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# Performance assessment of the Anvil Way Compensation Basin living stream: 2004 – 2013

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**Performance assessment of the Anvil Way Compensation Basin living stream: 2004-2013**
*Integrated multi-functional urban water systems* (C4.1)
*Hydrology and nutrient transport processes in groundwater/surface water systems* (B2.4)
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# Executive summary

This report summarises the results of a performance assessment of the Anvil Way Compensation Basin (AWCB) restoration project. AWCB is an artificial wetland on the Swan Coastal Plain of Western Australia with an area of 9,000 $m^2$ and maximum volume of 11,400 $m^3$. It was constructed to improve the quality of urban and industrial stormwater runoff and reduce nutrients and other contaminants entering the Canning River via the Mills Street Main Drain (MSMD), which has an overall catchment area of 12 $km^2$. AWCB sits relatively high in the Mills Street catchment and has a variable contributing area due to a network of upstream compensation basins in the upstream basins. The contributing area ranges from 1.8 $km^2$ (permanently connected sub-catchments) to 3.6 $km^2$ (when all the upstream compensation basins are connected to AWCB). The site was restored in November 2010 and reshaped with a meandering low flow path and associated vegetation. The system has been the subject of regular monitoring of hydrology, water quality and ecology for the past 10 years - pre and post implementation of the restoration efforts. Since the restoration, the wetland system has also been called a “living stream” and both names are used interchangeably in this report.

This report covers an analysis of all available historical data that has been collected over the past decade with an overarching aim of gaining insights into the overall effectiveness of the wetland in treating urban stormwater. In particular, the data analysis was undertaken to evaluate the changes that occurred after construction of the living stream. It attempts to give answers to a series of knowledge gaps related to the dynamics and performance of the urban wetland and recommends future monitoring and research activities.

The analysis includes three main components: a hydrological assessment, an analysis of the water (including surface and groundwater) and sediment quality, and an assessment of nutrient storage in macrophytes.

The hydrological assessment established a basic water balance for the wetland system and used data collected from June 2012 to December 2013, when high-resolution data was available, to assist in the interpretation of the water quality data. It was found that for the period after the reconstruction the water contribution from ungauged areas (drains and groundwater) was variable (13-80%) depending on the nature of the rainfall event and the initial state of the wetland. Transit times for the inflow into the wetland varied from 4.8 to 1.2 hrs for early flows (autumn) and wet winter conditions, respectively.

The analysis of water and sediment quality data identified temporal and spatial variability of pollutant levels across the wetland, with a focus on assessment of the compliance of outgoing nutrient and metal concentrations to HRAP and ANZECC guidelines. The results indicated that the concentrations of pollutants were generally reduced by the wetland, but not always sufficient to meet the long-term water quality targets, and in general, the levels of pollutants in the outflowing waters surpassed the target values (with some exceptions). Pollutant levels were also identified to be high in groundwater. Differences in nitrogen and phosphorus were observed, and while total nitrogen (TN) complied with the targets on most sampling occasions, the wetland failed to reduce total phosphorus (TP) concentrations below the target values.

Attempts were made to assess the efficiency of the wetland in removing nutrients and metals from the inflowing water. Several limitations were encountered in trying to quantify the efficiency due to the presence of ungauged inputs, and therefore an alternative method was adopted in this analysis for assessing wetland performance over time. Although this method was not able to provide an exact value of wetland efficiency in absolute terms, it was able to: a) provide a range of performance values for different compounds of interest, b) highlight the importance of the impact that ungauged sources have on the assessment, and c) demonstrate the relative differences in performance over time. The results highlighted the effect of seasonality on the overall capacity for pollutant reduction, in response to changes in retention time, and also potentially due to dilution during periods of high connectivity with the local groundwater. Due to the limitation of the data, it is difficult to assess if the reconstruction of the wetland in 2010 has been beneficial, however, TN and TP were both reduced significantly after this time. Additionally, the new system is still in transition and the conclusion is sensitive to whether estimates from Mars Street inlet are accounted for in the calculation, again highlighting the uncertainty generated due to ungauged sources.

The analysis also identified the important role sediments play in trapping nutrients. The sediments were a significantly greater store of nutrients than that stored in 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 also depending on the season. The assimilation of phosphorus into the sediment pool with time was less evident. The increase in total nitrogen in the sediment pool was greater than that seasonally lost by the vegetation, suggesting that the soils/sediments are assimilating nutrients from surface water or groundwater inputs.

