrm{m}\,, \\ 0.6\ \ \mathrm{m^3}/s, & \text{else}\,. \end{cases} \quad (3)$$

$$Q_{outlet} = 0.01558e^{1.05(H_{res})}\ \ \mathrm{m^3}/s, \quad (4)$$

$$0.002\ \mathrm{m^3}/s \leq Q_{outlet} \leq 0.038\ \mathrm{m^3/s}.$$

$$Q_{bypass} = \begin{cases} 0\,, & if\ H_{inlet} < 0.37\mathrm{m}\,, \\ \frac{A}{0.013} \times R_H^{2/3} \times\ 0.002^{\frac{1}{2}}\ \ \mathrm{m^3}/s, & \text{else}\,. \end{cases} \quad (5)$$

The model utilises a straightforward first-order forward Euler approach, as the flows are relatively low compared to the volumes and the time step is 5mins.

$$\frac{dV_{surge}}{dt} = \ Q_{inlet} - Q_{outlet.} \quad (6)$$

The maximum flux of a contaminant in flow can be found by multiplying the concentration with the flowrate, thus a mass of pollutant relation can be formed:

$$\frac{dm_{res}}{dt} = \ Q_{inlet}c_{inlet} - Q_{outlet}c_{outlet} \quad (7)$$

Due to the relative magnitude of the flows and volumes, there is no need for any limitations on the time-stepping, so a 5-minute timestep was used, (mirroring the recorded level data interval). Concentrations are determined using a mass balance based on the modelled flows in and out of the wetland as shown in Figure (7). This does not consider the processes occurring within the wetland (sedimentation, adsorption etc.); and observed DO, temperature, conductivity, pH, turbidity and ammonium, which were all monitored by sensors installed at the wetland's inflow and outflow. This appendix focuses on ammonium due to its environmental impact.

A6.4 Method

At this site, several challenges posed difficulties for flow gauging. Low flows were hard to measure as velocities were small. High flow events made structures unsafe to enter, thus limiting measuring opportunities to outside the structures.

