Salmons Brook Healthy River Challenge: The start-up performance of three constructed wetlands at improving water quality.

Water sampling, analysis and report by Dr. Nathalie Gilbert, Thames21. May 2016

Executive Summary

This report assesses the start-up performance of three constructed wetlands at improving water quality in the period immediately after construction and planting. The systems were located in the catchment of the Salmons Brook, a tributary of the River Lea, in Enfield north London and consisted of: i) an integrated wetland (Glenbrook), ii) an infiltration basin (Grovelands Park) and a reedbed (Grovelands Park).

Water quality was investigated by a twice-monthly regime of water sampling (April – November), laboratory testing and statistical analysis of concentrations of nutrients (total nitrogen, ammonia, nitrate, phosphate), heavy metals (copper, zinc, lead, cadmium) and coliform bacteria. Additionally, on three occasions each of the six basins of the integrated wetland were sampled in order to assess the performance of each basin at improving water quality.

Results indicated that all three constructed wetlands were all highly effective at removing nitrogen compounds and coliform bacteria. Statistically significant differences in these parameters were reported, with average reductions between the inflow and outflow to the system of up to 67% of ammonia, 68% of nitrate, and 55% of total nitrogen. According to EU bathing water standards (the only standards available for this parameter, but not applicable to non-designated bathing water areas), classification improved from poor (imperative) at the system inflows to good at the outflows. During all but the highest flows, the infiltration basin (Grovelands Park) captured all polluted water and allowed it to slowly filter into the ground, indicating almost total effectiveness in preventing all pollutants from entering the Salmons Brook. Ortho phosphate was reduced by a mean of 30% between the inflow and outflow of the Glenbrook integrated wetlands.

At all sites, heavy metals were only detected intermittently in inflow and outflow water samples. This may be related to their intermittent presence in surface run-off, which in turn may be linked to rainfall volume and the duration of dry spells in the period prior to sample collection. Complex chemical binding and sedimentation processes within the constructed wetlands are also likely important. Due to insufficient data, no conclusions were made concerning heavy metal removal by the constructed wetlands and heavy metal data is not presented in this report.

Abbreviations

CFU -Colony forming units

CSO - Combined Sewer Overflow

^{0}C – degrees centigrade

DO – Dissolved Oxygen

EC – European Community

L – Litre

mg - milligram

ml – millilitre

min -minimum

max - maximum

p – probability

s.e. – standard error

TCC – total colony count

WFD – Water Framework Directive

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1. Introduction to the Salmons Brook

All sites mentioned in this report are located in the catchment of the Salmons Brook in Enfield, north London. The Salmons Brook is a tributary of the River Lea (or Lee). At approximately 6km long, the Salmons Brook originates near Potters Bar and flows through Enfield before joining the Pymmes Brook at Edmonton, then the River Lea at Tottenham, Figure 1. The lower course is predominantly urban developments and industry, including the Deephams Sewage Treatment Works at Edmonton. The Salmons Brook is currently failing EU Water Framework Directive (WFD) standards for water quality.

Enfield has a separate sewage system, meaning foul water and surface run off are carried by separate pipe networks and treated differently. Household wastewater (bathroom, dishwasher and washing machine waste) is carried to sewage plants for treatment, whilst rainfall is carried by storm water into local rivers. Pollutants enter the Salmons Brook through misconnected plumbing, cross connections and the dumping of industrial and domestic waste into surface water drains. Also, rain running off roads picks up oils and heavy metals from cars and carries it directly into rivers. We are unaware of any Combined Sewer Overflows (CSOs) in the area.

Consequently, the overall water quality of the Salmons Brook has been evaluated as poor and heavily polluted (Davies 2011) and the Salmons Brook is not on target to achieve good status under WFD guidelines (Environment Agency 2009). A particular problem is Phosphate, with levels rated as poor (Environment Agency 2009) and total coliforms were measured as high (above imperative, Davies 2011), indicating the presence of disease causing pathogens. The threat of urban diffuse pollution to the Salmons Brook catchment prompted the creation of the 'Salmons Brook Healthy River Challenge' by Thames21 in 2012.

The Salmons Brook Healthy River Challenge

This project was initially funded by the Department of Energy, Food and Rural Affairs (DEFRA) and aimed to address the WFD failure of water quality in the Salmons Brook catchment by reducing urban diffuse pollution through the installation of constructed wetlands. Following the completion of the DEFRA funding, the project was extended with funding from Thames Water's Community Investment Fund, which included funding for this report. Bioremediation systems (swales, reedbeds, wetlands) are an economic and sustainable way of reducing urban diffuse pollution, slowing flow to reduce flood risk and creating wildlife habitat. As part of the Salmons Brook Healthy River Challenge, 5 bioremediation systems were created and completed in 2016. This paper reports on the results of 3 constructed wetlands created as part of this Challenge.

2. Objectives

The aim of this report was to assess the start-up performance of three constructed wetlands systems at improving water quality in the period immediately after construction and planting. The systems were located in the catchment of the Salmons Brook, a tributary of the River Lea, in Enfield north London and consisted of: i) an integrated wetland (Glenbrook), ii) an infiltration basin (Grovelands Park), and iii) a reedbed (Grovelands Park).

Water quality was investigated by a twice-monthly regime of water sampling, laboratory testing and statistical analysis of concentrations of nutrients (total nitrogen, ammonia, nitrate, phosphate), heavy metals (copper, zinc, lead, cadmium) and coliform bacteria. Results are discussed with reference to water quality standards including the Water Framework Directive and the EC Bathing Water Directive (although not strictly applicable to wetland treatment systems, it is the only available standard for Coliforms).

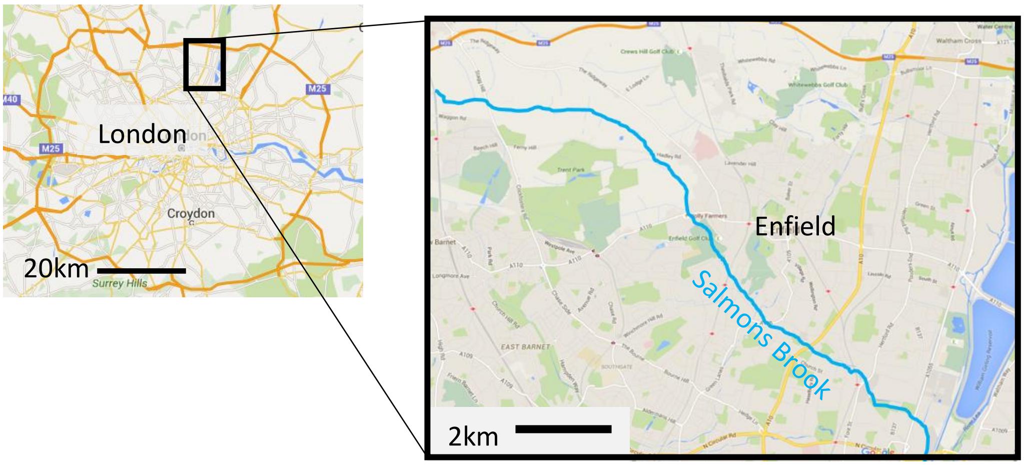

Figure 1: Left, the location of the Salmons Brook. Right, the course of the Salmons Brook.

3. Site descriptions and sampling locations

The location of the three monitored sites in the Salmons Brook catchment is shown in Figure 2.

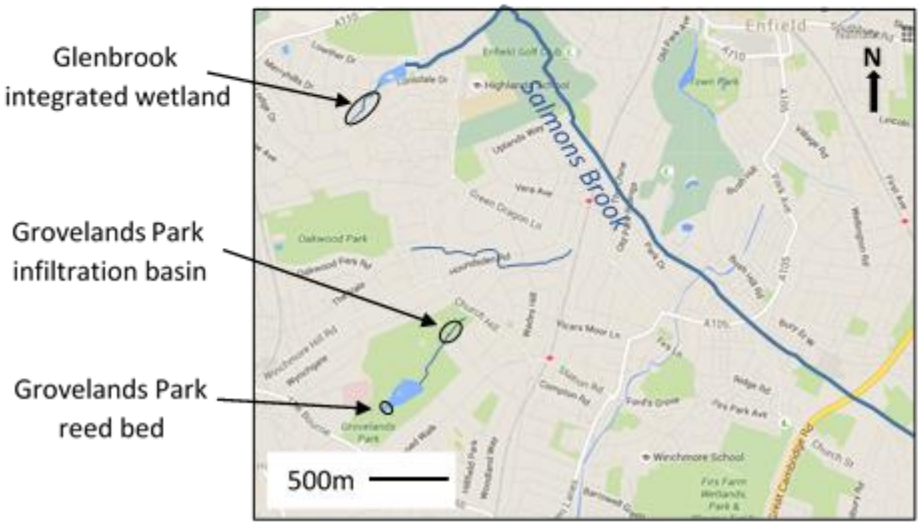

Figure 2: The location in the Salmons Brook catchment of the three monitored sites.

(adapted from Google Maps)

3.1 Integrated wetland, Glenbrook

The Glenbrook, a tributary of the Salmons Brook, emerges from a culvert in Lonsdale Drive and runs in a north westerly direction for approximately 300m before draining into Boxers Lake (Ordnance Survey Grid Reference TQ303960). It has a catchment size of approximately 42 hectares. This watercourse is known to receive significant levels of misconnections. Odour have previously been reported by local residents and fish kills have occurred in Boxers Lake. While this monitoring was occurring Thames Water were undertaking a misconnection investigation to identify the sources of the pollution and subsequently undertake the appropriate enforcement actions. This was not complete before the end of the monitoring of the site.