Finally, this report discusses recommendations on future actions that should be taken in order to improve our understanding of the wetland's biogeochemical function and to cover those questions that were not able to be addressed in this analysis due to the restrictions of the historical data set.

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# Introduction

## Background

Constructed wetland systems are well-documented water sensitive urban design (WSUD) elements able to assimilate nutrients and other contaminants from stormwater (Carleton et al., 2000; 2001; Delectic et al., 2014). The performance of these systems for stormwater treatment is known to vary widely depending on the nature of the design, the hydrological regime they experience as well as soil conditions and vegetation characteristics. Therefore, while general design guidelines exist (e.g., Kadlec and Wallace, 2009; Melbourne Water, 2010), it remains unclear as to the expected performance of systems in any given context, and in particular, how to optimise them when used within the Swan Coastal Plain environment of Western Australia where sandy soils and high groundwater tables dominate hydrological and biogeochemical aspects of wetland function.

Over the past decade the Swan River Trust has invested substantial resources in constructed wetland systems on the Swan Coastal Plain (Perth, Australia) as part of the Swan-Canning Clean-up Program and the Healthy Rivers Action Plan (HRAP) to protect the water quality of the Swan-Canning estuary. The focus of this report is on the Anvil Way Compensation Basin (AWCB) restoration project, located on a tributary of the Canning River termed the Mills Street Main Drain. The system has been the subject of regular monitoring of hydrology, water and sediment quality and ecology for the past 10 years - pre and post implementation of the restoration project. To better understand the performance of the system and to gain insights more generally into Swan Coastal Plain wetland function, it is necessary to undertake a critical analysis of the historical data.

The work presented herein has been undertaken as part of two related research projects within the Cooperative Research Centre (CRC) for Water Sensitive Cities: 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 Water Sensitive Urban Design (WSUD) elements, across a range of urban environments, with a specific focus on systems impacted by groundwater – surface water interactions.

## Aims and scope of work

Following discussions between Peter Adkins (Swan River Trust), Matthew Hipsey (UWA) and Carolyn Oldham (UWA) in May 2014, it was agreed The University of Western Australia would undertake a detailed review and assessment of the past performance of the Anvil Way Project (AWP), as motivated by several specific questions outlined below. This work has been conducted to supplement existing Project C4.1 and B2.4 research activities and provide important contextual information for guiding the focus of ongoing research activities within these projects.

For the AWP the following specific questions were initially put forward by the Trust, to focus the data analysis effort:

a) Is the installation meeting HRAP targets (TN <1mg/L, and TP <0.1mg/L)?
b) 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)?
c) What are the differences in nutrient levels and speciation between the inlets and outlet?
d) Are the wetlands meeting ANZECC WQ targets (95% protection)?
e) How effective are sediment and vegetation at removing nutrients and other pollutants?
f) How effective are the specific features and components within the design at collecting nutrients and pollutants?
g) How does the efficiency differ between N and P?
h) Does N:P stoichiometry differ depending on the hydrologic condition?
i) What about partitioning (i.e., organic vs inorganic fractions) of nutrients in the water?
j) Is the efficiency related to the hydrologic residence time of the systems?
k) What are the dominant N and P reduction processes in the wetlands?

l) Does ephemerality of the wetlands affect nutrient uptake/release?
m) What is the net assimilation rate of N and P per unit area of wetland?
n) What is the cost per kg of N and P removal?
o) Does the wetland improve waterway ecological integrity?
p) Could the wetland be manipulated/managed differently to be more effective?

It was acknowledged in the May scoping meeting, that several of these questions are beyond the scope of the present analysis given limitations associated with the historically collected monitoring data. Where this is the case, recommendations for future monitoring and research that can be undertaken to more fully address the questions.