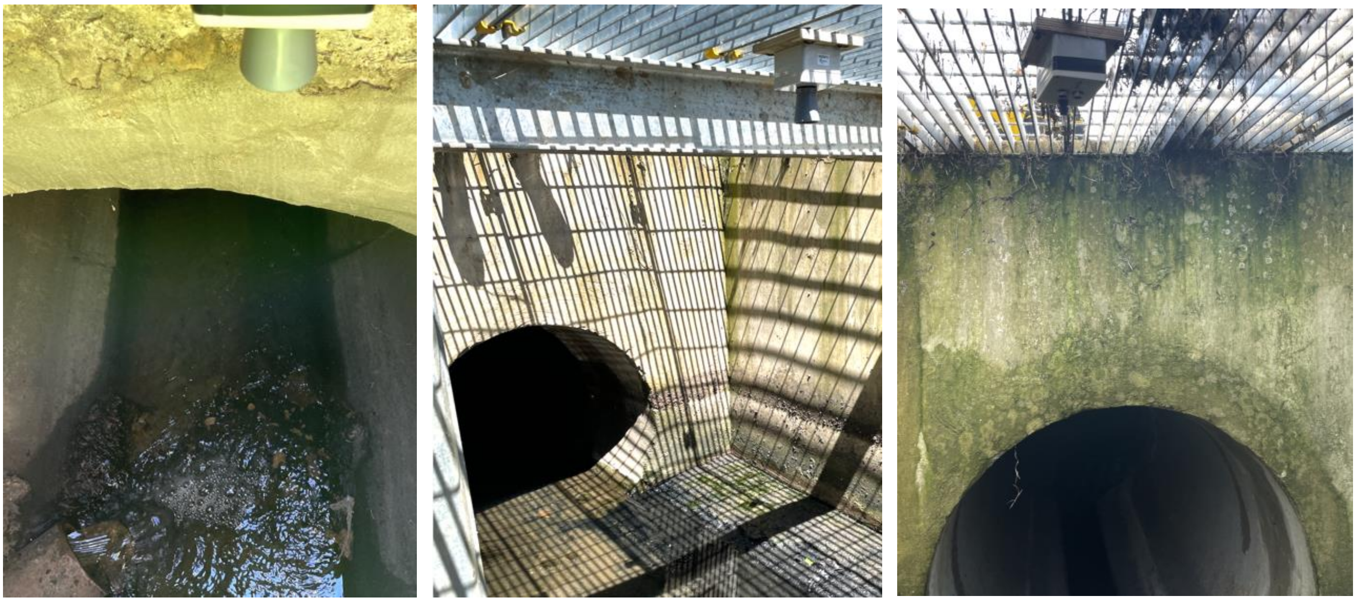

Figure A6.4: Photos of the Installed Level, River.io sensors on the outlet (left), inlet (middle) and a CAMELLIA sensor on the bypass.

During the summer period River.io level sensors (that use MB7318-100) were installed, on the inlet and outlet flow. These low-powered ultrasonic sensors take readings every 5 minutes. The MB7318 has a 3.5m range with a 1cm resolution with the River.io circuit board. This has a battery life of 10 years and is very robust (anecdotally spiders have nested inside the emitter without impacting the data). During the winter logging period, an Adafurit feather-based level logger (using an HC-SRO5 sensor) was installed just above the bypass flow. The HC-SRO5, has a range of 400cm and quoted similar accuracy, though it is less expensive than the MB7318-100, it is less robust and has higher power requirements. The data from both were manually downloaded from an SD card. Two problems were encountered, with the sensors:

- The backing up of the water was an issue and invaded the outflow sensor during an August storm event. Once it was dried out the sensor was reinstalled successfully.
- An HC-SRO5 low-cost sensor on the underside of the bridge over the reed pond was lost due to inundation.

A6.5 Results

This section briefly outlines the results from the level gauging and modelling and discusses their significance.