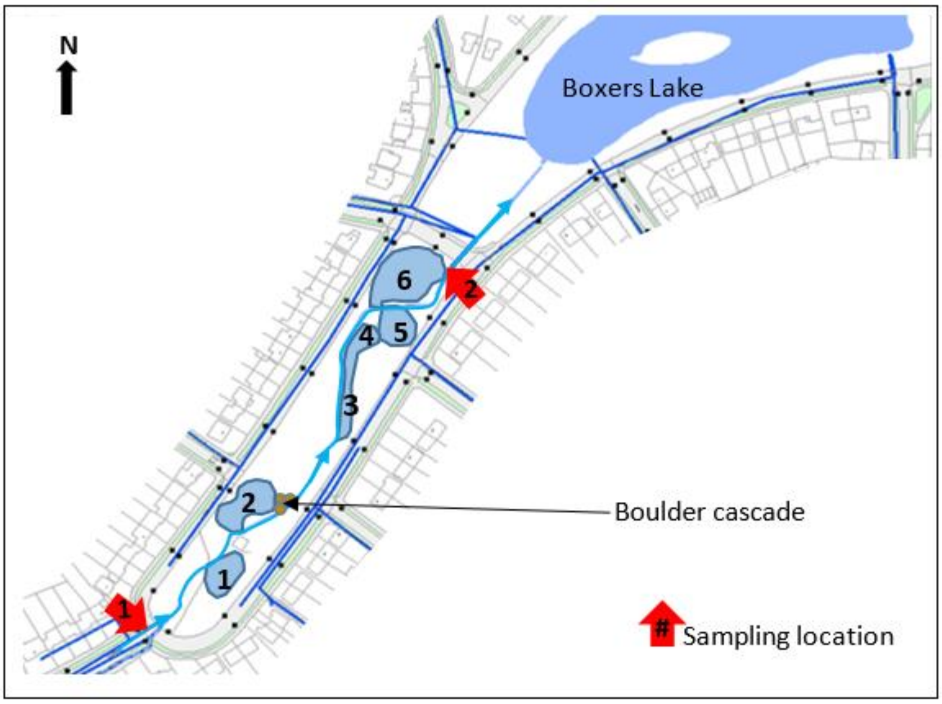

Figure 3: The six basins and regular sampling locations at the integrated wetland, Glenbrook. Not to scale. (Map adapted from the surface drainage map)

Table 1: The regular water sampling locations in the integrated wetland, Glenbrook. Sampling location numbers correspond with those in Figure 3.

Sampling Location	Description
1	**Inflow**, where the Glenbrook becomes deculverted (photo Figure 5).
2	**Outflow**, sample taken as water flowed over the weir out of the final treatment basin (basin 6).

A series of six linked wetland treatment basins (approx 1.3 ha in size) were constructed in September 2014 to filter pollutants before they enter Boxers Lake (Figure 3). In all but high flow conditions, weirs divert the Glenbrook through the basins. However, throughout the duration of this investigation, treatment basins 3 and 4 were off line. This was due to erosion under the weir that was intended to direct water in to basin 3. This is due to be repaired in June 2016.

The basins were initially planted with plug-plants, however these failed to establish due to disruption by unusually heavy winter rain events and heavy pollution from a large number of plumbing misconnections. Consequently, in late April 2015, the basins were replanted with pre-established coir pallets (Figure 4) planted with a native species mix appropriate for shallow water (Appendix A). The plants are expected to expand outwards and colonise the basins as they mature. Heavy pollution was apparent throughout the testing period, as evidenced by scum and odour at the inflow, and heavy sewage fungus in the first treatment basins (Figure 5). Thames Water were carrying out investigations to resolve these issues.

Three locations were sampled regularly (Figure 3, Table 1). Additonally, on 3 occasions, intensive sampling of each treatment basin was carried out. This consisted of sampling water at the entry and exit point of each basin, in addition to the regular sampling locations.

Figure 4: Left, basin 1 outflow weir with the Glenbrook in the foreground. Middle and Right, pre-planted coir pallets in position in basins 3 and 6 respectively.

Figure 5: Left, the polluted Glenbrook where it becomes deculverted at the head of the constructed wetland basins. Right, sewage fungus in wetland basin 1.

3.2 Infiltration Basin, Grovelands Park

In July 2014, an infiltration basin was completed at the north east end of Grovelands Park. The total catchment area is approximately 11 hectares. Surface runoff is diverted from two storm water drains, originating in Branscombe Gardens and Seaforth Gardens, to emerge above ground at rock outfalls and pass through meandering swales before entering an infiltration basin (Figures 6 and 7). During low and normal flows, the cleaned water naturally soaks into the ground, whilst during the highest flows water returns to the Grovelands Park stream, a tributary of the Salmons Brook, by overtopping a weir at the lowest end of the infiltration basin (Figures 6 and 7).

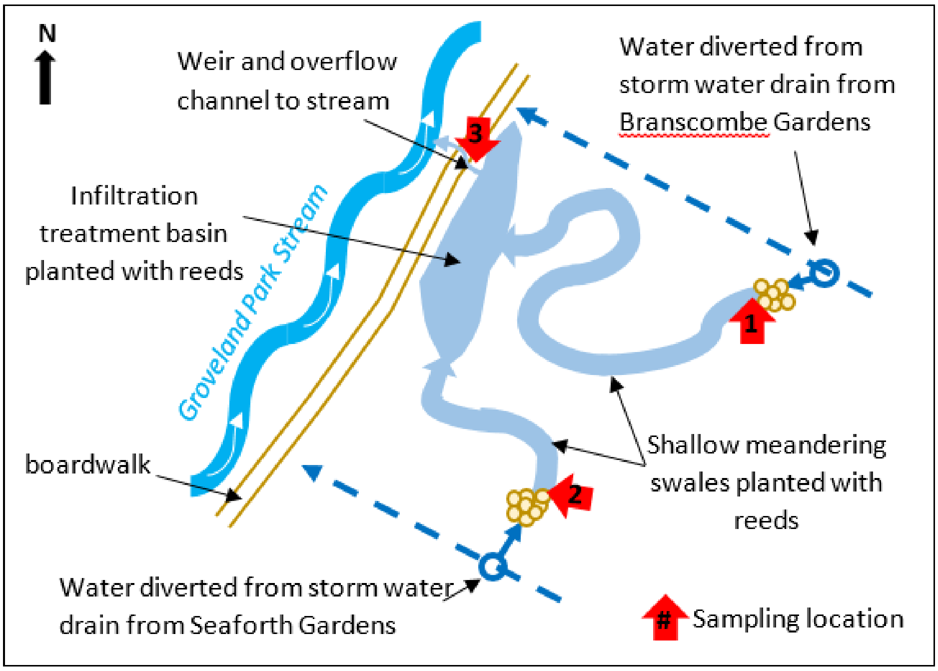

Figure 6: The infiltration basin at Grovelands Park showing sampling locations. Not to scale.
(Adapted from concept map from Robert Bray Associates)

Table 2: The regular water sampling locations in the inflitration basin, Grovelands Park. Sample number corresponds with those in Figure 6.

Sampling Location	Description
1	**Branscombe Gardens stormwater drain**, where it emerges above ground (Figure 7)
2	**Seaforth Gardens stormwater drain,** where it emerges above ground
3	**Weir and overflow channel**, on the two occasions water flowed out of the constructed basin (Figure 7).

Although supposedly carrying surface water only, misconnected houses are known to pollute the two diverted stormwater drains. Toilet paper was regularly observed in the outlet from Branscombe Gardens and the outlet from Seaforth Gardens contained sewage fungus. At the time of this investigation, it was known that Thames Water were carrying out misconnection investigations and associated enforcement actions. The investigation was completed after the end of the monitoring.

Figure 7: Left, the rocky outfall and swale diverting water from the Branscombe Gardens stormwater drain. Right, the infiltration basin, weir and outflow channel leading to the Grovelands Park Stream.

(Outfall image courtesy of Stefano Folini)

3.3 Reedbed, Grovelands Park Lake

In June 2015 a reedbed was installed at the south west end of Groveland Park lake. It was positioned in a swathe across the main outfall of a large network of stormwater drains that enters the lake (Figure 8). This outfall is polluted with urban road runoff and misconnections, obvious signs of which included sewage fungus, sediment and surface scum (Figure 9). Park users have complained about the odour. The reedbed was designed to improve water quality in the lake by trapping polluted water and sediments before they enter the lake, as well as improve biodiversity and amenity value. At the north eastern end of the lake, water drains out of the lake into Grovelands Park stream and, after 1.2km, into the Salmons Brook. Under the Reservoirs Act 1975 the lake is classified as a reservoir (London Borough of Enfield Council 2013).

The 200m^2 bed was constructed using young emergent reed species suitable for shallow water (eg common reed, *Phragmites australis*). These were pre-established on coir matts that were anchored in place with wooden stakes. The reedbed was initially fenced to protect it from geese. When fully established, it is anticipated that the reedbed will have extended out and colonised the shallow water between the current maximum extend and the nearby island.

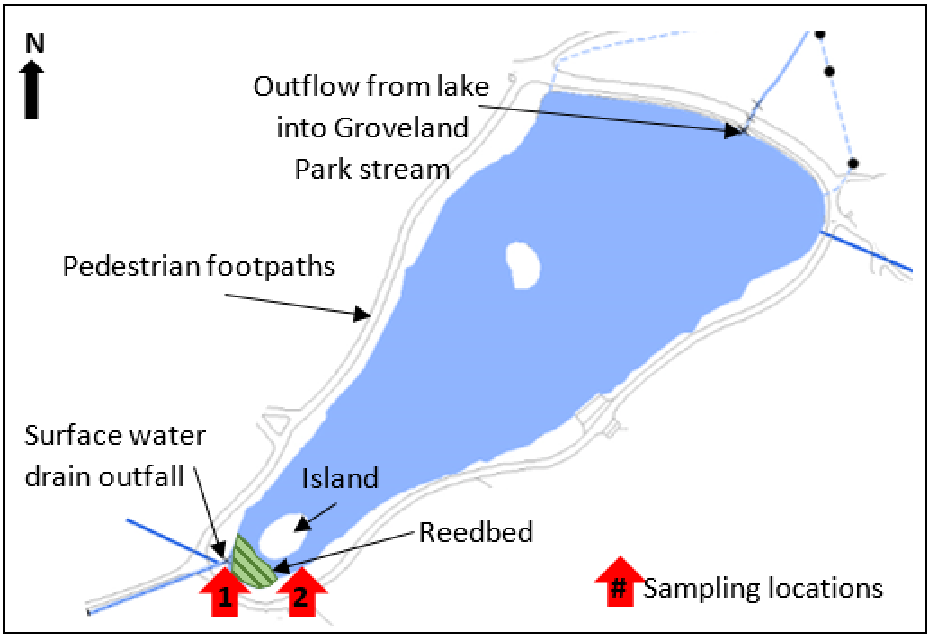

Figure 8: Grovelands Park lake showing the position of the reedbed installation and water sampling locations. Schematic not to scale. (Adapted from surface drainage maps).

Table 3: Description of the regular water sampling locations in the Grovelands Park reedbed and lake. Sample number corresponds to those in Figure 8.

Sampling Location	Description
1	**Stormwater drain outfall**, where the drain enters the lake (Figure 9)
2	**Reedbed maximum extent**, from the bank

Figure 9: Left, the reedbed viewed looking south west. The outfall is visible as the rectangular opening in the wall behind the reedbed. Right, the reedbed viewed from the outfall. Note the visibly poorer water quality in the area in front of the reedbed, compared with immediately after it in the previous picture.