## Overview of the Anvil Way Compensation Basin restoration project

The Mills Street Main Drain (MSMD) runs through Welshpool and drains a 12 km² residential industrial catchment before discharging to the Canning River. MSMD was identified in the Swan-Canning Cleanup Program Action Plan (SRT, 1999) as a priority catchment for retrofitting due to high export rates of nutrients and contaminants (SRT, 2008). MSMD pollution inputs are known to be significant due to a high degree of urbanization, light industrial and commercial land uses, connectivity to shallow groundwater, and significant impervious surfaces including roofs, car parks, roads and high density traffic ways (SRT, 2008). The Anvil Way Basin was initially built as a drainage compensation basin with limited capacity to retain water and impact upon water quality. In 2003 a Drainage Improvement Framework for the MSMD catchment was prepared (SRT, 2003) that ultimately led to the restoration project being undertaken. Removal and treatment of approximately 1,400 m³ of potentially acidic sediment, which contained elevated levels of metals and hydrocarbons, occurred in November 2010, and the basin form was then realigned to create a meandering flow path or “living stream” for low flows, and associated revegetation efforts were undertaken. The 9,000 $m^2$ re-constructed AWCB drains between 1.8 and 3.6 $km^2$ of the Mills Street catchment, depending on whether the upstream compensation basin network is hydraulically connected to AWCB. Both “wetland” and “living stream” are used interchangeably in this report.

The AWP was implemented through a partnership between:

- Swan River Trust
- South East Regional Centre for Urban Landcare (SERCUL)
- City of Canning
- Water Corporation
- Public Transport Authority
- State NRM Office

The AWP aimed:

- to maintain the required hydrological capacity of the drainage system;
- to improve the quality of urban stormwater runoff and reduce nutrients and other contaminants entering the Canning River via MSMD;
- to enhance habitat and ecological value of the site; and
- to provide the basis for the promotion of improved stormwater and pollution management to local landholders.

Although other aforementioned aims have been anecdotally achieved through the projects implementation, the focus of this report is on the performance assessment of the project specifically as it relates to water quality improvement.

Features of the AWP include a sedimentation pond for settlement of particulate material at the inlet and to facilitate periodic removal of deposited material entering the basin; a meandering low-flow path through the basin that increases residence time and contact with wetland macrophytes during periods of low flow; densely vegetated shallow benches or floodplain areas that are engaged during moderate to high flows and to encourage sedimentation and pollutant removal and containing low sand bunds to reduce risk of short-circuiting of flows between inlet and outlet; a low flow diversion from the Mars Street Drain to the inlet of the system to allow treatment of low flows through the entire flow path of the “living stream”; and an adjustable outlet weir that can facilitate maintenance and allow system gauging (Figure 1).

