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Performance assessment of Wharf Street Constructed Wetland 2009-2014

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Australian Government
Department of Industry, Innovation and Science

Business
Cooperative Research Centres Programme

Performance assessment of Wharf Street Constructed Wetland 2009-2014
Integrated multifunctional urban water systems (Project C4.1)
C4.1 – 1 - 2015

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Publisher

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Date of publication: December 2015

An appropriate citation for this document is:

Adyel, T.M, Ocampo, C., Tareque, H., Oldham, C.E., Hipsey, M.R. (2015) Performance assessment of Wharf St Constructed Wetland 2009-2014. Cooperative Research Centre for Water Sensitive Cities, Melbourne, Australia.

Executive summary

This report summarises the results of a performance assessment of the Wharf Street Constructed Wetland (WSCW). WSCW is an artificial wetland on the Swan Coastal Plain of Western Australia with an area of about 1 hectare. It was constructed to improve the quality of urban stormwater runoff and reduce nutrients and other contaminants entering the Canning River from an urbanised 129ha catchment. The wetland is a multistage hybrid system containing vegetated and open water surface flow (SF) and vegetated subsurface flow (SSF) components. For this report the WSCW is segmented into four compartments, each containing at least one inflow and outflow. Initially the SSF compartment was constructed using recycled concrete material (RCM). But due to an alkalinity problem, in June 2012 approximately 1500 m³ of RCM was removed (all of SSF 1 and roughly half of SSF 2) and replaced by 25-40 mm screened washed laterite aggregate sourced from a quarry in the Perth hills. Minimum wetland water levels are maintained via a combination of pumped re-circulating wetland water and extraction from the superficial aquifer. The system has been the subject of regular monitoring of hydrology, water quality and ecology for the past seven years.

This report covers an analysis of all available historical data that has been collected from 2009 to 2014, with an overarching aim of gaining insights into the overall effectiveness of the wetland in treating urban stormwater. It attempts to give answers to a series of knowledge gaps related to the dynamics and performance of the urban wetland and recommend future monitoring and research activities.

The analysis includes four main components: a hydrological assessment, an analysis of the water quality (base flow and event flow) and nutrient attenuation, sediment quality and an assessment of nutrient storage in macrophytes.

The hydrological assessment establishes a basic water balance for the wetland system. There is a tendency for the wetland to lose water during isolated rainfall events (small or large) with dry antecedent conditions, or under pumping cycles in spring and autumn. There are large volumetric contributions from ungauged areas during the periods of frequent rainfall events that occur during winter-spring and when large rainfall events activate runoff from the Bebington Court drain catchment, which enters ~50m upstream of the wetland outlet.

The analysis of water quality data identified the temporal and spatial variability of pollutant levels across the wetland, with a focus on assessment of outgoing nutrient and metal concentrations for compliance with the Healthy Rivers targets and Australian and New Zealand Environmental Conservation Council (ANZECC) guidelines. The results indicated that the concentrations of pollutants were generally reduced, but not always sufficiently to meet water quality targets.

Attempts were made to assess the efficiency of the wetland in removing nutrients and metals from the inflowing water. Several limitations were encountered due to the presence of ungauged input from the Bebington Court drain, and from groundwater top-up, and therefore an alternative method (calculating standardized delta concentrations, SDC) was adopted for assessing wetland performance during base flow condition. This method able to: a) provide a range of performance values for different compounds of interest, b) highlight the importance of ungauged sources for the assessment, and c) demonstrate changes in performance over time. However during event sampling, simultaneous nutrient and flow were measured and hence event mean and load could be calculated. These results highlighted the effect of seasonality on pollutant reduction, in response to changes in retention time, and also potentially due to dilution from ungauged inputs. The maximum nutrient attenuation occurred during dry summer periods.

WSCW attenuated an average of 62% ammonium nitrogen (NH_3), 16% nitrate/ nitrite (NOx) and 11% total nitrogen (TN) during baseflow. Nutrient attenuation followed the seasonal trend, with higher nutrient reduction during summer. SDC for dissolved organic nitrogen (DON) was low (up to 15%) compared to other parameters in the system. After long term operation, the wetland can act as a source of organic nutrients. DON may be released from the open water bodies, likely from the sediment or senescent plant material. Average attenuation of filterable reactive phosphorus (FRP) and total phosphorus (TP) in the wetland was 58% and 65%, respectively during dry periods (i.e. baseflow). Overall, the system attenuated P species more effectively than N species. SSF compartments showed higher attenuation of P.

A total of six rainfall events were monitored and during these events the system attenuated up to 67%, 92% and 87% of TN, TP and total suspended solids (TSS) load, respectively. The average TN and TP load reduction was 41% and 66%, respectively. Three events released TSS. Nutrient attenuation depended on the amount, duration and intensity of rainfall, as well as antecedent dry conditions, hydraulic residence times, volume of inflows and outflows. The total nutrient mass retention by WSCW was estimated. Over the five years of monitoring (2010-2014) the total mass of TN retained was 1,658 of 2,526 kg input (or approximately 65% removal) and the total mass of TP retained was 129 kg of 286 kg input (or approximately 45% removal).

The measured effectiveness of the WSCW was compared with pre-construction predictions. The average outlet concentrations of TN and TP under baseflow was 0.81mg/L and 0.04 mg/L, respectively, agreeing with the pre-constructions predictions (1.01mg/L and 0.055 mg/L for TN and TP, respectively). TP attenuation was 65% during baseflow agreeing with predictions of 57%. However, TN attenuation was lower than predicted. There were some occasions when outlet TN concentration was higher than inlet concentration and Bebington Court drain may be a possible source of such TN.

The analysis also confirmed the important role sediments play in trapping nutrients. The sediments were a significantly greater pool of nutrients than the wetland vegetation. The sediment continues to accumulate organic carbon and nitrogen with time, while the vegetation was seen to be a highly variable nutrient store, both between sites and across seasons.

Finally, this report discusses recommendations to improve our understanding of the wetland's biogeochemical function and answer questions that could not be addressed by this analysis due to constraints in the historical data set.

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Acronyms and glossary

AHD	Australian Height Datum
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
BDL	Below detectable limit
CRC	Cooperative Research Centre
DM	Discharge Measurement
DNIP	Drainage Nutrient Intervention Program
DO	Dissolved oxygen
DoW	Department of Water
DPaW	Department of Parks and Wildlife (formerly Swan River Trust)
DWC	Dry Weather Condition
EMC	Event Mean Concentration
FF	First Flush
HRAP	Healthy Rivers Action Plan, also referred to as Healthy Rivers
HRT	Hydraulic retention time
ISQG	Interim Sediment Quality Guideline
MUSIC	Model for Urban Stormwater Improvement Conceptualization
PE	Pumping event
RCM	Recycled Concrete Material
SCP	Swan Coastal Plain
SCCP	Swan Canning Cleanup Program
SDC	Standardised Delta Concentration
SDC_ave	Average Standardised Delta Concentration
SERCUL	South East Regional Centre for Urban Landcare
SF	Surface flow
SRT	Swan River Trust
SSF	Subsurface flow
VCUS	Volumetric Contribution of Ungauged Sources
WIN	Water Information Network (sites)
WIR	Water Information Reporting
WSCW	Wharf Street Constructed Wetland
WSMD	Wharf Street Main Drain
WSUD	Water Sensitive Urban Design

Introduction

Background

Constructed wetlands (CWs) are well-documented water sensitive urban design (WSUD) elements able to assimilate stormwater nutrients and other contaminants (Carleton et al., 2000; 2001). The performance of these systems for stormwater treatment varies depending on the nature of the design, the hydrological regime they experience as well as soil conditions and vegetation characteristics. While general design guidelines exist, the performance of specific systems remains unclear, especially within the sandy Swan Coastal Plain (SCP) environment where episodic pulses dominate hydrological and biogeochemical aspects of wetland function.

Over the past decade the Swan River Trust (the Trust) and their partners have invested substantial resources in constructed wetland systems on the SCP as part of the Trust's Healthy Rivers Action Plan (HRAP) to protect water quality of the Swan-Canning river system. The focus of this report is on the Wharf Street Constructed Wetland (WSCW), a lined hybrid system with vegetated and open water surface flow (SF) and subsurface flow (SSF) components. Macrophyte species are dispersed across the dominant flow path and fringing around the open water bodies of the system as well as on top of the SSF zones. The system contains multistage SF and SSF components and has been the subject of regular monitoring of hydrology, water quality and ecology for the past six years. To better understand the performance of the system and to gain insights more generally into SCP wetland function, a critical analysis of the historical data was required.

This work was undertaken by two related research projects within the Cooperative Research Centre for Water Sensitive Cities (CRCWSC): Project C4.1 "*Multi-functional urban water systems*", and Project B2.4 "*Hydrology and nutrient transport processes in groundwater/surface water systems*". Together these projects aim to quantify and optimise the effectiveness of WSUD elements for treating stormwater across a range of urban environments. A complementary study of Anvil Way Compensation Basin (AWCB) has similarly been undertaken (Ruibal-Conti et al., 2015).

Aims and scope of work

Following discussions between Peter Adkins (the Trust), Matthew Hipsey (UWA) and Carolyn Oldham (UWA) in May 2014, it was agreed that UWA would undertake a detailed review and assessment of the past performance of the WSCW, as motivated by several specific questions outlined below. This work has been conducted to supplement existing Project C4.1 and B2.4 activities and provide important contextual information for ongoing research activities.

For the WSCW the following specific questions were initially asked by the Trust, to focus subsequent data analysis.

- Is it meeting HRAP targets (TN <1mg/L and TP <0.1mg/L)?
- What is the wetland treatment efficiency for a range of different parameters (nutrients, suspended sediment, metals etc.) under different hydrological conditions (baseflow, rising limb, falling limb of various storm events)?
- What are the differences in nutrient levels and speciation between the inlets and outlet?
- Is the wetland meeting ANZECC water quality targets (95% protection)?
- How effective are sediment and vegetation at removing nutrients and other pollutants?
- How effective are the specific features and components within the design at collecting nutrients and pollutants?
- How does the efficiency differ between N and P?
- Does N: P stoichiometry differ in hydrologic condition?
- What about partitioning i.e. organic vs inorganic of nutrients in water column?
- Is the efficiency related to the hydrologic residence time of the system?
- What are the dominant N and P reduction processes in the wetland?
- Does ephemerality of the wetland affect nutrient uptake/release?

- What is the net assimilation rate of N and P per unit area of wetland?
- What is the cost per kg of N and P removal?
- Does the wetland improve waterway ecological integrity?
- Could the wetland be manipulated or managed differently to be more effective?
- Other questions like nutrient reduction in surface and subsurface flow system etc

It was acknowledged in the May scoping meeting that some of these questions may not be answered by the historical data. Where this is the case, recommendations for future monitoring and research that can be undertaken to more fully address the question are made.

Overview of the Wharf Street Constructed Wetland

The Wharf Street Constructed Wetland and Civic Parkland project was initiated under the Swan River Trust's (the Trust) Drainage Nutrient Intervention Program (DNIP). The wetland, designed by consultants Syrinx Environmental, was implemented through a partnership arrangement involving the Trust, City of Canning and South East Regional Centre for Urban Landcare (SERCUL). The wetland intercepts the Wharf Street Main Drain (WSMD) which delivers stormwater from a 129 ha urban area within the Canning Plain Catchment, to the Canning River just upstream of the Kent Street Weir. The wetland is designed to remove nutrients and other pollutants from the stormwater before it enters the Canning River, which can experience water quality degradation including de-oxygenation and occasional fish kill events. High flows can bypass the wetland and continue down the main drain so that hydraulic conductivity during storm events is maintained (Syrinx 2007, SRT 2013).

Specific objectives were:

- to improve the quality of water entering the Kent Street Weir pool, with a particular focus on reducing the delivery of nutrients in summer and autumn (when the weir boards are in place) and the risk of algal blooms is high;
- to detain and treat stormwater flows emanating from the Wharf Street Catchment to reduce the delivery of contaminants to the Canning River;
- to provide information on wetland maintenance requirements and costs, both in terms of the establishment and long term phases; and
- to fill knowledge gaps on the performance of wetlands in improving water quality.

Secondary objectives of the site were to provide a passive recreational and educational asset, to provide an ecological link between the Canning River Regional Park and the Canning River Council Gardens, and to enhance the habitat of the area by returning endemic species and habitat types. These secondary objectives were not addressed in this assessment.

The approximately 1ha wetland consists of vegetated and open water SF and SSF components (Figure 1). SF components have been 'online' since late 2008, whereas the SSF components were originally isolated due to the recycled concrete material (RCM) used in their construction. This RCM was heavily abraded during installation and continued to degrade after installation resulting in an elevated alkalinity in the SSF components. Several attempts were made to reduce the alkalinity by i) dosing effluent water with HCl acid in a closed circuit; ii) addition of a low nutrient mulch blend and humates to encourage biological activity and production of natural acids; iii) addition of fulvic acid; and iv) testing at a bench scale the addition of ferrous sulphate monohydrate, on its own and in combination with a $CaCO_3$ liquor to coat the material and stop further material degradation. These approaches were unsuccessful so in June 2012 approximately 1500m³ of RCM was removed (all of SSF 1 and roughly half of SSF 2) and replaced with laterite aggregate. The RCM under the turf area of SSF 2 was left in-situ, isolated and the alkalinity allowed to bleed off at a low rate. This allowed the SSF's to be brought online and connected into the flow path whilst allowing realisation of the alkalinity benefits as was originally intended through the use of the RCM (SRT 2013).

Minimum water levels in the wetland are maintained by a pump-back system that recirculates water from the outflow point back to the inflow point (Figure 1); water from the local superficial aquifer is also added. The main purpose of top-up program is to sustain an adequate flow regime for aesthetic purposes. It has been estimated that the pump runs at a rate 3 L/sec and that its effect on the overall water balance of the wetland is small (less than 5%) (DoW 2013). The volume of groundwater added to the wetland is not monitored.

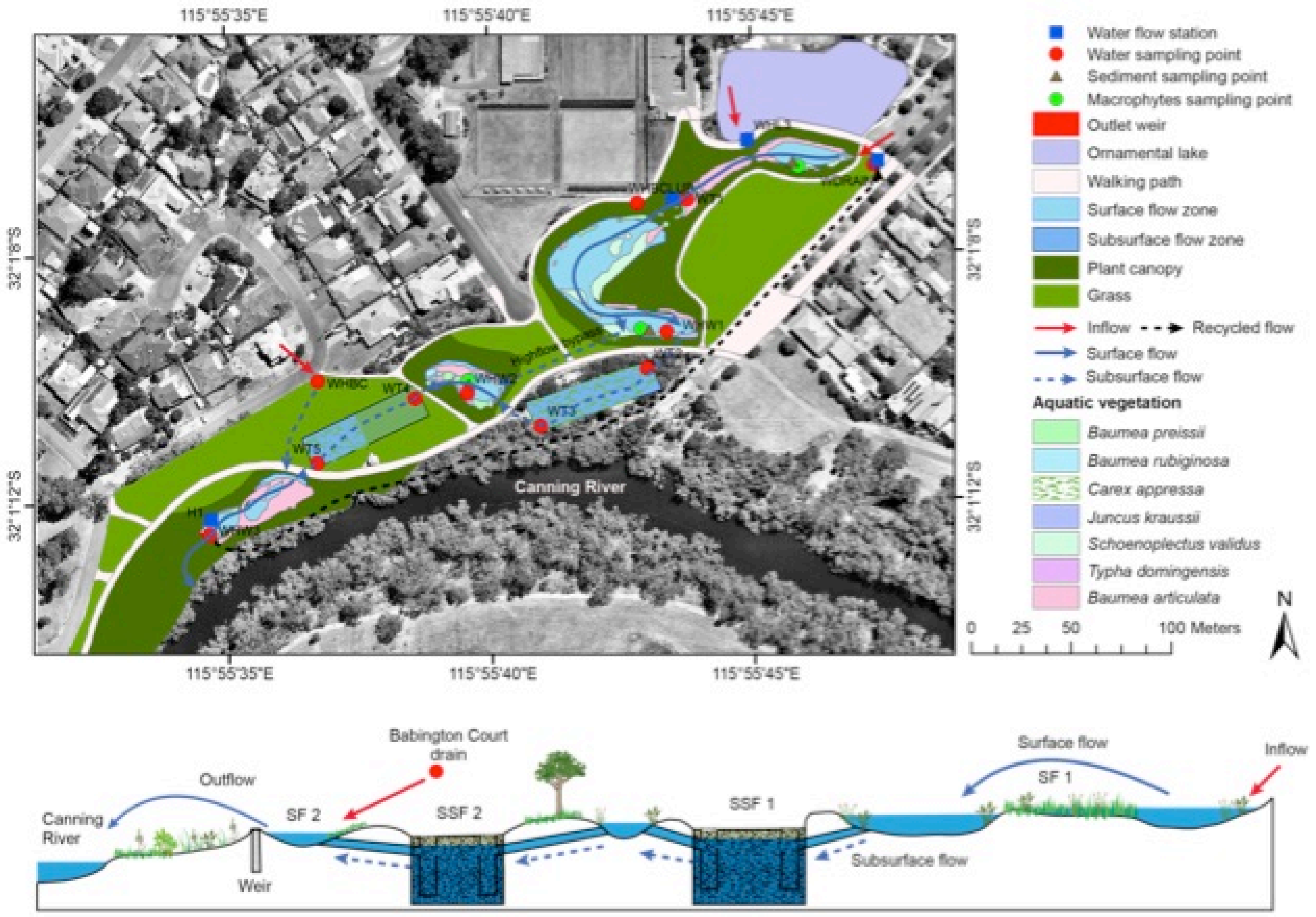


Figure 1. (Top panel) Map of Wharf Street Constructed Wetland indicating different sampling points of surface water, flow, sediment and macrophytes. (Bottom panel) Cross-section of flow path of the system through multistage surface flow and laterite-based subsurface flow components. Additional pipes allow sub-surface systems to be bypassed under high flow conditions and half of SSF2 is covered by grass.

Monitoring program summary

Overview of data used in the analysis

The primary objective of the Wharf Street Constructed Wetland monitoring program was to assess the performance of the wetland in treating and improving the quality of urban stormwater runoff entering the Canning River and to determine compliance with relevant water quality guidelines. Data collected between 2009-2014 is assessed in this report.

For our analysis, the available data was categorised into four main areas:

- *Hydrological data* - surface flows
- *Water quality* - nutrient, contaminant and other relevant measures of water quality within the wetland
- *Sediment dynamics* - nutrients, contaminants and other properties of surficial wetland sediment
- *Vegetation dynamics* - nutrients in vegetative biomass as a nutrient uptake pool

The locations of the sampling points are summarised in Table 1 and details are also given in Appendix A.

Table 1. Summary table of available data, monitoring period, and sources relevant for the Wharf Street Constructed Wetland assessment.

Data	Station Names	Variables	Time period	Source/ Comment
Hydrology and flow	WDRAIN (AWRC ID: 616137) WT1 (AWRC ID: 6164300) WHL3 (AWRC ID: 616131) H1 (AWRC ID: 616135)	Water level Discharge	16/06/2009 to onward	Collected by DoW
Surface water quality	<u>Baseflow sampling</u> WDRAIN (WIN ID:23035117) WHBC (WIN ID:2303517) WHBCLUB (WIN ID:23032976) WHL3 WHW1 (WIN ID:23035119) WT2 (WIN ID:23035123) WT3 (WIN ID:23035124) WHW2 (WIN ID:23035120) WT4 (WIN ID:23035125) WT5 (WIN ID:23035126) WHW3 (WIN ID:23035121) <u>Event sampling</u> WDRAIN (WIN ID:23035117) WHW3 (WIN ID:23035121)	Nutrients (NH_3, NOx, TKN, DON, TN, FRP, TP) Heavy metals and metalloids (Al, As, Cr, Cu, Fe, Mn, Ni, Pb, Zn)	Variable, but generally monthly, or quarterly for DON, from 2009to 2014 for SF and 2012 to 2014 for SSF component Event sampling: 17/11/2009 22/03/2010 20/05/2011 07/02/2012 07/05/2014 17/06/2014	Collected by DoW
Sediment quality	WHSED1(WIN ID:23042135) WHSED2(WIN ID:23042136) WHSED3(WIN ID:23042137)	Sediment quality Nutrient (N, P, C), Bulk density Heavy metals and metalloids (Al, As, Cr, Cu, Fe, Mn, Ni, Pb, Zn)	Mainly six monthly June 2010 April 2011 October 2011 May 2012 October 2012 May 2013 October 2013 May 2014	Collected by DoW
Vegetation dynamics	WHMAC1 (WIN ID:23046430) WHMAC2 (WIN ID:23046431) WHMAC3 (WIN ID:23046432)	Vegetation quality Nutrient (N, P and total organic carbon) Above and below ground biomass	Six monthly November 2010 February 2011 October 2011 March 2012	Collected by DoW and SERCUL

Hydrological data

Weather data from the Swan-Avon Welshpool Depot (Site ID: 509359) rainfall and meteorological station were used. This station is located within the catchment, approximately 4 kilometres north-west of the site. Rainfall is measured using an automatic tipping bucket rain gauge and the station has provided data for Perth Metropolitan Area since 2008.

The main inflow to the wetland is measured at Station 6164300 (see location WT1, Figure 1) via a structure comprising a rock riffle (primary flow control) with a set of three bypass pipes (under the riffle) and a hydrostatic water level probe to provide water stage information. The rating curve for the site was constructed using five flow discharge measurements by the Department of Water (DoW). Due to the importance of changing hydraulic functioning of three bypass pipes (prone to blockage) under low flow conditions, DoW developed two rating tables for the system (under blocked and unblocked conditions) using a total of five flow discharge measurements. Note that the poor structural control on flow conditions and low flow rates (discharge) at the site resulted in high error code and uncertainties associated with this site.

The outflow Station 616135 (see location H1, Figure 1) constitutes the only monitored outflow point from the WSCW system. A concrete V-notch weir and a set of three bypass pipes serve as flow control structures with the former being the primary control. Water stage at the site is measured using a water level transducer in a floatwell system which provides continuous water level records at 1 mm accuracy. A total of 12 discharge measurements were used for quality control at the site. Similar to the inflow station, two rating tables were developed for the three bypass pipes under fully blocked and unblocked conditions and verified using two discharge measurements for each condition. Field observations by DoW personnel confirmed that most of the time the pipes were capped, thus resulting in a stable site for flow control via the calibrated structure (rectangular concrete structure with a V-notch component). Consequently, this site offers very reliable information on flow discharge (low error code).

The wetland has another flow discharge station at the “ornamental lake 3 overflow” point (site 616131, see, location WHL3, Figure 1) to monitor an occasional additional inflow point to the WSCW. The station comprises a sharp crest weir as a primary flow control and a transducer sensor to provide water stage information. A theoretical rating curve has been used to produce discharge estimates and it is considered to be adequate for the application. Water flow leaving the station is measured again by the downstream main inflow (Site 6164300).

Water quality data

Surface water quality was reviewed and grouped for the purpose of this report into the following categories:

- Physico-chemical parameters
- Nutrients
- Metals
- Hydrocarbons
- Organic compounds

The elements included in the last two categories were only monitored intermittently, and therefore are not included in this analysis. Physico-chemical attributes including temperature and oxygen were analysed, and whilst other variables were reported such as electrical conductivity and pH, they have not been included since the properties were consistent over the period and not critical to overall assessment of performance. All surface water grab samples for nutrients and metals were collected by DoW and analysed in accordance with their standard procedures using methods described in AS/NZS 5667.1.1998 (AS/NZS 1998) and the General Monitoring Methods and Procedure (GHD, 2008).

Sediment data

Over the period 2009-2014, sediment was monitored for various chemicals at three different locations, at a maximum depth of 18 cm, and at variable frequency. The sampling locations have been consistent since the wetland was constructed. The monitoring frequency varied between half yearly and annual (Table 1). Sediment sampling occurred at the same time as the macrophyte sampling: early spring (October) and autumn (May).

The main purposes of the collection and analysis of wetland sediment samples was to infer sedimentation volumes, internal removal efficiencies and gradients in sediment quality between the inlet and the outlet. Different contaminants were measured including: nutrients, general physico-chemical properties and heavy metals, hydrocarbons, pesticides, PAHs, PCBs and VOCs.

All wetland sediment samples were collected, labelled, prepared and analysed in accordance with the methods described in AS/NZS 5667.1.1998 (AS/NZS 1998) and General Monitoring Methods and Procedure (GHD 2008).

Vegetation data

A variety of locally native macrophyte species were planted in the wetland post construction. Macrophyte sampling and monitoring used 0.0625 m^2 quadrats at different sites (Table 1) which were used to estimate:

a) Minimum, maximum and mean length of leaves;
b) Stem density (stems per quadrat);
c) Percentage of leaf stages (new, mature and senescent leaf parts); and
d) Presence of flowers and number of inflorescences.

In addition each sample was analysed for:

a) Dry weight of above- and below-ground biomass (g dry weight);
b) TKN in above- and below-ground biomass (mg/g dry weight); and
c) TP in above- and below-ground biomass (mg/g dry weight)

Water balance analysis

The objective of this section is to establish a basic water balance for the WSCW based on existing hydrometric and flow discharge data collected by DoW from February 2011 to December 2013. The water balance aims to assist the interpretation of existing water quality data and to assess the effectiveness of the WSCW in improving water quality of flow discharge from the WSMD to meet long-term water quality targets.

The following main activities have been conducted:

- Review and assessment of available data for rainfall, water stage (level) and flow discharge records (at 5-minute intervals) at the existing stations in WSCW;
- Selection of appropriate methodologies for estimating the water balance, given the existing data; and
- Conclusions and recommendations for hydrological monitoring for future water balance assessment.

The water balance analysis used information from the main inflow and outflow stations in the wetland. The analysis focused on the water balance for individual rainfall and pumping events under different hydrological conditions to understand the hydrological functioning of the system and to identify and quantify ungauged sources of water contributing to the outflow station. The ultimate goal of the analysis was to identify potential water gains and losses that could impact on the interpretation of the water quality data and to assess retention times.

A total of 101 individual rainfall and pumping event hydrographs were selected over the period April 2011 - December 2013 which consist of simultaneous inflow and outflow data at 5-minute time intervals. Selected events that are reported here comprise: a) single pumping event (water recirculation), b) combined pump-rainfall events, c) large rainfall events, and d) isolated rainfall events under different wetness antecedent conditions. Methods used in this report follow those presented by Ruibal-Conti et al. (2015) for the Anvil Way Compensation Basin project.

Water flow regimes

Single pumping events[1]

Based on information provided by City of Canning, the recirculation system runs for 157.5 hours per week at a flow rate of 4500 L/hr. DoW (2013) stated that the pump runs only during dry months and is a small (~ 5%) proportion of the total flow. However inspection of the 5-minute data revealed that the pump operated most of the year including during rainfall events.

Our findings:

- Individual pumping event (PE) volume (Vol) has increased over time, from a minimum value of 300m^3 per pumping event (early 2011) to 2245m^3 by October 2013 (Figure 2, left). The increase in the pumping rate is clearly observable in July 2013 and since October 2013, which coincides with the dry spell in the Perth region. Flow discharge peak mean values at the inflow station also increased from 39 L/s (2011-2012) to 56 L/s during 2013 (Figure 2, right).

- An important change in the hydrological functioning of the wetland seemed to take place from mid-July 2013, as a negative water balance was observed ($Vol_{Outlet} < Vol_{Inlet}$). On average, only 45% of the total volume at the inflow station reached the outlet point, with the remaining 55% being either stored in the surface wetland areas, subsurface media or lost from the system. This change may have occurred due to a change in the antecedent storage for this period and a detailed estimation of the storage capacity of the lakes and subsurface media may help to confirm this. Additionally, some inaccuracy in the inflow gauge may also be leading to uncertainty in the low flow volumes.

[1] Single pumping events have previously been referred to as “re-circulated pump-back system” (DoW, 2013).

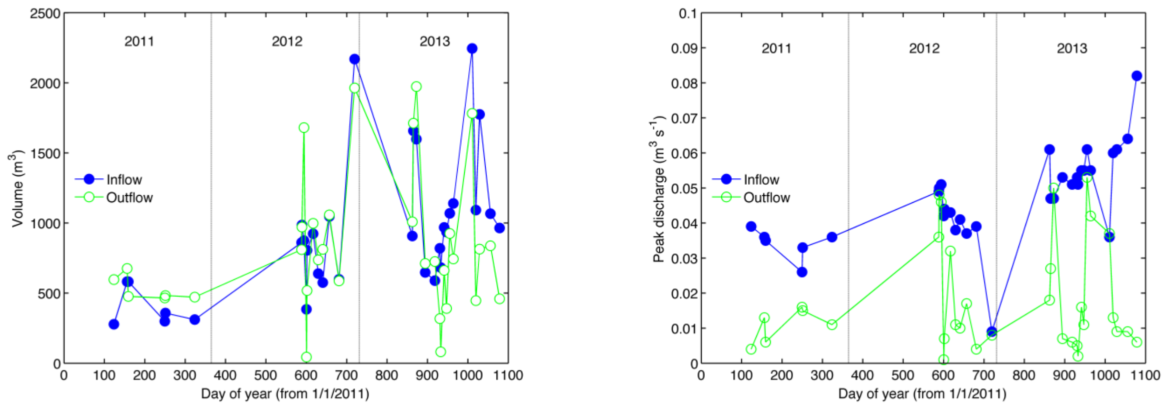


Figure 2. Temporal variability of pumping event characteristics over the study period: total water volume (left) and peak discharge (right) for each individual event.

- A positive water balance ($Vol_{Outlet} > Vol_{Inlet}$) for single PE occurred when:

Wet antecedent conditions in the wetland were caused by rainfall in the preceding days (creating baseflow). The data indicated that an unknown source of water (other than the main inflow) contributed to the flow at the outflow station and thus extended the recession of the outflow hydrograph for up to an extra 1.5 days (Figure 3). The source of this water could be remnant low flows from ungauged inputs from Bebington Court and/or Lake 3 overflow, which would be more likely to contribute if there have been wet antecedent conditions in the surrounding catchment or local seepage into the lakes.

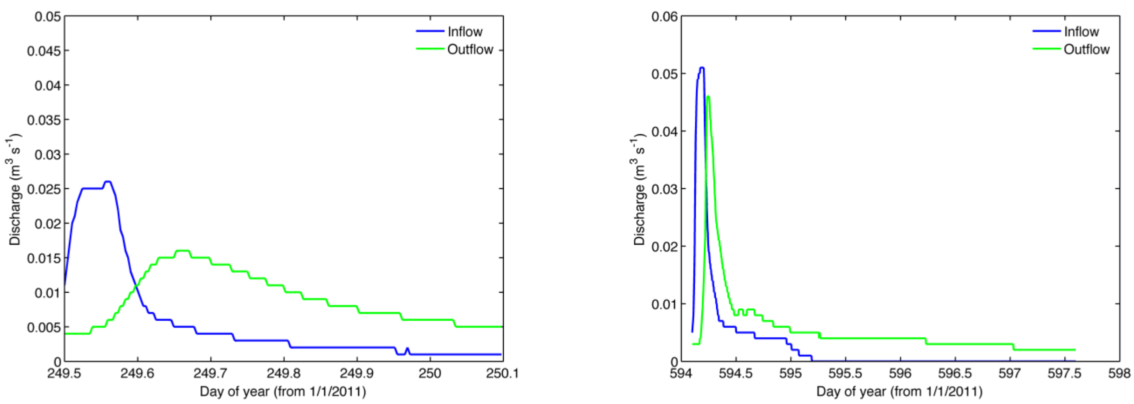


Figure 3. Pumping event hydrographs under wet antecedent condition, on 06/09/2011(left) and 16/08/2012 (right).