4. Description of water quality parameters

The Water Framework Directive, WFD, (Directive 2000/60/EC) is a European union directive which states that all rivers, lakes, reservoirs, streams, canals, estuaries, coastal and groundwater need to be restored to good ecological health by member states. Water bodies are assessed according to the status of biological, hydromorphological, physio-chemical and chemical factors. Key WFD pollutants assessed by this report include phosphate, nitrate and ammonia.

Phosphate

Phosphorus is an essential element for growth of photosynthesising plants and microorganisms. It is retained in soils so is usually scarce in water bodies and is the growth limiting nutrient. Excess quantities of nutrients, especially phosphate, can cause eutrophication. In this process, nutrient excess stimulates overproduction of algae. After algal death, the abundance of organic matter and decomposing organisms depletes dissolved oxygen levels which deprives other aquatic life of oxygen. In anaerobic conditions, digestion of organics by bacteria promotes the conversion of sulphur into hydrogen sulphide, which has an eggy smell.

Phosphorus may be present in freshwater environment in forms with different bioavailabilities. Orthophosphate, the readily available dissolved fraction, is measured by the Water Framework Directive. Other inorganic (reactive and condensed) and organically bound forms may be colloidal or particulate and are less available. Total phosphate is the sum of the inorganic and organically bound fractions plus dissolved phosphate.

In urban catchments, phosphates may enter waterways from point sources such as sewage systems and misconnected houses; and also from diffuse sources such as fertilizer runoff from parks and gardens. They also derive from laundry detergents. In sustainable urban drainage systems, the main removal mechanisms for dissolved phosphate are uptake by plant roots, conversion to less bioavailable forms of phosphate and binding to soil sediments (Vymazal 2007).

Total nitrogen, ammonia and nitrate

Nitrogen is more water soluble than phosphate and is present in several forms as part of the nitrification cycle. In this process, ammonium (NH_4^+) or ammonia (NH_3) is oxidized by bacteria first into nitrite (NO_2^-) then into nitrate (NO_3^-). Nitrate is the most stable form, therefore the most abundant. Total nitrogen (T_N), as the name implies, is a quantitative measure of all three forms of nitrogen. The relationship between them is shown in figure 12.

Similar to phosphate, nitrogen compounds cause excess nutrient availability and eutrophication. They derive from similar point source and diffuse pollution sources as phosphate and are also present in industrial and domestic cleaning products. Sewage treatment plants oxidise ammonia to nitrite then nitrate, so the presence of significant concentrations of ammonia in water samples may indicate the presence of raw sewage. Ammonia is toxic to aquatic species. The current Environmental Quality Standard for good status ammonia is 0.6 mg/l, however concentrations of >0.1 mg/L can cause eye and gill damage (hyperplasia) and impact hatching success in some fish (Salmonid) species. At higher concentrations it causes convulsions and death and is suspected to be a leading cause of fish deaths.

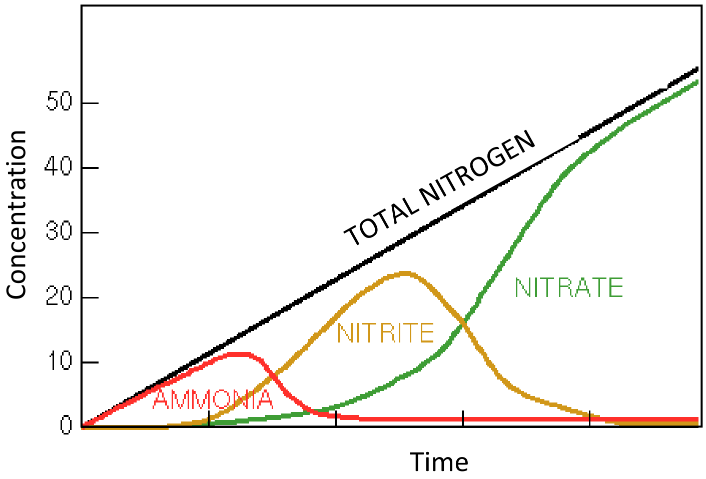

Figure 12: The relationship between ammonia, nitrite, nitrate and total nitrogen in a closed system. (Adapted from Spotte 1991)

In constructed wetlands, the main removal mechanisms for nitrogen are conversion of the most toxic form (ammonia) into less harmful forms (nitrate) by the nitrification process, and the removal of nitrate by conversion into gaseous compounds of nitrogen by bacteria(denitrification). Denitrification occurs in sediments and decaying plant material (van Oostrom and Russell 1994, Bachand and Horne 2000 Vymazal 2007). Total removal of nitrogen is higher in planted wetlands than unplanted ones (Bachand and Horne 2000, Lin *et al* 2007).

4.2 Total coliform bacteria counts

Faecal coliforms enter the environment through contamination with faecal waste of animal or human origin. This may include poorly or untreated sewage plant effluent, leaky septic tanks, and agricultural waste. Faecal coliforms do not cause disease but indicate the presence of disease-causing bacterial pathogens in the aquatic environment. Faecal coliform tests assess the presence/absence of *Escherichia coli* (E. coli) colonies. The risk of infection is correlated with the degree of contamination in water, indicated by total coliform counts (TCC). This counts faecal E. coli and other coliform bacteria such as Salmonella spp., and Campylobacter spp that may cause diseases such as gastroenteritis, and salmonellosis. Total coliform counts are reported as colony forming units (CFU) per 100/ml of water, however it is not possible to verify that these faecal coliforms derive from humans without carrying out DNA tests.

5. Methods

5.1 Sample collection

Samples were collected approximately twice monthly between April and November 2015 (9 – 12 occasions) from the same sampling locations in each of the constructed wetlands (Figures 3, 6, 8 and 10). To guarantee representative samples, water was taken directly from drainage pipes flowing into the system or as it outflowed over weirs. Water bottles were rinsed a minimum of 3 times in the local water and surface scum was cleared away prior to taking a sample. Samples were stored in a cool-bag on ice blocks until analysis. Total coliforms were measured by introducing water to a La Motte biopaddle for 15 seconds.

5.2 Analysis of parameters in the field

Water temperature, conductivity and pH were measured on site using a Hanna HI98129 probe, previously calibrated using standard solutions. Dissolved oxygen saturation (%) was measured using a Hanna HI-9146N handheld meter. Where possible surface flow was estimated using one of two methods: i) by recording the average length of time (3 trials) a float took to travel 10 metres downstream, or ii) by timing (3 trials) how long a jug of known volume took to fill with water. Surface flow estimates and field parameters are not presented in this report.

5.3 Laboratory analysis and verification

Analysis

Water samples were analysed as soon as possible after collection (nutrients same day, heavy metals within 24 hours). Spectrophotometric determination of all nutrients and metals was undertaken at the Bow Locks lab of Thames21, London, using ready to use reagent cuvette test kits produced by Hach Lange and a Hach DS9000 spectrophotometer. Hach Lange standard working methods were followed and links to the individual working procedures are listed in Appendix B.

Results are reported in milligrams per litre (mg/L) ± standard error (s.e.) and in a form that a corresponds directly with measures used in the WFD, for example total ammoniacal nitrogen (NH_3-N) is reported instead of ammonium (NH_4^+) or ammonia (NH_3). Ammoniacal nitrogen is a measure of the amount of nitrogen present as ammonia. Similarly, nitrate-nitrogen (NO_3-N, the amount of nitrogen present as nitrate) and is reported rather than nitrate (NO_3).

La Motte Biopaddles were incubated for 20 hours before total colony counts (TCC) per 100ml were estimated using standard methods (Appendix B).

Verification of laboratory data

The accuracy of results obtained at the Bow Locks laboratory was validated by duplicate analysis with a UKAS accredited lab (Scientific Analysis Laboratories Ltd, Braintree, CM7 2RT). This consisted of analysis of all nutrients (except total nitrogen) and the four species of heavy metal from 10 water samples taken from the standard sampling locations at Glenbrook and Grovelands Park. Analysis of nutrients was by directly comparable methods in both labs (spectrophotometric analysis of the same colour change reaction). The Bow Lab determined heavy metal concentrations by spectrometric methods, whereas the accredited lab used mass spectrometry. This measures presence by weight rather than a colour change reaction. Duplicate analysis results for nutrients are presented in Appendix C.

5.4 Assessment of water quality

Results were compared to comparable standards and updated criteria for surface water quality from the UK Water Framework Directive. The only standard available for interpretation of coliforms was the EU Bathing Water Directive, Table 4. Total nitrogen is currently not measured under the WFD, although total nitrogen emissions into rivers from urban waste water treatment plants are controlled by EU Directives (91/271/EEC) and contributors of the international European Nitrogen Assessment (ENA) call for its inclusion in the WFD. Instead the ENA classification scale was used for total nitrogen.

For determination of the appropriate phosphate classification scale, all sites were determined to be type 3n based on altitude and mean alkalinity (WFD 2010).

Table 4: Water quality parameters and classification scales used by this report.

Parameter	**Classification Scale** Nutrients:(mg/L), Coliforms: (CFU/100ml)				**Source**
Total Nitrogen		Good ≤ 0.5	Moderate 0.6 – 1.5	Poor > 1.5	1
Ammoniacal-nitrogen WFD	Very Good ≤ 0.6	Good 0.7 – 1.1	Moderate 1.1 – 2.5	Poor > 2.5	2
Nitrate-nitrogen WFD		Good ≤ 10	Moderate 11 – 20	Poor > 30	3
Orthophosphate WFD		Good ≤ 0.2	Moderate 0.3 – 0.8	Poor > 0.8	4
Total Coliforms		Good ≤ 500	Poor > 500		5

Graphs in the results section use the same colour codes to highlight water quality threshold boundaries. Parameters measured under the Water Framework Directed are indicated as WFD.

[1] Sutton *et al* 2011 The European Nitrogen Assessment: Sources, Effects and Policy Perspectives

[2] The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015

[3] Water Framework Directive 2000/60/EC

[4] UKTAG 2012 A revised approach for setting WFD phosphorus standards

[5] EC Bathing Water Directive 76/160/EEC

6 Constraints

6.1 Estimating flow rate

It was not possible to robustly measure flow or discharge in the majority of locations (in order to relate chemical concentrations with flow volume). During normal conditions, flow in stormwater drains was too low to be captured effectively and reeds impeded the passage of a float in planted swales. Where necessary, flow was related to rainfall derived for the nearest weather station, acquired from www.wunderground.com. Sufficient data was collected to observe broad trends in inflow and outflow water quality, despite lag in the passage of individual storm events through the wetland system.

6.2 Access to wetlands

Water samples could not be taken directly after the reedbed because this was open water. Samples were taken from the bank at the point closest to the reedbed maximum extent, approximately 10 metres in front of the reedbed.