A6.5.1 Level Data

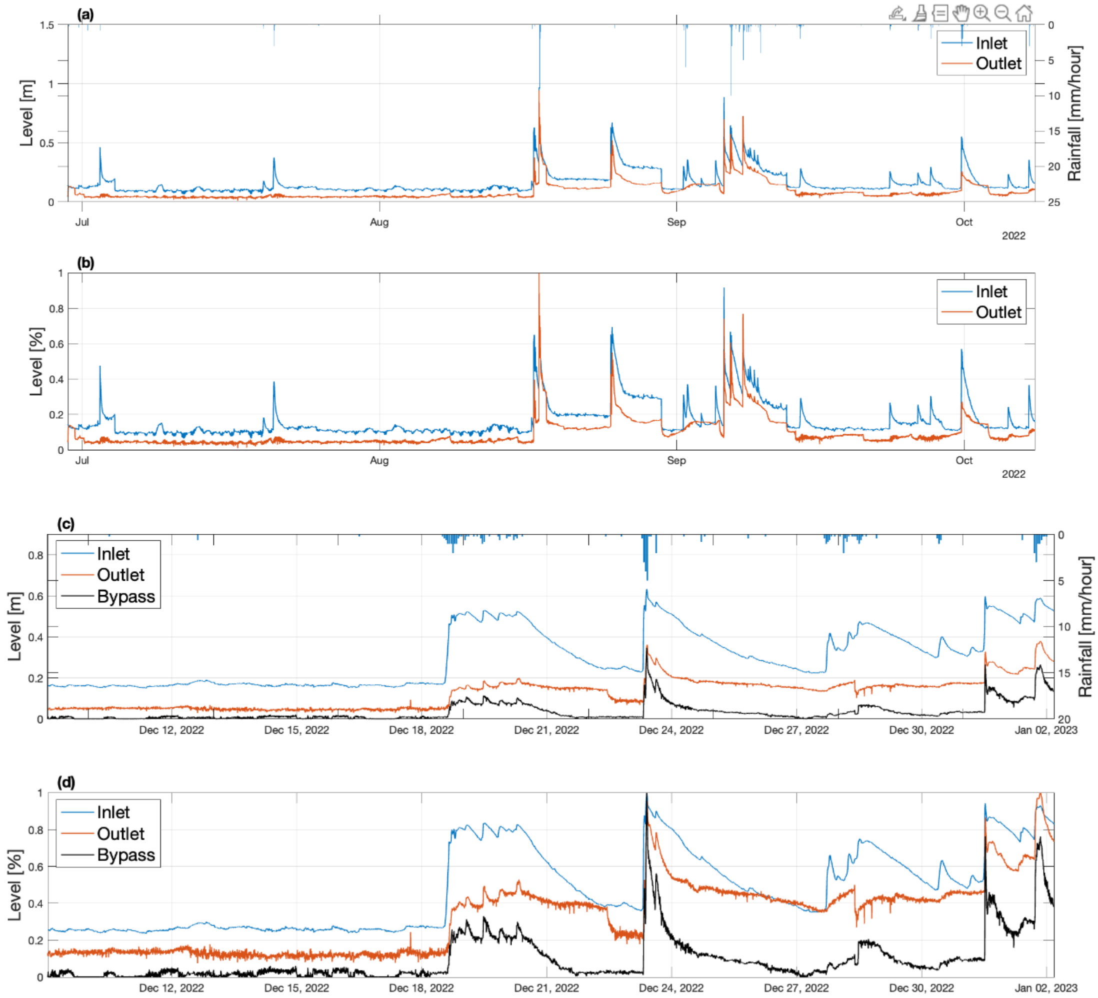

Figure A6.5: Level data from the Summer (a) & (b) and Winter (c) & (d) periods showing water level as both level (a) & (c) and percentage of max level values (b) & (d). Rainfall is also shown across the top of plots (a) & (c).

It is evident from Figure A6.5 that there is a diurnal signal, especially evident in the summer inlet level data. This can be attributed to cross-connections and misconnections between the storm and foul sewers within the stormwater system feeding the moat and wetland. This implies that some raw sewage is likely entering the system. As impacts on water quality in the moat are generally worse in summer, this demonstrates an important benefit from the wetland in addition to its primary function of flood alleviation. From the summer signals, it is also possible to see the effects of blockages on the outlet on the 17th of July and on the inlet on the 4th of July and 30th of August, the level is artificially high, and the blockage is cleared at around 9am. Continuous live monitoring of the levels could aid in streamlining maintenance schedules.

In Figure A6.5 (c) & (d), the wetland is operating at high capacity, with the inlet backing up continuously above the normal level from December 18th. From all the data, it is evident that the wetland is attenuating the flow into the moat during surge events.