Combined pump-rainfall events

These events occur when a single pumping event is quickly followed by a rainfall event. The resulting hydrograph is characterized by a rapid rising limb (as a result of the pumping) followed by a plateau period. This plateau presents multiple hydrographs superimposed, due to rainfall events. Finally, the outflow hydrograph shows a single and rapid recession limb after rainfall stopped. The water balance calculations indicated:

- A net gain of water ($Vol_{Outflow} > Vol_{Inflow}$) was consistently observed for this hydrological regime. The differences in water volume between inflow and outflow stations reached 102% for a rainfall event on 26/10/11, with a high wetness antecedent condition (Figure 4, left). The right panel in Figure 4 shows an additional runoff source in response to a rainfall event (probably corresponding to inflow from the Bebington Court drain).
- On average, the percentage of ungauged water contributing to the outflow station decreased over time with average values of 56% (2011), 39% (2012), and 27% (2013) likely reflecting the impact of decreasing mean annual rainfall and dry antecedent conditions.

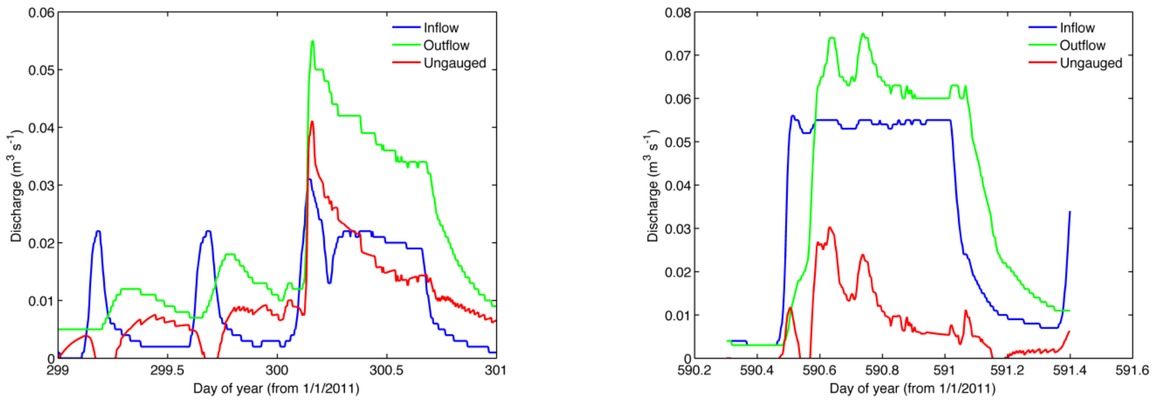


Figure 4. Resulting hydrographs from a combined pump-rainfall events on 26/10/2011 (left) and 11/08/2012 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

Large rainfall events

A total of 13 large rainfall events were selected to assess the water balance in the wetland and to identify the ungauged runoff contribution from the Bebington Court drain towards the outflow station. The results indicated:

- Ungauged runoff during the period 2011-2012 contributed on average 48% of the total flow measured at the outflow station (Figure 5).
- Ungauged runoff contribution significantly decreased for large rainfall events under dry antecedent conditions observed in 2013, reflecting the impact of decreasing rainfall to the wetland. Ungauged runoff represented between 2-20% of the total runoff measured at the outflow station (Figure 6). Two rainfall events in July 2013 showed negative water balance ($Vol_{Inlet} > Vol_{Outlet}$) which suggests that no runoff was generated from the Bebington Court drain catchment under dry conditions.

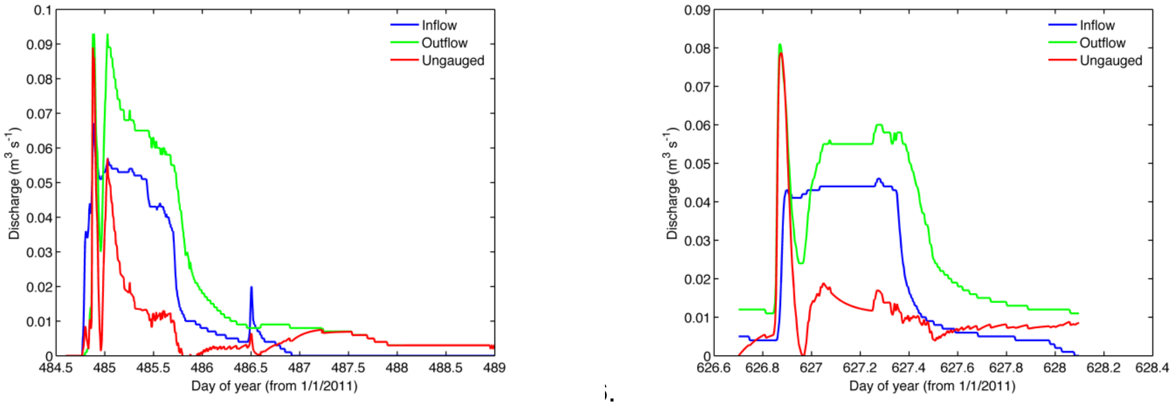


Figure 5. Resulting hydrographs from large rainfall events under wet antecedent conditions on 28/04/2012 (left) and 17/09/2012 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

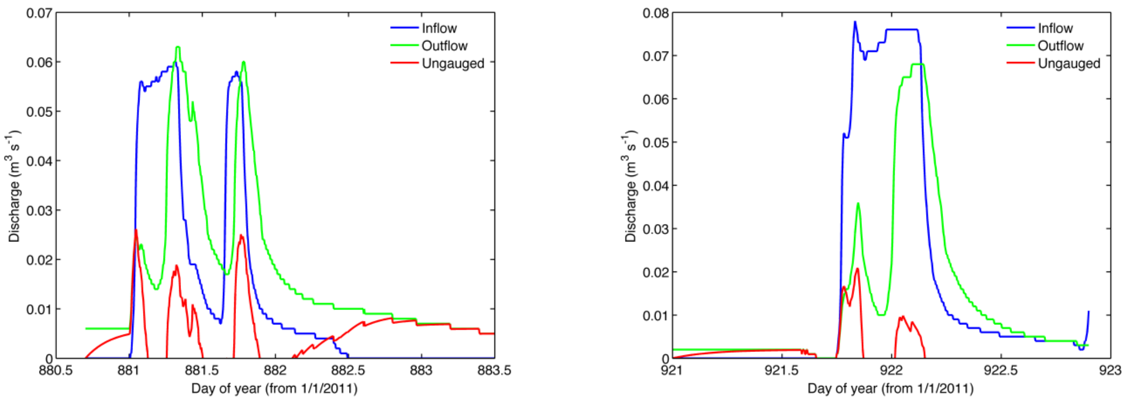


Figure 6. Resulting hydrographs from large rainfall event under dry antecedent conditions on 29/05/2013 (left) and 09/07/2013 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

Other rainfall events

Rainfall event characteristics (intensity and duration) and antecedent wetness conditions will have an impact on the resulting water balance in the wetland area. While rainfall events with short duration highlight runoff production from local areas, rainfall events with long duration will activate runoff generation from the whole catchment.

A total of 34 rainfall events of different characteristics were used to compute the water balance and identify the relative contribution of ungauged runoff contributing to the outflow station. The results indicated:

- Frequent rainfall events observed during the winter and spring 2011 resulted in ungauged runoff contribution reaching an average value of 69% of the total flow observed at the outflow station (Figure 7).

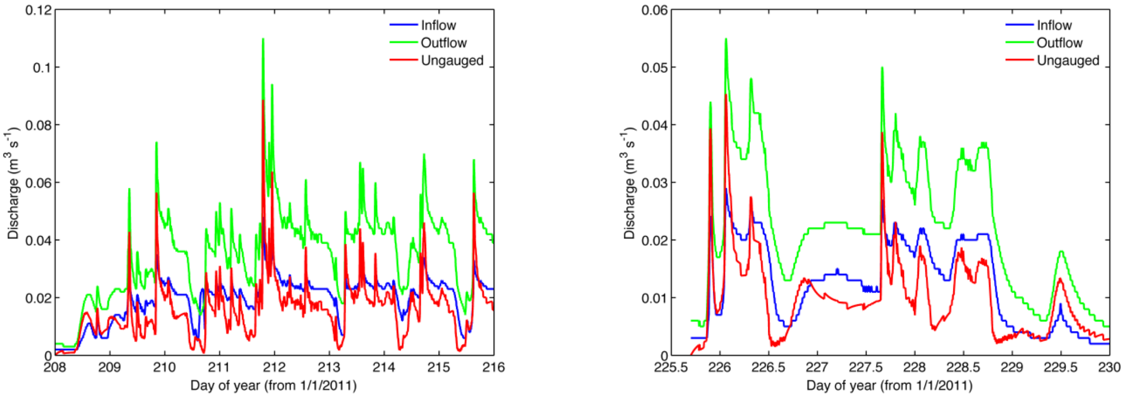


Figure 7. Resulting hydrographs from frequent rainfall events under wet antecedent conditions on 27/07/2011 (left) and 13/08/2011 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

- High intensity and short duration events have resulted in ungauged runoff contributing between 85% and 100% of the total volume of inflow hydrograph (Figure 8). In other words, the volumetric contribution of the ungauged runoff is equal to the inflow hydrograph.

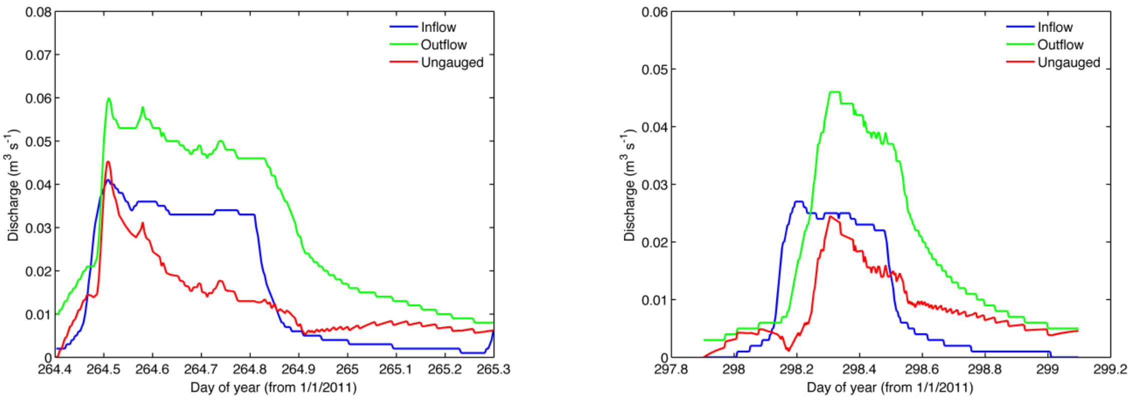
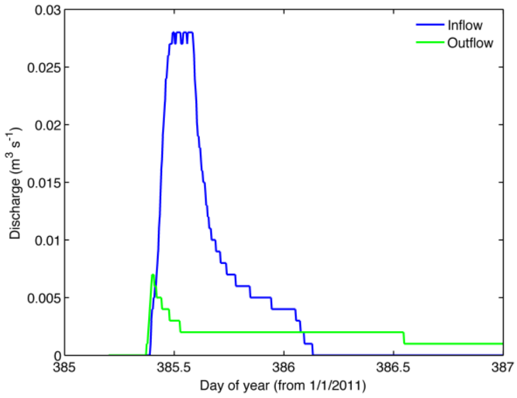


Figure 8. Resulting hydrographs from high intensity rainfall events on 21/09/2011 (left) and 24/10/2011 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

- Small rainfall events under dry antecedent conditions revealed the lack of contribution of runoff from ungauged areas as illustrated by two rainfall events on 20/01/2012 and 04/04/2012 (Figure 9). Approximately 40% and 75% of the inflow volume reached the outlet location for the above-mentioned events. Similar figures for the volumetric contribution under dry conditions were observed for events recorded between late spring and early summer seasons (October-December).



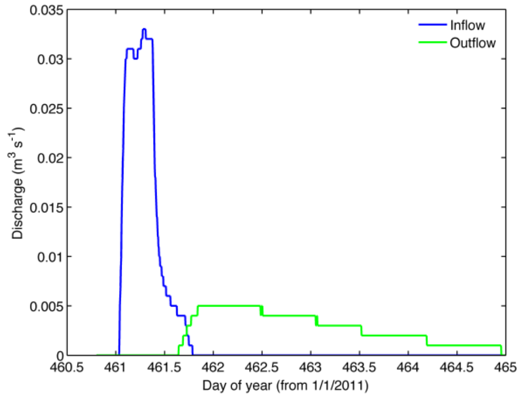
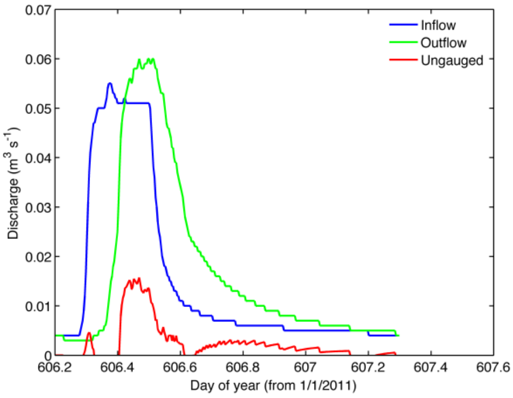


Figure 9. Resulting hydrographs from small rainfall events under dry antecedent conditions on 20/01/2012 (left) and 04/04/2012 (right).

- In most cases, across different years isolated rainfall events under wet antecedent conditions showed a small contribution of runoff from ungauged areas. The volumetric contribution towards the outflow station varied from 1.6% to 20% (Figure 10). Only one rainfall event on 29/05/2013 resulted in a maximum contribution from ungauged areas of 40% that corresponded to a long duration rainfall event triggering runoff production from the Bebington Court drain catchment.



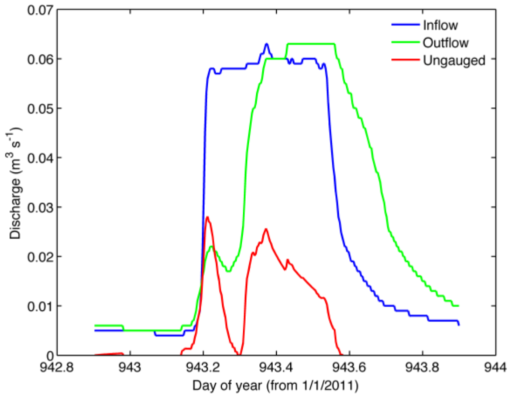


Figure 10. Resulting hydrographs from single-isolated rainfall event under wet antecedent condition: Events on 28/08/2012 (left) and 30/07/2013 (right). Ungauged hydrograph (red line) was obtained as the difference between outflow hydrograph and the routing of the inflow hydrograph using a linear storage routing technique.

Water quality

The objective of this section is to review and assess the water quality of the WSCW based on data collected by DoW for the period 2009-2014. The analysis of the quality data aims to evaluate the performance of the wetland in improving water quality of flow from the WSMD. The assessment has focused on four main aspects:

- Analysis of spatial and temporal variability of the pollutants;
- Comparison of pollutant concentrations against HRAP targets and ANZECC guidelines;
- Analysis of pollutant concentration levels under different hydrological conditions (dry and wet season); and
- Analysis of the effectiveness of the wetland in reducing concentrations of pollutants by assessing differences in pollutant loads and concentrations in the inlet and outlet.

Routine surface water sampling was undertaken by DoW at different points of the wetland such as the major (WDRAIN, in this report as main inlet) and minor (WHBC, WHBCLUB, WHL3) inlets, open water bodies (WHW1 and WHW2) and the outlet (WHW3) (Figure 1). Water samples from the main drain inflow were collected from the silt pit located between the splitter box and the bubble up pit (WDRAIN). The small Bebington Court drain (WHBC) was sampled when flowing from a stormwater pit near the corner of Bebington Court. This discharged into the bubble-up pit upstream of WHW3. The Lake 3 overflow (WHL3) was sampled when flowing. Station WHW1 was considered representative of the water quality after initial treatment through the first two open water ponds, vegetated SF wetland areas and the cascade. Station WHW2 was located at the end of the second open water pond of the wetland and after the first laterite-based subsurface flow path. Due to the distance between the low flow pipework and high flow bypass pit at WHW1, under high flow the sample was taken near the high flow bypass pit. When the water level was low, the sample was collected near the low flow pipework. So during high flow some water passed from the bypass pit at WHW1 to WHW2. When the water flow was low at WHW1, water passed from the low flow pipe to WHW2 via the laterite SSF 1 component. Station WT2 was located in the silt pit at the northern end of the SSF 1 system, while WT3 was located in the silt pit at the southern end of the SSF 1 system. WT4 and WT5 were located in the silt pits near the outlet of the third open water body and the southern end of the SSF 2, respectively. Station WHW3 was the last monitored location in the wetland and represented the outlet of the system.

For this report, the wetland system was divided into four different components (Table 2), comprising the multistage SF wetlands (SF 1 and SF 2) and laterite-based units SSF 1 and SSF 2. Each component had both inflow and outflow data and we analysed concentrations of dissolved and particulate inorganic and organic N and P (NH_3, NO_x, TKN, DON, TN, FRP and TP). Spatial and temporal variability of nutrients were determined and concentrations compared with ANZECC guidelines (ANZECC 2000) and HRAP targets (SRT 2013b).

Table 2. Segmentation of DoW and Trust sampling points in the Wharf Street Constructed Wetland, into four components (See Figure 1).

Component (Code)	Reported site for flow status	DoW and Trust monitoring site	Nutrient attenuation (SDC) inputs and outputs
Component 1 : Surface flow wetland 1 (SF 1)	Inflow	Wharf St Main Drain inlet (WDRAIN), Lake 3 outflow (WHL3)	Inflow: WDRAIN Outflow: WHW1
	Outflow	Open water pond 2 (WHW1)	
Component 2: Laterite-based subsurface flow wetland 1 (SSF 1)	Inflow	Subsurface flow wetland 1 inlet sump (WT2)	Inflow: WT2 Outflow: WT3
	Outflow	Subsurface flow wetland 1 outlet sump (WT3)	
Component 3: Laterite-based subsurface flow wetland 2 (SSF 2)	Inflow	Subsurface flow wetland 2 inlet sump (WT4), open water pond 2 (WHW2)	Inflow: WHW2 and WT4 Outflow: WT5
	Outflow	Subsurface flow wetland 2 outlet sump (WT5)	
Component 4: Surface flow wetland 2 (SF 2)	Inflow	Bebington Court drain (WHBC)	Inflow: WHBC Outflow: WHW3
	Outflow	Outlet (WHW3)	

Physico-chemical data

Among the different physicochemical parameters of water sampled, dissolved oxygen (DO) and temperature were synthesized for this report (Figures 11 and 12)..

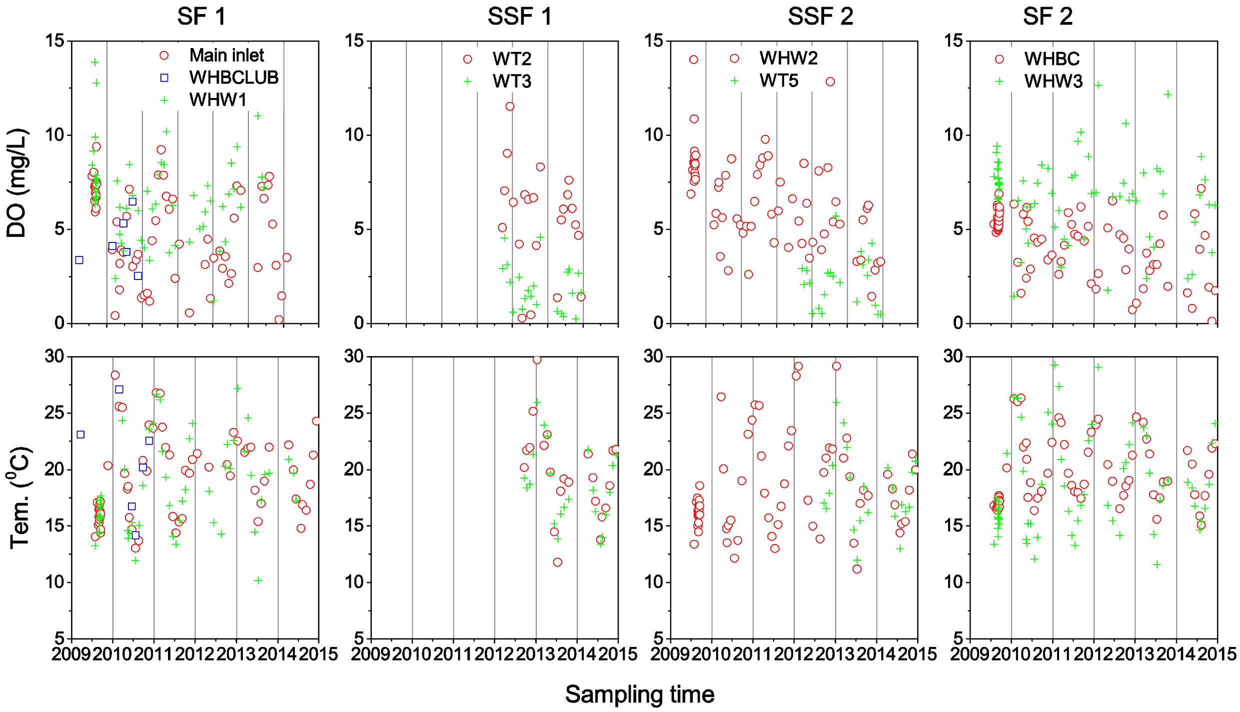


Figure 11. Spatial and temporal variation of dissolved oxygen (DO) concentration and water temperature (Tem) at different sampling points throughout the components of Wharf Street Constructed Wetland. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

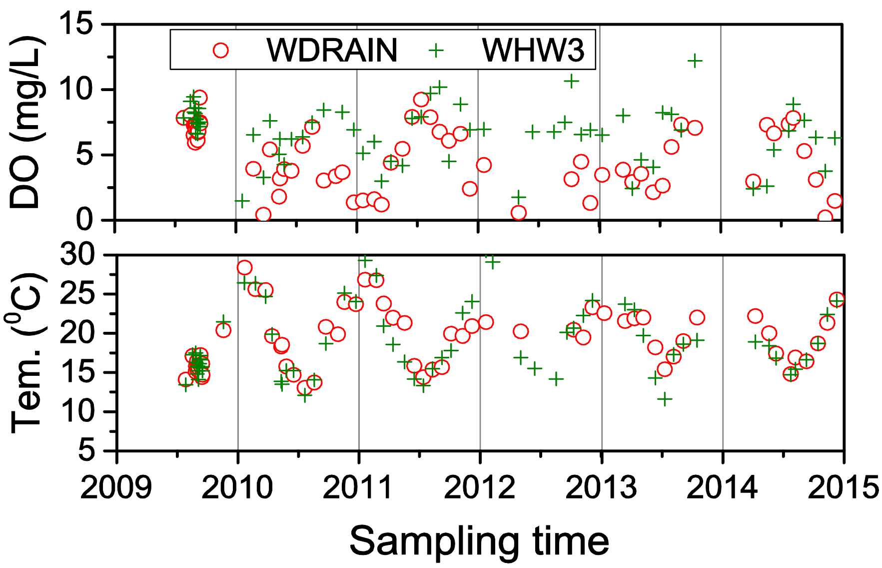


Figure 12. Variation of DO concentrations and water temperature at main inlet (WDRAIN) and main outlet (WHW3) of Wharf Street Constructed Wetland from 2009 to 2014.

DO is a significant water quality parameter and can impact ecosystem processes, with lower levels of DO driving anaerobic respiration which may release phosphorus and heavy metals from particulates and sediments. A range of factors influence the concentration of DO, including temperature (impacting solubility), flow and wind (influencing aeration), photosynthesis and the biochemical and sediment oxygen demands (BOD and SOD). The outlets of the SF components contained higher DO than the inlets, indicating low oxygen water input from the urban drains was oxygenated as it passed through the SF components. A different scenario was observed in the SSF components where the outlet DO level was lower than the inlet, reflecting the reduced contact of water with the ambient air in these components and lower primary productivity (compared to the surface water components). DO concentrations were relatively low at the main inlet, the outlet of SSF components and at the Bebington Court drain.

Nutrient concentrations

Trends in nitrogen (N) species at different sampling points within the WSCW are shown in Figure 13 – 14, as point data at the resolution of the sampling regime (monthly to quarterly) and also as an annual box plots. For the inlet and outlet of the laterite-based SSF 1 (WT2 and WT3, respectively) and outlet of SSF 2 (WT5), only data from October 2012 were considered, i.e. after the RCM removal. For the other sampling points, data from 2009-2014 are presented. Figure 15 shows the variability in nutrient concentrations at main inlet and outlet. Stormwater runoff from the surrounding catchment enters the WSCW at the main inlet of SF component 1 (WDRAIN), where the highest concentrations of pollutants were generally recorded.

Total Nitrogen (TN) concentrations in WSCW were compared with ANZECC guidelines and Healthy Rivers target values. TN concentration at the main inlet ranged from 0.25 to 3.1 mg/L (mean: 1.06 mg/L). The outflow of the SF 1 component showed a reduction in TN concentrations and ranged from 0.39 to 2.6 mg/L (average 0.82 mg/L). During the sampling period, TN at the main inlet (WDRAIN) of the SF 1 component exceeded the Healthy Rivers target (1.0 mg/L) nine times, and the ANZECC guidelines (1.2 mg/L) six times. Mean concentrations of TN at WT2 and WT3 of SSF 1 component was 0.78 and 0.53 mg/L, respectively. The average TN concentration was 0.81 and 0.51 mg/L at WHW2 and WT5, respectively. WHBC contributed variable concentrations of TN throughout the year, ranging from 0.56 to 5.8 mg/L (mean: 2.06 mg/L). The average concentration of TN at WHBC exceeded the ANZECC guidelines and Healthy Rivers target values. Almost 50% of the samples collected at WHBC exceeded the Healthy Rivers target values. However the WSCW quickly diluted the TN entering from WHBC and only 9 samples at the outlet exceeded the Healthy Rivers target values. The main outlet average TN concentration was 0.81 mg/L (range: 0.37 to 3.1 mg/L).

Ammonia (NH_3) concentration at the main inlet (WDRAIN) ranged from below detectable limit (BDL: 0.01 mg/L) to 0.33 mg/L (average: 0.14 mg/L). Almost half of the water samples entering the system contained NH_3 concentrations above the prescribed ANZECC guideline (0.08 mg/L), and the 5-year average NH_3 concentration was also higher than the guideline. There was a significant reduction in NH_3 concentrations at the outlet of SF 1 component. From 2012 onwards, WHW1 showed ongoing reductions in nutrient concentrations. The NH_3 concentration at WT2 ranged from BDL to 0.35 mg/L (mean: 0.052 mg/L). The outlet of SSF 1 component (WT3) also showed a reduction in NH_3 concentrations compared to the inlet (WT2), with a mean of 0.04 mg/L (ranging from BDL to 0.17 mg/L). The SSF 2 system receives water from WHW1 and WT3 during high flow and only from WT3 during low flow. NH_3 concentrations in the open water pond 3 (WHW2) ranged from BDL to 0.48 mg/L (mean: 0.055 mg/L). NH_3 concentrations at the outlet (WT5) of SSF 2 varied from BDL to 0.77 mg/L, with an average 0.029 mg/L. The mean values of NH_3 concentrations at WHW2 and WT5 were below the ANZECC guideline. NH_3 concentrations at WHBC ranged from BDL to 0.43 mg/L (mean: 0.057 mg/L). Only three water samples exceeded the ANZECC guideline at the main outlet (WHW3). The average NH_3 concentration in WHW3 was 0.027 mg/L (ranged from BDL to 0.18 mg/L).

Nitrate-nitrite (NOx) concentrations measured at the main inlet (WDRAIN) ranged from BDL (0.01 mg/L) to 1.1 mg/L (average: 0.21mg/L) with the average concentration exceeding the ANZECC guideline (0.15 mg/L). All samples from WHBCLUB were above the ANZECC guideline. NOx concentrations at WHW1 ranged from BDL to 0.79 mg/L (mean: 0.21 mg/L) indicating little reduction through this component. SSF 1 operated from October 2012. The average NOx concentrations at the inlet and outflow of this component were 0.08 and 0.11 mg/L, respectively. In contrast, NOx varied from BDL to 0.76 mg/L at WHW2. The mean concentration (0.25 mg/L) at this point also exceeded the ANZECC guideline. The outlet of SSF 2 showed NOx concentrations BDL to 0.88 mg/L (mean: 0.13 mg/L). Average NOx concentrations at the inlet and outlet of SSF 2 compartment were below the ANZECC guideline. NOx from WHBC ranged from 0.22 to 5.3 mg/L (mean: 1.55 mg/L) and 100% of the samples exceeded the ANZECC guideline (0.15 mg/L). NOx concentrations at WHBC did not show any particular trend, however during dry conditions the concentrations were relatively high. WHW3 showed an average NOx concentration of 0.021 mg/L (ranging from 0.011 to 1 mg/L) and the average NOx concentration at main outlet was below the ANZECC guideline.