6.3 Wetlands not functioning as designed

For the duration of this investigation treatment basins 3 and 4 of the Glenbrook integrated wetland were offline. The Glenbrook had eroded under a weir whose function was to divert all but high water flows out of the stream and into these basins. It is anticipated that once the weir is repaired and water is routinely treated through two additional basins, water quality will further improve.

7 Statistical analysis

Statistical analysis was carried out in R (Development Team 2008). Statistical methods are presented separately for each constructed wetland in the relevant subsections.

8 Results and discussion

8.1 Inter-comparison with a UKAS accredited laboratory

Overall, reported concentrations of nutrients (ammonia, nitrate, phosphate) were consistent between labs (Appendix C), so values presented in this report are deemed to be representative of actual concentrations in water samples.

8.2 Integrated wetland, Glenbrook

8.2.1 Statistical analysis

Mean differences in inflow and outflow water quality

Data pairs were not normally distributed. To compare the difference in mean values between the inflow and outflow, a Wilcoxon signed rank test was used for ammonia. Sign rank tests were used for all other parameters because the distribution of differences between pair was not symmetrical.

The effect of accumulated rainfall on nitrate concentrations

A sensitivity analysis tested the relationship between nitrate concentrations and rainfall, a proxy for flow rate. A Spearmans rank correlation was used to assess the strength of the relationship between accumulated rainfall over the previous 1, 2, 4, 5 and 7 days and nitrate concentration in inflow and outflow water samples. Rainfall parameters that correlated with a strength lower than 0.7 were included in a generalised linear model where nitrate was the dependent variable and accumulated rainfall over 2, 4 and 7 days were the independent variables. Sampling day was included as a random factor.

8.2.2 Integrated wetland results and discussion

Ammonia enters the integrated wetland at levels harmful to aquatic life

Heavy contamination by domestic misconnections was evident in water sampled at the system inflow (pictured in Figure 5) through presence of high ammonia and total coliform bacteria counts, both indicative of raw sewage (Figures 15 and 16, Table 5). Ammoniacal-nitrogen at the system inflow was present in concentrations of up to 14.7 mg/L (Figure 15, Table 5, Appendix D), levels known to be harmful to aquatic life and which could potentially cause fish death if allowed to enter directly into Boxers Lake. In a study of 32 freshwater fish species, the mean acute (un-ionised) ammonia toxicity was 2.79 NH_3 mg/L (Saeger *et al* 1988), and <1.0 NH_3 mg/L for many benthic invertebrate species (Environment Agency/SNIFFER 2007). Low dissolved oxygen concentrations, frequently reported in outfalls contaminated by misconnections, are known to increase the effects of acute ammonia toxicity (Saeger *et al* 1988). The integrated wetland system serves the important function of detaining and slowing polluted water from entering Boxers Lake, thereby allowing the particularly toxic, un-ionised form of ammonia to undergo nitrification into other less harmful forms.

Throughout the study period, there was no trend in parameter concentrations at the inflow over time (Appendix D). This means that changes in nutrient concentrations over time result from the functioning of the constructed wetlands.

The integrated wetland is effective at improving water quality

The integrated wetland system is effective at improving water quality in terms of both nutrient and total coliform bacteria concentrations.

Between the inflow and outflow there were statistically significant reductions in mean concentrations of total nitrogen (*n*= 12, *p*= 0.006), ammoniacal-nitrogen (*n*= 15, Z= -2.103, *p*= 0.035) and orthophosphate (*n*= 15, *p*= 0.007), Figure 15. These differences in mean water quality were independent of flow conditions and represent mean reductions of 42.8% in total nitrogen, 67.2% in ammonia and 22.7% in orthophosphate concentration in the water flowing out of the constructed wetland. These are typical of removal percentages noted in other wetland systems (Vymazal 2007). According to the WFD standards, this represents a transition from poor to moderate levels of ammoniacal-nitrogen. Orthophosphate levels, although improved, remained classified as poor. Total nitrogen levels remain above the threshold of low risk of eutrophication (European Nitrogen Assessment 2011).

The decrease in total coliform bacteria colony counts between inflow and outflow samples was also highly significant (*n*= 14, *p*= <0.001), Figure 16. This represented an overall mean reduction of 78% and a transmission of classification from imperative to good.

There was no change in the concentration of nitrate-nitrogen between the inflow and outflow (, *n*= 15*p*= 0.609, Figure 15). The volume of nitrate entering the system did not change over the study period (Appendix D). This was also not related to rainfall volume in preceding days because mean differences remained non-significant even after samples were grouped as either normal or high antecedent rainfall conditions (p= 0.678). Nitrate-nitrogen reduction in the wetland treatment basins is likely being masked by chemical processes occurring as part of the nitrification cycle (section 4.1). Briefly, nitrogen speciates from ammonia to nitrate, the most stable form of nitrogen, during nitrification. Consequently, as the amount of ammonia decreases, the amount of nitrate increases, resulting in no nett loss of nitrate. Ammonia concentrations from inflow samples were high (up to 14.7 mg/L, Table 5), the highest of all constructed wetlands investigated by this report, suggesting the ammonia fraction of total nitrogen to be high. Importantly, the decrease in concentration of total nitrogen (all nitrogen compounds), is highly significant, indicating that the integrated wetland system is an effective remover of nitrogen compounds.

8.2.3 Water quality improvement by individual treatment basin: improvements likely largest in the first basins.

Water was sampled at the inflow and outflow of each of the 6 treatment basins in the integrated wetland on 3 occasions, Figure 17 and 18. Indication from limited data is that the biggest improvements in nutrient parameters occurred primarily in basin 1, but also in basin 2. Water quality improved by smaller increments thereafter.

Nutrient concentrations were highly variable between the three sampling occasions, due to factors including time elapsed since the last significant rainfall. Also, it is unlikely that results from each basin track the same body of water through the wetlands. This is due to lag time of water moving through the basins, one result of which included parameter concentrations that were more concentrated at the basin exit compared to the basin entrance (for example ammonia, figure 17, E. coli, figure 18). In order to overcome this and draw more robust conclusions about individual basin performance, it is recommended that more data be collected to minimise the importance of event specific factors.

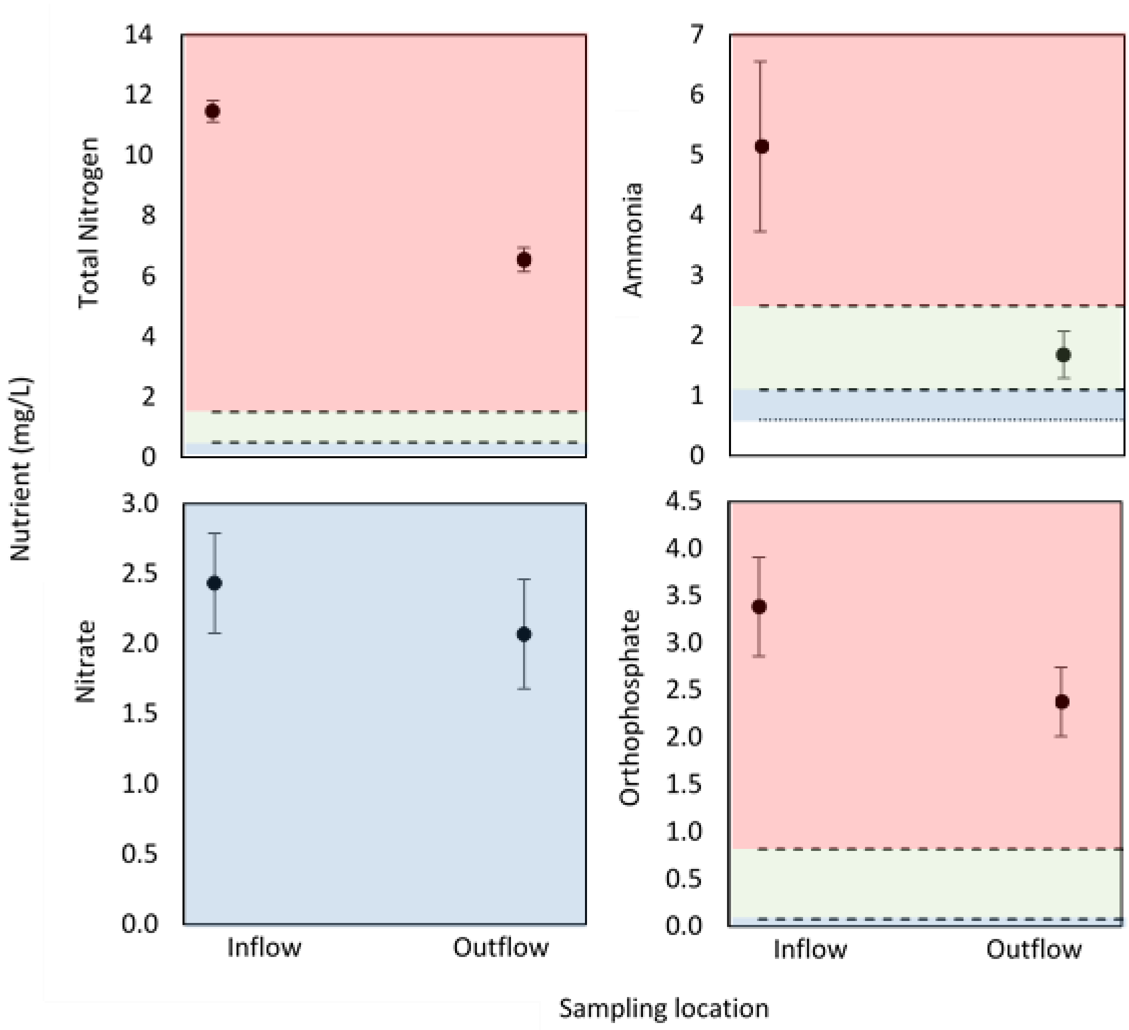

Figure 15: Mean (±s.e.) concentrations of nutrients (total nitrogen, ammoniacal nitrogen, nitrate-nitrogen, orthophosphate) from the inflow and outflow of the integrated wetland, Glenbrook. Sampling locations correspond with those in Figure 1 and Table 3. Dashed lines represent threshold standards in water quality from the WFD, simplified as poor (red), moderate (green), good (blue), very good (no colour).

Table 5: Mean (min-max) parameter concentrations of nutrients (mg/L) and total coliform bacteria (CFU/100ml) from water samples from the inflow and outflow of the integrated wetland, Glenbrook.