A6.5.2 Modelled Flows

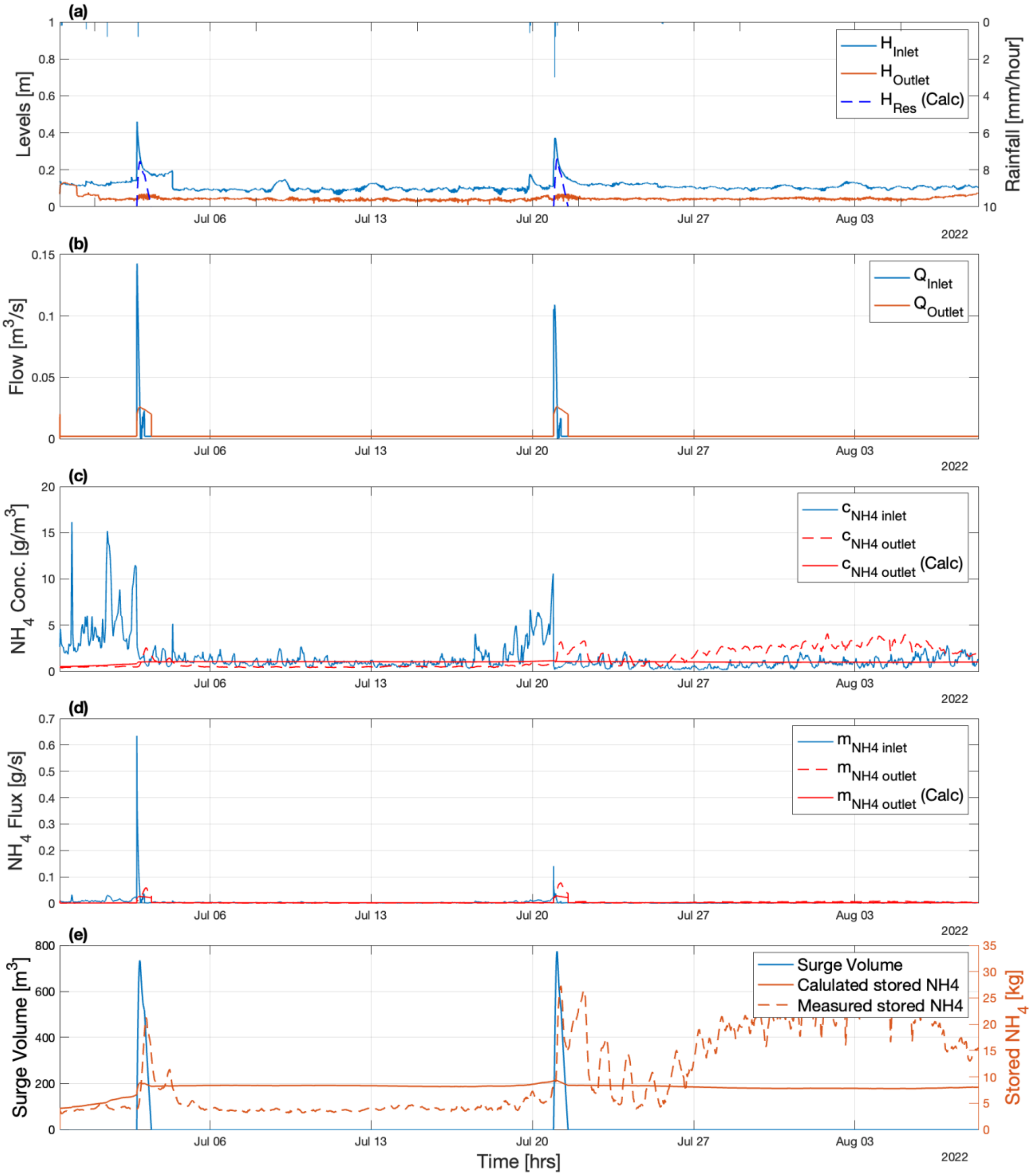

Figure A6.6: Modelled results from the wetland during the winter period showing: water levels, for the inlet, outlet and modelling reservoir height, as well as rainfall, (a); the flows for the inlet and outlet (b), the concentrations of NH_4 , both recorded and computed (COMP) in (c), the mass flow rate of NH_4 in (d) and the surge volume and stored NH_4 (both computed and measured) in (e).

Flows at the wetland's inlet and outlet, as well as bypass flows to the moat have been calculated using the above equations and are shown for both summer and winter periods. Please note: these periods are shorter than the those shown for the level data due to the limited time the water quality sondes were deployed. The calculated surge volume and net ammonium through the wetland are also shown.