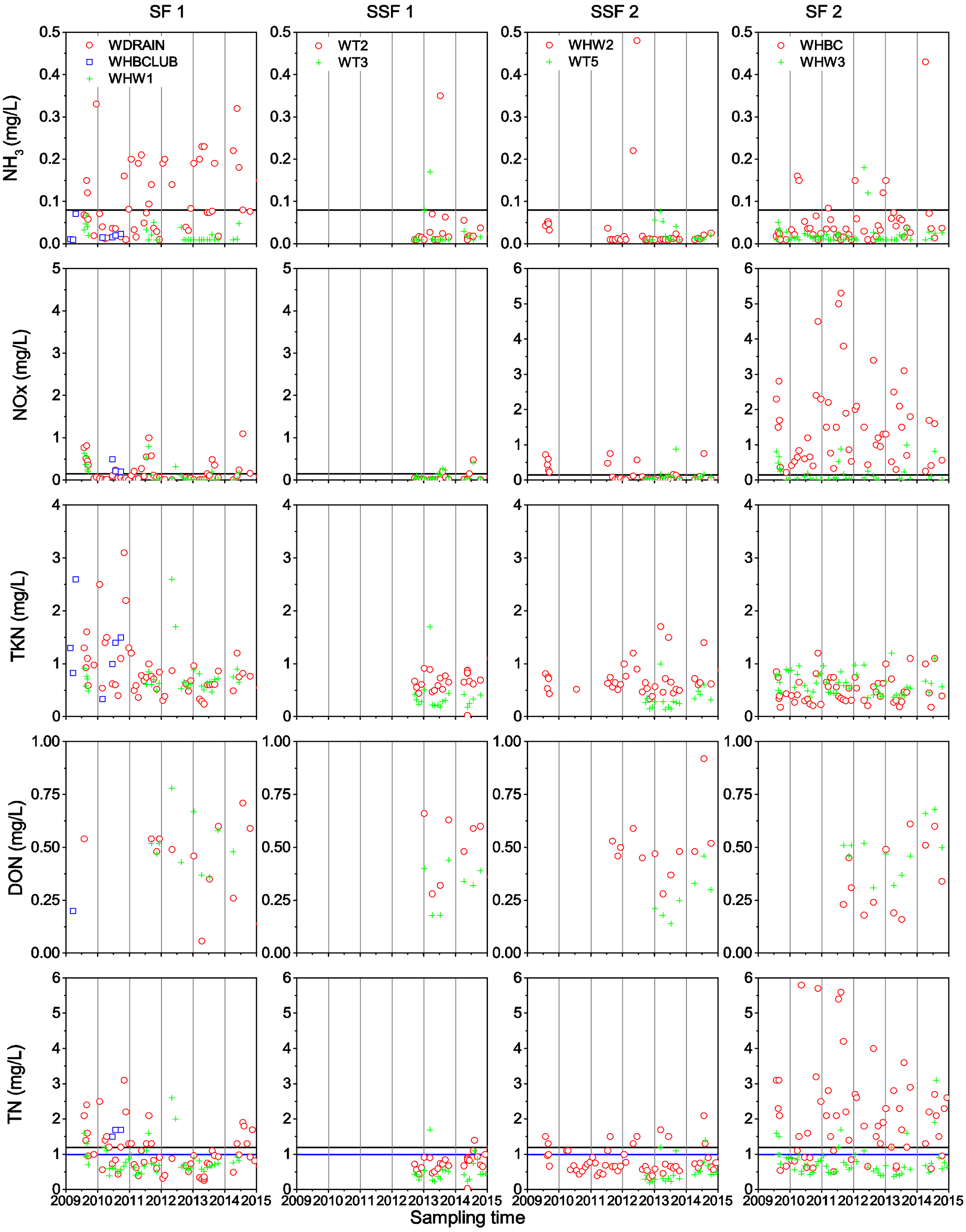


Figure 13. Spatial and temporal variation of concentrations of nitrogen species in water at different sampling points throughout the components of the Wharf Street Constructed Wetland. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Healthy Rivers target values. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

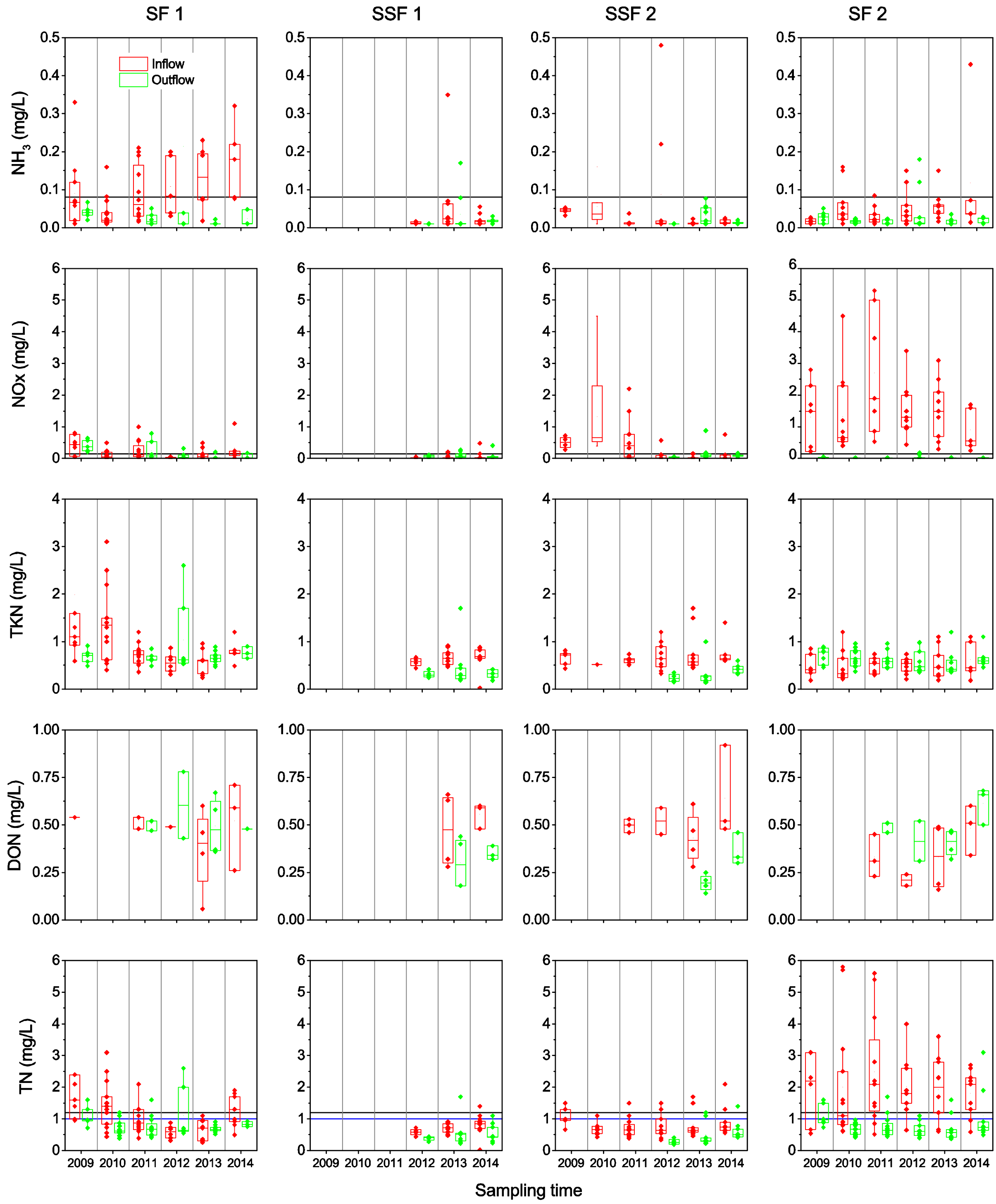


Figure 14. Annual distribution of nitrogen species in water within different components of the Wharf Street Constructed Wetland. Solid horizontal lines within individual boxes indicate the median value of the data set and lower and upper parts of the boxes indicate 75 and 25 percentile of data. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Healthy Rivers target values. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

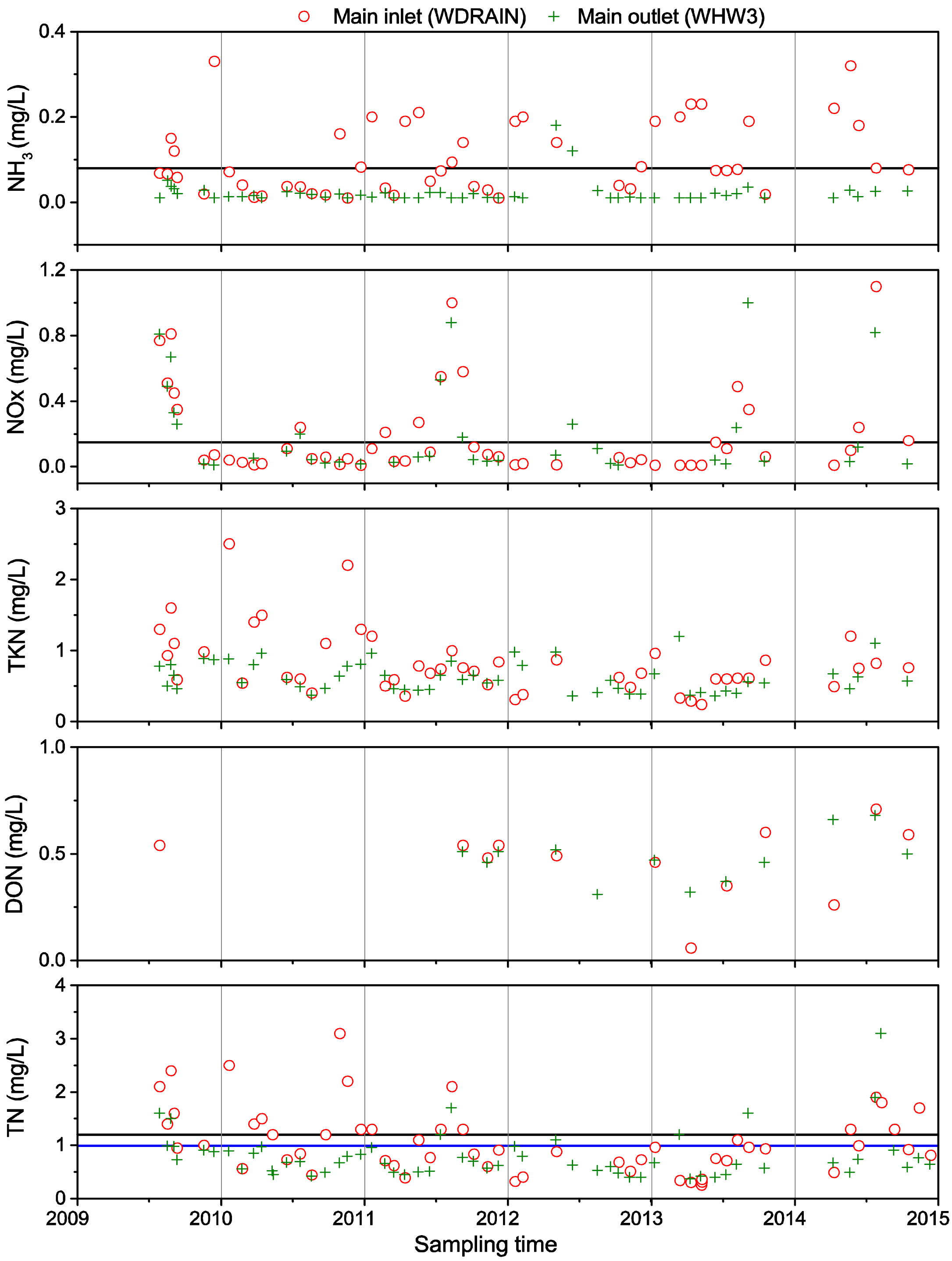


Figure 15. Variation of concentrations of nitrogen species in water at main inlet (WDRAIN)m and main outlet (WHW3) of Wharf Street Constructed Wetland. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Healthy Rivers target values.

Total Kjeldahl Nitrogen (TKN) concentrations were highly variable throughout the sampling regime within the SF 1 component. The range of TKN at the main inlet (WDRAIN), WHBCLUB and WHW1 was 0.24 to 3.1 mg/L, 0.33 to 2.6 mg/L and 0.47 to 2.6 mg/L, respectively. The main inlet also showed a seasonal pattern: an increase in concentrations during dry periods and a reduction in concentrations during the wet period. This may be due to dilution of nutrients under wet conditions. WT3 showed relatively lower concentrations than WT2. SSF 2 showed a higher concentration of TKN. Average TKN concentrations in WHW2, WHBC and WT5 were 0.71, 0.51 and 0.33 mg/L, respectively. TKN at the main outlet (WHW3) also followed a seasonal trend. Concentrations increased during dry periods and reduced during wet weather, again probably due to dilution. Average TKN concentration at the main outlet of the wetland was 0.63 mg/L (range: 0.36 to 1.2 mg/L).

Quarterly Dissolved Organic Nitrogen (DON) data showed higher concentrations during dry periods. The average concentrations at the main inlet (WDRAIN) and WHW1 were 0.44 mg/L (range: 0.058 to 0.71 mg/L) and 0.52 mg/L (range: 0.36 to 0.78 mg/L). Around 50% of samples from this component showed DON concentration higher in the outflow than inflow, possibly due to the release of organic N from sediments or senescent macrophytes. The average DON concentrations at the inflow and outflow of SSF 1 were 0.68 and 0.32 mg/L, respectively. At the same time, the mean DON concentrations at WHW2 and WT5 were 0.51 and 0.32 mg/L, respectively. Bebington Court drain also input DON to the wetland with an average concentration of 0.36 mg/L. The DON concentration increased to the main outlet (mean: 0.48 mg/L). This may be also due to the release of organic nutrients from sediment or plant material.

Water quality of different sampling points for phosphorus species throughout the WSCW is plotted in Figure 16 - Figure 18. Figure 16 indicates the scatter of data collected over the monthly to quarterly sampling regime and Figure 17 represents annual averaged data as a box plot. Figure 18 represents temporal trend of filterable reactive phosphorus (FRP) and total phosphorus (TP) at the main inlet and outlet. The average TP concentration at the main inlet of SF 1 was 0.17 mg/L, ranging from 0.02 to 1.7 mg/L. TP reduced at the outlet of SF 1, SSF 1, SSF2 and the main outlet average concentration was below the ANZECC guidelines (0.065 mg/L) and Healthy Rivers target value (0.1 mg/L). The main inlet contributed the highest levels of TP, followed by Bebington Court drain. Higher TP concentrations were found over the summer period, however the wetland had reduced the TP concentration by the outlet. SSF 1 component was most effective at reducing TP concentrations followed by SSF 2 component. Average TP concentrations at inlet and outlet of SSF 1 were 0.052 and 0.27 mg/L, respectively. WHW2 and WT5 showed mean TP concentrations of 0.042 and 0.023 mg/L, respectively. At the main outlet, around 8% of samples showed higher concentrations than the Healthy Rivers target value. In contrast, only 2 samples crossed the ANZECC guideline at the main outlet. Moreover due to the incorporation of the laterite SSF system, the overall TP concentration was reduced compared to previous years (2009-2012). The mean TP concentration at the main outlet of WSCW was 0.031 mg/L.

The average FRP concentration at the main inlet was 0.04 mg/L, ranging from BDL (0.005 mg/L) to 0.15 mg/L. The mean concentration of FRP exceeded the ANZECC guideline. FRP concentrations increased under dry conditions and decreased during the wet periods. The outlet FRP concentrations of SF1 averaged 0.015 mg/L. FRP concentrations at the inlet and outlet of SSF 1 component was 0.013 and 0.006 mg/L, respectively. Around 90% of samples at the SSF 1 outlet contained FRP concentrations below detectable limit (0.005 mg/L).The concentrations at the inlet and outlet of the SSF 1 compartment were below the ANZECC guideline. The average FRP concentrations were at 0.016, 0.03 and 0.01 mg/L at WHW2, WHBC and WT5, respectively. The average FRP concentration WT5 was below the ANZECC guideline. The mean FRP concentration at the main outlet was 0.013 mg/L (range: 0.005 to 0.04 mg/L).

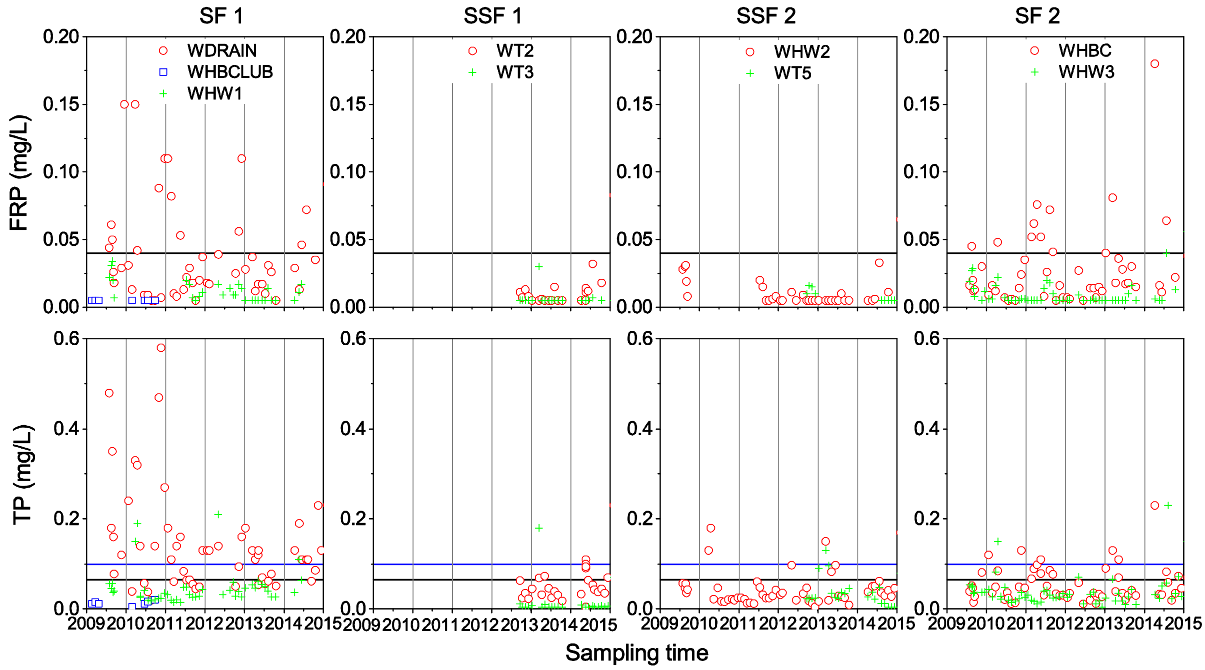


Figure 16. Spatial and temporal variation of concentrations of phosphorus species in water at different sampling points throughout the components of Wharf Street Constructed Wetland. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Health Rivers target values. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

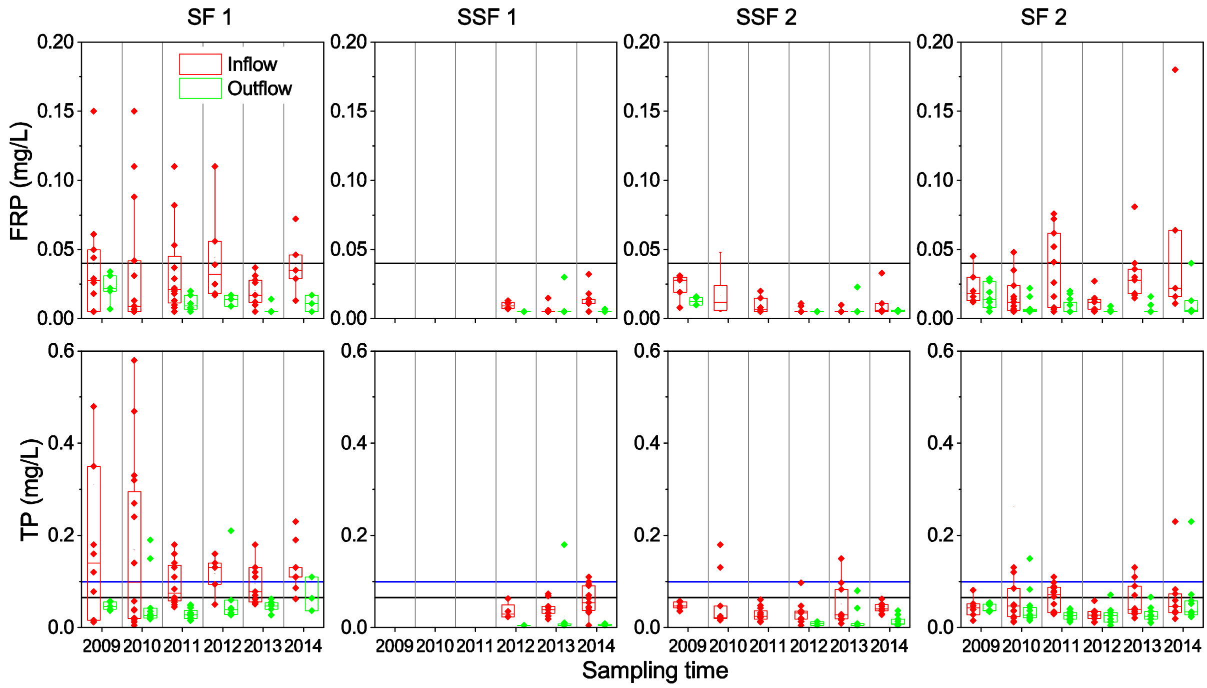


Figure 17. Annual distribution of phosphorus species in water at different components of Wharf Street Constructed Wetland. Solid horizontal lines within individual boxes indicates the median value of the data set and lower and upper parts of the boxes indicate 75 and 25 percentile of data. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Healthy Rivers target values. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

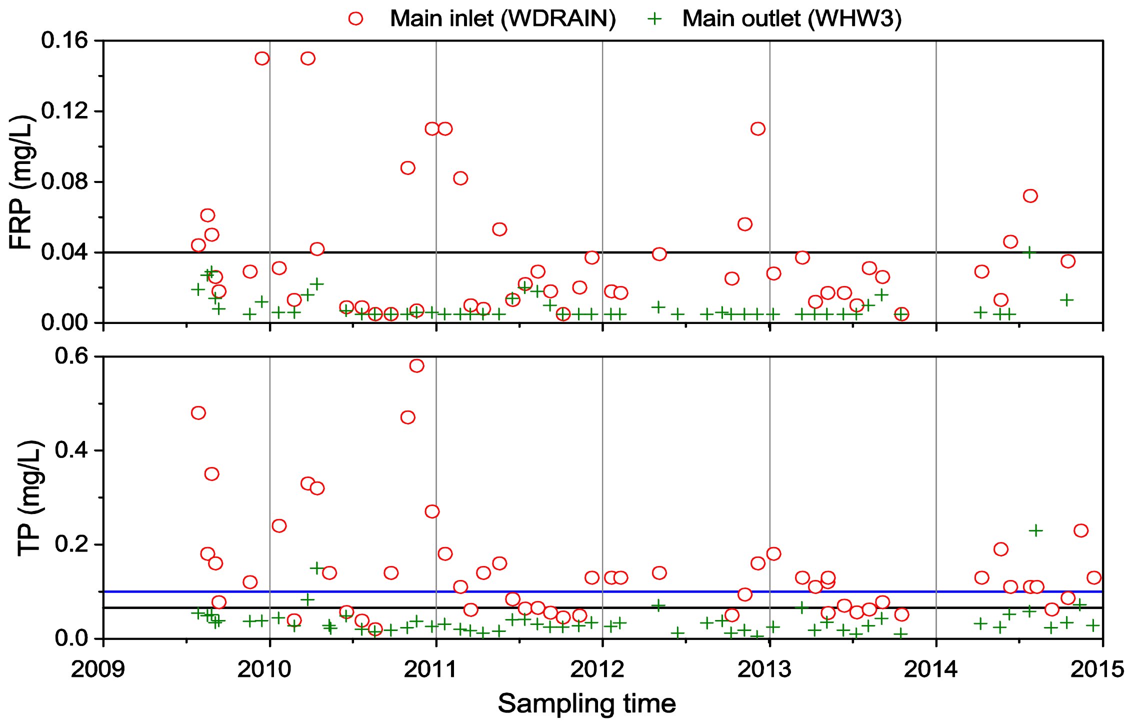


Figure 18. Variation of concentrations of phosphorus species in water at main inlet (WDRAIN) and main outlet (WHW3) of Wharf Street Constructed Wetland. Solid horizontal dark lines show the ANZECC guidelines and horizontal blue lines show Healthy Rivers target values.

Soluble and total metals concentrations

The soluble and total fractions of metals have been monitored since 2009, usually on a quarterly basis. In this report, data for nine metals (Al, As, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were explored (Figure 19 to Figure 21). Metal concentrations were compared with the ANZECC 80% and 95% trigger values for the protection of freshwater ecosystems. The main inlet and Bebington Court drain were dominant sources of metals. The concentrations at the outlets of all components were consistently lower than at the inlets. The concentration of Cr, Cu, Ni, Pb and Zn were below detectable limit (BDL) for almost half of the samples. The concentration of Cd, Hg, Se and Th was BDL at all sampling locations and time. The average concentration of Al at the main inlet was 0.13 mg/L. Half of the samples that came from WHBC exceeded the 80% and 95% trigger values for freshwater ecosystems. One sample from this site exceeded the 80% protection limit for As and the rest of the samples were below the 95% protection limit. Almost half of the Cu concentrations measured in water from WHBC and WDRAIN exceeded the 95% protection limit. Ni and Pb concentrations at SSF 1 were BDL. In the case of the main inflow, one sample exceeded the 80% protection limit and two samples exceeded the 95% protection limit for Pb. Comparing the two inlets, WDRAIN contributed more Ni and Zn compared to WHBC. Interestingly, the two SSF compartments contained low metal concentrations in water samples, both at their inlets and their outlets. Initially polished water entered the SSF 1 and SSF 2 components. Fe concentrations in the outlet of SF 1 and SF 2 were relatively higher than that of SSF components. This may have been caused by a) higher concentrations of Fe entering the wetland through the main inlet and Bebington Court drain, while laterite-based SSF components received relatively polished water. In addition laterite material may have absorbed metals ions.

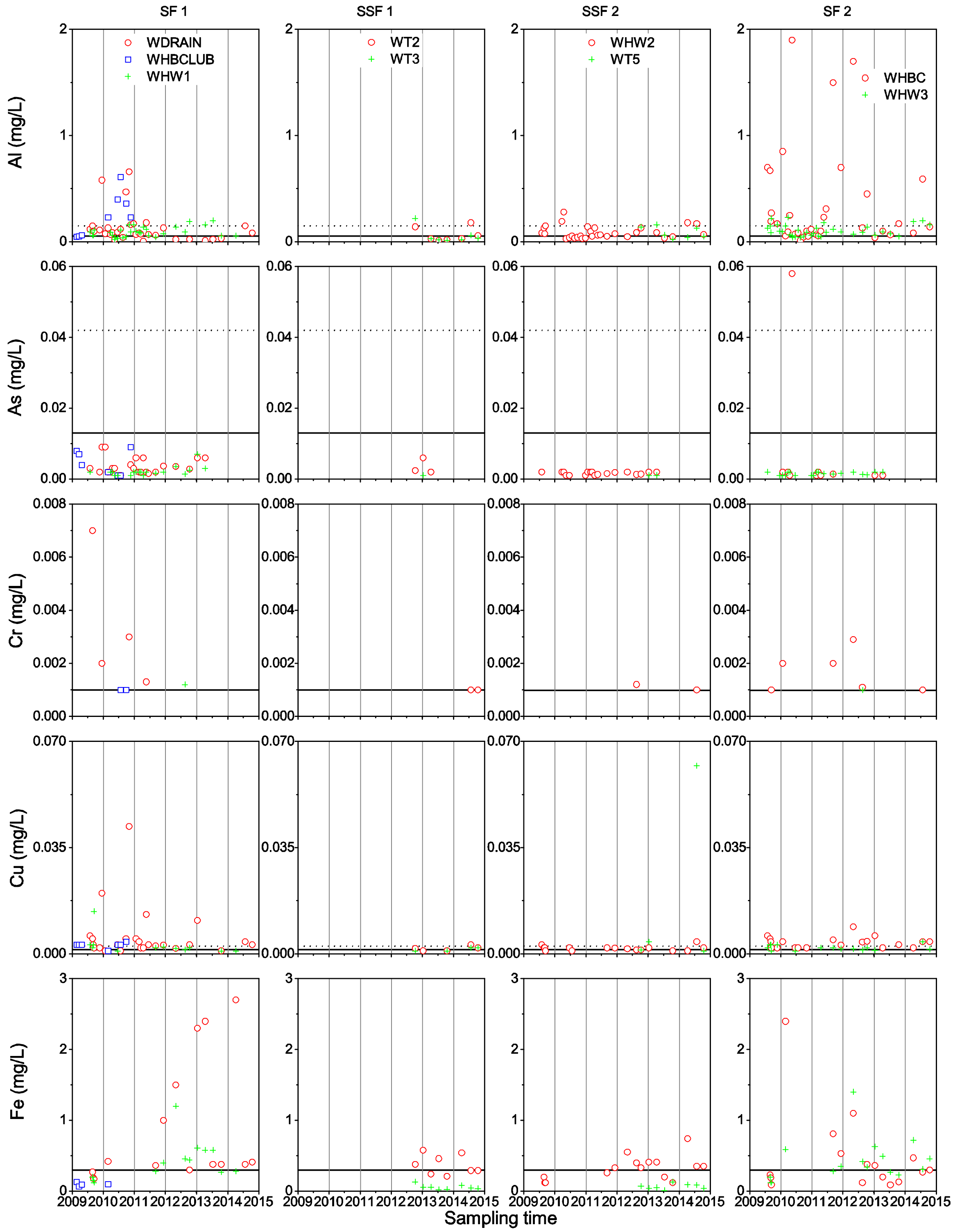


Figure 19. Spatial and temporal variation of metal content in water at different sampling points throughout the compartments of Wharf Street Constructed Wetland. Horizontal dashed and solid lines show the ANZECC 80% and 95% trigger values respectively. BDL denotes below detectable limit. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

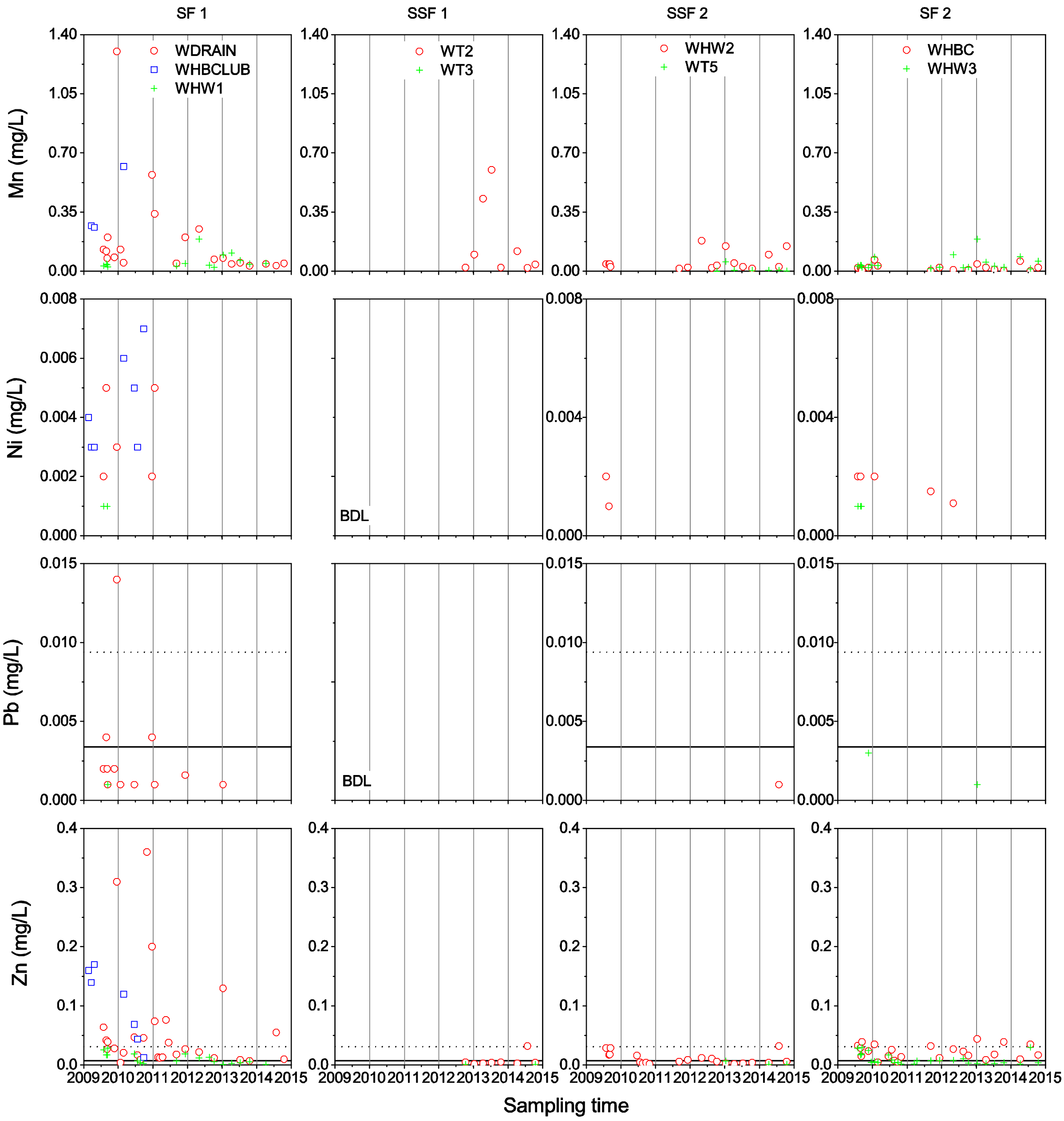


Figure 20. Spatial and temporal variation of metal concentrations in water at different sampling points throughout the components of Wharf Street Constructed Wetland. Horizontal dashed and solid lines show the ANZECC 80% and 95% trigger values respectively. BDL denotes below detectable limit. Laterite-based SSF 1 and SSF 2 started operation in October 2012.