Sampling location	Total Nitrogen	Ammonia-nitrogen	Nitrate-nitrogen	Ortho Phosphate	Total coliform bacteria
1, Inflow	11.5 (4.5 - 19.8)	4.8 (0.0 – 14.7)	2.4 (0.3 – 4.8)	3.4 (1.1 – 7.6)	1350 (625 – 2500)
2, Outflow	6.6 (4.6 – 14.7)	1.7 0.0 – 4.6)	2.1 (0.6 – 4.6)	2.6 (0.8 – 7.1)	285 (50 – 750)

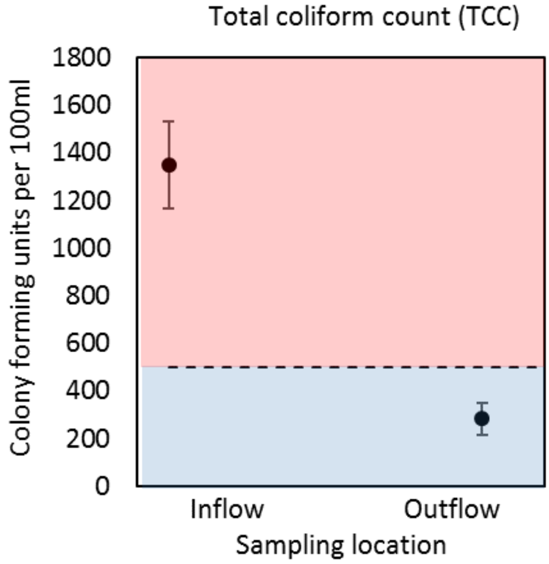

Figure 16: Mean (±s.e.) concentrations of total coliform bacteria colony forming units (CFU/100ml) from the inflow and outflow of the integrated wetland, Glenbrook. Sampling locations correspond with those in Figure 1 and Table 3. Dashed lines represent threshold standards in water quality from the EU Bathing Water Directive, where ≤ 500 CFU/100ml is imperative (red) and ≥500 is guideline (blue).

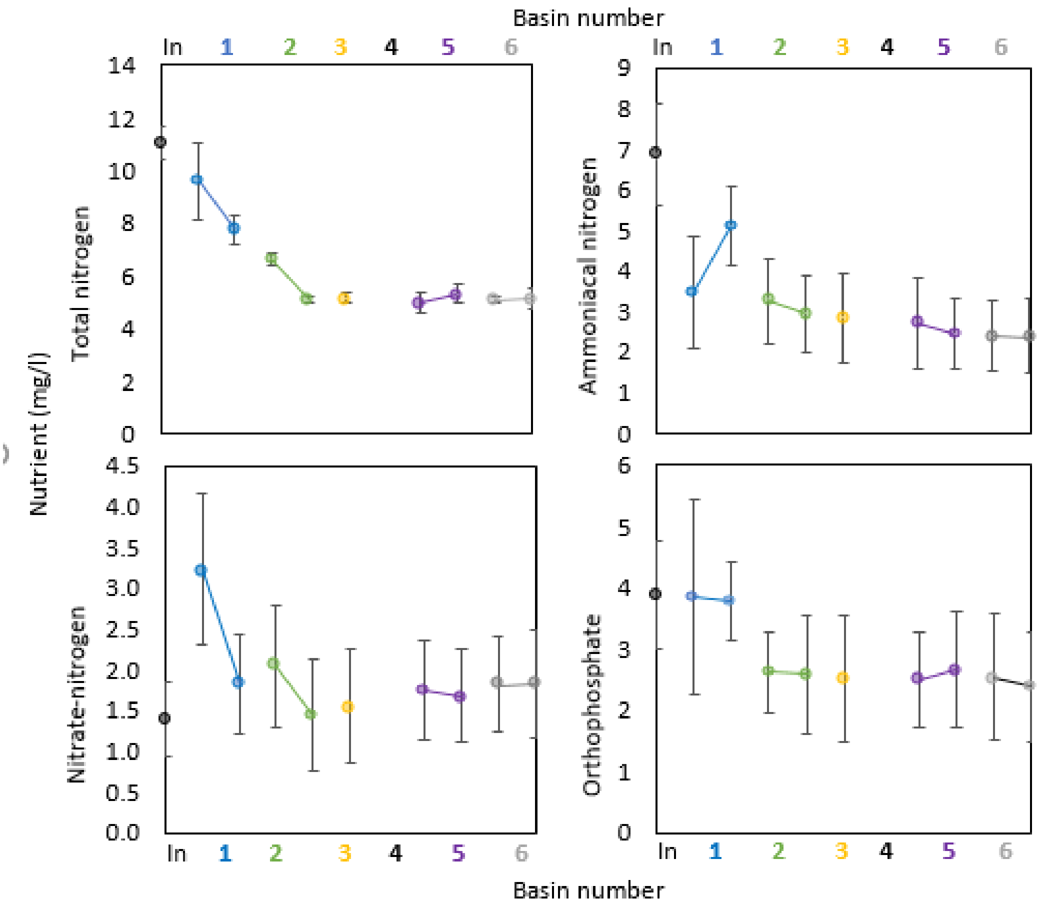

Figure 17: Mean (± se) concentrations of nutrients in water sampled on 3 occasions at the main inflow (In) plus the inflows and outflows of each treatment basin of the integrated wetland, Glenbrook. Each basin (1-6) is represented by a different colour, the inflow and outflow linked by a line of the same colour. Basins 3 and 4 were off line. Water flow in the system from basin 1 through to basin 6.

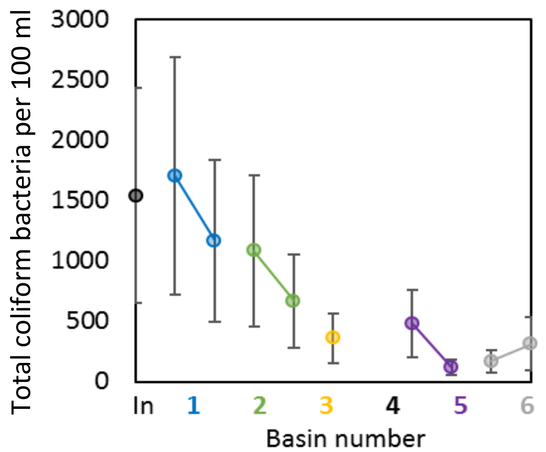

Figure 18: Mean (± se) concentrations of total coliform colonies in water sampled on 3 occasions at the main inflow (In) plus the inflows and outflows of each treatment basin of the integrated wetland, Glenbrook. Each basin (1-6) is represented by a different colour, the inflow and outflow linked by a line of the same colour. Basins 3 and 4 were off line. Water flow in the system from basin 1 through to basin 6.

8.3 Infiltration basin, Grovelands Park

8.3.1 Statistical analysis

Normal flow conditions captured all surface water diverted into the basin, so statistical analysis was not performed.

8.3.2 Infiltration basin results and discussion

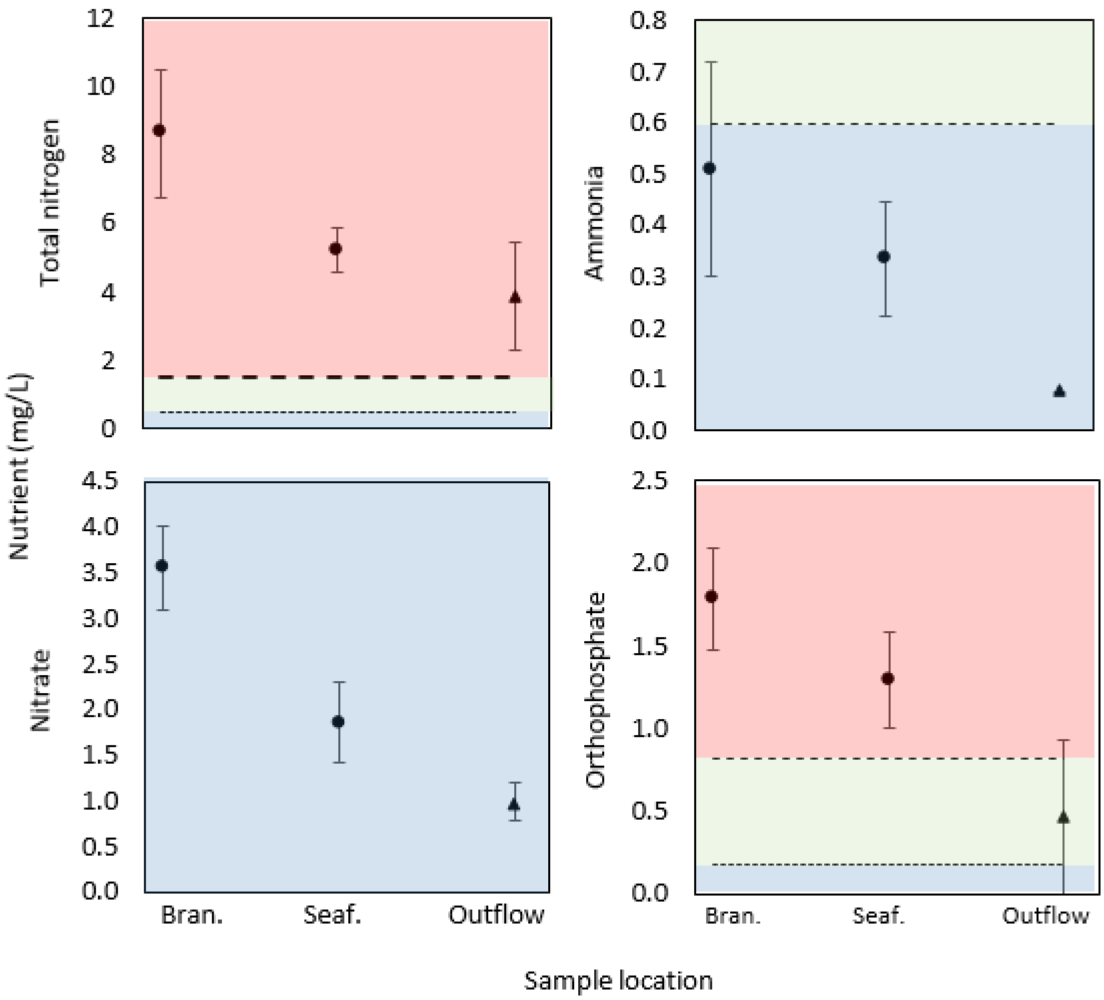

Figure 19: Mean (±s.e.) concentrations of nutrients (total nitrogen, ammoniacal nitrogen, nitrate-nitrogen, orthophosphate) from sampling locations in the infiltration basin, Grovelands Park. Sampling locations: inflow stormwater drains from Branscombe Gardens and Seaforth Gardens (filled circles) and the infiltration basin outflow weir (filled triangle), see Figure 6, Table 2. Dashed lines represent threshold standards in water quality from the WFD simplified as poor (red), moderate (green) and good (blue).