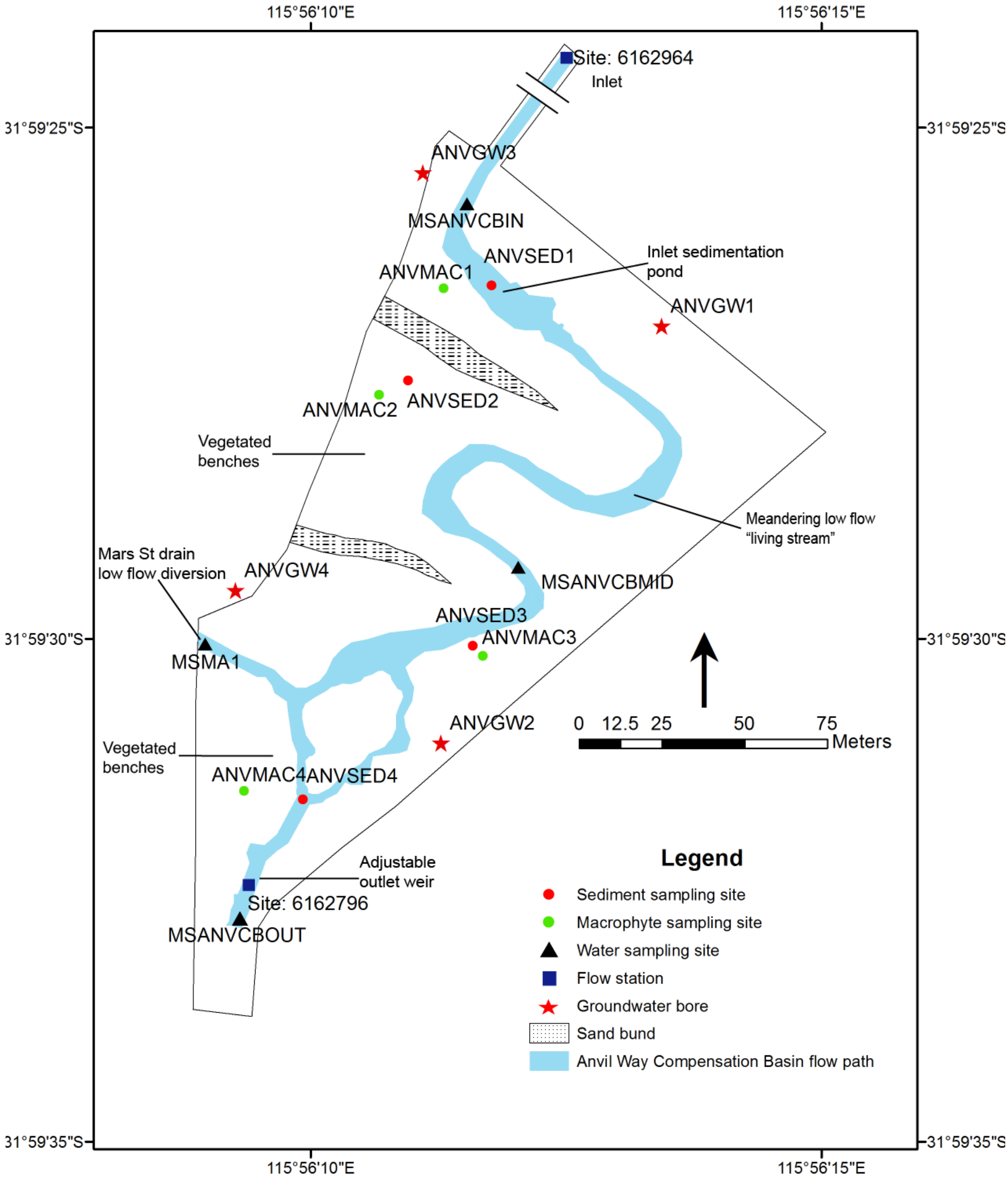


**Figure 1. Map showing current (DoW) monitoring points for surface water, groundwater, macrophyte and sediment in the AWCB. Stormwater enters the basin through the main inlet (MSANVCBIN) and mid inlet (MSMA1) before exiting the main outlet (MSANVCBOUT) and ultimately discharging to the Canning River. AWRC reference Site: 6162964 and Site: 6162796 represent the flow station at inflow and outflow of the basin, respectively.**

# Monitoring program summary

## Overview of data used in the analysis

Before final construction of the wetland in 2010, monitoring of the drain and compensation basin was undertaken from 2004, providing an extensive base-line dataset. Since November 2010, a detailed monitoring program has been underway with the aim of answering the questions outlined in the introduction.

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

- *Hydrological data* - surface flows and groundwater levels
- *Water quality* - nutrient, contaminant and other relevant measures of water quality within the wetland and nearby groundwater
- *Sediment condition* - nutrients, contaminants and other properties of surficial wetland sediment
- *Ecosystem health* - vegetation biomass; macroinvertebrate surveys and other measures of ecosystem integrity have been undertaken but are not explored here.

A summary of the available data considered during the analysis is given in Table 1. Summary table of available data, monitoring period, and sources relevant for the AWCB assessment. The location of the sampling points are summarised in Figure 1 and further details are given in Appendix A and B.

## Hydrological data

Weather data from the Welshpool Depot (WIN site ID: 509359) rainfall and meteorological station were used. This station is located within the catchment, approximately 800 m north-west of the AWCB. Rainfall is measured using an automatic tipping bucket rain gauge and the station has provided data for Perth Metro Area since 2008.

Two flow stations have been established to monitor water inflows and outflows for AWCB. An inflow station (WIN site ID: 6162964) monitors the discharge from the Abernethy Road branch of the MSMD. A Starflow ultrasonic instrument (UnidataTM) is installed inside a 760 mm diameter concrete pipe beneath Orrong Road (Figure 1) and simultaneously records water level (via a pressure transducer) and flow velocity (Incoherent Acoustic Doppler technique). Point velocity measurements by the instrument are then correlated to the flow mean velocity via independent flow discharge measurements (DM). Detailed information on the procedure for this correlation technique can be found in DoW (2014). Discharge values for the station at each time interval are then computed from Starflow's water level (area) and corrected velocity values using the standard Velocity-Area method. Flow discharge records are automatically produced by the Hydstra hydrological database software.