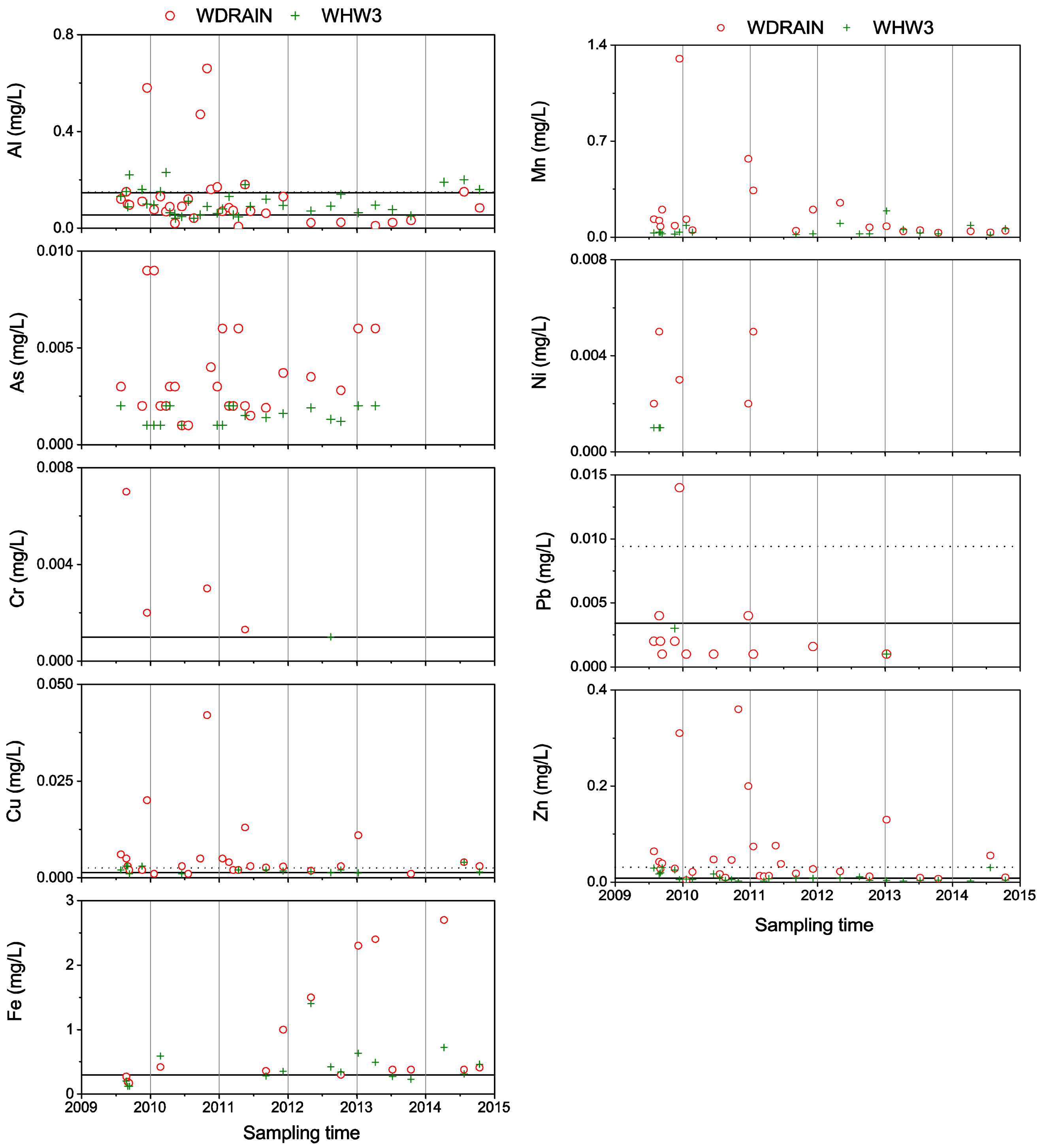


Figure 21. Metal concentrations in water at the main inlet and main outlet of Wharf Street Constructed Wetland. Horizontal dashed and solid lines show the ANZECC 80% and 95% trigger values respectively.

Nutrient attenuation approaches

This section presents the effectiveness of WSCW to treat stormwater runoff. The spatio-temporal variability of nutrients at different sampling points and components is shown in Table 2. Wetland efficiency is typically calculated as the difference between pollutant load in the inlet (L_{inlet}) and outlet (L_{outlet}) or the difference between pollutant event mean concentration (EMC) in the inlet (EMC_{in}) and outlet (EMC_{out}). For the computation of the load and EMC, pollutant concentration and water flow needs to be monitored simultaneously at the inlet and outlet. In the WSCW, there are major (WDRAIN, in this report referred to as the main inlet) and minor (WHBC, WHBCLUB and WHL3) inlets, open water bodies (WHW1 and WHW2) and the outlet (WHW3). Flow data was available for the sites closest to the main inlet (Site code: WT1) and outlet (Site code: H1). There was also water level data from the ornamental lake 3 overflow (Site code: WHL3). Unfortunately, there was no flow data for Bebington Court drain or the SSF compartments. So efficiency estimates for specific components was not always possible. Nutrient attenuation during base flow conditions was therefore assessed based on the standardised delta concentration (SDC). SDC is the difference in nutrient concentrations from the inlet to the outlet of the component. Nutrient attenuation during events when flow and nutrient concentration were monitored was calculated from the event mean concentration (EMC) at the inlet and outlet.

Estimation of SDC

This is the standardised difference in nutrient concentration between the inlet and outlet. It is only an indicative value as differences in concentration can be mediated by dilution processes driven by ungauged sources.

$$\mathrm{SDC} = \frac{\mathrm{C_{inlet}} - \mathrm{C_{outlet}}}{\mathrm{C_{inlet}}}$$

where C_{inlet} is the nutrient concentration at the inflow and C_{outlet} is the nutrient concentration at the outflow of each component. If there are multiple inflows then SDC is modified as SDC_ave.

$$\mathrm{SDC\_ave} = \frac{*\,\mathrm{C_{inlet}} - \mathrm{C_{outlet}}}{*\,\mathrm{C_{inlet}}}$$

where $*\,C_{inlet}$ is the average nutrient concentration of different inflows.

SDC can either be positive or negative. Positive SDC indicates nutrient reduction by the compartment (nutrient attenuation or dilution), while negative SDC represents nutrient enhancement by the compartment (nutrient release or evapo-concentration). If data were unavailable for either inflow or outflow of the components, SDC was not calculated.

*Estimation of load reduction during event*s

This was calculated on occasions where there were simultaneous nutrient concentration and flow data, at the main inlet and outlet. In this case, total volume of water passed through the inlet and outlet, load of total nutrients, EMC of nutrient at two sites (main inlet and main outlet) were calculated.

The load, EMC and load attenuation were calculated as follows:

$$\mathrm{Load\ (mg/s)} = \mathrm{QC}$$

$$\mathrm{EMC\ (mg/L)} = \sum_{\mathrm{i}}^{\mathrm{n}} \mathrm{V_i\, C_i/V}$$

$$\mathrm{Load\ attenuation\ (\%)} = \frac{\sum \mathrm{Inlet\ load} - \sum \mathrm{Outlet\ load}}{\sum \mathrm{Inlet\ load}}$$

where, Q is flow rate (m^3/s), C is nutrient concentration (mg/L), V_i is volume proportional to the flow rate at time i (m^3), C_i is the nutrient concentration at time i (mg/L), n is the number of total samples and V is the total run off volume per event (m^3).

Nutrient attenuation using the SDC approach

Historical data (2009 to 2014) from WSCW were assessed to quantify how effectively the system attenuates nutrients, particularly N and P species. In the case of laterite-based SSF 1 and SSF 2, data from October 2012 to December 2014 were used (once these components came online). The wetland components showed different SDC at different spatial and temporal scales (Figure 22 to Figure 26).

Water enters the WSCW via the SF 1 component. In June 2012, all of the RCM in SSF 1 and approximately half of the RCM in SSF 2 was replaced with laterite, enabling the SF 1 component to be connected to the SSF components. Before June 2012, the NH_3 attenuation capacity of SF 1 ranged from around 30 to 90%, with few negative SDC episodes. Once the SF 1 compartment was connected to the SSF compartments, a continuous flow was established through all components of the WSCW. After October 2012, the SF 1 compartment attenuated NH_3 up to 95% on six occasions with an average 84% without any increase of NH_3. Overall, the SDC for NOx varied from -185 (May 2012) to 97% (September 2013). During dry periods, a greater percentage of NH_3 and NOx was attenuated. SDC for TKN in SF 1 did not show any trend. SDC for TKN ranged from -198 to 53%. DON was analysed on a quarterly basis and based on that small dataset, SDC varied from -85 to 3.7% in SF 1. Overall, SF 1 was unsuccessful in attenuating DON, and was actually a source. TN concentrations varied at the inlet and outlet of the SF 1 component with SDC showing a seasonal pattern. During summer, SF 1 attenuated a higher percentage of TN than in winter. Up to 78% of TN was attenuated on one sampling occasion (October 2010), but the overall SDC for TN was around 29% (omitting the negative SDCs).

The SSF 1 and SSF 2 components began operation in September 2012. SSF 1 and SSF 2 attenuated around 45 and 12% NH_3 (considering only positive SDC), respectively. However during January and March 2013, some NH_3 was released from these components. The SSF 1 inlet concentration of NO_X was BDL (0.001 mg/L) but the outlet had a higher concentration. The individual event that caused the highest NOx SDC in SSF 1 occurred in June 2014 (71%), followed by August 2014 (58%). The maximum NOx SDC (77%) at SSF 2 occurred in July 2014. SDC for TKN at SSF 1 varied from -91 (which was the only negative SDC) to 79.5%, with an average of 43.4%. There was no negative SDC for TKN at SSF 2. In the SSF 2 component, TKN was attenuated from 20 to 88% (average 51.3%). The SSF components were also effective at attenuating DON with an average SDC of 37% (ranging from 29 to 45.7%) in SSF 1 and 46.4% (ranging from 31.25 to 62%) in SSF 2. TN attenuation increased in the dry seasons. TN SDC at SSF 1 and SSF 2 was 37.8 and 41.4%, respectively (neglecting one negative SDC for SSF 1 and two for SSF 2). SSF 1 and SSF 2 attenuated TN up to 73.6% and 79.3%, respectively.

By considering data from the main inlet and outlet, it was possible to assess the overall nutrient attenuation effectiveness of WSCW (Figure 23). However we note that the Bebington Court drain at times influenced the overall SDC. WSCW attenuated up to 95.7% NH_3 (average 61.9%, considering both positive and negative SDCs; and 68.2%, considering only positive SDCs). During its operation, WSCW experienced three occasions where the outlet nutrient concentrations were higher than the inlet concentrations. The WSCW also attenuated NOx by around 16% (considering positive and negative SDCs) and 50% (considering positive SDCs). The NOx SDC for the whole system varied from -545 to 90%. SDC for NOx indicated higher attenuation during dry periods. TKN showed higher attenuation during dry periods, up to 2013. After that, TKN showed periodic increases and decreases in the overall SDC. The average SDC for TKN was 33.8%. The overall SDC for DON was low compared to other parameters. WSCW attenuated up to 15% of DON. After long term operations, a wetland may act as a source of organic nutrients and DON may be released from the open water bodies, likely from the sediment or senescent plant material. TN attenuation was also higher during summer. There were some sampling periods where the outlet concentrations were higher than the inlet resulting in negative SDCs. WHBC contributed additional TN into the system. Storm events in the wet season can add TN to the system. Up to 88% TN (December 2009) was attenuated by the system, with the average being 35.4% (considering only positive SDCs).

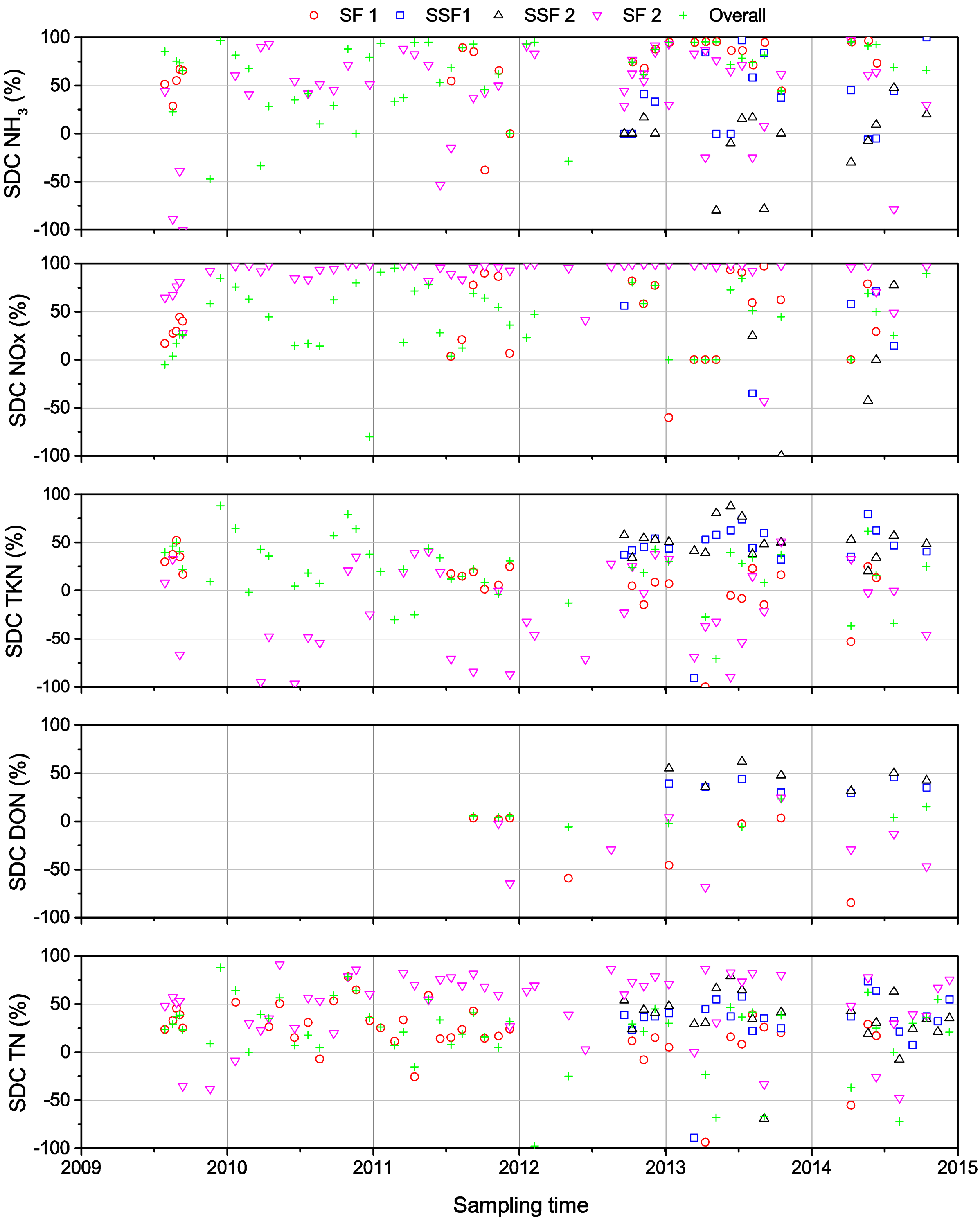


Figure 22. Attenuation (%) of nitrogen species at different components of the Wharf Street Constructed Wetland from 2009 to 2014. Positive and negative SDC indicate nutrient reduction and increase, respectively. See Table 1 for nomenclature of the different components.

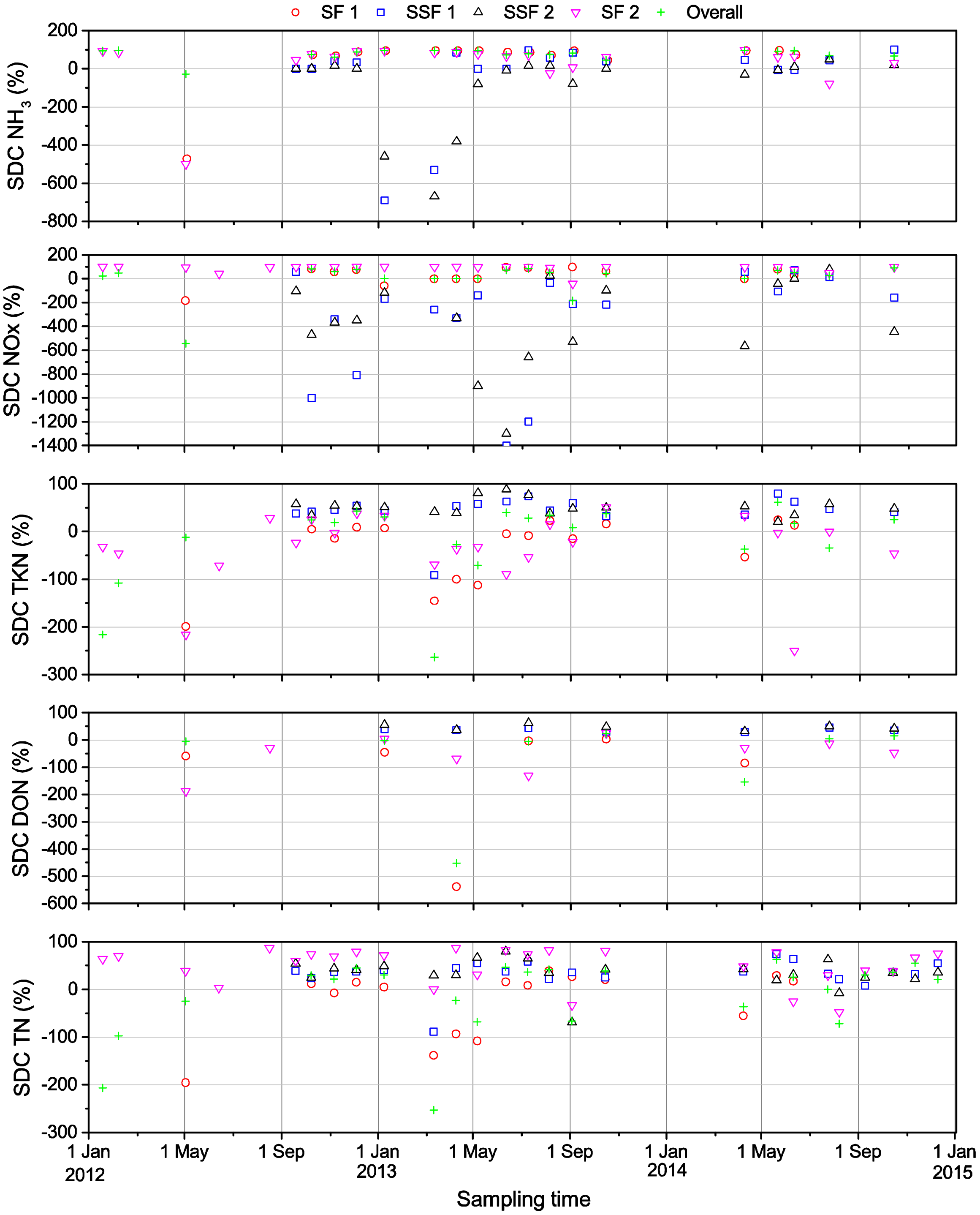


Figure 23. Attenuation (%) of nitrogen species at different components of the Wharf Street Constructed Wetland from 2012 to 2014. Positive and negative SDC indicate nutrient reduction and increase, respectively. See Table 1 for nomenclature of the different components.

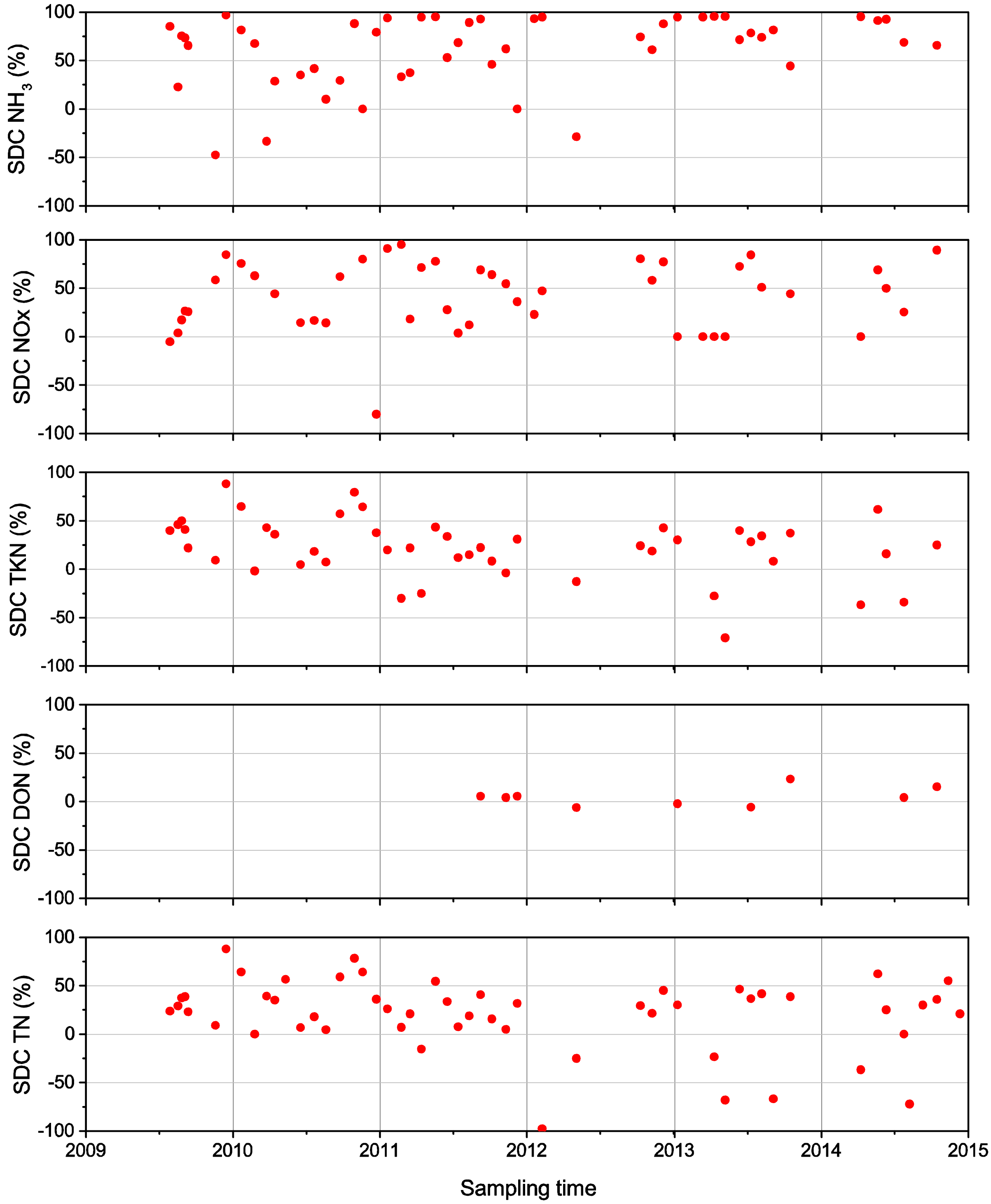


Figure 24. Overall attenuation (%) of nitrogen species by the Wharf Street Constructed Wetland from 2009 to 2014. Baseflow nutrient data from the main inlet and main outlet were considered. Positive and negative SDC indicate nutrient reduction and increase, respectively.

Attenuation of FRP and TP by different components of WSCW was assessed (Figure 25 to Figure 27). SF 1 was effective at attenuating FRP. Apart from two sampling occasions (September 2011 and October 2012), all FRP SDC were positive with an average of 60.4%. FRP showed higher attenuation in dry periods. The average attenuation for FRP at SSF 1 and SSF 2 was 52.8 and 48.5% (considering only positive SDCs), respectively. However the SDC for FRP at SSF 1 and SSF 2 varied from -500 to 72.2% and -360 to 81.8%, respectively (Figure 25). FRP attenuation in the vegetated SF 2 component ranged from -75 to 96.6% (mean of 41%). The overall WSCW system attenuated FRP 65.4% (considering only positive SDCs) and up to 98.4% FRP. Only once did a negative FRP SDC occur (-7.7% in June 2011). There were 14 sampling occasions where the WSCW attenuated more than 80% FRP.

At SF 1 SDC for TP varied from -50 (only negative event was in March 2013) to 95.8%, with an average of about 60% (Figure 24). At SSF 1 and SSF 2 the average SDC for TP was 73.1 and 57.2%, respectively (considering both positive and negative SDCs). However the two sites could attenuate up to 95.5 and 96.3% TP, respectively. When considering only positive SDC for these two components, the average SDC changed to 83.71 and 69.8%, respectively. The SSF 2 components showed only a few incidents of negative SDC for TP. There were some periods where the overall TP attenuation at SF 2 was negative. WHBC usually contributed those TP that travel shortly to reach at main outlet. Throughout the data collection years, WSCW attenuated more TP than N species. The overall system SDC for TP varied from -109 to 95.1% (mean: 65.5%). When considering only positive SDC values, the overall average performance increased to 68.8%. TP also showed increased SDC in dry periods and decreased SDC under wet conditions.

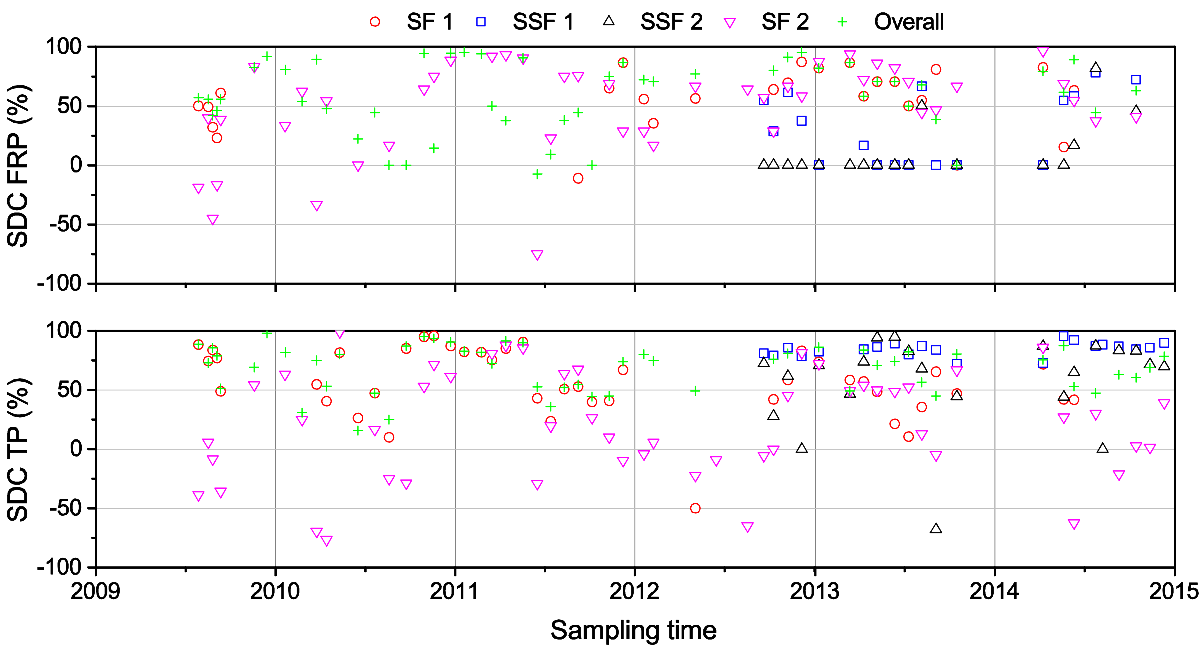


Figure 25. Attenuation (%) of phosphorus species at different components of the Wharf Street Constructed Wetland from 2009 to 2014. Positive and negative SDC indicate nutrient reduction and increase, respectively. See Table 1 for nomenclature of different components.

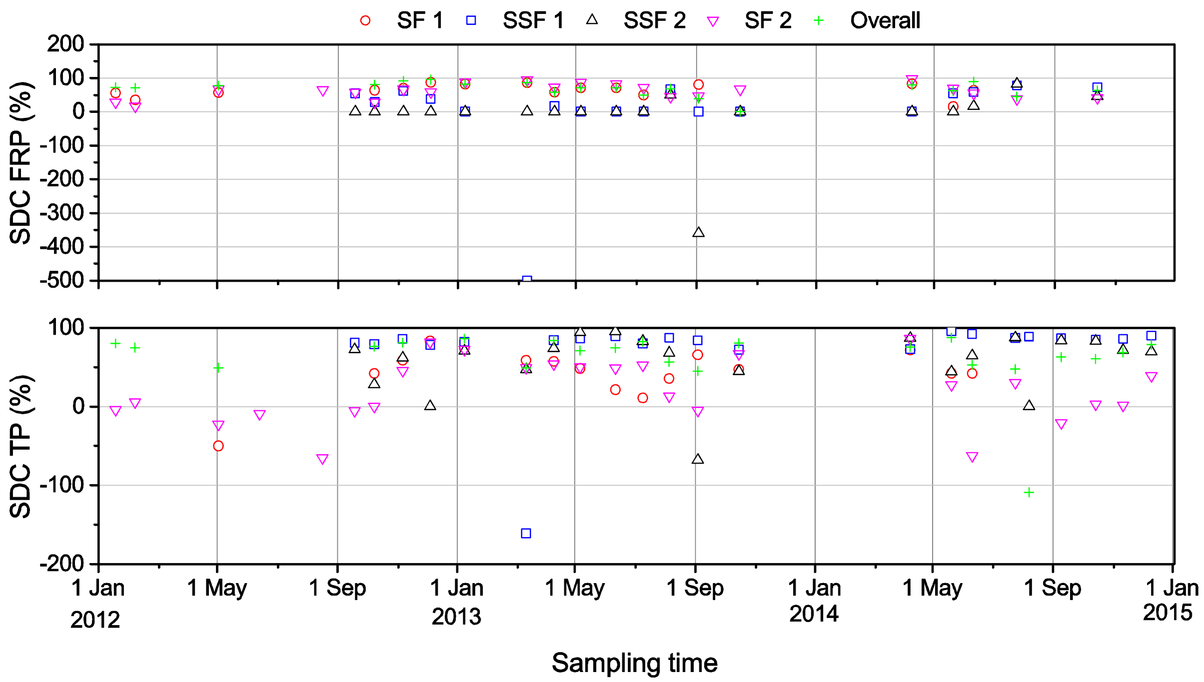


Figure 26. Attenuation (%) of phosphorus species at different components of the Wharf Street Constructed Wetland from 2012 to 2014. Positive and negative SDC indicate nutrient reduction and increase, respectively. See Table 1 for nomenclature of different compartments.