Table 6: Mean (min-max) parameter concentrations of nutrients (mg/L) and total coliform bacteria (CFU/100ml) from water samples from the infiltration basin, Grovelands Park. See Figure 6 and Table 2 for a description of sampling locations. Water was only encountered exiting the infiltration basin on 2 occasions, so the mean has not been calculated for the outflow weir.

Sampling location	Total Nitrogen	Nitrate-nitrogen	Ammoniacal nitrogen	Ortho phosphate	Total coliform bacteria
Branscombe Storm Drain	8.6 (3.0 – 20.9)	3.6 (0.0 – 5.0)	0.5 (0.0 – 2.2)	1.8 (0.3 – 3.7)	602 (150 – 1250)
Seaforth Storm Drain	5.2 (3.3 – 8.7)	1.9 (0.5 – 5.2)	0.3 (0.0 – 1.2)	1.3 (0.3 – 3.2)	713 (200 – 1250)
Outflow weir	(2.31 – 5.48)	(0.42 – 1.54)	(0.0 – 0.1)	(0.0 – 0.9)	(75 – 75)

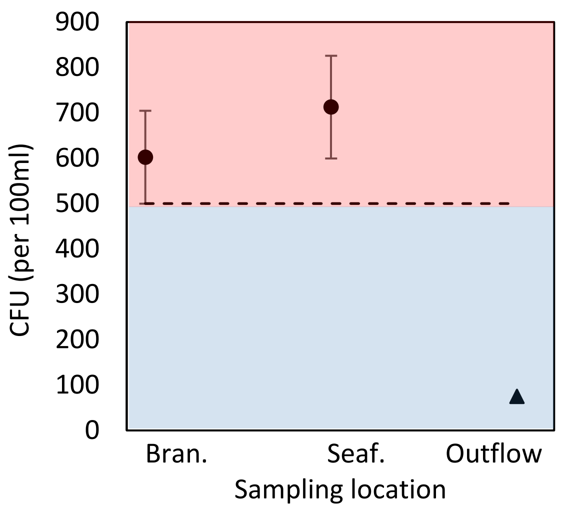

Figure 20: Mean (±s.e.) concentrations of total coliform bacteria colony forming units (CFU/100ml) from sampling locations in the infiltration basin, Grovelands Park. Sampling locations are: the inflow strom water drains from Branscombe Gardens and Seaforth Gardens and the infiltration basin outflow weir (sampled twice only) (see Figure 6, Table 2). Dashed lines represent threshold standards in water quality from the EU Bathing Water Directive, where ≤ 500 CFU/100ml is imperative (red) and ≥500 is guideline (blue).

Infiltration basin is effective at improving water quality

The infiltration basin prevents the majority of polluted water from Branscombe Gardens and Seaforth Gardens from entering the Grovelands Park stream (and subsequently the Salmons Brook). Water only exits over the basin weir into the stream in times of very high flow (observed on 2 sampling occasions). During normal flow conditions, water is retained within the basin and released slowly into the ground through permeable soils. This makes the basin highly effective at preventing polluted water from entering the stream.

Concentrations of total nitrogen, ammoniacal nitrogen, nitrate-nitrogen and total coliform bacteria in surface water diverted from Branscombe Gardens and Seaforth Gardens were significantly higher than those entering the Grovelands Park stream (Figures 19 and 20, Table 6). Total nitrogen and orthophosphate levels in the entry drains were rated as high risk of eutrophication and poor quality respectively, whilst bacteria levels were classified as imperative in both entry drains. It was not possible to estimate total quantities of pollutants trapped by the infiltration basin due to lack of flow data from both the Branscombe and Seaforth stormwater drains.

On the two occasions when water was sampled exiting the infiltration basin over the weir, concentrations of all nutrients and total coliforms were significantly improved in comparison to the quality of water entering the basin. However, the first flush was not captured so it is recommended that more data be gathered during peak flow in order to draw robust conclusions. In particular, sampling as water first overtops the exit weir would be highly informative.

8.4 Reedbed, Grovelands Park Lake

8.4.1. Statistical analysis

Nutrients data were not normally distributed. Pair-wise post hoc analysis was carried out using Wilcoxon signed rank tests with a Bonferroni adjustment to avoid type 1 error (over estimating the differences between the pairs).

Total coliform bacteria were normally distributed so a paired t-test was used to compare water quality above and below the reedbed.

8.4.2 Reedbed results and discussion

Reedbed is effective at improving water quality

Water sampled immediately after the reedbed was significantly cleaner than water sampled before it. There were significant reductions in compounds of nitrogen: total nitrogen (n= 7, Z= -2.197, p= 0.028), ammoniacal nitrogen (n= 8, Z= -2.028, p= 0.043 and nitrate-nitrogen (n= 8, Z= -2.521, p= 0.012) and in total coliform bacteria (n= 8, t(7)= 6.988, p= 0.000), Figures 21 and 22, Table 7. This represented a 55.3% reduction in total nitrogen, a 36.8% reduction in ammoniacal nitrogen and a 68.7% reduction in nitrate nitrogen entering the lake. As a result of reedbed treatment processes, ammonia classification improved from poor to good quality, according to WFD thresholds. Total coliform counts are classified as poor (imperative) before the reedbed and are within guideline levels after the reedbed. This demonstrates that, from immediately after installation, the reedbed is effectively treating water.

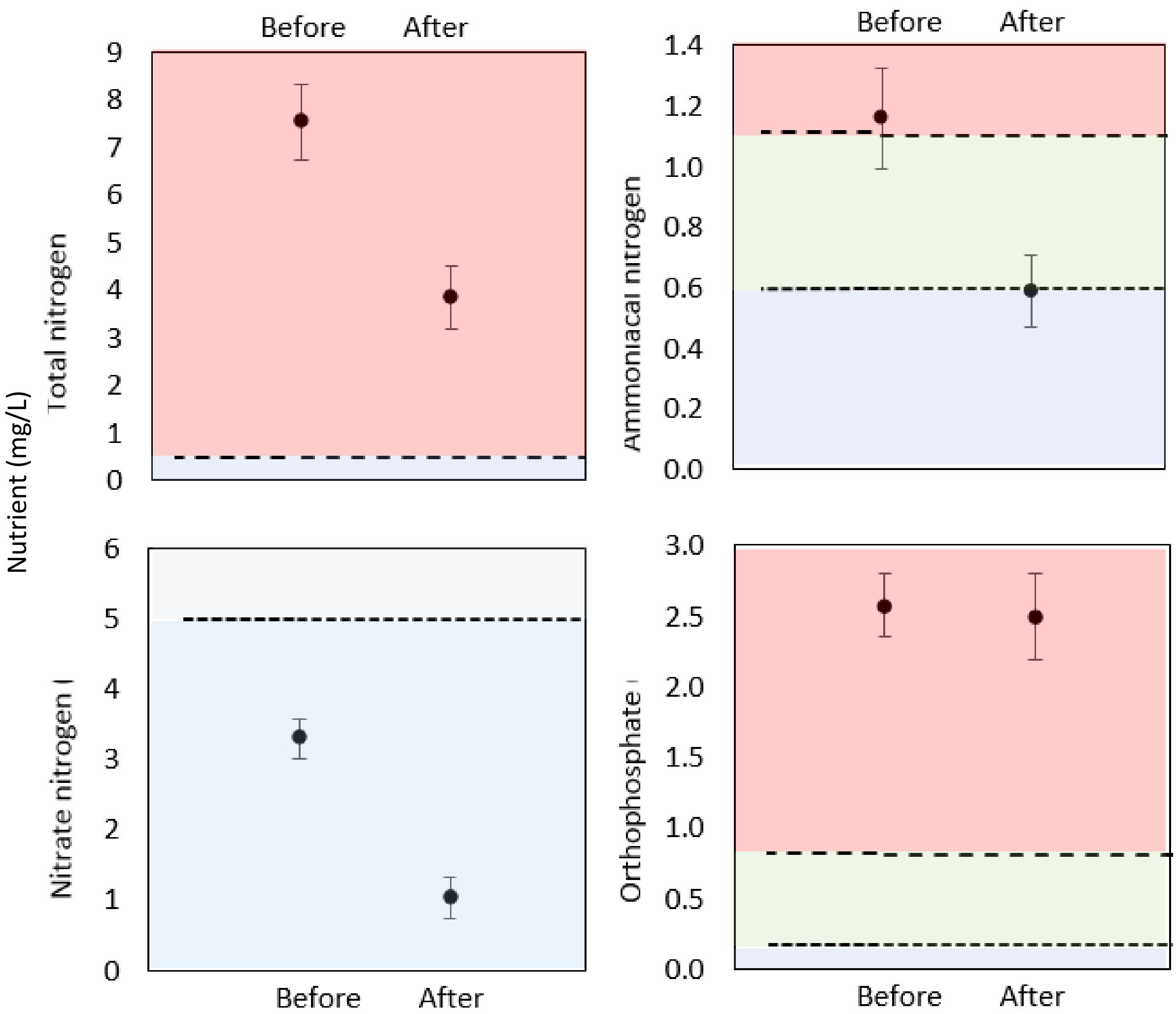

Figure 21: Mean (± s.e.) concentrations of nutrients (total nitrogen, ammoniacal nitrogen, nitrate-nitrogen, orthophosphate) from sampling locations around the reedbed on Grovelands Park Lake. Sampling locations are: the outfall immediately before the reed bed (before), water sampled immediately after the reedbed (after). Dashed lines represent threshold standards in water quality from the WFD, simplified as poor (red), moderate (green) and good (blue). Nitrate-nitrogen only is subdivided into good (pale grey) and very good (blue).

Table 7: Mean (min-max) parameter concentrations of nutrients (mg/L) and total coliform bacteria (CFU/100ml) from the reedbed, Grovelands Park Lake. Sampling locations are: the outfall immediately before the reed bed (before) and water sampled immediately after the reedbed (after). See Figure 6 and Table 2 for sampling locations.