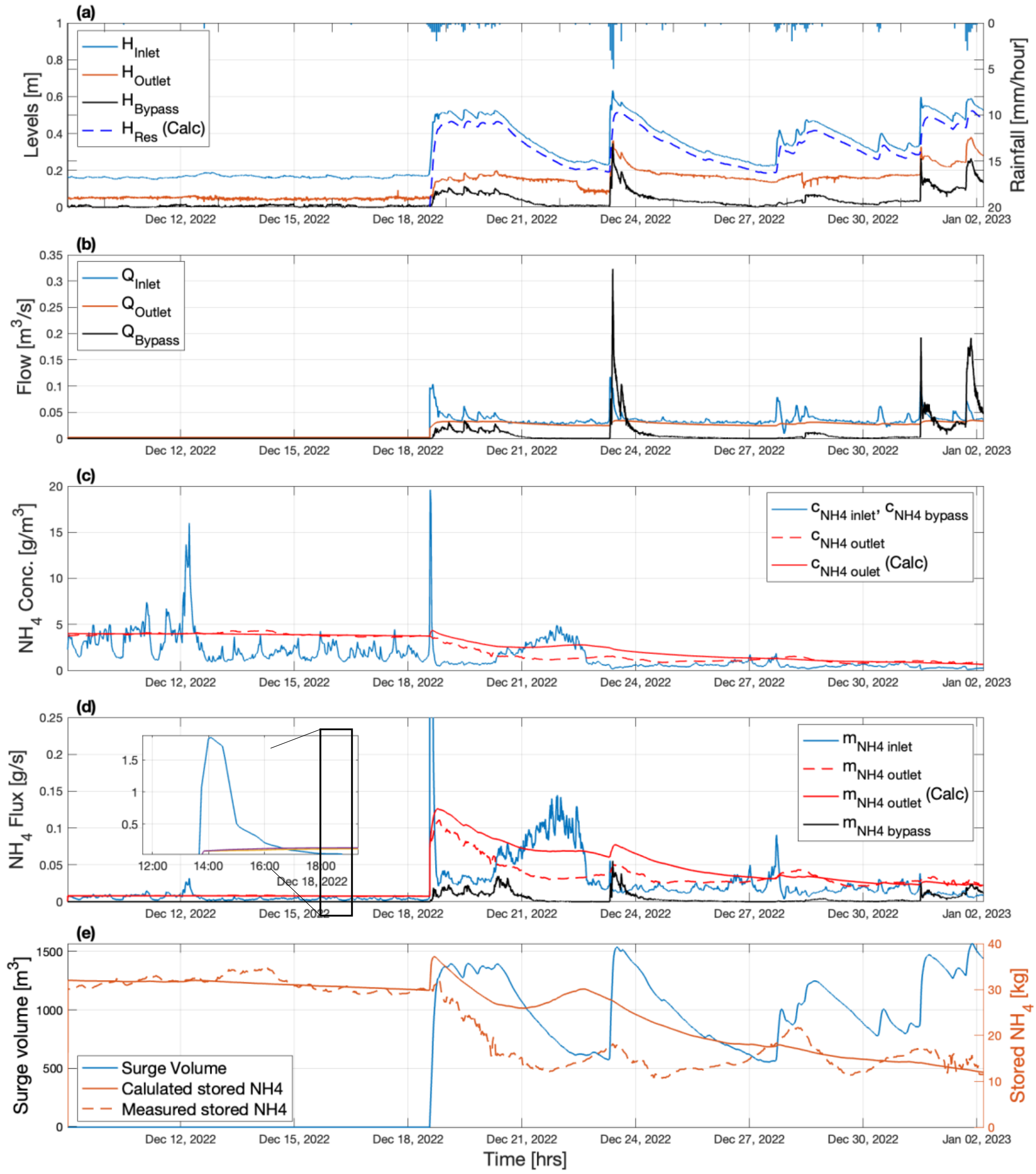

Figure A6.7: Calculated flows for the Winter period of monitoring showing: water levels, for the inlet, outlet, bypass and computed reservoir height) as well as rainfall (a); the flows for the inlet outlet and bypass (b), the concentrations of NH_4 , both recorded and computed (Calc) in (c), the mass flow rate of NH_4 in (d) and the surge volume and stored NH_4 (both computed and measured) in (e).