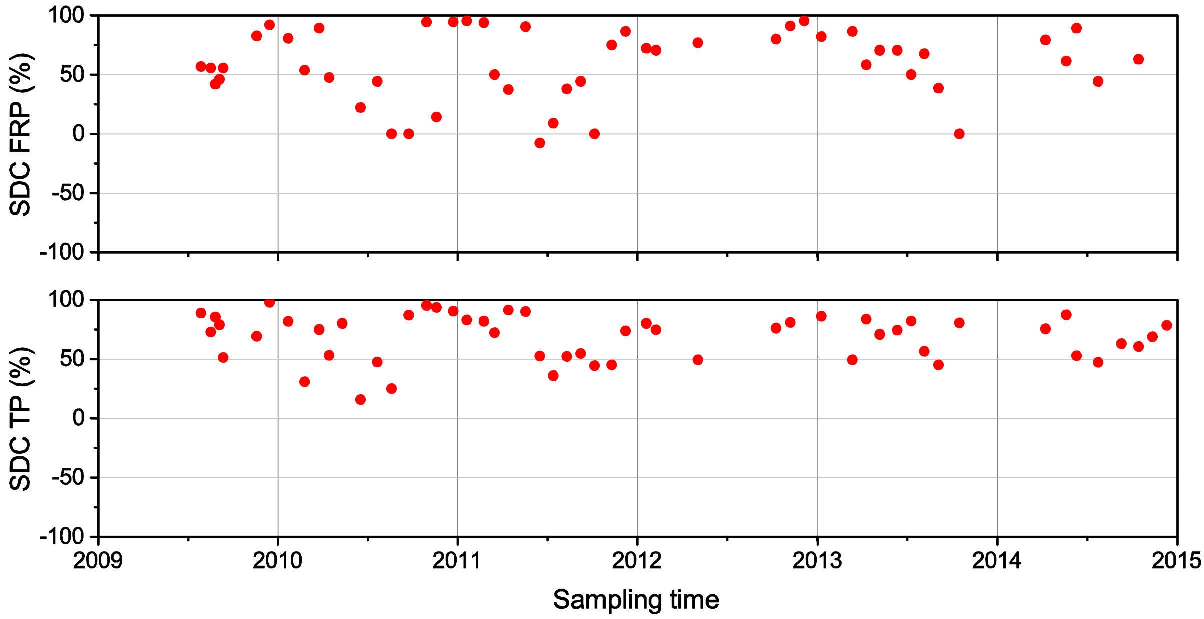


Figure 27. Overall attenuation (%) of phosphorus species by Wharf Street Constructed Wetland from 2009 to 2014. Baseflow nutrient data from the main inlet and main outlet were considered. Positive and negative SDC indicate nutrient reduction and increase, respectively.

Nutrient attenuation - Event analysis

In this section nutrient attenuation was calculated using an EMC analysis. Water samples were collected at the inlet and outlet every 2 to 3 hours for up to 58 hours during a particular storm event. Nutrient attenuation across six different events was analysed.

Event 1: 17-20 November 2009

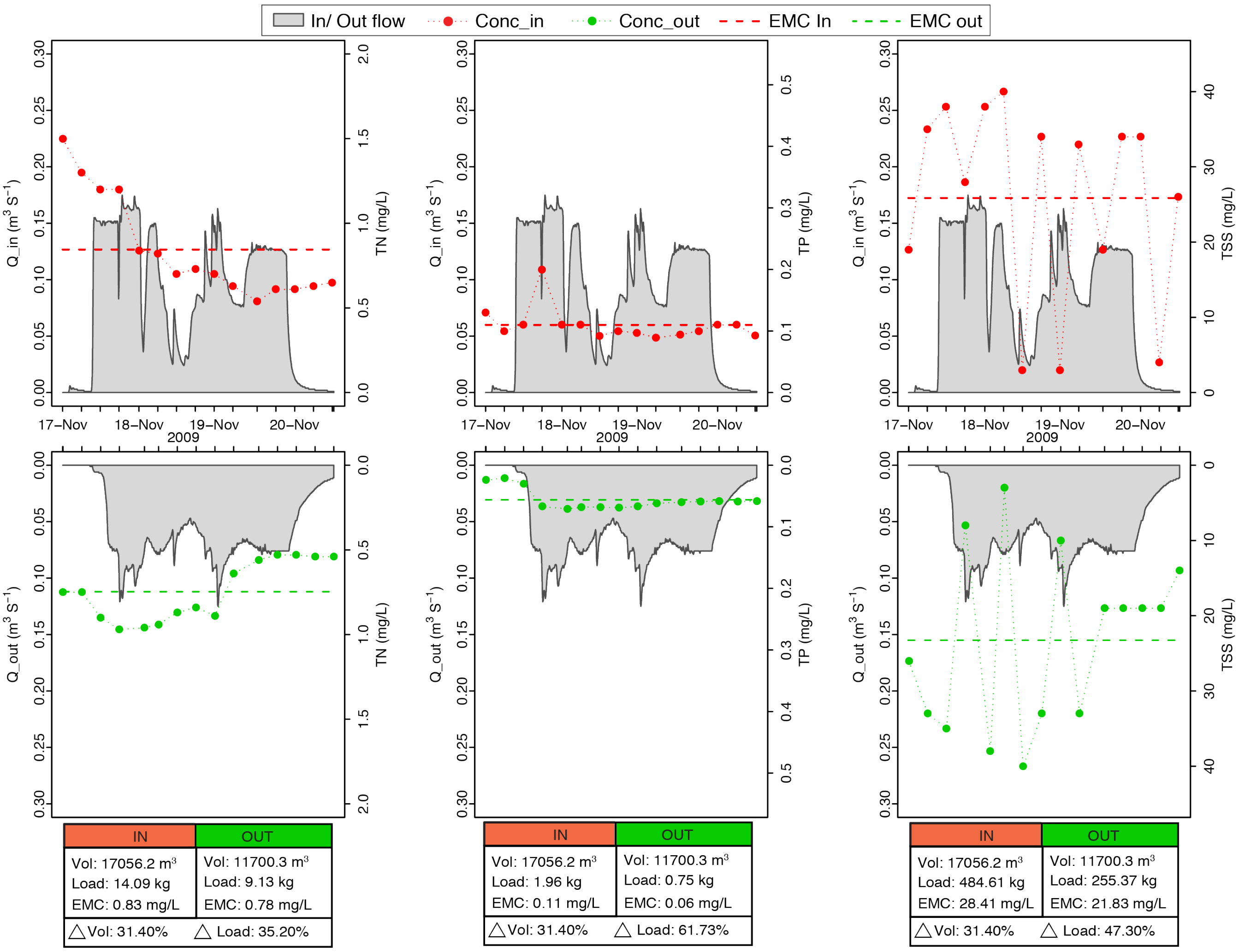


Figure 28. Flow and nutrient dynamics at the main inlet and outlet from 17 to 20 November 2009.

During this event, a total of 17,056 m^3 entered the WSCW and 11,700.3 m^3 was discharged from the main outlet (Figure 28). 31.40% of the water remained in the system, stored in the three open water ponds. A total of 14.09, 1.96 and 484.61 kg of TN, TP and total suspended solids (TSS) respectively entered the system. EMC_{in} and EMC_{out} at the main inlet for TN were 0.83 and 0.78 mg/L, respectively. However EMC_{in} and EMC_{out} for TP varied, with 0.11 and 0.06 mg/L at the inlet and outlet, respectively. The WSCW was able to attenuate around 35.2 and 61.73% of TN and TP, respectively. TN concentration increased followed by a second flow peak at the inlet and outlet. The TN concentration was higher during the first couple of hours of sampling at the inlet, likely due to the first flush (FF) mechanism. During FF, stormwater runoff carries accumulated nutrients from impervious areas of the catchment. Nutrient concentration in the subsequent inflows generally reduced, but increased in a couple of later samples. In contrast, the concentration of nutrients at the outlet from the initial sampling was low, possibly due to dilution of stored water from precipitation. Pulses of high nutrient concentrations were seen at the outlet a few hours after the storm event, and subsequently, the nutrient concentrations reduced at the outlet. TSS did not follow any particular trend, showing intermittently high and low levels at both inlet and outlet.

Event 2: 22 to 25 March 2010

The second event lasted from 22 to 25 March, 2010. A total of 6,408.9 m^3 stormwater flowed into the WSCW through the main inlet (Figure 29) and, 6,599.7 m^3 was discharged at the main outlet. Additional water may have come from the Bebington Court drain. EMC_{in} and EMC_{out} of TN during this event were 2.0 and 1.38 mg/L, respectively. At the same time EMC_{in} and EMC_{out} for TP were 2.12 and 0.95 mg/L, respectively. A total of 12.84 and 2.12 kg of TN and TP entered the system and 29.13 and 55.19%, respectively, of the load was attenuated by the WSCW. TN and TP concentration increased at both sites after the FF and second pulse. During this event, TSS increased by 41.24%.

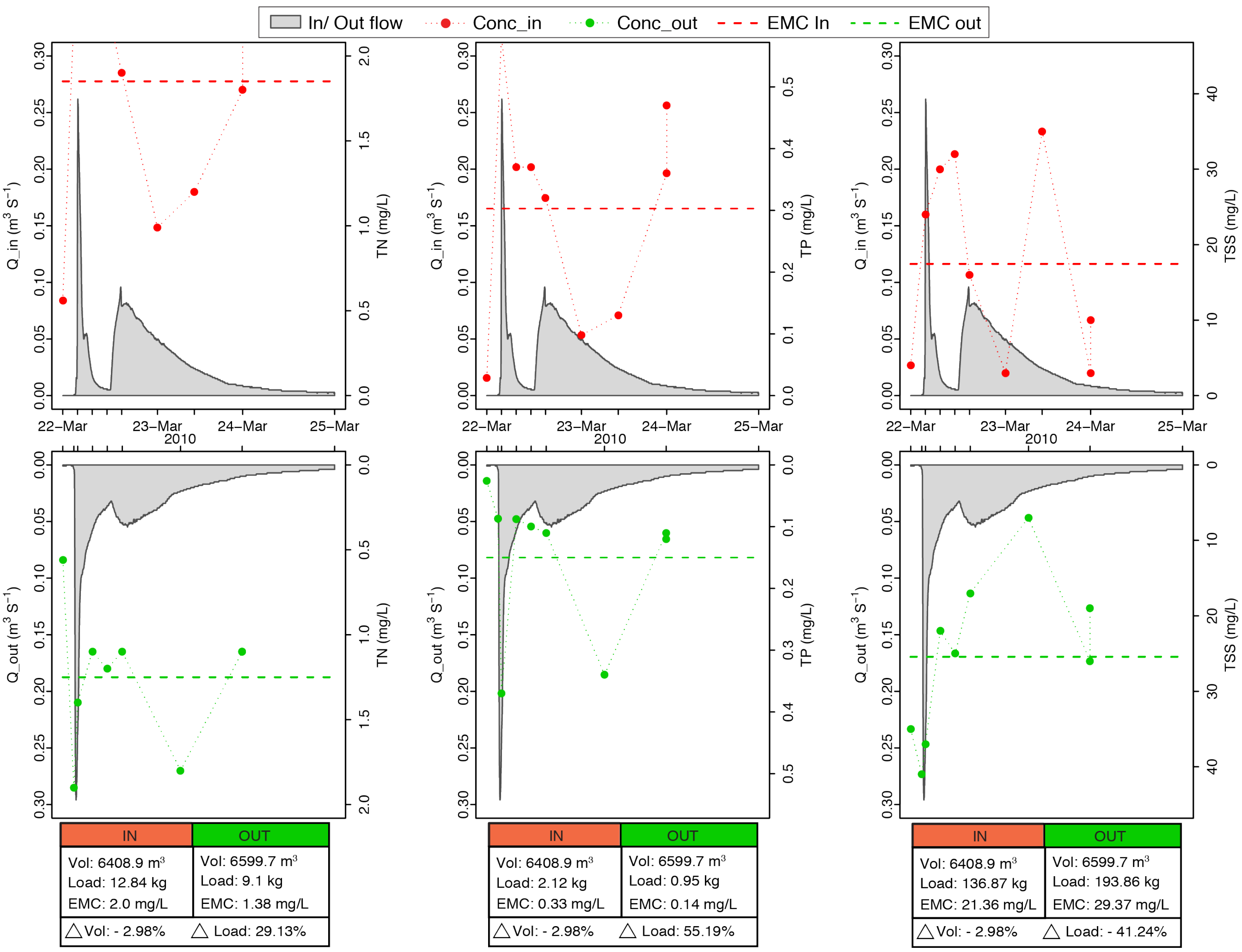


Figure 29. Flow and nutrient dynamics at the main inlet and outlet from 23 to 25 March 2010.

Event 3: 20-21 May 2011

The third event lasted from 20 to 21 May 2011. The total inflow and outflow was 1,928.10 and 2,518.50 m^3, respectively, and there was a 30.26% increase in the volume of water passing through the main outlet (Figure 30). EMC_{in} and EMC_{out} for TN were 1.28 and 0.72 mg/L, respectively. During this event 26.02 and 68.89% TN and TP, respectively, was attenuated by the WSCW. However TSS increased by 74.6% at the outlet (EMC_{in}: 13.5 and EMC_{out}: 18.04 mg/L).

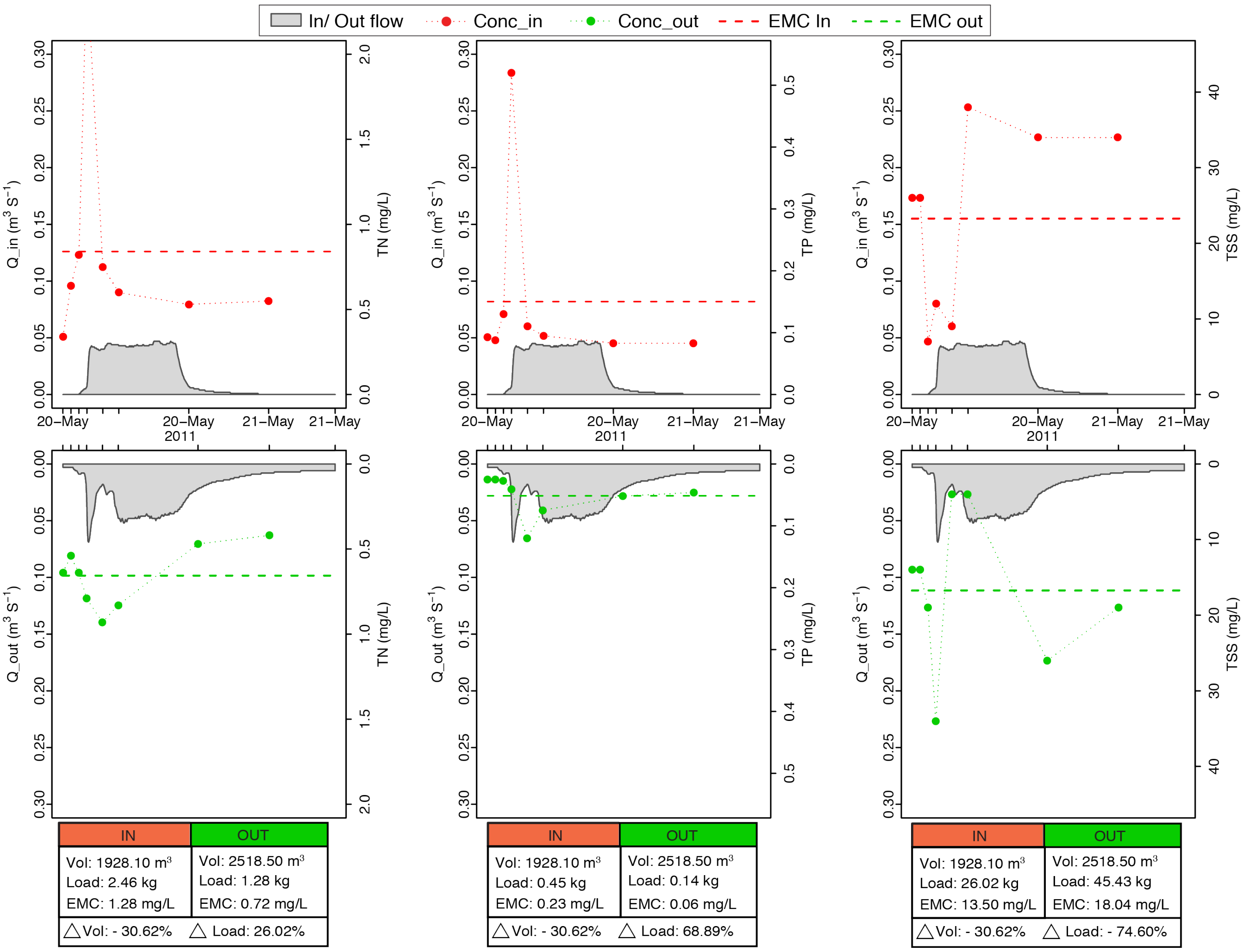


Figure 30. Flow and nutrient dynamics at the main inlet and outlet from 20 to 21 May 2010.

Event 4: 1-4 February 2012

This was a relatively small event, experiencing a 1,329 m^3 inflow and 444 m^3 outflow (Figure 31). The WSCW retained about 66.6% of the total volume of water. EMC at the inflow and outflow for TN varied, from 0.90 to 0.88 mg/L, respectively. TN and TP concentration showed that the flow peak-nutrient concentration increased after the first flush. This event attenuated the highest TP (92.6%) and TSS (87.6%) load.

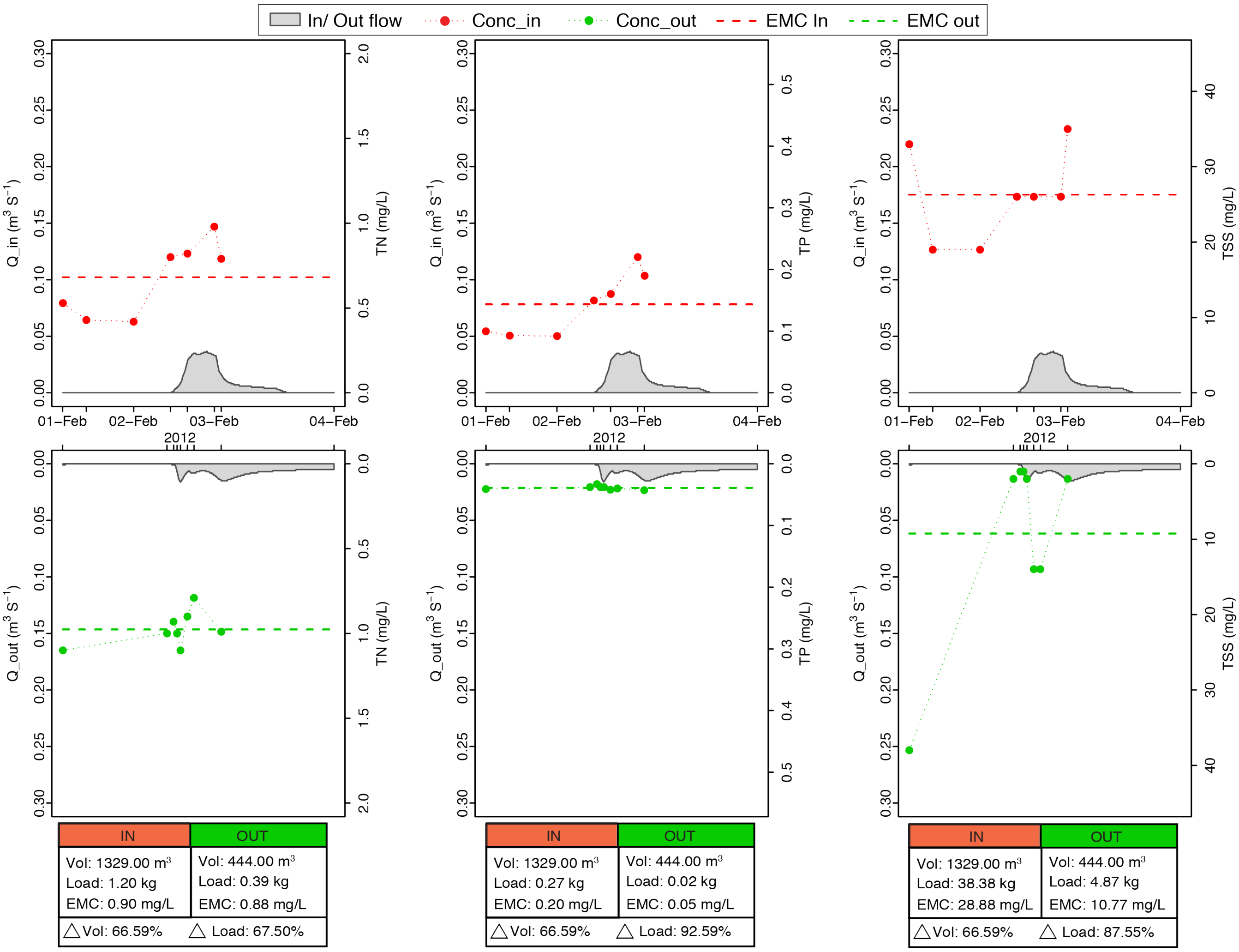


Figure 31. Flow and nutrient dynamics at main inlet and outlet from 1 to 4 February 2012.

Event 5: 7-12 May 2014

During this event, the WSCW received a total of 9,722.1 m^3 water through the inlet and discharged 9,144 m^3 at the outlet, indicating a total retention of around 6.25% (Figure 32). Water entered the system from the Bebington Court drain. The event brought in around 10.36 kg of TN and 1.72 kg of TP. EMC_{in} and EMC_{out} for TN was 0.92 mg/L and 0.88 mg/L, respectively. TN concentration at the main inlet increased following the first peak flow. It then decreased but again increased after a small flow peak. A similar pattern was seen at the main outlet. The TP concentration at the main inlet was highest during initial sampling, and then deceased over time. Overall this event attenuated around 43.63 and 65.7% TN and TP, respectively. The TSS concentration increased immediately during the event and again after the second peak flow at the inlet. However, this event flushed 35.45% more TSS out of the system than was entering the system. The additional TSS likely came from the Bebington Court drain, or from sediment within the WSCW.

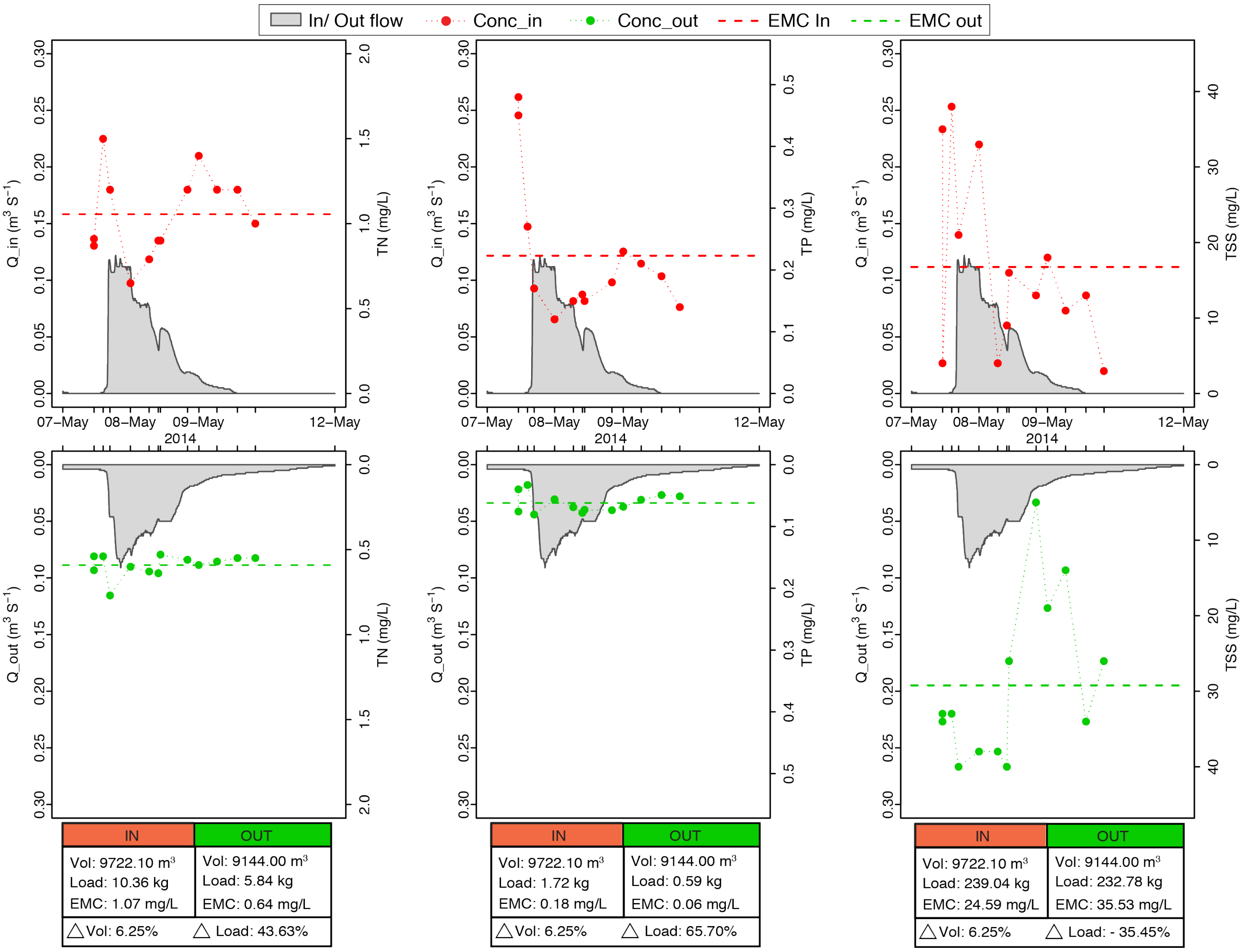


Figure 32. Flow and nutrient dynamics at the main inlet and outlet from 7 to 12 May 2014.

Event 6: 17-20 June 2014

This was the largest monitored event, based on the total water volume entering the system. During this event, about 18,361.80 m^3 of water entered and 14,970.3 m^3 exited the system (Figure 33). EMC_{in} and EMC_{out} for TN were 1.04 and 0.78 mg/L, respectively. At the same time EMC_{in} and EMC_{out} for TP were 0.09 and 0.05 mg/L, respectively. The WSCW attenuated about half the total load of TN and TP. The TN concentration increased immediately after the first flush at the main inlet and outlet, and then decreased. TN concentration increased again following the second and third flow peak. The TP concentration increased during the first and second flow peak. The outlet concentration of TP changed with flow. The event attenuated around 43% of the input TSS. At the inlet, TSS showed a trend of intermittent increase and decrease and TSS at the outlet also fluctuated throughout the event.

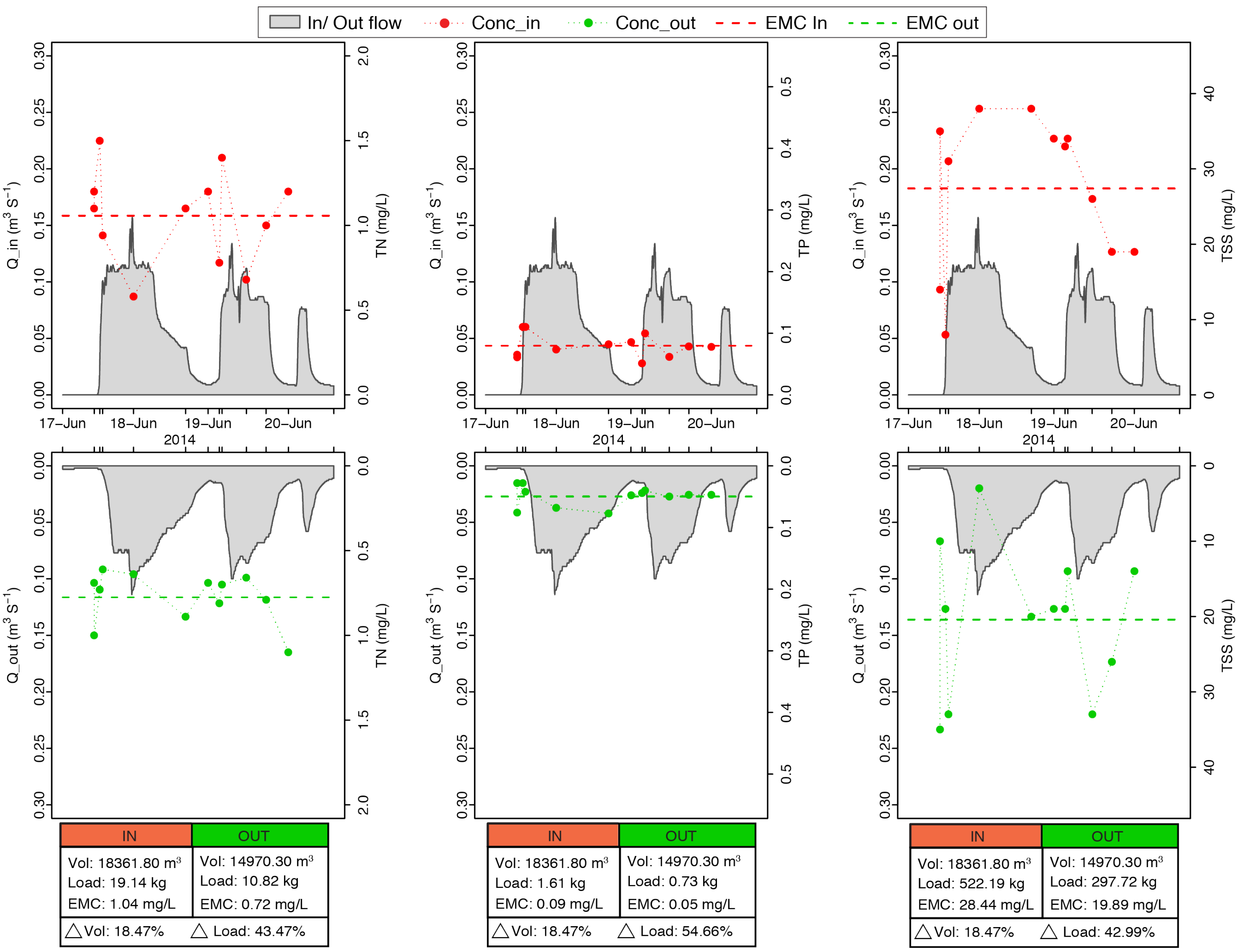


Figure 33. Flow and nutrient dynamics at the main inlet and outlet from 17 to 20 June 2014.

Figure 34 to Figure 36 show the relationship between nutrient attenuation and travel time. TN, TP and TSS attenuation during storm events were linked to travel time, considering both hydraulic retention time (HRT) and the volume of the wetland, and the difference between flow volume at the inlet and outlet during the events. As expected, it was found that the longer the HRT, the greater capacity for the wetland to attenuate nutrients.

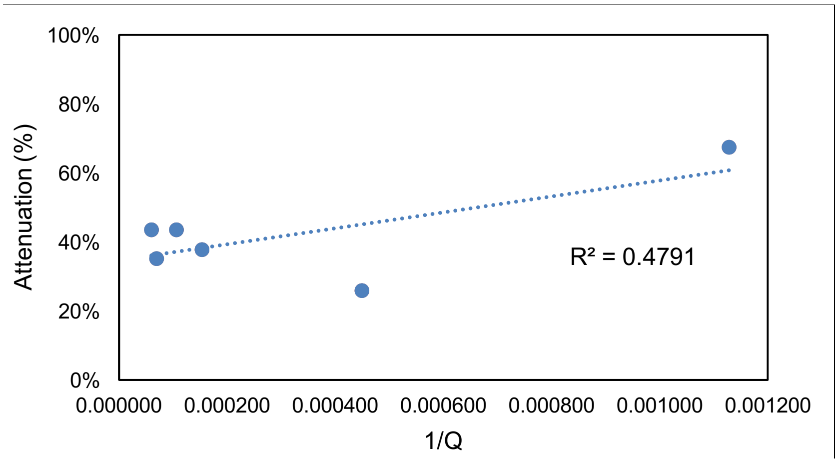


Figure 34. TN attenuation based on storm magnitude (1/Q, relative units) during six storm events.