The outflow station (WIN site ID: 6162796), located approximately 600 m downstream of the inflow station, uses an existing concrete drop structure (variable height weir) to compute flow discharge based on water level records from a float well sensor located upstream of the weir. The rating (flow discharge quantification) for low and mid flow conditions is controlled by the weir but under high flow conditions additional controls include excessive vegetation growth in the channel and a tailwater effect from the culvert entrance structure at Welshpool Road (ultimate flow control at a downstream location).

A total of seven and eight discharge measurements (DM) have been reported by DoW for the inflow and the outflow stations, respectively, over the period August 2012 - August 2013. The independent DM measurements were used for flow velocity indexing (correlation between point velocity and mean flow velocity) and the construction of rating curves (also known as Tables within the Hydstra software) for the outflow station. Table A1 (Appendix A) summarises the station information and length of the records currently available from the Water Information Reporting (WIR) system maintained by DoW.

Rainfall, hydrometric data (water stage) and flow discharge data at 5-minute time intervals were requested via the WIR system. In general, water level data (stage) has been coded as 1 (uncertainty +/-2%) while an uncertainty level of +/-10% has been allocated to the flow discharge values.

QA/QC reporting for the hydrometric data collected at the inflow and outflow stations during the 2012-2013 period provides further insights into data-related issues that could bias the results and interpretation of the water balance of the AWCB.

There are four shallow groundwater bores in the vicinity of the AWCB (Figure 1). Groundwater levels and quality are monitored around the basin. Bores are 5 m deep and the covers are trafficable and flush with the surface of the ground. During bore installation the soil profile to 5 m below the surface was noted to be very similar at all bore sites. The depth to groundwater was around 2.5 m below surface level at these bores.

Typical soil profile of the bore site was:

- 0 - 0.5 m: fine grain, grey sand;
- 0.5 - 1.5 m: fine grain, grey/brown sand;
- 2.0 - 4.5 m: medium grain, grey/brown sand;
- 4.5 - 5.0 m: clayey sand, light grey.

Groundwater level/depth was monitored on a monthly basis and reported as depth from top of the casing (TOC). Groundwater levels were converted to Australian Height Datum (AHD) using DoW survey data.

## 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
- PAHs
- PCBs
- Surfactants
- VOCs

Elements included in the categories related to nutrients and metals were the focus of this report.

Monitoring sites changed over time, with a total of ten different monitoring stations used over the years, however, four key monitoring sites have been consistently sampled over the ten years (those on Figure 1). These four sites include: wetland main inlet (MSANVCBIN), Mars Street Drain Inlet (MSMA1), middle of the wetland (MSANVCBMID) and wetland outlet (MSANVCBOUT). Samples were collected at a variable frequency but generally on a monthly basis. The detailed frequency of sampling as well as number of samples per monitoring campaign is presented in Appendix B.

All surface water grab samples were collected by DoW 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).

Groundwater quality was assessed from April 2010 in three bores and in 2012 a fourth bore was added to the monitoring programme. Samples were collected at a depth of 4.00 - 4.16 m and the sampling frequency varied in different years (refer to Figure 1 for sites and Table B2, Appendix B for further detail).

## Sediment and soil data

The objectives of the sediment and soil analyses were to determine sedimentation volumes, internal removal efficiencies and gradients in sediment quality between the inlet and the outlet. Physico-chemical properties of the sediment and soils were measured along with content of nutrients, heavy metals, hydrocarbons, pesticides, PAHs, PCBs and VOCs.

Over the period 2004-2013, sediment was monitored at 15 different locations, to a maximum depth of 25 cm and at variable frequency, according to methods outlined in the General Monitoring Methods and Procedure, GMMP (GHD 2008). The sediment sample locations varied over the years, however four locations were consistently used: in-stream sediment at the inlet (ANVSED1), two soil sampling points on the wetland benches (ANVSED2 and ANVSED3) and in-stream sediment at the outlet (ANVSED4) (Figure 1). The monitoring frequency varied between annual and biannual. Sediment sampling occurred at the same time as the macrophyte sampling, early spring (October) and autumn (May).