Sampling location	Total Nitrogen	Nitrate-nitrogen	Ammoniacal nitrogen	Ortho phosphate	Total coliform bacteria
Before	7.5 (5.7 – 10.8)	3.3 (2.9 – 5.2)	1.2 (0.5 – 1.8)	2.6 (1.8 – 3.8)	1090 (500 -1250)
After	3.4 (1.8 – 6.4)	1.0 (0.4 – 3.0)	0.6 (0.1 – 0.9)	2.5 (1.3 – 4.1)	315 (175 – 750)

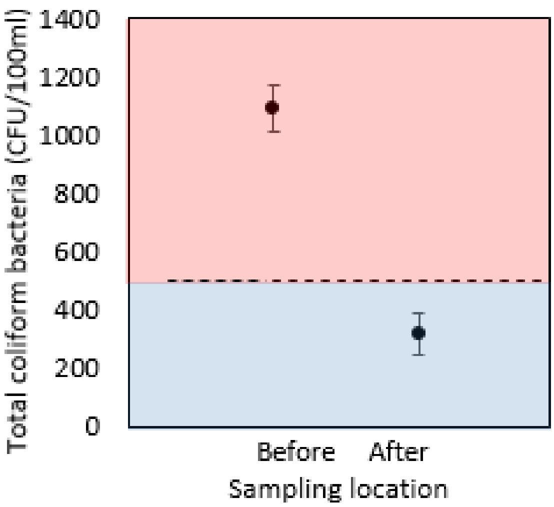

Figure 22: Mean (±s.e.) concentrations of total coliform bacteria colony forming units (CFU/100ml) from sampling locations on the reedbed, Grovelands Park Lake. Sampling locations are: the outfall immediately before the reedbed (before) and water sampled immediately after the reedbed (after). See Figure 6 and Table 2 for sampling locations. Dashed lines represent threshold standards in water quality from the EU Bathing Water Directive, where ≤ 500 CFU/100ml is imperative (red) and ≥500 is guideline (blue).

The difference in water quality above and below the reedbed is visually striking. The space before the reedbed is often turbid with a persistent surface scum, whereas the area immediately after the reedbed is noticeably cleaner (images, Figure 9).

Over the study period there was no change in the quality of water entering the lake from the culverted outfall, except in terms of an increase in nitrate-nitrogen (Appendix D). This suggests that reductions in parameter concentrations are the result of reedbed processes rather than a reduction in misconnections and pollution entering the lake. However, this data must be interpreted with caution because the reedbed potentially retains and concentrates polluted water in the space before the reedbed, so water samples may not be a true reflection of concentrations of parameters exiting the outfall.

There was no change in orthophosphate concentrations

There was no significant reduction in orthophosphate resulting from processes occurring in the reedbed (n= 8, Z= -0.840, p= 0.401). This means that the reedbed is not currently an effective remover of bioavailable phosphate and the entire system remains classified as poor according to WFD thresholds.

Water testing began the week after installation of the reedbed, before plants had established or colonised the gaps between the coir pallets. Plants such as *Phragmites australis*, used in construction of the reedbed, are demonstrated to be good removers of phosphorus (Tian *et al* 2009, Rezaie and Sahlezadeh 2014) so it is likely that phosphate uptake will improve over time with reed growth and as macrophytes and microorganisms colonise the rhizomes. This will also trap sediments which may improve phosphate removal by sedimentation and immobilization by abiotic adsorption (binding) onto the surface of sediment particles. However, these important process of phosphate removal are redox (reduction-oxidation) sensitive (Braskerud *et al* 2003). This means that changes in pH and oxygen availability may cause phosphate to remobilise, resulting in continued detection of phosphate in water samples.

Due to its designation as an above ground reservoir, the lake margins are mostly artificial with little emergent or semi aquatic vegetation. Consequently, the performance of the reedbed will be key in improving water quality. Further monitoring of water quality and reedbed performance as it matures is strongly advised.

9 Conclusions

There was a statistically significant improvement in water quality in each of the constructed wetland systems monitored by this report. This was particularly evident in terms of total nitrogen, ammonia and total coliform bacteria.

9.1 Integrated wetland, Glenbrook

In the six-basin wetland system on the Glenbrook stream, a tributary of the Salmons Brook, there was a 43% reduction in total nitrogen, a 67% reduction in ammonia and a 30% reduction in orthophosphate in water sampled exiting the system, compared to flowing into the system. According to WFD standards for ammonia, water quality classification improved from poor before the constructed wetland, to moderate after it. Water quality for total nitrogen and orthophosphate improved but remained classified as poor.

Analysis of water samples taken from the entrance and exit of each wetland basin indicated that basins one and two are having the highest impact on water quality.

It is anticipated that effectiveness at water treatment will continue to improve in the future for two reasons: Firstly, repair of the eroded weir will bring basins 3 and 4 back online so water treatment will occur in additional wetland basins. Secondly, as plants on the coir pallets mature and colonise the gaps between pallets. This will provide additional opportunities for water treatment by plant uptake, sedimentation and the action of microorganisms on plant rhizomes.

9.2 Infiltration basin, Grovelands Park

In all but the highest flows conditions, polluted water from Branscombe Gardens and Seaforth Gardens is entirely retained by the infiltration basin rather than entering the Groveland Park stream (subsequently the Salmons Brook). This represents almost total effectiveness at capture and treatment of polluted water before it enters the river. Water entering the infiltration basin was classified by WFD standards as poor quality in terms of nitrate and phosphate. Total nitrogen levels were classified as high risk of eutrophication and total coliform bacteria as imperative (high risk).

Water was only sampled flowing out of the basin on two occasions, and not during the first flush, so conclusions during high flow conditions are only tentative. However, in comparison to water entering the basin, the water exiting the basin was significantly improved in concentrations of all nutrients, bacteria, copper and lead.

9.3 Reedbed, Grovelands Park

Immediately after installation, the reedbed was effective at removing nutrients except orthophosphate. It was also effective at removal of coliform bacteria. This indicates that installation of the constructed wetlands is having a positive impact on water quality in the tributary stream of the Salmons Brook that drains the lake.

10 Recommendations

10.1 Continued sampling of the constructed wetlands as they mature

This investigation took place in the wetland start-up phase before plants had fully matured or colonised spaces between the coir planting matts. There is therefore potential for greater efficiencies in nutrient removal as the wetland ecosystem (plants and associated microorganisms essential for nutrient removal) mature. The robustness and full impact of these constructed wetlands on improving the quality of water entering the Salmons Brook can only be understood with further monitoring of inflow and outflow water chemistry in well established, mature systems. Furthermore, it will also be important to continue monitoring the constructed wetlands beyond maturation to assess their ongoing effectiveness when factors such as sediment deposition become important.

In addition, these wetlands also have high potential as sites for other monitoring programmes. For example, investigations into trends in benthic fauna within the basins or the impact of the installations on wetland species colonisation and biodiversity.

10.2 Real-time monitoring of water chemistry

A limitation of this report is that spot samples were only collected twice monthly and it was not possible to respond to rainfall events to capture first flush. Real-time monitoring by probes deployed in the inflow and outfall of each wetland system would allow high resolution, detailed assessment of individual wetland performance over a range of flow conditions and temporal scales, for example performance during individual flood rainfall events. This invaluable insight into urban wetland basin processes would represent a genuine contribution to advancing current scientific understanding, as well as informing assessment of individual constructed wetland performance. This is particularly so with regard to effects of urban runoff i.e. heavy metals, oils and high sediment loads which lead to DO crashes and fish kills.

10.3 Monitor other constructed wetlands within the Salmons Brook

Three out of the six urban drainage treatment systems planned as part of the Salmons Brook Healthy River Challenge are discussed by this report. Monitoring of water quality parameters in the remaining installations would be beneficial to insure they are delivering WFD improvements. This is particularly important because installations (such as the integrated wetland, Glenbrook in this report) are mainly impacted by misconnections, whilst others, (for example the wetland cells which have been recently completed beside the A10, Great Cambridge Road) are impacted more by urban runoff.

10.4 Demonstration of these Constructed Wetlands in further locations

As evidenced by this report and other studies (Ellis *et al* 2003, Dickie *et al* 2010, Andrés-Valeri *et al* 2014) constructed wetlands are a robust, effective method of addressing urban water quality issues in order to meet WFD targets. There is a definite call for further funding to be directed into the creation and monitoring of sustainable urban drainage wetland systems to improve water quality elsewhere on the Lea and other urban catchments impacted by misconnections and urban runoff.

10.5 Demonstration of these techniques on a catchment scale

The Salmons Brook Healthy River Challenge was undertaken largely as an experiment into how constructed wetlands can deliver real WFD improvements to waterbodies affected by Urban Diffuse Pollution issues. This report shows the real improvements that these systems can deliver. However, the Salmons Brook Healthy River Challenge did not undertake a detailed analysis of the sources of pollution entering the river, but merely identified locations where these techniques could be used to demonstrate to resolve real problems. Funding should be sought to develop a detailed water quality model for a waterbody including identification of sources of pollution. This should then be used to develop a programme for the resolution of these pollution sources through constructed wetlands treatment processes.

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12. Appendices

Appendix A -Coir pallet plant species

Juncus effusus [Soft Rush]

Lythrum salicaria [Purple Loosestrife]

Carex acutiformis [Lesser Pond Sedge]

Iris pseudacorus [Yellow Flag Iris]

Caltha palustris [Marsh Marigold]

Mentha aquatica [Water Mint]

Myosotis palustris [Water Forget-me-Not]

Ranunculus flammula [Lesser Spearwort]

Alisma plantago [Water Plantain]

Appendix B - Hach Lange working procedures

All links accessed 17/02/2015

- **Total Nitrogen**

Method: Unfiltered sample. Koroleff Digestion (Peroxo-disulphate), and Photometric Detection with 2.6-Dimethylphenol
http://uk.hach.com/laton-total-nitrogen-cuvette-test-1-16-mg-l-tn-sub-b-sub/product?id=26370268941
http://uk.hach.com/laton-total-nitrogen-cuvette-test-5-40-mg-l-tn-sub-b-sub/product?id=26370269003&callback=qs

- **Ammonia**

Method: Filtered sample (0.45 µm membrane filter). Indophenol blue
http://uk.hach.com/ammonium-cuvette-test-2-0-47-0-mg-l-nh-sub-4-sub-n/product?id=26370269011&callback=qs
http://uk.hach.com/ammonium-cuvette-test-0-015-2-0-mg-l-nh-sub-4-sub-n/product-downloads?id=26370269012

- **Nitrate**

Method: Filtered sample (0.45 µm membrane filter). 2.6-Dimethylphenol
http://uk.hach.com/nitrate-cuvette-test-0-23-13-5-mg-l-no-sub-3-sub-n/product?id=26370291438
http://uk.hach.com/nitrate-cuvette-test-5-35-mg-l-no-sub-3-sub n/product?id=26370291439 &callback=qs

- **Phosphate**

Method: Unfiltered sample, Phosphomolybdenum Blue
http://uk.hach.com/phosphate-ortho-total-cuvette-test-0-05-1-5-mg-l-po-sub-4-sub-p/product?id=26370291448
http://uk.hach.com/phosphate-ortho-total-cuvette-test-2-0-20-0-mg-l-po-sub-4-sub-p/product?id=26370291449&callback=qs