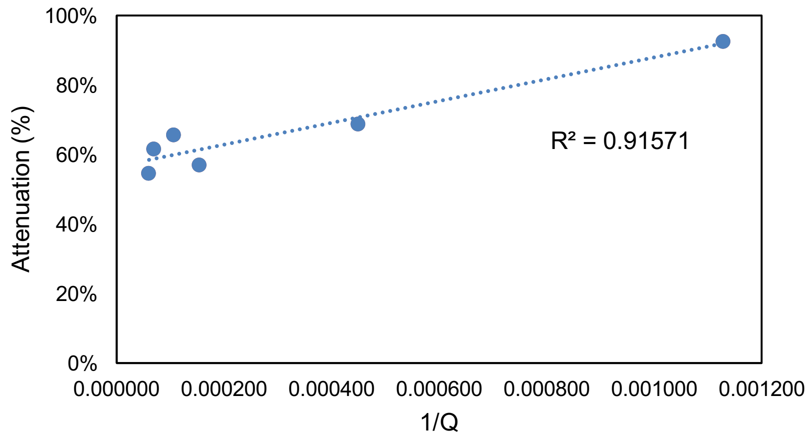


Figure 35. TP attenuation based on storm magnitude (1/Q, relative units) during six storm events.

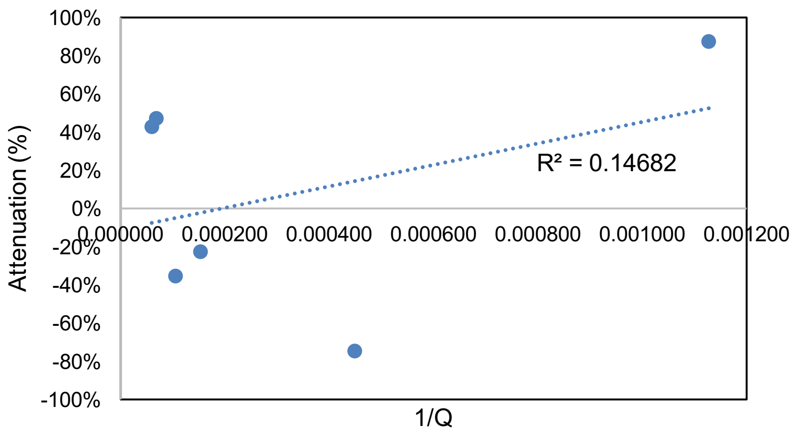


Figure 36. TSS attenuation based on storm magnitude (1/Q, relative units) during six storm events.

Nutrient load attenuation during base and event flow

We partitioned the data into two flow regimes: a) event flow: the flow rate was equal to or greater than 0.005 m^3/s, b) base flow: the flow rate was less than 0.005 m^3/s. For base flow conditions, the yearly mean nutrient concentrations were derived from DoW / Trust monitoring data for the inlet and outlet (as summarised in Figure 13 and 16) to define typical dry weather concentrations (DWC). The event mean concentrations (EMC) were estimated based on detailed event data analysis (Figures 22-27) where intra-storm data were used to estimate load reductions. Since the effectiveness of event nutrient attenuation depended on the size of the event (Figure 27-32), the relationship between retention time and attenuation was factored in and applied to each event that occurred.

2010

During base flows, WSCW received and discharged about 162 and 83 kg of TN, respectively. So approximately 78 kg TN (49% of total received) was retained by the wetland. Additionally, WSCW also received about 14 kg of TP and discharged 5 kg. The wetland retained about 9 kg TP (64% of total received).

During event flows (61 days), the WSCW received approximately 992 kg TN and discharged 243 kg and retained approximately 748 kg (76% of incoming load). During the same conditions, a total of around 100 kg TP entered the system and 65 kg was discharged. So ultimately WSCW retained 34 kg TP (34% of incoming).

2011

During base flows, WSCW received approximately 18 kg of TN and 1.8 kg TP. WSCW discharged approximately 14 kg TN and 0.5 kg TP. Therefore WSCW retained around 4.8 kg (26%) of TN and 1.3 kg (72%) of TP.

During event flows (135 days), WSCW received 290 kg and discharged 160.8 kg of TN. So WSCW retained approximately 160 kg TN (55% of total incoming load). 29 kg of TP entered WSCW during event flows and discharged about 20 kg. So, approximately 8.5 kg of TP was retained by the system, 29% of the total load.

2012

During base flows, the total incoming and outgoing TN load was 4.7 and 1.8 kg, respectively. About 2.9 kg of TN (62%) was retained by WSCW. 1 kg of TP entered WSCW and 0.6 kg was discharged. The system retained around 0.34 kg TP (36%).

During event flows (96 days), a total of 166 kg of TN entered the system and 68 kg was discharged. Therefore a total 98 kg was retained by WSCW (59% of the incoming load). 16.7 kg of TP entered WSCW and 10.7 kg was discharged. The wetland retained 5.9 kg TP (35% of the incoming load).

2013

During base flows, 25.7 kg of TN entered WSCW and 24.9 kg was discharged. WSCW retained 0.75 kg TN (3%). The system received 3.8 kg of TP and discharged about 0.04 kg. WSCW retained about 3.7 kg of TP (98% of the incoming load).

During event flows (119 days), WSCW received about 324 kg TN. 54% of TN was retained by WSCW (173 kg) and 150.5 kg was discharged. 32.6 kg of TP entered WSCW and 23.7 kg was discharged. About 8.8 kg TP was retained (27% of incoming load).

2014

During base flows, 52.3 kg TN was received and 52.8 kg discharged. WSCW received about 4 kg of TP and discharged 3.6 kg. The system retained 0.37 kg TP (9%).

During event flows (24 days), 490 kg of TN entered WSCW and 100 kg was discharged from the system. WSCW retained about 389 kg (79% of incoming load). 83 kg of TP entered WSCW and 26.7 kg was discharged from the system. WSCW retained about 56 kg of TP (67%). Overall load retention by WSCW from 2010 to 2014 is shown in Table 3.

Table 3. Estimates of total input load and load retention by Wharf Street Constructed Wetland.

		TN				TP			
Year	Flow type	Inlet load (kg)	Outlet load (kg)	Δ Load (kg)	Load removal (%)	Inlet load (kg)	Outlet load (kg)	Δ Load (kg)	Load removal (%)
2010	Base	162.09	83.27	78.82	49%	14.492	5.11	9.37	65%
	Event	991.90	242.95	748.94	76%	99.71	65.79	33.91	34%
2011	Base	18.89	14.02	4.86	26%	1.8102	0.49	1.32	73%
	Event	290.17	129.31	160.85	55%	29.17	20.60	8.56	29%
2012	Base	4.696	1.80	2.89	62%	0.939	0.59	0.34	36%
	Event	166.07	67.66	98.41	59%	16.69	10.76	5.92	36%
2013	Base	25.71	24.95	0.75	3%	3.84	0.04	3.79	99%
	Event	324.30	150.57	173.73	54%	32.60	23.79	8.81	27%
2014	Base	52.25	52.86	-0.60	-1%	3.96	3.583	0.37	10%
	Event	490.21	100.66	389.55	79%	83.10	26.73	56.36	68%

Nutrient attenuation - modelled vs actual

In their conceptual design report, Syrinx (2007) estimated that WSCW would treat 42% of the first flush volume and 97% during the summer period. They subsequently modelled the expected performance of WSCW using MUSIC (Model for Urban Stormwater Improvement Conceptualisation) (Syrinx 2008). In that analysis, it was predicted that the wetlands would treat approximately 90% (on an annual basis) of the runoff volume from the catchments prior to discharge to the Canning River. During storm events WSCW treated up to 94% of water. However, among six studied storm events, two events discharged more water through the outlet than recorded at the inlet (Figure 29 and Figure 30). This additional water may be come from Bebington Court drain and rainfall within the system. WSCW is a complex system with multiple inlet (main inlet, ornamental lake and Bebington Court drain), surface and subsurface water storage. WSCW losses water during isolated rainfall events (small or large) under dry antecedent conditions and pumping cycles between spring and autumn. Large volumetric contributions from ungauged areas also found during frequent rainfall events of winter-spring and large rainfall events.

The MUSIC analysis predicted that the mean TN and TP concentrations exiting WSCW would be 1.01 and 0.055 mg/L, respectively. Both predicted results were within the Swan Canning Cleanup Program (SCCP) and Healthy Rivers target (1.0 mg/L TN and 0.1 mg/L TP) and ANZECC guidelines (1.2 mg/L TN and 0.065 mg/L TP). When overflows and system bypasses were factored in, the nutrient concentrations were predicted to be 1.02 mg/L TN and 0.057 mg/L TP.

In their conceptual design report, Syrinx (2007) estimated the reduction of TN and TP would be 13 and 36% during the first flush and 58 and 72% during summer conditions. It was suggested that attenuation would be higher during the summer and lower during the winter/first flush period. MUSIC analysis predicted the average TN and TP removal by the wetland to be 34 and 57%, respectively (Syrinx 2008).

Syrinx (2008) undertook a cumulative frequency analysis on the MUSIC-predicted water quality exiting the wetlands. This analysis indicated that TP concentrations would meet the SCCP long-term targets approximately

87% of the time and ANZECC guidelines approximately 66% of the time. Similarly, TN was expected to meet the SCCP long-term targets approximately 40% of the time and ANZECC guidelines approximately 57% of the time.

The current report has used historical empirical data to quantify the nutrient attenuation in WSCW under different hydrological conditions. The average outlet concentrations of TN and TP under baseflow conditions were 0.81 and 0.04 mg/L, respectively. During storm events the average outlet concentrations of TN and TP were 0.86 and 0.06 mg/L, respectively. In general, the measured outlet concentrations agreed with model predictions, with the exception of TP concentrations during overflows/storm events. The wetland met the Healthy Rivers long-term goals and ANZECC guidelines for TN approximately 85 and 90% of the time, respectively. The wetland met the Healthy Rivers long-term goals and ANZECC guidelines for TP approximately 95 and 88.33% of the time, respectively. The mean TN and TP attenuation by WSCW during base flow conditions was 11.5 and 65%, respectively. There were some sampling periods where the outlet concentrations of TN and TP were higher than the inlet concentrations; these periods decreased the estimated average nutrient attenuation. The empirical data analysis supported model predictions that nutrient attenuation would be higher during summer and lower during winter (considering base flow conditions). Table 4 compares predicted versus measured water quality and nutrient reduction at the main outlet..

Table 4. Comparison of modelled and measured nutrient concentrations and attenuation under different flow conditions at the Wharf Street Constructed Wetland.

Condition		Modelled/ predicted results (Syrinx 2008)	Measured results
Baseflow	TN concentration at outlet	1.01 mg/L	0.83 mg/L
	TP concentration at outlet	0.055 mg/L	0.032 mg/L
Event flow	TN concentration at outlet	1.02 mg/L	EMC: 0.67 mg/L
	TP concentration at outlet	0.057 mg/L	EMC: 0.11 mg/L
Overall	TN reduction efficiency	57%	Baseflow load: 28% event load: 65% Storm event load: 41%
	TP reduction efficiency	34%	Baseflow load: 34% event load: 39% Storm event load: 66%

Metal attenuation - SDC approach

Figure 37 shows the system-scale attenuation of six metals, considering the main inlet and main outlet. All metals showed increased attenuation during dry periods. However, Al, Fe, Mn and Zn on occasions had negative SDCs, highlighting that these metals can be released by the wetland. The WSCW removed up to 90% of As (mean: 47%). After April 2013, Cu attenuation reduced to almost zero. Fe showed clear seasonal trends in attenuation, showing negative SDC during wet periods. The Bebington Court drain likely contributed Fe to the system, which increased outlet concentrations. The average Fe attenuation was 32% (maximum 73%) during the first two years of operation. Up to 97% of Mn was initially attenuated, after which it reduced, with only episodic increases of attenuation. Zn was released on three different sampling events; the remainder of the time the WSCW attenuated an average 61.4% of Zn. Zn attenuation was higher during dry periods and lower during wet periods. The Bebington Court drain was found to be a significant source of Zn from the surrounding urban area, influencing the overall estimation of metal attenuation.

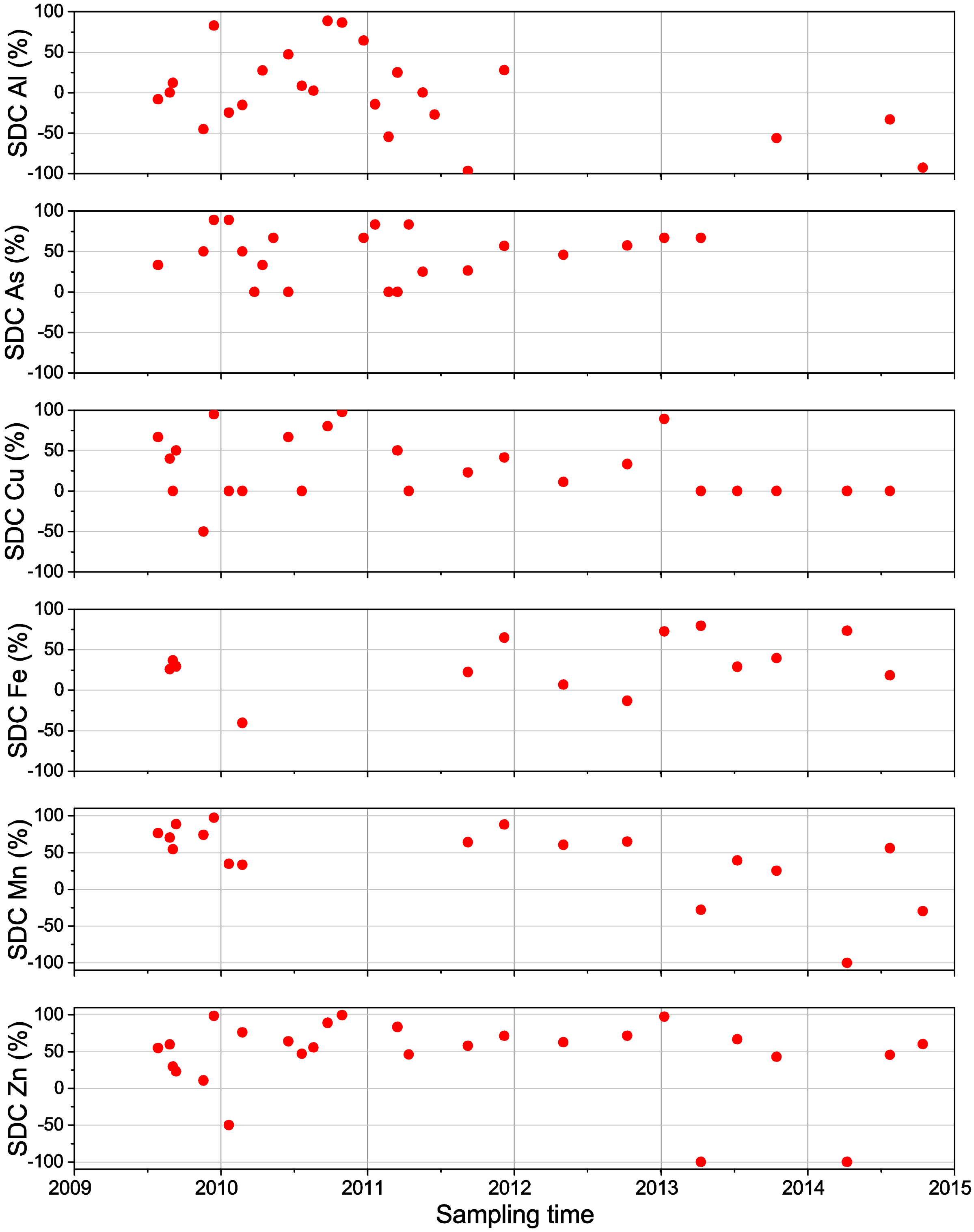


Figure 37. Metal attenuation (%) in the Wharf Street Constructed Wetland from 2009 to 2014. Positive SDC indicates metal reduction while negative indicates metal increases.

Sediment quality

Nutrients and total organic carbon

Sediment nutrient concentrations (TKN, TN, TP) in the wetland have been monitored since 2010, with samples collected approximately every six months. WHSED1 is located at the entry of the system and particulate nutrients settle likely out at this point. WHSED2 is located in the central part of the wetland, while WHSED3 is at the location that receives water from the diversion of WHW1 during high flow and the outlet of the laterite SSF 1. For TN, TP and total organic carbon (TOC) there was an obvious reduction in sediment nutrient concentrations from WHSED1 to WHSED3, in 2010 and 2011. However from 2012, the trends were more variable (Figure 38). In October 2013, WHSED3 contained higher concentrations of TN and TP than WHSED1 and WHSED2, and TOC concentrations were almost identical to that of WHSED2. During the initial three sampling events (2010-2011), the concentration of TN in WHSED1, WHSED2 and WHSED3 varied from 780 to 1190 mg/kg, 510 to 1230 mg/kg and 390 to 780 mg/kg, respectively. However, after that time period, the concentration of TN increased rapidly at all three sites. It was likely due to the periodic accumulation of sediments and particulate nutrients delivered in the stormwater runoff from the surrounding catchment. From October 2011 to May 2012, TN concentration was found to be almost four times higher. The following two sampling events in October 2012 and May 2013 showed a relatively low concentration of TN compared to May 2012. TN concentration reached in its maximum in October 2013 at sites WHSED2 (3700 mg/kg) and WHSED3 (3800 mg/kg).

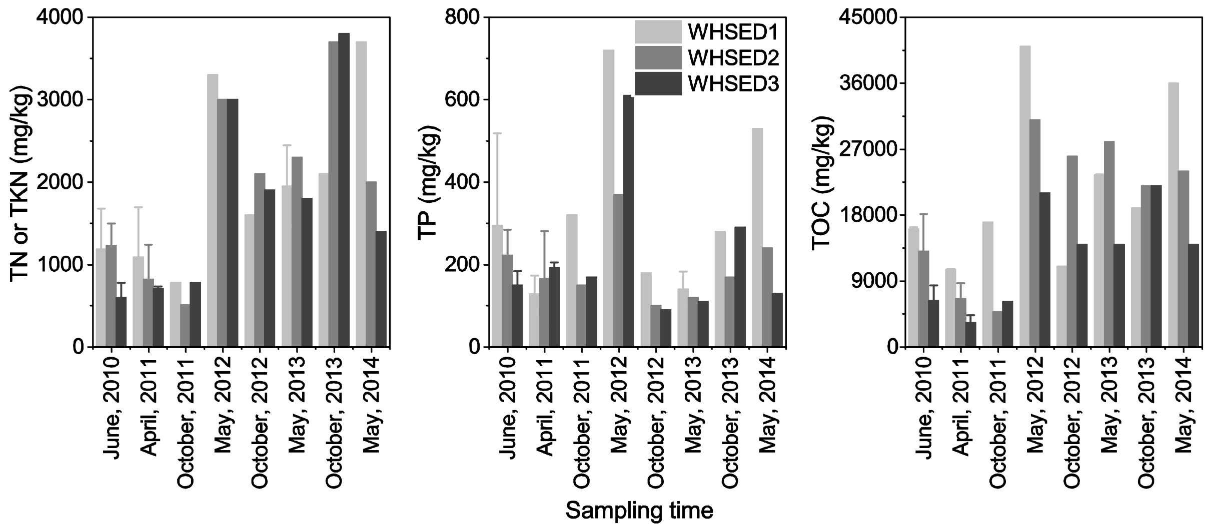


Figure 38. Spatial and temporal variation of TKN or TN, TP and TOC concentrations in the sediment at the Wharf Street Constructed Wetland (mean and standard deviations).

The TP concentration in the sediment varied from 140 to 720 mg/kg, 100 to 370 mg/kg and 90 to 610 mg/kg at site WHSED1, WHSED2 and WHSED3, respectively. Similar to TKN, TP increased sharply from October 2011 to May 2012. The maximum concentration of TP was found in May 2012 at WHSED1. This is due to the fact that this site receives the initial input of stormwater runoff, and it is the first opportunity for the particulate materials to settle out. Macrophytes in this area provide some resistance to the water flow and hence facilitate sedimentation. After a high concentration in May 2012, TP showed a decreasing trend for the next year which encompassed two sampling events.

There are no guidelines for nutrients in sediments so they are not compared to a target value. We used the TP guideline for soils as a reference (DEC, 2010) and the concentration of TP does not exceed the guideline for soils (2000 mg/kg).

Sediment in the WSCW was rich in TOC and the concentration varied from 10,600 to 41,000 mg/kg, 4,800 to 31,000 mg/kg and 3,350 to 22,000 mg/kg at site WHSED1, WHSED2 and WHSED3, respectively. From June 2010 to October 2011, TOC concentration was relatively low (1,700 mg/kg) at WHSED3. From then, the TOC concentration was two to three times higher throughout the wetland. Similar to N and P, the TOC concentration was higher in WHSED1.

The total mass of nutrients in the sediment was estimated by assuming that the concentration at each site was representative of inundated areas. Therefore a relevant area could be attributed to a nutrient concentration such that:

$$\text{Sediment nutrient (kg)} = \text{Sediment nutrient concentration (mg/kg)} \times \text{Sediment bulk density (kg/m}^3\text{)} \times \text{Sediment area (m}^2\text{)} \times \text{Sediment depth (m)}$$

Sampled sediment depth ranged from 0.1 to 0.3 m and the soil bulk density was measured after the samples were collected (ranging from 1100 to 1900 kg/m^3). Sediment nutrient mass varied at sites because of their different areas.

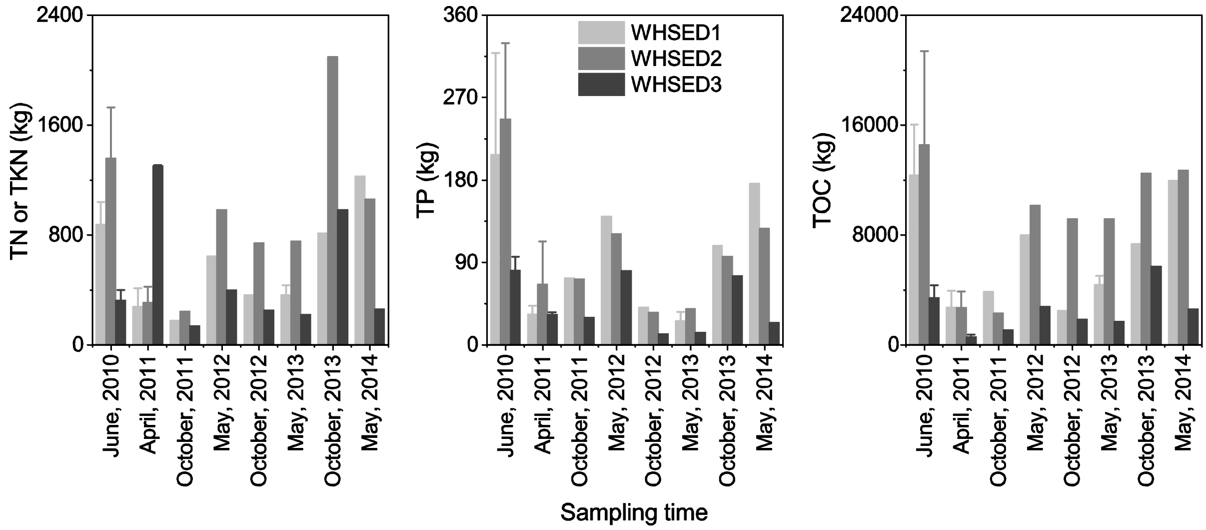


Figure 39. Spatial and temporal variability of nutrient mass in the sediments at the Wharf Street Constructed Wetland (average and standard deviations).

Sediment has the ability to store a large mass of nutrients (Figure 39). WHSED1 accumulated 365 to 878 kg of TN, 41 to 207 kg of TP and 2505 to 12350 kg of TOC. WHSED2 covered the greatest area and had the highest mass of TN found (October 2012). However from June 2010 to May 2013, TN mass showed little variation over three sites. After October 2013, TN mass rapidly increased at site WHSED2, which may have been due to long term accumulation of nutrients by the sediment. Nutrient adsorption, nutrient precipitation and senescent plant material likely influences the TN mass within the system.

Interestingly TP mass was highest during the first sampling period (June 2010), after which the TP mass remained relatively stable for the ensuing two years. From 2014, TP showed an increasing trend. As WHSED3 is the smallest site of the WSCW, it contained less mass of TP than the other two sites. The WSCW has high TOC masses at all three sediment sampling sites. Generally WHSED2 contained the maximum mass of carbon, being the biggest site among the three. The wetland began operation in 2009. WHSED2 has experienced an accumulation of TOC likely due to senescent plant materials and biogeochemical processes. Overall, the maximum mass of nutrients was found at the initial stage of wetland commissioning. This may be due to the accumulation of particulate nutrients in the sediment during the first year. More recently (2013-2014), the nutrient mass showed an increasing trend at all three sites. Table 5 shows total sediment nutrient content across the three sampling points, from 2010 to 2014.

Table 5. Total sediment nutrient content across the three sampling point of the Wharf Street Constructed Wetland, from 2010 to 2014.

Date	TN (kg)	TP (kg)	TOC (kg)
29/06/2010	2561.1	535.5	30354.1
19/04/2011	1890.4	132.6	6018.3
05/10/2011	559.9	174.8	7267.7
2/05/2012	2025.3	342.7	20947.6
9/10/2012	1357.5	88.2	13536.5
7/05/2013	1334.5	79.1	15244.5
16/10/2013	3894.5	279.9	25524.9
21/05/2014	2546.6	327.1	27250.8

Metals

Stormwater carries particulate metals from roadsides and commercial premises surrounding the WSCW. These metals are usually non-biodegradable and can be stored within the soil/sediment, assimilated in the biomass or washed from site by outflow. Nine metals were measured in the wetland sediments, from June 2010 to May 2014 (Figure 40), though As and Ni were not analysed in October 2013 and May 2014. Al concentrations were around 9000 mg/kg at WHSWD1 during the first sampling period (June 2010), and then increased up to October 2012. WHSED2 and WHSED3 contained higher Al concentrations. The highest metal content of all sites was usually found in May 2012. Al, As, Cr, Cu, Al, Mn and Ni concentrations were all below the prescribed limits (ISQG low and high trigger values), though one sediment sample exceeded the ISQG low and high trigger value for Zn in May 2012. At this time Pb also exceeded the ISQG low trigger value. A decreasing trend was seen at WHSED2 and WHSED3 after October 2014, particularly for As, Cr, Mn, Pb and Zn. The highest concentrations measured were for Fe, ranging from 9180 to 25500 mg/kg. WHSED1 generally contained higher metal content than the two other sites most likely due to particulate metals settling at WHSED1; the metals could then be transferred to the other parts of the system under high flows. Zn content in the sediment was low for all three sites up until October 2011, and then increased sharply at WHSED1 for the remainder of the time. Hg and Cd were both consistently below 0.0001 mg/kg.

WSCW accumulated metals within the sediment components as shown in Figure 41 and Table 6. Metal mass per unit area of WSCW was estimated for June 2010. During this time three sediment sampling sites contained relatively higher masses of metals. This may be due to the accumulation of metals washed in from the surrounding catchment during the first year after construction. Al mass showed a sharp increase in October 2012 at WHSED2, followed by a decreasing trend. Since May 2012, As mass reduced at all sampling sites. Cr mass was higher at WHSED2. WHSED1 showed higher mass of Cu and Zn accumulation in May 2012 and May 2014. After June 2010, Fe mass was relatively similar at WHSED1 and WHSED3. Pb mass showed periodic increase and decrease at WHSED1 and WHSED3. Mn mass was relatively stable at WHSED2 since October 2012. Average Al mass at WHSED1, WHSED2 and WHSED3 was 3,315, 5,821 and 3,830 kg, respectively. In May 2013 and October 2013, Al mass was higher at WHSED3 (2676.5 kg in May 2013 and 4658.5 kg in October 2013) than WHSED1 (2220.7 kg in May 2013 and 3047 kg in October 2013). Some Al may have been released from the laterite material of the SSF 1 component or the RCM. Zn storage in the three sites was 52.7, 23.7 and 10.6 kg, respectively. Pb storage at WHSED1, WHSED2 and WHSED3 was 8.9, 9.8 and 3.6 kg respectively.

Table 6. Total sediment metal content across the three sampling points of the Wharf Street Constructed Wetland from 2010 to 2014.

Date	Al (kg)	As (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Mn (kg)	Ni (kg)	Pb (kg)	Zn (kg)
29/06/2010	38043.4	9.2	46.5	30.4	81500.5	237.2	14.3	56.7	132.9
19/04/2011	10784.2	2.8	13.5	11.7	23056.7	83.9	4.5	17.5	37.2
05/10/2011	8809.3	4.9	9.7	8.3	15059.9	49.3	3.3	13.9	38.7
2/05/2012	9176.2	6.2	16.1	20.2	21697.8	95.0	6.3	20.3	130.3
9/10/2012	15192.8	2.9	14.7	10.0	18385.1	58.2	5.4	14.6	69.8
7/05/2013	13087.3	2.3	13.0	11.1	19410.5	67.9	4.4	15.9	81.9
16/10/2013	15077.3	0.0	16.0	15.0	22830.3	89.2	0.0	20.4	96.2
21/05/2014	14601.6	0.0	14.7	16.5	19596.7	79.3	0.0	20.0	109.4

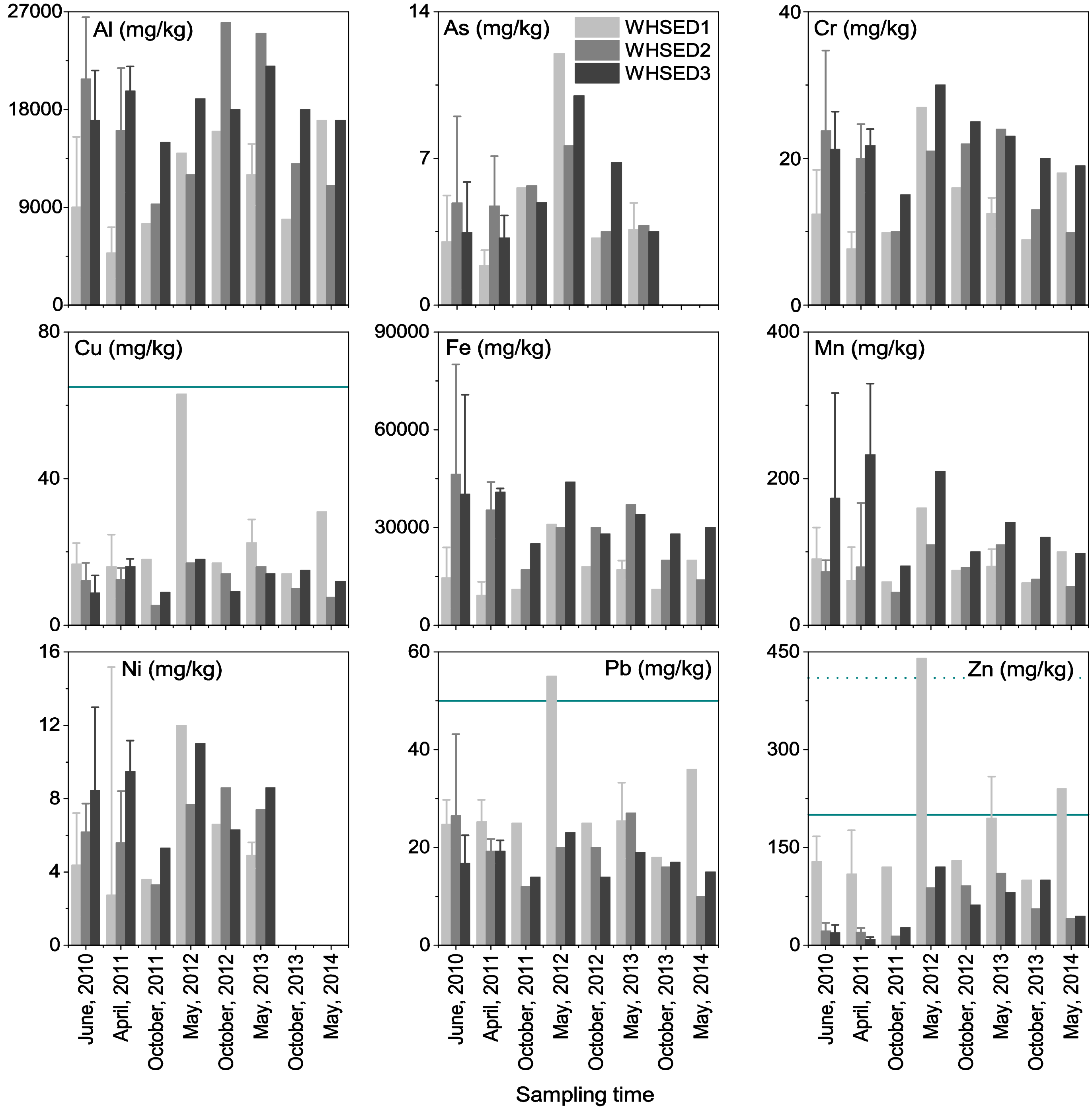


Figure 40. Spatial and temporal variation of metal content in the sediment of the Wharf Street Constructed Wetland. Horizontal solid and dashed dark lines in each plot represent the ISQG-low (trigger value) and ISHG-high (trigger value), respectively.