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

SERCUL planted the basin with *Schoenoplectus validus*, *Baumea articulata*, *Baumea juncea*, *Juncus pallidus* and *Juncus kraussii* (SERCUL 2011). Ground-truthing of species coverage was done once in July 2012. Macrophyte sampling and monitoring has been conducted in October 2012, May 2013 and October 2013. Quadrats (0.25m x 0.25m or 0.0625 $m^2$) were used at the macrophyte sampling sites (Figure 1), to estimate:

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

In addition each sample was analysed for:

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

**Table 1. Summary table of available data, monitoring period, and sources relevant for the AWCB assessment.**

| Data | Station Names | Variables | Time period | Source / Comment |
|---|---|---|---|---|
| Hydrology | WIN 509359 | Rainfall/ Meteorology | 06/10/2008 - present | Tipping bucket |
| | WIN 6162964 (Inflow at Orrong Road) | Starflow (water level and velocity) | 18/07/2012 - present | Collected by DoW<br>Vegetation growth, drift in transducer records, turbulence affecting Doppler |
| | WIN 6162796 (Outflow adjustable weir) | Oddysey Probe (water level)<br><br>Float well sensor | 22/07/2011 - 25/02/2012<br><br>25/02/2012 - present | Collected by DoW<br>Increase in water level from October (debris/veg. growth)<br><br>Vegetation growth, sedimentation, weir operation, tail water effect for high flow conditions |
| | WIN 23041042 (ANVGW1)<br>WIN 23041043 (ANVGW2)<br>WIN 23041044 (ANVGW3)<br>WIN 23044836 (ANVGW4) | Groundwater level | Monthly for ANVGW1-ANVGW3, from April 2010 to present<br>Monthly for ANVGW4, from 2012 to present | Collected by DoW<br>Five metre deep groundwater monitoring bores |
| Routine water quality sampling | **Surface water (AWRC ID)**:<br>**Inlet**:<br>AWRC 6162797 (MSANVCBIN)<br>**Within wetland**:<br>AWRC 6162962 (MSMA1)<br>AWRC 6162795 (MSANVCBMID)<br>**Outlet**:<br>**AWRC** 6162796 (MSANVCBOUT)<br>**Less regular:**<br>AWRC 6162770 (MSDIVCBOUT)<br>AWRC 6162665 (MILLS ST MAIN DRAIN)<br>AWRC 6163317 (MSMA2)<br>AWRC 6162770 (MSDIVCBOUT) | Physico-chemical<br>Hydrocarbons<br>Pesticides (herbicides, insecticides)<br>Heavy metals<br>Metalloids<br>Nutrients<br>Organics<br>PAHs<br>PCBs<br>Surfactants<br>VOC | **Surface water:** Variable, but generally monthly, from 2004 – end of 2013 | Collected by DoW |
| | **Groundwater (AWRC ID)**:<br>AWRC 61611396 (ANVGW1)<br>AWRC 61611397 (ANVGW2)<br>AWRC 61611398 (ANVGW3)<br>AWRC 61611399 (ANVGW4) | Physico-chemical<br>Hydrocarbons<br>Heavy metals<br>Metalloids<br>Nutrients | **Groundwater**:<br>Variable, but generally monthly, from April 2010 – December 2013 | Collected by DoW |
| | UWA ad hoc sampling | Ongoing sampling focusing N, P and C species | 2013 - Ongoing | Collected by UWA |
| Sediment | **AWRC** 6163939 (ANVCB10)<br>**AWRC** 6163935 (ANVCB6)<br>**AWRC** 6163936 (ANVCB7)<br>**AWRC** 6163937 (ANVCB8)<br>**AWRC** 6163938 (ANVCB9)<br>**AWRC** 6164610 (ANVSED1US)<br><br>**Main sites:**<br>AWRC 6164500 (ANVSED1)<br>AWRC 6164501 (ANVSED2)<br>AWRC 6164502 (ANVSED3)<br>AWRC 6164503 (ANVSED4)<br>AWRC 6164611 (ANVSED4DS)<br>AWRC 6163328 (MSANVCB1) | Physico-chemical<br>Nutrients<br>Metals<br>Hydrocarbons<br>Pesticides(herbicides, insecticides)<br>Organics<br>PAHs<br>PCBs | Variable, but mainly biannual;<br>from 2004 to 2013 | Collected by DoW |

| Data | Station Names | Variables | Time period | Source / Comment |
|---|---|---|---|---|
| | AWRC 6163329 (MSANVCB2)<br><br>**Inlet:**<br>AWRC 6162797 (MSANVCBIN)<br>**Middle:**<br>AWRC 6162795 (MSANVCBMID)<br>**Outlet:**<br>AWRC 6162796 (MSANVCBOUT)<br>**Drain outflow 1:**<br>AWRC 6162962 (MSMA1) | | | |
| Vegetation | AWRC 6164605 (ANVMAC1)<br>AWRC 6164606 (ANVMAC2)<br>AWRC 6164607 (ANVMAC3)<br>AWRC 6164608 (ANVMAC4) | Vegetation quality<br>Nutrients | May,2012,<br>May 2013, and<br>October 2013 | Collected by DoW and SERCUL |