It is important to note that this modelling is indicative only, and while several interesting features are observed, further work is needed to validate this model (which is constrained by the assumptions listed above and limited resources for this project).

The model appears to perform reasonably well. It does not exceed the 1500m^3 of surge capacity and, from a visual inspection, offers apparently reasonable flows and behaviours.

From a comparison of Figures A6.6 and A6.7, it is clearly unfortunate that no significant rainfall events were captured during the summer period to demonstrate the wetland's performance. As Figure A6.7 shows, comparing outflow concentrations to those derived from the simple mass balance calculation, the wetland appears to be retaining some NH_4, as the calculated NH_4 concentration generally tracks above that of the model. The measured and calculated stored NH_4 shown in Figure A6.7 show a good agreement giving a degree of confidence to the model.

The winter period shows some interesting features, including a "first flush" event with a high NH_4 concentration on the 18th of December indicative of a high pollutant load. This flush is effectively attenuated by the wetland, as confirmed by the very low bypass flow height and minimal changes in NH4 concentrations. This feature is examined further in Figure A6.8, which shows two rainfall events from Figure A6.7; on the 18th of December, there was sustained rainfall for several hours, whereas the event of the 23rd is a shorter but more intense rainfall, which overwhelms the wetland causing bypass flow to occur much earlier in the event. The left-hand plot of Figure A6.8 shows how well the wetland captures nearly all of the ammonium spike, as the bypass level, and hence bypass flow to the moat, does not respond for a full two hours after the initial rise in the inlet water level, indicating that all of this highly polluted water is captured by the wetland.