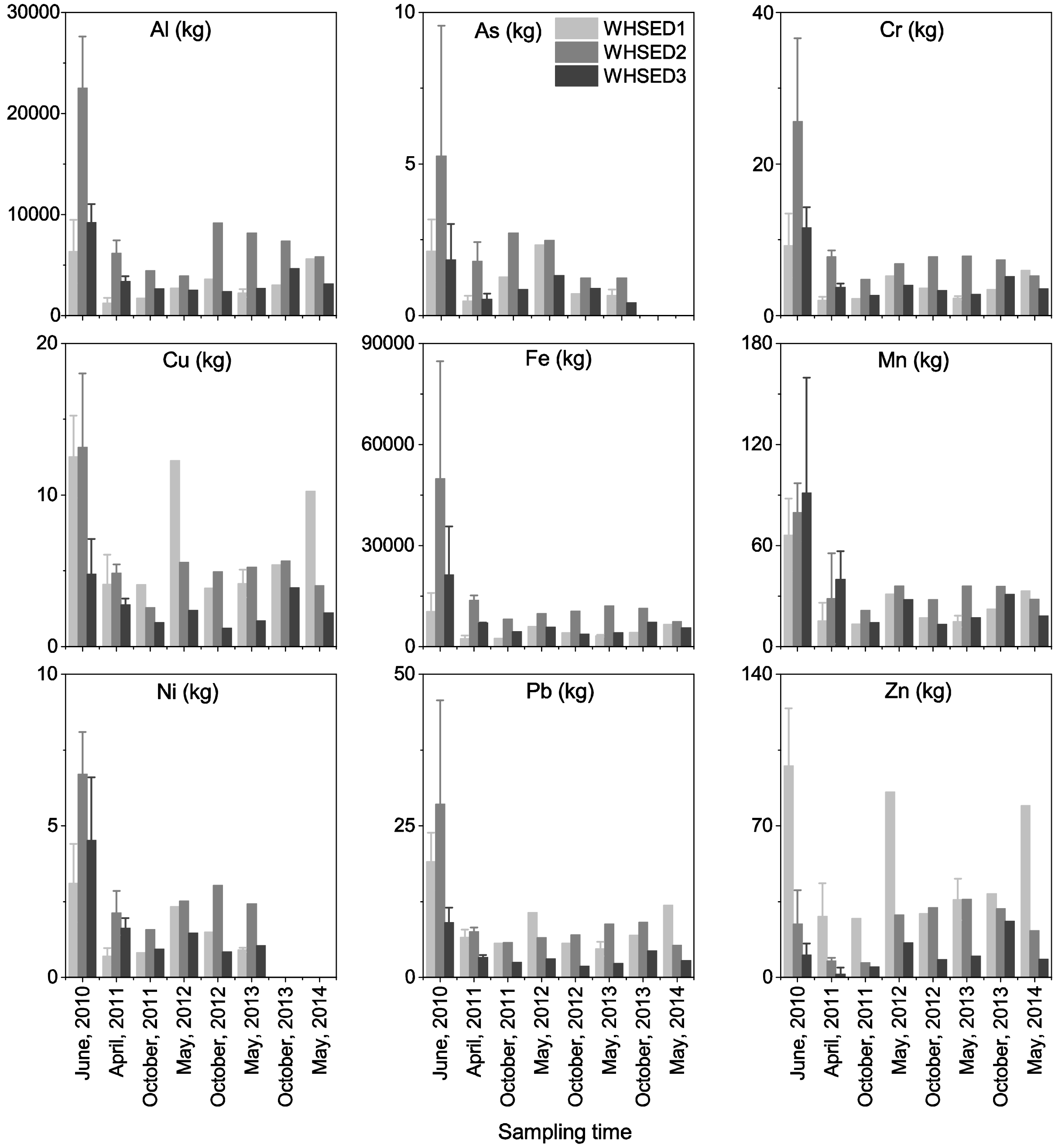


Figure 41. Spatial and temporal variability of mass of metals in the sediment at Wharf Street Constructed Wetland. Vertical line and bar indicates the standard deviation.

Vegetation dynamics

Dominant aquatic macrophytes or vegetation in constructed wetlands include macroscopic flora such as aquatic spermatophytes, pteridophytes, bryophytes and sometimes charophytes. Overall these species can be categorized into four groups: emergent macrophytes, floating leaves macrophytes, free floating macrophytes and submerged macrophytes. The macrophyte monitoring program aimed to monitor spatial variation in the macrophyte nutrient pool across the WSCW, particularly in the surface flow wetland system. Nutrients are stored in plant biomass during their growth phase and some plants also store trace metals and other potential toxins, and are therefore a critical component of nutrient and pollutant removal. Uptake rates of stormwater nutrients and contaminants can be estimated from repeated harvesting and analysis of macrophyte tissue. Macrophytes in the water column can serve as a biofilm substrate, excrete oxygen and reduce water velocity thereby enhancing sedimentation of suspended solids. Moreover, some macrophytes typically uptake and store nutrients directly and thus polish surface waters. They also support biodegradation of nutrients and transport approximately 90% of the oxygen available in the rhizosphere that ultimately stimulates both aerobic decomposition of organic matter and promotes the growth of nitrifying bacteria. During high flow periods, the increased hydrological roughness due to the vegetation supports the sedimentation of particulate matter.

Major macrophyte species in WSCW include *Baumea articulata, Baumea rubiginosa, Baumea preissii, Carex appressa, Juncus kraussii, Schoenoplectus validus* and *Typha domingensis.* Three sites were studied for nutrient content (TKN and TP) in above ground (shoot and leaves) and below ground (root and rhizosphere) biomass (Figure 42). Physico-chemical and nutrient content were studied for the four dominant macrophyte species: *B. articulata, B. rubiginosa, B. preissii and S. validus.*

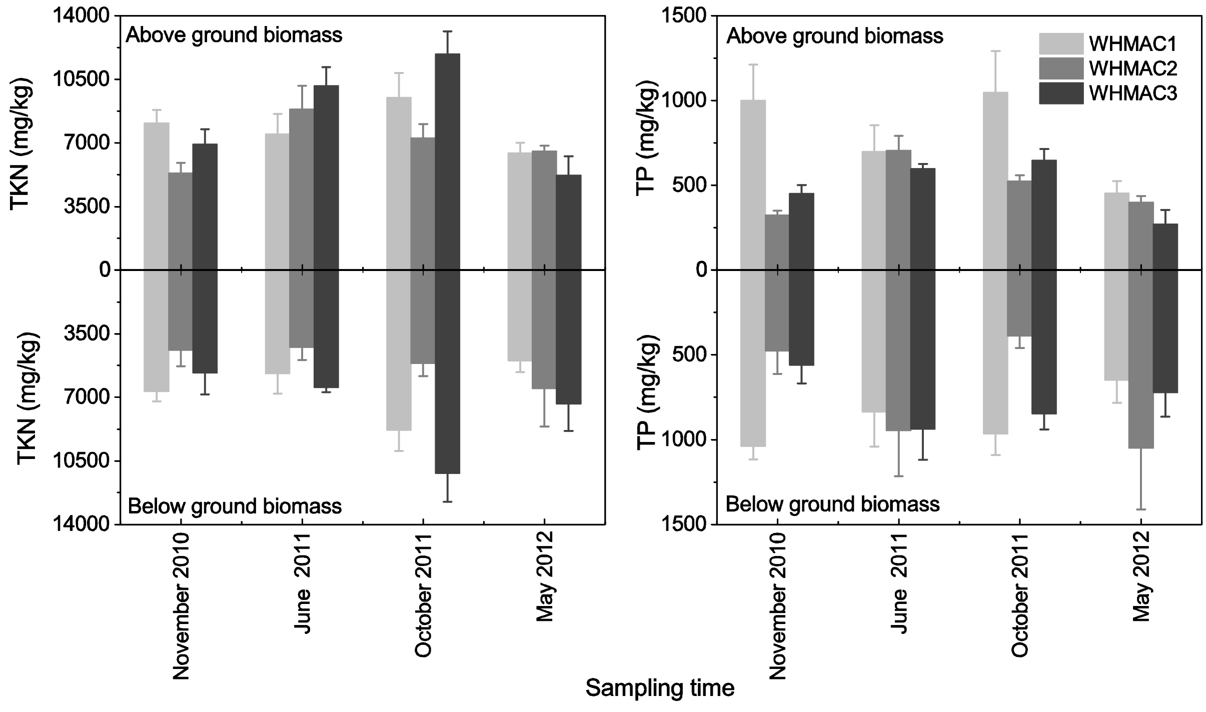


Figure 42. Spatial and temporal variability in nutrient concentration in macrophytes at Wharf Street Constructed Wetland. TKN in above ground biomass (left-top), TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

TKN concentration in above and below ground biomass increased for the first two years of sampling. This period represented the growth stage of macrophytes and hence uptake of the maximum concentration of nutrients. After that time the mature macrophytes may have reached the maximum nutrients storage. Site 2 (WHMAC2) represented relatively less TKN concentration than the other two sites. Macrophytes at WHMAC1 usually uptake and filter nutrients after initial contact with stormwater. WHMAC3 is the location where wetland water from the subsurface components mixes with inflows from the Bebington Court drain. Therefore macrophytes at this location may be exposed to higher concentrations of TKN. A similar pattern of TP storage occurred in the above and below ground biomass. Data from May 2012 suggests that the new macrophytes, in their early life stage, contained low concentrations of TKN and TP.

Figure 43 illustrates the proportion of TKN and TP in above and below ground biomass. The proportion of TN in above and below ground biomass is relatively similar at site 1 (WHMAC1). However there are some changes in WHMAC2 in February 2011, where above ground biomass contained almost double the proportion of below ground biomass. At WHMAC3, above ground biomass contained a higher proportion of TKN than below ground biomass. TP proportion was higher in below ground biomass. The maximum proportion was found in March 2012 in WHMAC2 and WHMAC3. WHMAC3 represents a relatively small area. Overall, no clear trend of nutrients in above and below ground biomass was observed. Senescence might influence the overall nutrient content in the biomass.

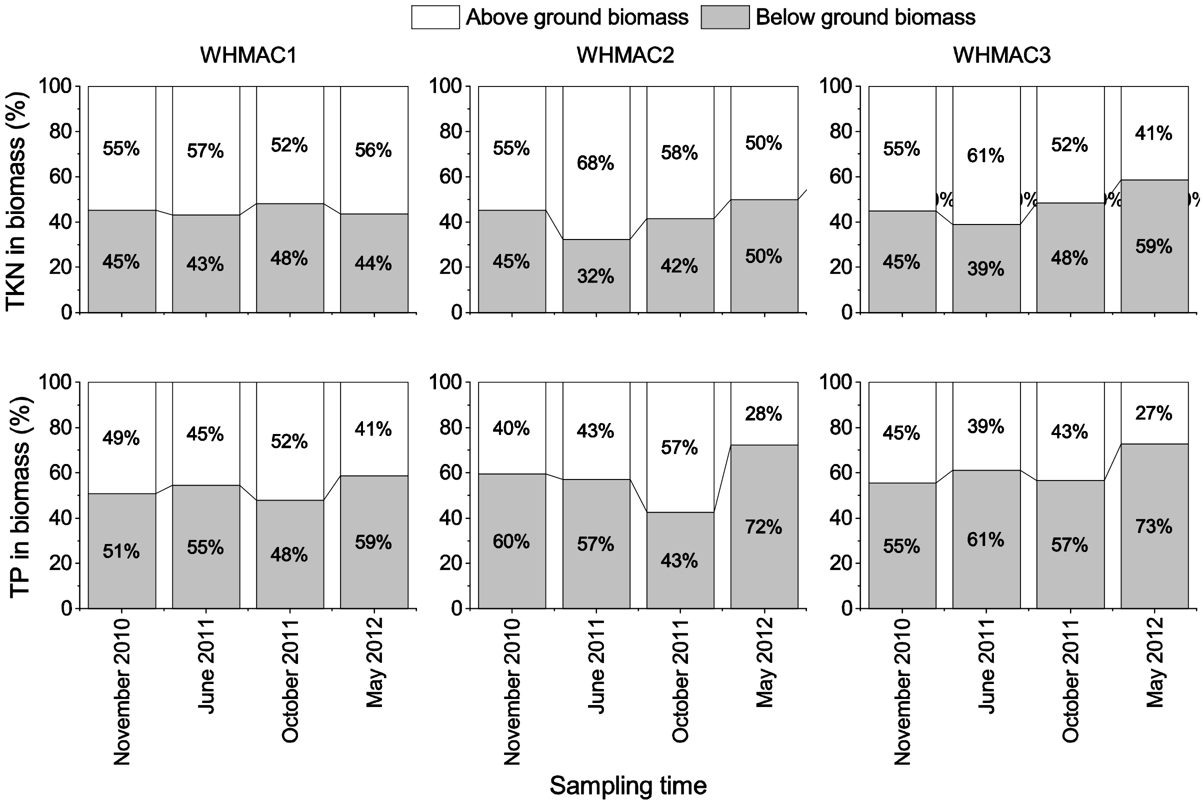


Figure 43. Proportion of nutrients in above and below ground biomass of macrophytes of Wharf Street Constructed Wetland.

The total macrophyte dry weight biomass per unit area was estimated by assuming that each of the sampling sites was representative of a specified area of wetland, such that:

Biomass (kg/ m^2) = DW (g)/(quadrat area as 0.0625 m^2 X 1000)

The mass of nitrogen and phosphorus contained in the vegetation was then estimated by again assuming that each of the sampling sites was representative of a specified area of wetland, such that:

Tissue-Nutrient as TKN or TP (g/ m^2) = Tissue-TKN or TP (mg/kg) x DW (g) /(quadrat area as 0.0625 m^2 X 1000)

B. articulata samples were collected from site 1 and 3 on four sampling occasions (November 2010, June 2012, October 2011 and May 2012), but only in November 2010 for site 2 (Figure 44). *B. articulata* is a truly aquatic species and rhizomatous herb that can grow in standing water up to 1m deep, in wet black waterlogged sand. With slow initial development and productivity, the sedge will eventually form tall (up to 2m) dense stands exhibiting little seasonal dieback. This species is dominant throughout the WSCW. Above ground biomass contained relatively higher concentration of TKN. On the other hand below ground biomass contained more TP concentration. TN content increased at WHMAC1 from November 2010 to October 2011, and then slightly decreased in May 2012 in both above and below ground biomass. Above and below ground TP increased during the first two sampling periods, then slightly decreased. This species contained two to three times higher biomass per unit area below ground than above ground (Figure 45). At the same time, below ground biomass contained more TP and TKN per unit area. WHMAC3 and WHMAC1 contained the larger amount of nutrients in above and below ground biomass, respectively. Site WHMAC1 experiences the initial contact with water allowing particulate material to settle and possible allowing macrophytes to uptake nutrient from the sediment. At WHMAC3, the water passing through is higher in dissolved nutrients and the emergent and shoot areas could directly assimilate nutrients.

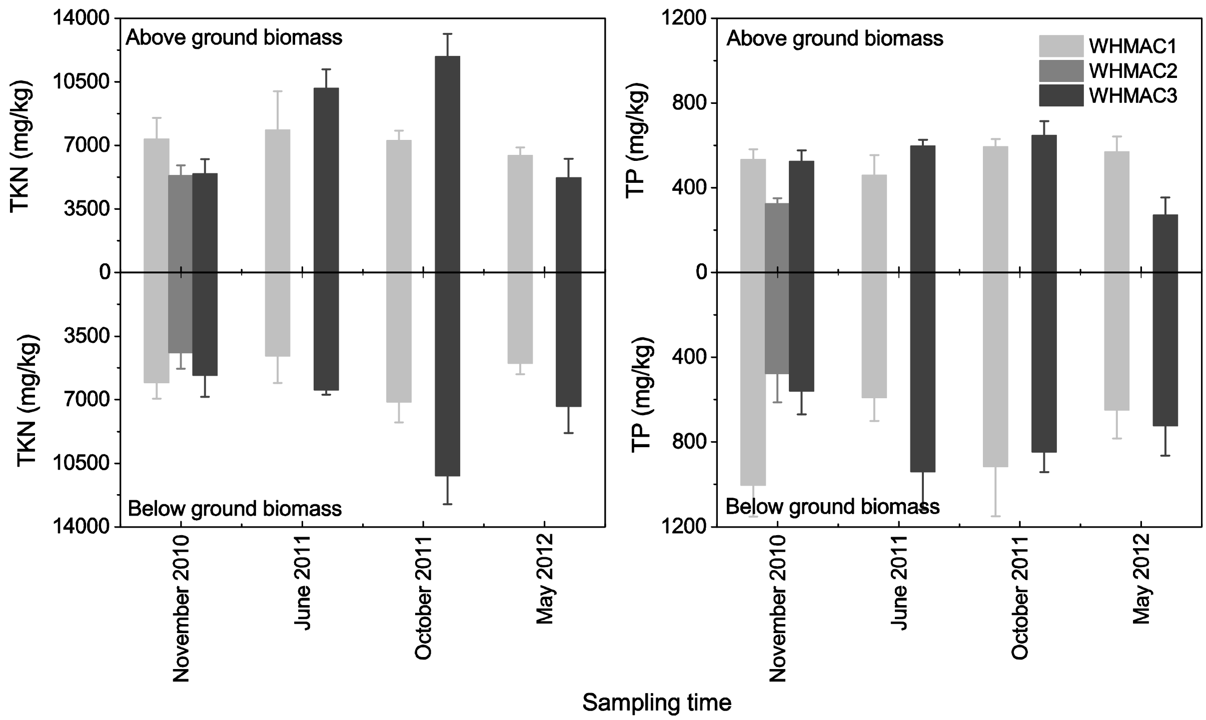


Figure 44. Spatial and temporal variability of nutrient concentration in *Baumea articulata* at Wharf Street Constructed Wetland. TKN in above ground biomass (left-top), TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

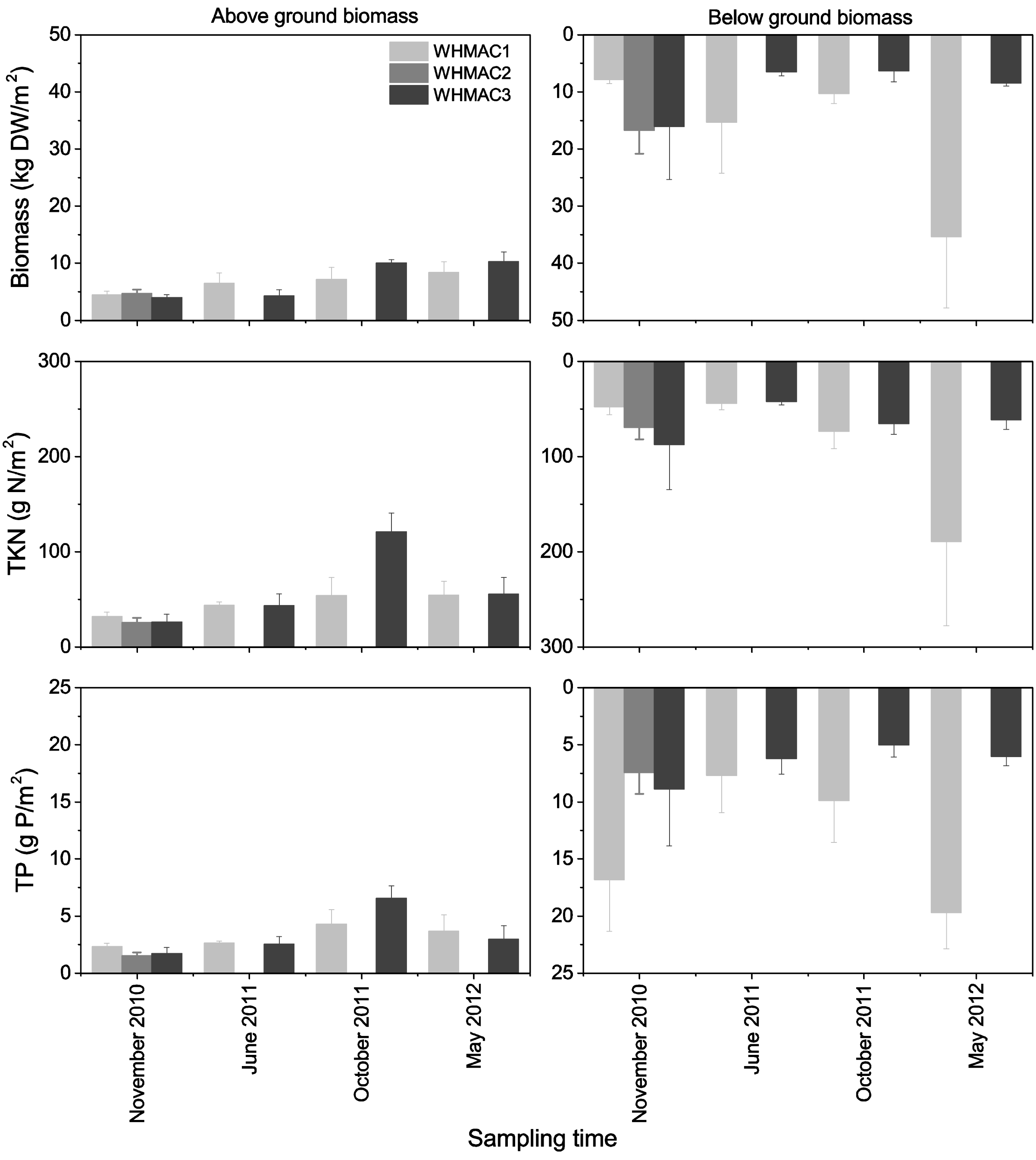


Figure 45. Spatial and temporal variability of biomass and nutrient at per unit area of *Baumea articulata* at Wharf Street Constructed Wetland. Left and right panels represent above ground and below biomass, respectively, TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

B. preissii is a rhizomatous, robust, colonising perennial, grass-like or herb (sedge). It is well distributed in Western Australia and can grow 0.2-2 m high in silty sand, waterlogged soils, swamps, bordering lakes and watercourses. This species was only sampled at WHMAC2 in June and October 2011 (Figure 46 and Figure 47). The above ground biomass contained a slightly higher concentration of TKN than the below ground biomass. Below ground biomass contained greater TKN and TP content per unit area during the first sampling period (June 2011). In October 2011, the above ground biomass contained higher nutrient content than the below ground biomass.

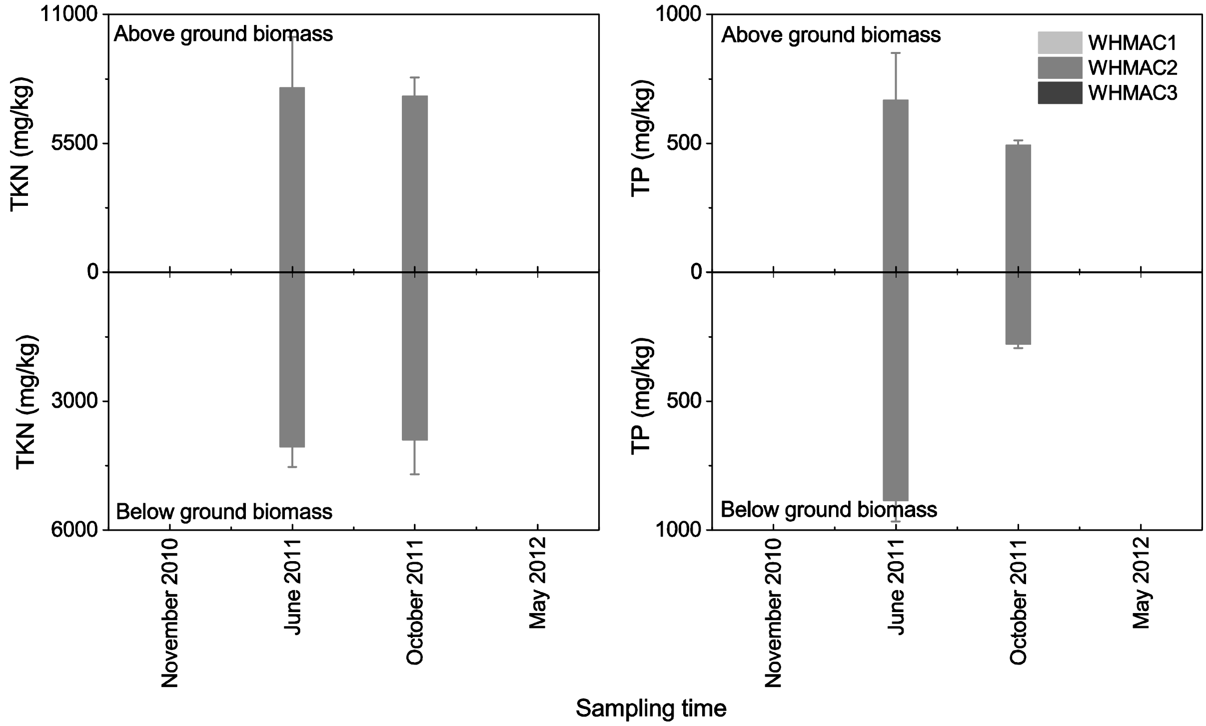


Figure 46. Spatial and temporal variability of nutrient concentration in *Baumea preissii* at the Wharf Street Constructed Wetland. TKN in above ground biomass (left-top), TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

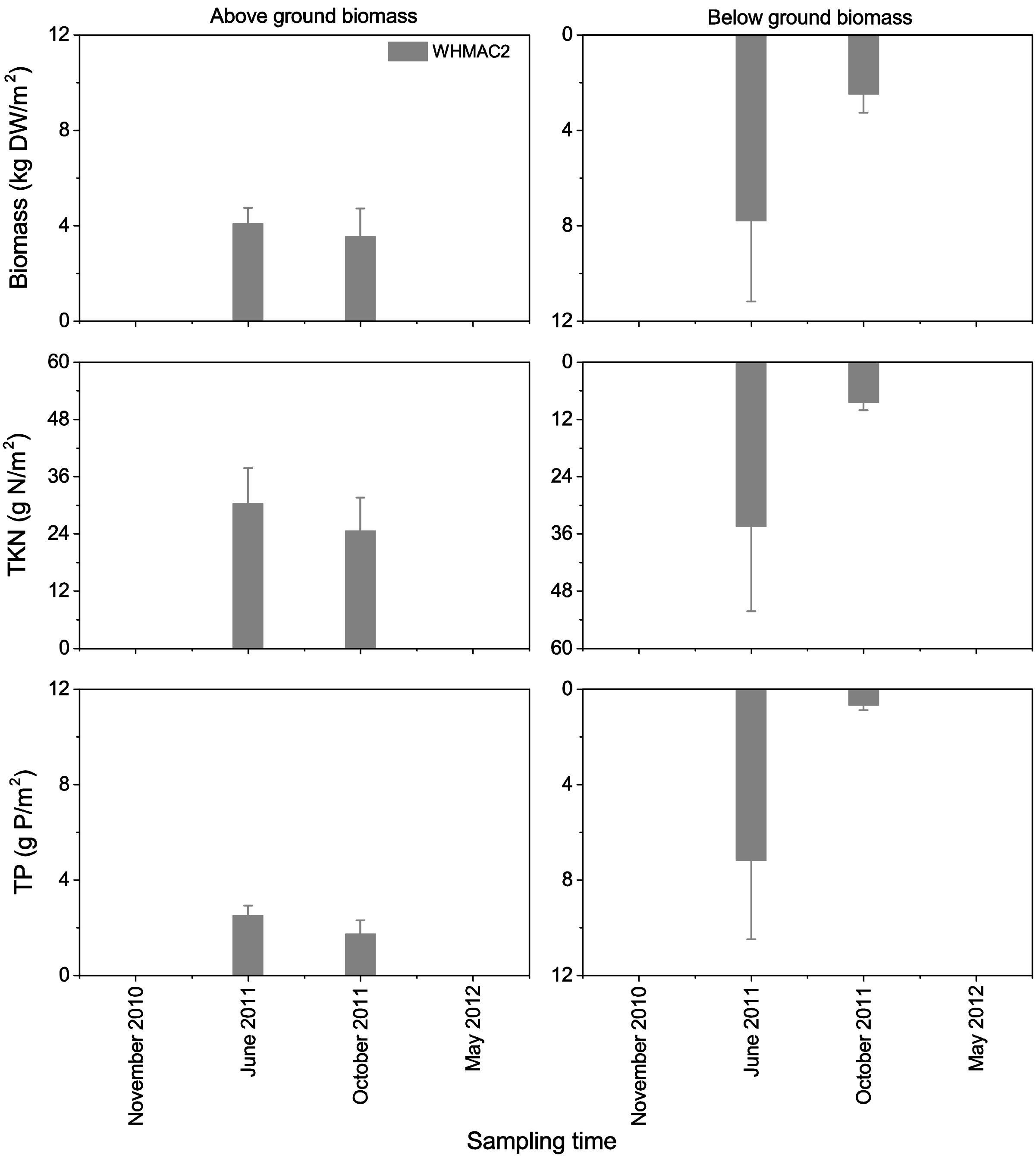


Figure 47. Spatial and temporal variability of biomass and nutrients per unit area of *Baumea preissii* at Wharf Street Constructed Wetland. Left and right panels represent above ground and below biomass, respectively, TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

B. rubiginosa is a rhizomatous macrophyte that forms dense swards of foliage. It is an ideal macrophyte for constructed wetlands as a transition plant between high and low water. It can tolerate periods of inundation, low-nutrient soils, poor water quality and can grow from 700 mm to 1 m. This species was sampled and analysed at only WHMAC2 (Figure 48 and Figure 49). The above ground biomass contained a greater nutrient content than the below ground. But below ground biomass contained a higher mass of TKN and TP per unit area than that of the above ground biomass. Below ground biomass contained up to 89 and 14 g TKN and TP, respectively.