# Water balance analysis

The objective of this section is to establish a basic water balance for the AWCB based on existing hydrometric and flow discharge data collected by the Department of Water (DoW) from June 2012 to December 2013. The water balance aims to assist the interpretation of existing water quality data and to assess the effectiveness of the AWCB in improving water quality 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 the AWCB.
- Selection of appropriate methodologies for estimating the water balance, given the existing data.
- Conclusions and recommendations for hydrological monitoring for future water balance assessment.

## Prior water balance estimates

A preliminary quantification of the water balance for the water year July 2012-July 2013 was reported by DoW (2014) and indicated a difference in water volume of 121,150 $m^3$ between the outflow (Site 6162796) and inflow (Site 6162964) of the AWCB. This difference represented approximately 10% of the total volume of water over the period and it was attributed to unmeasured (ungauged) flow sources from local drains to the AWCB and possible groundwater contribution. The result came from a comparison of cumulative flow discharge volumes over the period using daily flow discharge values.

The DoW (2014) report also corroborated the above results by using seven instantaneous flow discharge measurements (DMs, Q in $m^3/s$) taken between May and August 2013. The DMs provided an average value of 0.9 for the ratio between the outflow and inflow discharge and it was concluded that the main drain inflow contributes 90% of the wetland outflow.

The above results suggested that the volumetric contribution of ungauged sources and/or water fluxes within the different components of a water balance (surface and subsurface storages and runoff, water losses, etc) played a minor role and these were the same order of magnitude as the uncertainties associated with flow discharge data. Given this situation, it is challenging to establish a realistic water balance for the AWCB. It is clear from the above that an alternative approach to analyse the data is required other than the use of daily flow data records.

## Approach used in this assessment

An alternative approach for the water balance was undertaken in this assessment also considering:

- The nature of the hydrological response for urban catchments (short time response).
- The need to identify and quantify water contribution from an ungauged catchment area.
- Issues identified with discharge data for baseflow and high flow conditions.

An analysis of the catchment area and degree of impervious areas revealed that approximately 25% of the total catchment area contributing to the AWCB (including that for the inlet location) was not measured or instrumented for flow discharge monitoring by the original Sampling and Analysis Program (SAP) (SRT, 2013). The Mars Street catchment has a total area of 57.89 ha with a compensation basin at Leach Highway that divides the catchment into two sub-catchments: a 26.52 ha area that is directly connected to the AWCB and the remaining 31.37 ha that contributes to the Leach Highway compensation basin prior to discharging into AWCB. It is expected that this sub-catchment will be contributing to the AWCB upon exceedance of the storage capacity of the Leach Highway compensation basin during large rainfall events and small events late in the winter and spring seasons. If that is the case, the volumetric contribution from the Mars Street catchment will exceed the reported 10% difference in volume and will present remarkable changes in contribution across the year.

An analysis based on individual rainfall and hydrograph events across the year allows us to overcome the limitations and uncertainties introduced by the rating problems at both inflow and outflow sites. Consequently, an event based volumetric contribution analysis across the year would produce a more realistic water balance for the AWCB and as such the rationale of the approach is presented below.

**Water balance at rainfall event time scale**

This analysis used a total of 28 rainfall events of different magnitude, intensity and duration over the period July 2012 - October 2013 and provides a fundamental time scale analysis of hydrological response of impervious areas to rainfall intensity and duration (Table 2).

Five-minute records of rainfall and discharge values for the inflow and outflow stations were used to compute the water volume resulting from each rainfall event. The observed inflow hydrograph, located approximately 600 m from the outflow station, required routing through the compensation basin using a linear reservoir routing technique (Chow et al., 1999). Routing parameters (one for storage and another for time lag) were fitted for five event hydrographs that preserved water mass (Volume inflow = Volume outflow). Calibrated parameter values were then used for the remaining event hydrographs.