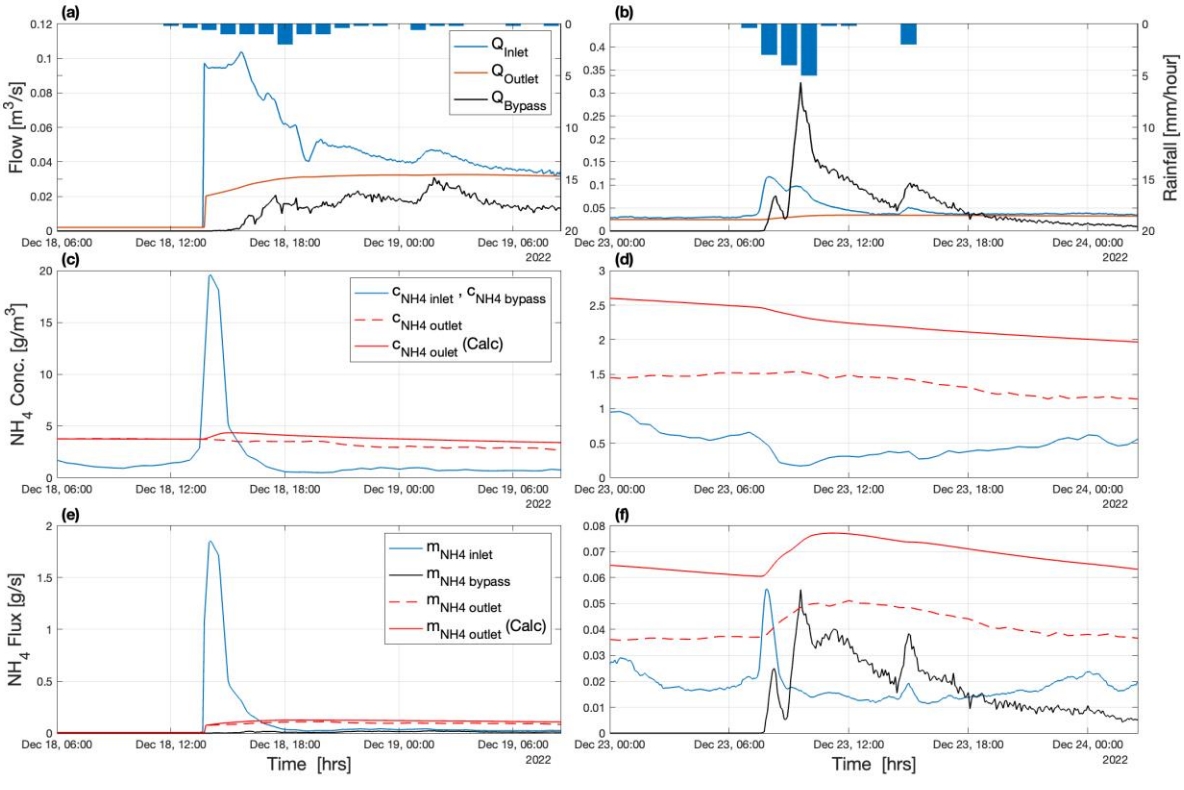

Figure A6.8: Shows higher resolution events for the First Flush event 18th December (a) (c) (e) and a second flow event 23rd December (b) (d) (f), showing the flow rate through and around the wetland in (a) & (b), the concentrations, both recorded and computed (COMP) in (c) & (d), the mass flow rate of NH_4 in (e) & (f).

When comparing the two events is crucial to note the differences in NH_4 input concentration, the first flush has far higher NH_4 loadings (up to 20g/m^3 inlet and around 4g/m^3 on the outlet (note 1 g/m^3 is equivalent to 1mg/l)) compared to an event on the 23rd December, (with a peak outlet concentration of 2.5g/m^3).

Figure A6.7 further shows that the NH_4 in the wetland (outlet) does not rise significantly after the surge events it only briefly exceeds a concentration of 4mg/l. When comparing the performance with that of the 18th of December, it is clear to see that the wetland captures a far smaller portion of the flow, but crucially, as this is not a first flush event, the concentration of NH_4 is far lower and stable. This indicates that the wetland is performing well at protecting the moat from high pollution (like first flush events) as well as high flows.

A6.6 Recommendations

For future wetland studies at the Headstone Manor Wetland, the following may be of use:

- **Place level gauges on all three ponds** – to improve the model and understanding of the flows.
- **Supplement level gauging with spot measurements** – the flow could be more accurately captured by the models' relations if flow gauging was done over several visits.
- **Ultrasonic Flow Gauging** – with a larger budget the grating structure could be monitored with an ultrasonic flow meter – enabling improvements to this model.

For future wetlands designs

- **Live level data** – Live data would aid greatly in the maintenance of wetlands, and the reduction of unnecessary callouts would easily cover the costs of a subscription. The interpretation of the data to assess for blockages is rudimentary and could aid even aid in flood management with enough granularity (small timestep between readings).
- **Sensor Accommodation in design** – At the design stage of these wetlands it would be easy to make minor adjustments to enable the incorporation of covered sensor installation points.

A6.7 Summary

This appendix has demonstrated the potential value of analysing the hydraulic features of wetlands through flow gauging, even when resources are limited. By combining the limited observed water quality data with the behaviour of known hydraulic control structures, a simplistic model was built. Despite the project having a scope of only four level sensors, one of which was destroyed by a high flow event, and the lack of rainfall over the investigation summer period, a rudimentary understanding of the hydraulic workings of the wetland was established. From the raw level data, it was possible to observe a semi-diurnal signature indicative of cross-or misconnections, as well as the high number of blockages the wetland faced during the summer. Furthermore, the wetland was found to be effective at attenuating flow into the moat and capturing highly polluted first-flush events.

This appendix has also presented several next steps for further work, including many that the authors wish they had performed beforehand (such as using multiple sensors and higher mountings). While these results need to be interpreted with caution, this work has demonstrated what can be achieved with a limited budget.

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