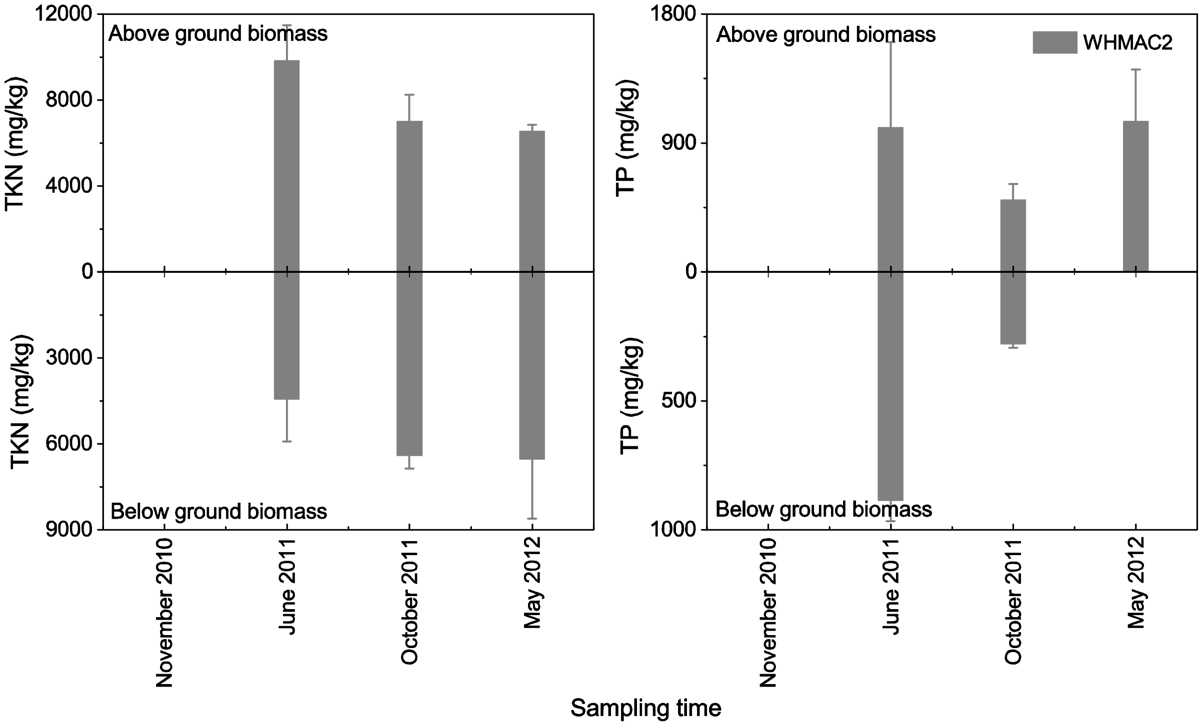


Figure 48. Spatial and temporal variability of nutrient concentration in *Baumea rubiginosa* at Wharf Street Constructed Wetland. TKN in above ground biomass (left-top), TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

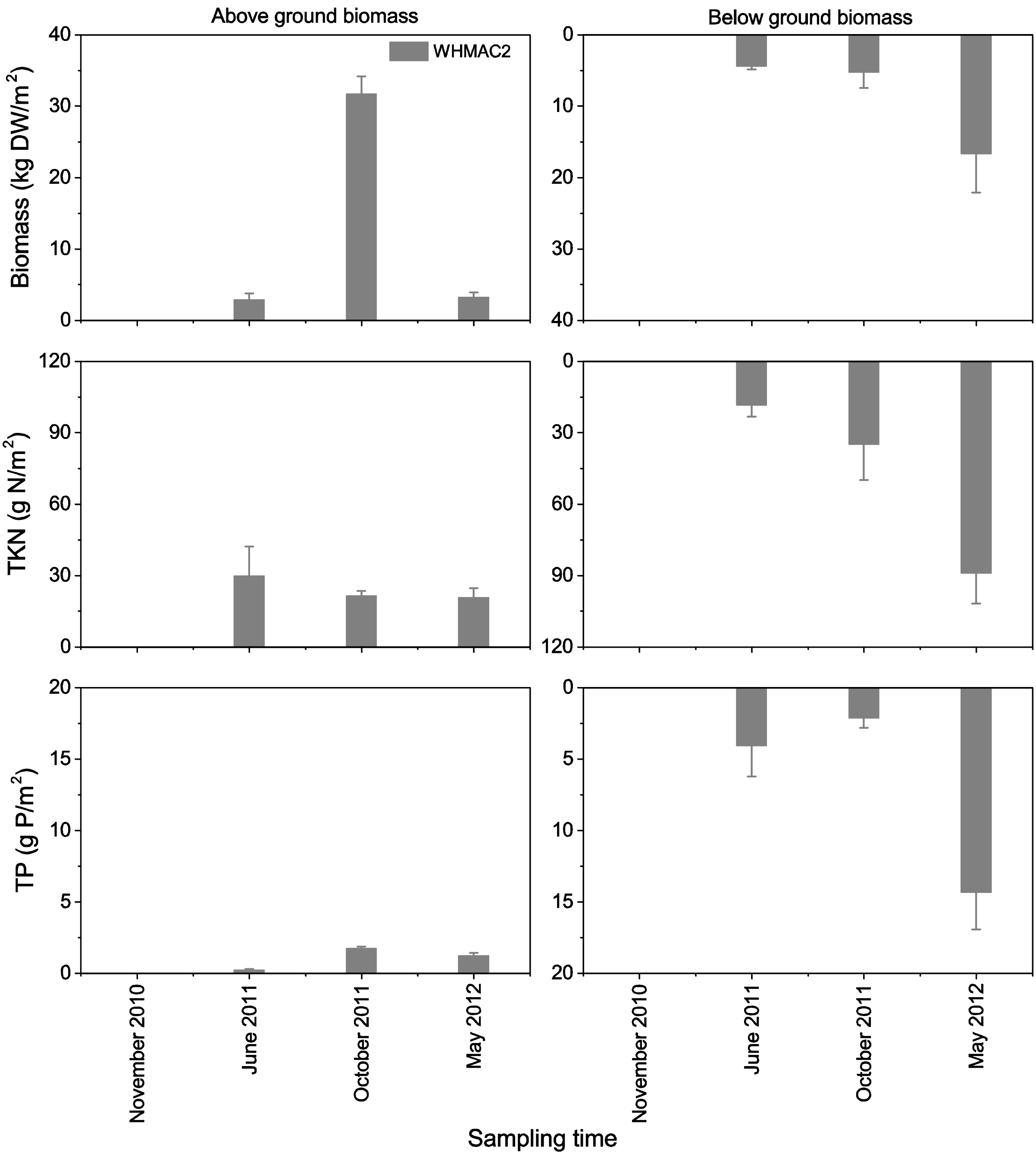


Figure 49. Spatial and temporal variability of biomass and nutrients at per unit of *Baumea rubiginosa* at Wharf Street Constructed Wetland. Left and right panel represent above ground and below biomass, respectively, TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

S. validus (lake or river club-rush) is a tall rhizomatous, robust perennial, grass-like or herb (sedge) that can grow 0.8-2 m high. It is a native species to Western Australia and spreads to colonize water edges in wetlands. *S. validus* is widely distributed in populations at WHMAC2, but only sampled at WHMAC1. This species shows good establishment and growth in constructed wetlands. Concentrations of TKN and TP in above ground biomass ranged from 7,166 to 11,733 mg/kg and 936 to 1,500 mg/kg, respectively (Figure 50). However, TKN and TP per unit area were higher in the below ground biomass than the above ground biomass. Above ground biomass contained up to 30 and 5 g TKN and TP per unit area, respectively (Figure 51), while the same samples in the below ground biomass contained around 32 and 18 g of TKN and TP per unit area, respectively.

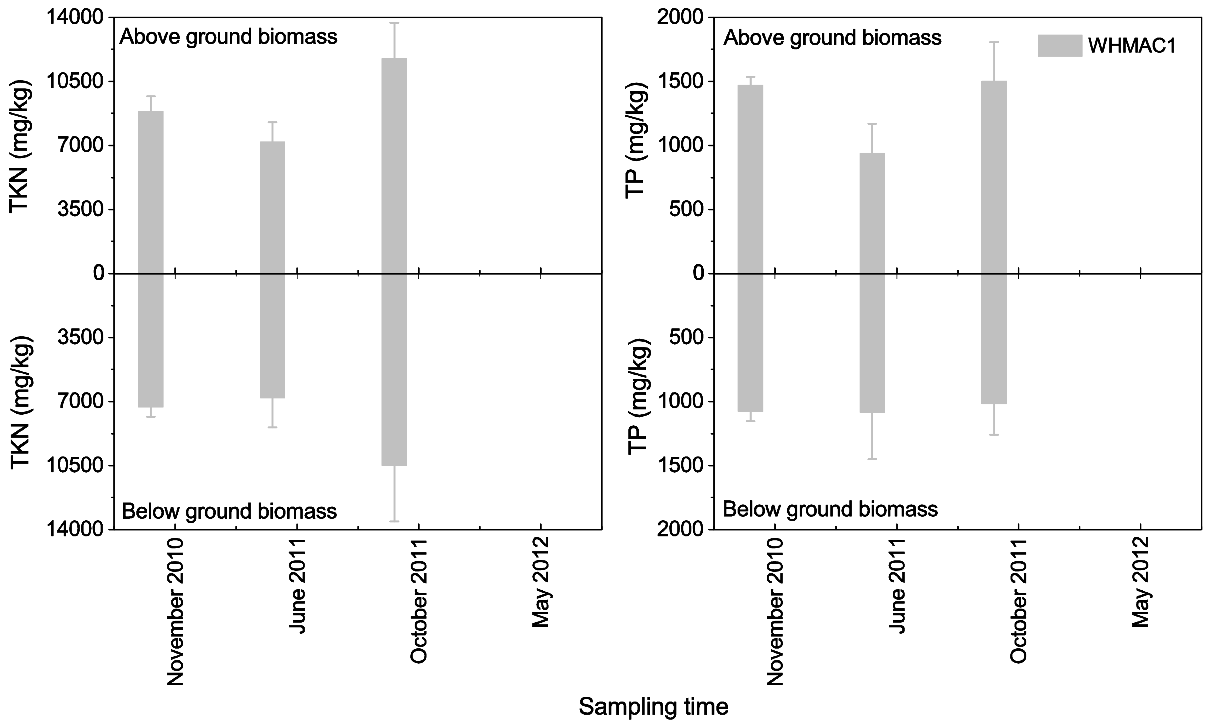


Figure 50. Spatial and temporal variability of nutrient concentration in *Schoenoplectus validus* at Wharf Street Constructed Wetland. TKN in above ground biomass (left-top), TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

Different hypothetical scenarios were considered to estimate the total nutrient pool stored in the aquatic macrophytes of the WSCW. This included multiplying the nutrient content per area for each species by the total area of a particular site. *B. articulata* was sampled and analysed at all sites at different time scales. If the wetland was 100% dominated by this species then the above and below ground vegetation TKN pool would be 277 and 398 kg, respectively. At the same time, the TP pool in the above and below ground biomass would be 17 and 51 kg, respectively. Overall, the total nutrient pool in this species would be 674 kg TKN and 68 kg TP.

If the wetland was 100% dominated by *B. preissii*, then the total vegetation nutrient pool would be around 257 kg TKN and 31 kg TP. If the WSCW was fully dominated by *B. rubiginosa*, then the total macrophyte TP nutrient pool would be approximately 375 kg TKN and 41 kg. If *S. validus,* also a common macrophyte species at the wetland, was 100% dominant, then the nutrient pool would be 659 kg TKN and 84 kg TP.

Overall, *B. articulata* and *S. validus* have the greatest capacity to store nutrients. Sites 1 to 3 were not fully covered by macrophytes, with exposed water being more prominent. The main outlet also contains different macrophyte species. The subsurface zones were planted with *Carex appressa* however no samples were collected of this species. Other grass, tree and shrub species were also planted at the wetland to provide aesthetic views.

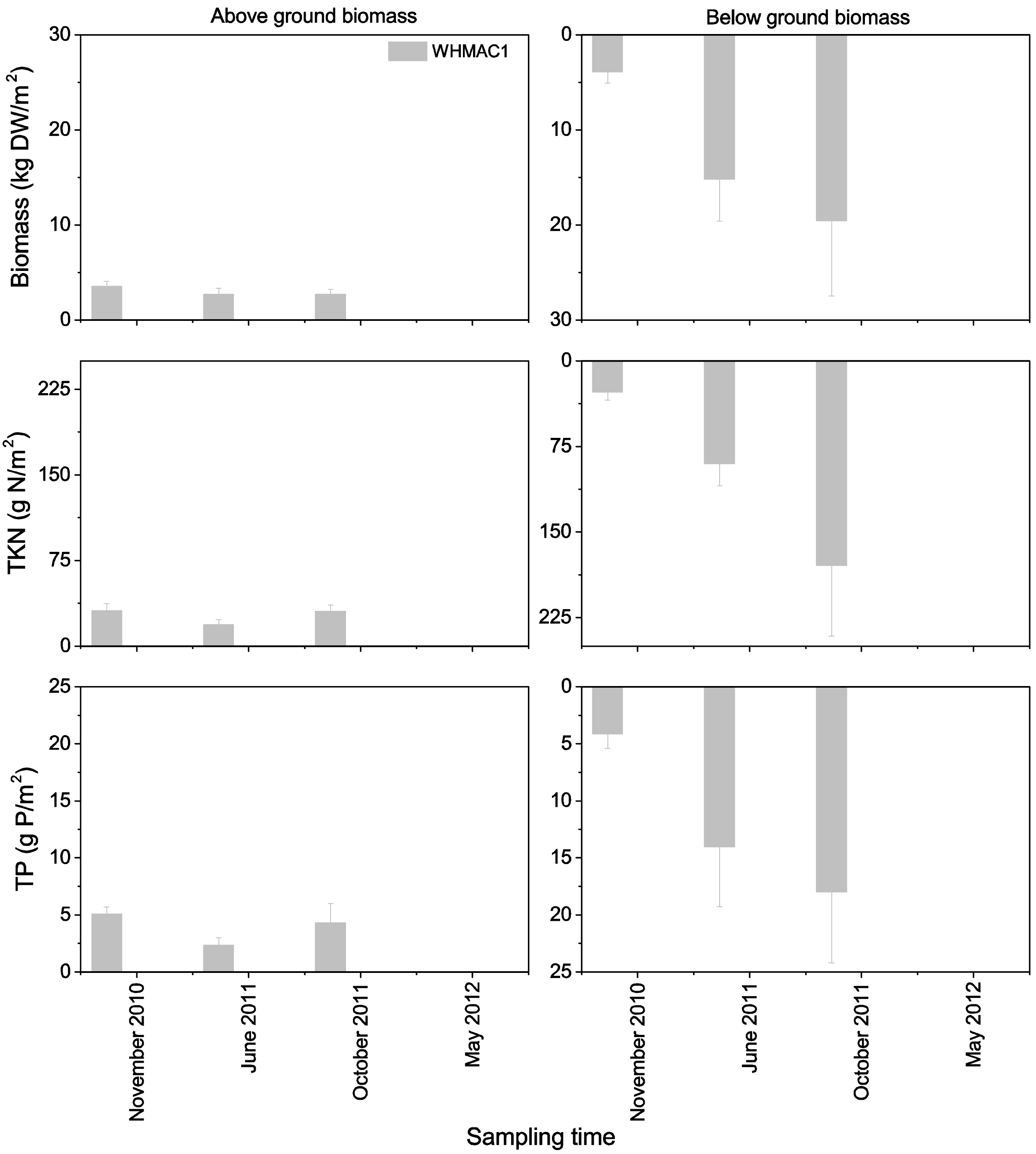


Figure 51. Spatial and temporal variability of biomass and nutrients per unit area of *Schoenoplectus validus* at Wharf Street Constructed Wetland. Left and right panel represent above ground and below biomass, respectively, TKN in below ground biomass (left-bottom), TP in above ground biomass (right-top) and TP in below ground biomass (right-below). The bar represents the standard error of the data set.

Conclusions and recommendations

This report reviewed and assessed the performance of the Wharf Street Constructed Wetland over the period 2009-2014. The analysis of hydrological, water and sediment quality and macrophyte attributes has aimed to develop a better understanding of the system's ability to effectively treat stormwater. The quality of the analysis of the wetland performance is dependent on the quality and consistency of the monitoring. The analysis of the data allowed us to provide answers to several of the key questions contained in the aims and scope of work. The previous chapters described the data analysis, and the main outcomes and recommendations of these analyses are presented below.

Water balance and hydrological dynamics

The following concluding remarks arise from the hydrological analysis:

- The wetland is subject to complex hydrological system dynamics involving multiple water entries that activate, on exceedance of thresholds, surface wetland storage, subsurface media storage, and alter water input characteristics. Main factors that must be taken into account are: a) the frequency and duration of rainfall events, b) antecedent catchment conditions (wet/dry), c) the rainfall amount and d) the magnitude and duration of the pumping cycles (water recirculation scheme).
- There is a general tendency for the wetland to display large water losses during: a) isolated rainfall events (small or large) under dry antecedent conditions, and b) pumping cycles between spring and autumn.
- There are large volumetric contributions from ungauged areas during: a) periods of frequent rainfall events that occur during winter-spring and b) large rainfall events that activate runoff from the Bebington Court drain catchment.
- Significant changes in water balance were observed from October to December 2013 likely due to the extreme dry spell experienced by the Perth Metropolitan Area (longest dry spell on record).
- Any estimates of nutrient balances and nutrient attenuation efficiencies of the system must consider the important (and complex) changes in water mass that occur within the wetland area over time.

Water, sediment and macrophyte analyses

The analysis has indicated how nutrient and metal concentrations have changed over time, and the typical reductions in concentrations that could be expected in future. Attempts to quantify the sediment and vegetation stores were made. The original questions raised at the beginning of the report are repeated here, clustered under similar topics, with our responses arising from analysis of the existing data.

Q. Is the wetland meeting HRAP targets (TN <1mg/L, and TP <0.1mg/L)?

Q. Is the wetland meeting ANZECC WQ targets (95% protection)?

Q. What are the differences in nutrient levels and speciation between the inlets and outlet?

Q. What about partitioning i.e., organic vs inorganic of nutrients in water column?

Pollutant concentrations in the different components of SF and SSF wetlands were compared with Healthy Rivers targets and ANZECC guidelines. Compliance to the guidelines was found to be variable and different for each nutrient species assessed. Almost half of the water samples contained an NH_3 concentration above the prescribed ANZECC guideline. At the main outlet, all water samples except two were within the ANZECC guideline for NH_3. DON was noted to be a very stable fraction of N with limited reduction across the wetland. TN complied with the guidelines on most sampling occasions. There were some occasions where NOx and TN concentrations at the main outlet increased above the ANZECC guideline. Bebington Court drain appeared to be the main reason for the sudden increase in nutrient concentrations. FRP and TP complied with the guidelines on most sampling occasions. Average outlet concentration of TN and TP during baseflow was 0.81 and 0.04 mg/L, respectively. During storm events average outlet concentrations of TN and TP were 0.86 and 0.06 mg/L, respectively. These concentrations were within Healthy Rivers targets and ANZECC guideline. The inorganic fraction of N species showed reductions at the outlet, but DON concentrations increased at the outlet. DON may be released from dead plant material, sediment fluxes etc.

The wetland attenuated TN and met the Healthy Rivers long-term goals and ANZECC guidelines approximately 85 and 90% of the time, respectively. TP attenuation met the Healthy Rivers long-term goals and ANZECC guidelines approximately 95 and 88.33% of the time, respectively.

Metal content was compared with the 80 and 95% protection limits for freshwater ecosystems. Levels of As, Cr and Pb were within the guidelines. There were some episodic increases of Al, Cu and Zn above the guidelines. At the main outlet, Fe content was above 0.3 mg/L on most of the sampling occasions. The Bebington Court drain was the major contributor of these metals. It is possible that metals could be released from the wetland sediments. This potential release can be quantified through sediment incubation experiments.

Q. What is the wetland treatment efficiency for a range of different parameters (nutrients, suspended sediment, metals, etc) under different hydrological conditions (baseflow and various storm events)?

Q. How does the efficiency differ between N and P?

Q. Is the efficiency related to the hydrologic residence time of the systems?

Q. Does N: P stoichiometry differ in hydrologic condition?

An approximation of pollutant removal efficiency during baseflow conditions was conducted by calculating the standardised difference in pollutant concentration between the inlet and outlet of each component of the wetland. This analysis was able to provide a relative estimation of wetland efficiency and highlighted the importance of the impact of ungauged sources. It also highlighted the effect of seasonality in the removal capacity. The SDC was also computed for soluble metals. EMC and load were calculated for TN, TP and TSS during six storm events considering nutrient concentrations, inflows and outflows.

The wetland reduced nutrient concentrations more effectively during summer periods. SSF 1 was more effective than SSF 2 at attenuating NH_3 and TKN, but SSF 2 was more effective for NOx and TN attenuation. Overall, when considering only the main inlet and outlet data, the average NH_3 and TN attenuation was around 62 and 35%, respectively. Although SSF components were effective at attenuating DON, SF compartments released DON. Both SF components were effective at attenuating FRP. The average FRP and TP attenuation by SF 1 was 61% and 60%, respectively. SSF 1 and SSF 2 were very effective at attenuating FRP and TP. The TP average SDC at SSF 1 and SSF 2 was 73% and 57%, respectively (considering both positive and negative SDC). However the two sites have the capacity to attenuate up to 95% and 96% TP, respectively. Overall, during the summer period, the system attenuated about 11.5 and 65% of TN and TP, respectively,

During event sampling, high resolution TN, TP and TSS data were collected along with flow measurements. TN attenuation (based on load reduction) ranged from 29 to 68%. However TP and TSS attenuation ranged from 55 to 93%, and -75 to 87%, respectively. Over the six events that were sampled, half the time the system attenuated TSS and half the time it enhanced TSS. All sampling events showed positive attenuation for TN and TP. Average TN and TP load reduction during six storm events was 41% and 66%, respectively.

WSCW was more effective in attenuating P than N. Moreover laterite based SSF components were effective in attenuating P. Both N and P species were attenuated more in summer periods than winter periods (considering base flow conditions). TN and TP load reduction during baseflow (flow rate less than or equal to 0.005 m^3/s) from 2010 to 2014 ranged from -1-55% and 10-99%, respectively. However the figures were 54-79 and 27- 68%, respectively for high flow rates (0.005 m^3/s). In summary, over the 5 years, of 2,526 kg TN input to the wetland, 1,658 kg was retained (65% efficiency); of the 286 kg TP input to the system 129 kg was retained (45% efficiency). When the water travel times were longer, a higher attenuation occurred.

Q How effective is sediment and vegetation at removing nutrients and other pollutants?

There are no guideline values for nutrient concentrations in sediment but levels of TN and TOC increased from June 2009 to May 2014. In May 2012, the maximum TP and TOC levels were found in sediment. All nutrient levels were higher at WHSED1, the site located within SF 1. TN in WHSED1, WHSED2 and WHSED3 varied from 780 to 1,190 mg/kg, 510 to 1,230 mg/kg and 390 to 780 mg/kg, respectively. TP concentrations in the sediment varied from 140 to 720 mg/kg, 100 to 370 mg/kg and 90 to 610 mg/kg at site WHSED1, WHSED2 and WHSED3, respectively. The sediments of the WSCW were found to be rich in TOC, with concentrations varying from 10,600 to 41,000 mg/kg, 4,800 to 31,000 mg/kg and 3,350 to 22,000 mg/kg at site WHSED1, WHSED2 and WHSED3, respectively. The total mass of sediment nutrients was estimated by assuming that the sediment nutrient concentration at each site was representative of specific areas of inundation. Interestingly TP mass was highest during the first sampling period (June 2010), after which the TP mass remained relatively stable over the following two years. From 2014, TP then showed an increasing trend.

Sediment was rich in Al, Fe and Zn. Similar to nutrient trends, the highest metal content was found in the sediment was during May 2012. The Zn level at WHSED1 in May of 2012, 2013 and 2014, exceeded the ISQG-low trigger value. Additionally Zn in May 2012 also exceeded the ISQG-high trigger value, but afterwards, the Zn levels reduced. There was only one occasion (9 May 2012) when Pb exceeded the ISQG-low trigger value guideline at WHSED1.

S. validus and *B. articulata* were the dominant species storing TN and TP. Nutrient content per unit area was significantly greater in these two species than other species. If a larger area was planted with a combination of these species, the system would result in more effective attenuation of nutrients. *B. articulata* showed a seasonal trend in nutrient storage per unit area. The above ground biomass and nutrient storage of *B. articulata* per unit area increased for three sampling events but then declined. The maximum amount of nutrients found in the below ground biomass during fourth sampling occasion (May 2012). It appeared that during the early stage of growth macrophytes absorbed more nutrients from the sediment and stormwater. Later, during senescence, some of the nutrient pool is released back into the water and sediment. The nutrient storage in the above and below ground biomass of *S. validus* declined in the second sampling period, but then sharply increased in the third sampling period.

Hypothetical scenarios were developed to assess the total nutrient pool in the macrophytes. If the wetland was covered by 100% *B. articulata*, then the total nutrient pool would be 674 kg TKN and 68 kg TP. *S. validus* is a common macrophyte of the WSCW and if this species was 100% dominant, then the nutrient pool would be 659 kg TKN and 84 kg TP. The SSF components consisted of scattered macrophyte species, and hence no estimate of the nutrient pool in those species was undertaken. The hypothetical vegetation TKN was less than sediment TN pool. TN content was an order of magnitude higher in sediments than in the macrophyte biomass. But interestingly, the hypothetical TP pool in the macrophytes was close to the sediment TP pool. The TOC pool in the sediment also increased over time.

Q. What is the net assimilation rate of N and P per unit area of wetland?

Q. What is the cost per kg of N and P removal?

This requires a full cost-benefit analysis across the wetland life-cycle that could not be completed on the available data. This is recommended for future work.

Q. How effective are the specific features and components within the design at collecting nutrients and pollutants?

The RCM in the SSF components was replaced with laterite aggregates in 2012. After that a continuous flow regime was established in the wetland. Laterite-based SSF components were effective at removing dissolved nutrients whereas SF components sometimes released nutrients, particularly DON.

Q. Does ephemerality of the wetlands affect nutrient uptake/release?

Q. What are the dominant N and P reduction processes in the wetland?

With the existing data, this question was unable to be answered.

Q. Does the wetland improve waterway ecological integrity?

Stormwater treatment wetlands can be important habitats for particular waterbirds. Visually the WSCW and surrounding civic parkland provide an aesthetic view and amenity for the community. The wetland integrates into the adjacent Canning River Regional Park, providing additional ecological corridors.

Recommendations

Based on the synthesis of the available data, the following recommendations are made. We have indicated where these recommendations are being tackled as part of on-going CRC WSC projects. Note that these recommendations are not in order of priority.

- Improve the inlet flow gauging accuracy.
- Improve estimation of the currently ungauged flows into the system, including from the Bebington Court drain and the pumped groundwater being input to maintain water in the system.
- Analyse the groundwater being input to maintain water in the system, for nutrients and metals.
- Extend the monitoring of sediment nutrients and metals at the site close to main outlet.
- Determine the metal accumulation in macrophytes to gain knowledge of efficiency of vegetation uptake metals.
- Monitor soil nutrients to determine if macrophyte nutrients are being transferred to the underlying soils. This task is expected to be covered by Project B2.4 Tranche 2 at Anvil Way Constructed Wetland. These results should be transferrable to WSCW.
- Vegetation species mapping should be undertaken at the time of vegetation tissue sampling.
- Understand the potential for hypoxia/anoxia to accelerate the release of nutrients (both organic and inorganic) and metals from the sediment and macrophytes (Project C4.1).
- Investigate the removal of senescent macrophytes periodically (at least before winter) from the wetland as these may be a source of organic carbon and nutrients to the system.
- Undertake a life-cycle cost benefit analysis for the wetland.

The understanding and quantification of the nutrient removal processes during different hydro-meteorological conditions is necessary. Sediment saturation can trigger intense biogeochemical processing and impact the effectiveness of riparian nutrient attenuation. Moreover the laterite SSF components provide effective adsorption sites for nutrient. This zone can also be a good chamber for biofilm growth which can influence nutrient reduction. Examination of these zones can provide insights of wetland function and contribute to explaining aspects of the variability described above.

Comparison of nutrient species and concentrations within the surface water and soil pore water can also be useful to inform future nutrient attenuation model setup for wetland design optimization. The dynamics of dissolved nutrients showed the impact of variable aerobic and anaerobic conditions. An indicator or proxy such as wetland metabolism may serve as a simple indicator of wetland function. A linkage is needed however to establish between nutrient attenuation and DO changes, hydraulic residence time during base flow, /seasonal flow, sediment saturation. It is expected that these issues will be answered through CRC Project C4.1. Nutrient release from the sediments to the water column needs investigation as occasionally the SF component acts as a source of nutrients. The overall contribution of macrophytes to nutrient uptake is potentially significant and should be further investigated.

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Appendix A

Sites and locations of monitoring stations

Table A 1. Station sites available for water balance assessment.

Site code	AWRC Code		Easting	Northing
WDRAIN	616137	Main inlet	398938	6457015
WT1	6164300	Inflow	398836	6456996
WHL3	616131	Lake 3 overflow	398873	6457025
H1	616135	Main inflow	398611	6456850

Table A 2. Surface water sampling sites and locations

Site code	Short description	WIN Site ID	Easting	Northing
WDRAIN	Main inlet	23035117	398936	6457013
WHBC	Bebington Court drain inlet	23035118	398661	6456904
WHBCLUB	Bowling club outlet	23032976	398818	6456994
WT1	End of surface flow vegetated wetland 1	23035122	398836	6456996
WHL3	Lake 3 overflow		398873	6457025
WHW1	Open pond 2 and end of SF wetland	23035119	398835	6456923
WT2	SSF 1 inlet sump	23035123	398822	6456916
WT3	SSF 1 outlet sump	23035124	398768	6456880
WHW2	Open pond 3	23035120	398713	6456898
WT4	SSF 2 inlet sump	23035125	398710	6456903
WT5	SSF 2 outlet sump	23035126	398659	6456864
WHW3	Main outlet	23035121	398611	6456850

Table A 3. Sediment sampling locations

Site code	WIN Site ID	Easting	Northing	Description
WHSED1	23042135	398920	6457010	Open Pond 1
WHSED2	23042136	398835	6456923	Open Pond 2
WHSED3	23042137	398713	6456898	Open Pond 3

Table A 4. Vegetation sampling locations

Site Code	WIN Site ID	Easting	Northing	Description
WHMAC1	23046430	398920	6457010	Open Pond 1
WHMAC2	23046431	398835	6456923	Open Pond 2
WHMAC3	23046432	398713	6456898	Open Pond 3

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