- **Metal digestion**

Method: Determination of total metal content included heating in an acid environment in the presence of an oxidising agent (cracking) as a pre-treatment.
http://uk.hach.com/crack-set-reagent-set-for-metal-digestions/product-downloads?id=26370291742&callback=qs

- **Zinc**

Method: Unfiltered sample. Cracking then 4-(2-pyridylazo)- resorcin (PAR)
http://uk.hach.com/zinc-cuvette-test-0-2-6-0-mg-l-zn/product?id=26370291457

- **Copper**

Method: Unfiltered sample. Cracking then PAR
http://uk.hach.com/copper-cuvette-test-0-1-8-0-mg-l-cu/product?id=26370291428

- **Cadmium**

Method: Unfiltered sample. Cracking then Cadion
http://uk.hach.com/cadmium-cuvette-test-0-02-0-3-mg-l-cd/product?id=26370291404

- **Lead**

Method: Unfiltered sample. Cracking then PAR
http://uk.hach.com/lead-cuvette-test-0-1-2-0-mg-l-pb/product?id=26370291402&callback=qs

Appendix C –Duplicate analysis with a UKAS accredited lab

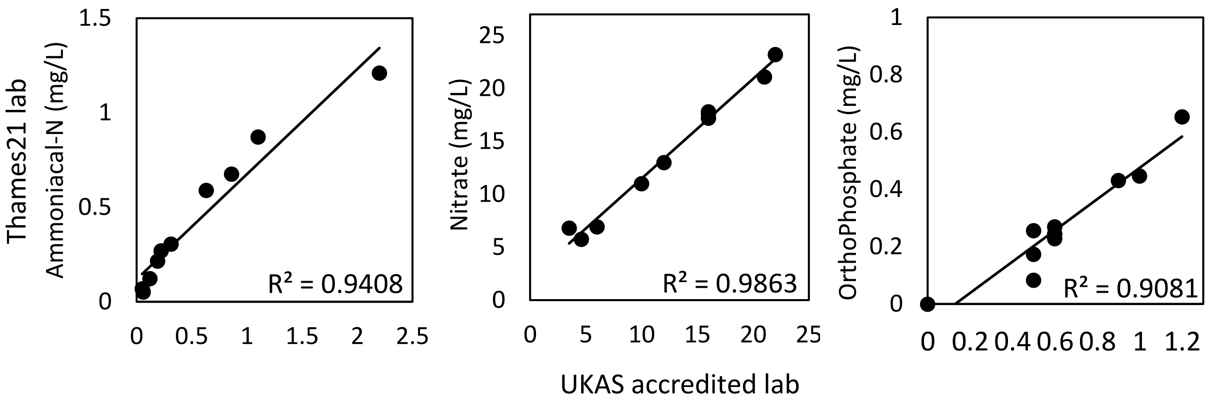

Figure 23: Results of duplicate analysis with a UKAS accredited laboratory of nutrients (ammoniacal nitrogen, nitrate and orthophosphate) from 10 samples.

Linear regressions were used to explore the strength of the correlation between analysis undertaken at Thames21's inhouse laboratory and an independent United Kingdom Accreditation Service (UKAS) registered laboratory. All parameters demonstrate R^2 values over 0.9, indicative of very strong, linear relationship between values determined by each laboratory. This means parameter concentrations reported in this document are representative of actual values occurring in the constructed wetlands.

Orthophospate displayed the weakest correlation. This was likely influenced by due to two factors. 1) Samples were filtered prior to phosphate analysis by the UKAS accredited lab but were not filtered by Thames21's Lab. Filtering removes reactive phosphotous that may be present in particulate form in the water column. As a result, Thames21's lab reported results that were on average 0.2 mg/L (s.e. ± 0.1) higher than values reported by the UKAS accredited lab. Values were consistently different, which suggests the Thames21 lab was performing well. Discrepancies were not suffcient to alter the WFD classification of any sample, therefore values were not corrected to account for the lack of prefiltering as this may introduce further error.

2) Differences in limits of detection (Thames21 Lab: 0.05 mg/L, UKAS lab: 0.5 mg/L and decimmal places in reporting) meant that UKAS lab results were less sensitive. As a result, 3 samples were below detection limits in the UKAS accredited lab.

Appendix D – Trends in inflow parameter concentrations over time

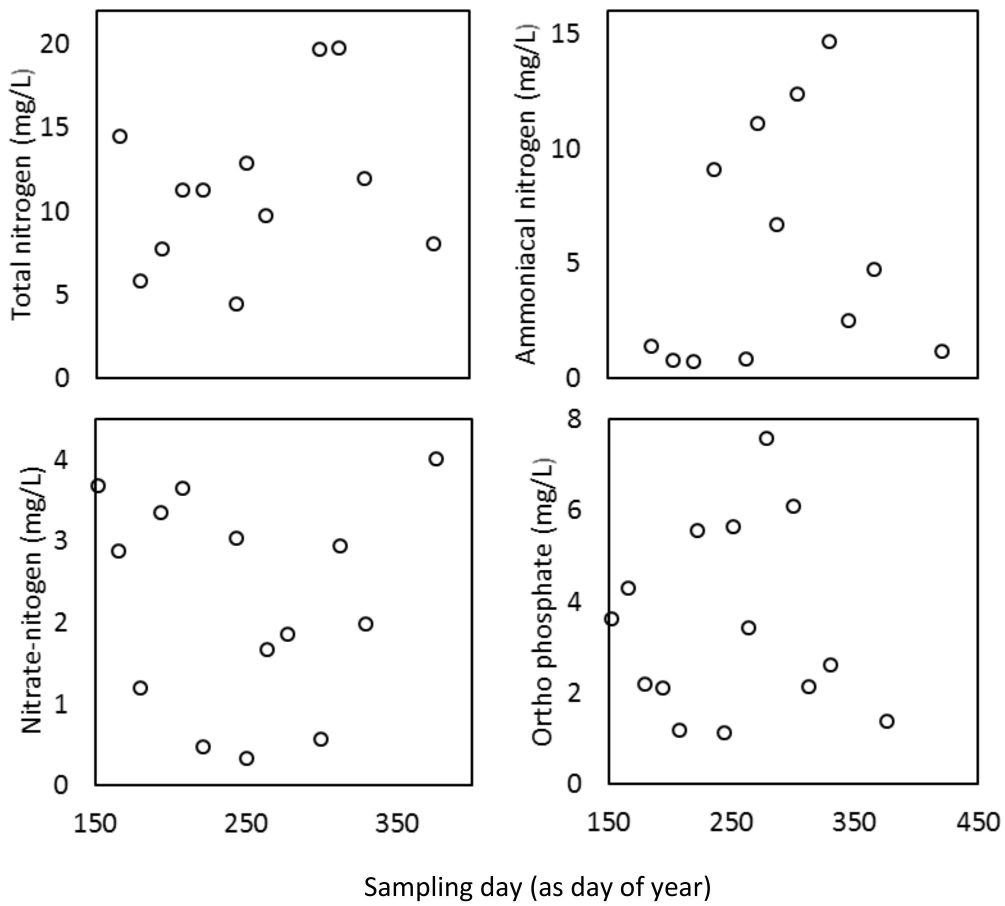

Figure 24: Trends in concentrations (mg/L) of nutrient parameters (total nitrogen, ammoniacal nitrogen, nitrate-nitrogen and orthophosphate) over measured in the inflow to the integrated wetland system, Glenbrook (pictured Figure 5). Time is shown as day number of the year. Concentrations of nutrients entering the wetland system do not change over time during the study period.

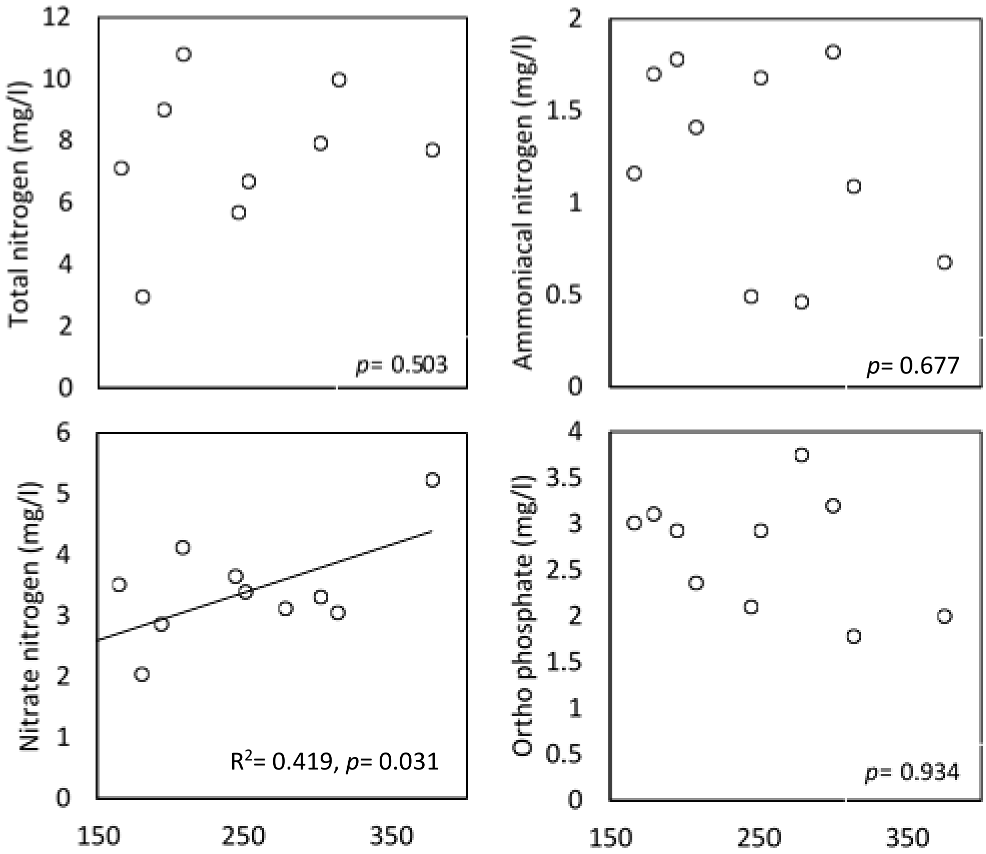

Figure 25: Trends in concentrations (mg/L) of nutrient parameters (total nitrogen, ammoniacal nitrogen, nitrate-nitrogen and orthophosphate) over measured in the inflow to Grovelands Park Lake above the reedbed. Time is shown as day number of the year. There is a statistically significant increase in the amount of nitrate-nitrogen entering the lake. Concentrations of the other nutrients parameters does not change over time during the study period.