The flow discharge for the ungauged area or water sources (at 5 minute intervals) was obtained as the difference between the observed outflow and the routed-inflow discharge values. Finally, the volumetric contribution for ungauged areas was computed by numerical integration of the discharge hydrograph over the specified duration of the event (discharge value equal to its pre-event flow value).

This approach allowed isolation of fundamental hydrological signals from the ungauged catchments including:

- Identification of very localised water source contributions (not recorded by the inflow station) for small rainfall events with short duration (e.g. the Mars Street directly connected impervious area).
- Identification of other local water sources contribution (not recorded by the inflow station) for small rainfall events with duration larger than the time of concentration of surrounding catchment areas.
- Increasing water volumetric contribution and peak flow discharges from ungauged areas due to changes in catchment wetness condition and/or connection of additional contributing areas (e.g. upstream areas of Leach Highway's compensation basin).

The relative contribution of water to the outflow (in percentage) was then computed for both the inflow and the ungauged areas. No attempt to remove the baseflow component for each event hydrograph was made as the approach assumes that ungauged catchments will only produce the direct runoff (no baseflow) component.

**Table 2. Summary of selected rainfall events and the resulting peak flow discharges and volumetric contributions to the AWCB during 2012-2013.**

| Date | Day of year (1/1/2012) | Rainfall (mm) | Duration (hr) | Imax_15 (mm/h) | ARI | Qp_in ($m^3/s$) | Qp_out ($m^3/s$) | Vol_in ($m^3$) | Vol_out ($m^3$) | Difference (%) | Qp_VCUS ($m^3/s$) | Vol_VCUS ($m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/08/2012 | 214 | 4.2 | 2.92 | 9.5 | <1 | 0.16 | 0.161 | 5324.9 | 5368.8 | 0.82 | 0.078 | 59.26 |
| 02/08/2012 | 215 | 9.5 | 31 | 6.3 | <1 | 0.375 | 0.361 | 17023 | 17638 | 3.49 | 0.074 | 627.47 |
| 12/08/2012 | 225 | 16.2 | 3.67 | 10.2 | <1 | 0.488 | 0.593 | 24473 | 28489 | 14.10 | 0.134 | 4091.2 |
| 21/08/2012 | 234 | 14.2 | 12 | 14.1 | <1 | 0.305 | 0.312 | 17347 | 18676 | 7.12 | 0.047 | 1324.5 |
| 28/08/2012 | 241 | 6.7 | 1.9 | 23.7 | <1 | 0.345 | 0.299 | 10740 | 11332 | 5.22 | 0.144 | 648.17 |
| 03/09/2012 | 247 | 18.5 | 2.5 | 15.4 | <1 | 0.922 | 1.076 | 37717 | 50127 | 24.76 | 0.31 | 13441 |
| 17/09/2012 | 261 | 9.3 | 1 | 23.7 | <1 | 0.297 | 0.303 | 12513 | 15436 | 18.94 | 0.264 | 2903.3 |
| 21/09/2012 | 265 | 17.2 | 7.7 | 26.9 | <1 | 0.659 | 0.811 | 24992 | 32651 | 23.46 | 0.255 | 7741.5 |
| 24/09/2012 | 268 | 25.1 | 69 | 7.1 | <1 | 0.579 | 0.602 | 41452 | 47600 | 12.92 | 0.117 | 6111.8 |
| 13/10/2012 | 287 | 3 | 2.4 | 4.68 | <1 | 0.03 | 0.052 | 2065.9 | 3534 | 41.54 | 0.0297 | 1466.7 |
| 22/10/2012 | 296 | 5 | 2.4 | 7 | <1 | 0.063 | 0.076 | 5010.2 | 6353.3 | 21.14 | 0.0416 | 1334.4 |
| 03/11/2012 | 308 | 17.5 | 4.58 | 24.13 | <1 | 0.974 | 1.09 | 56765 | 72328 | 21.52 | 0.278 | 15695 |
| 12/12/2012 | 347 | 19.8 | 1 | 54.4 | 5 | 0.714 | 0.71 | 33551 | 44337 | 24.33 | 0.2972 | 10802 |
| 25/06/2013 | 542 | 7 | 9 | 15.2 | <1 | 0.22 | 0.157 | 10658 | 10337 | -3.11 | - | - |
| 03/07/2013 | 550 | 3.6 | 2.4 | 4.8 | <1 | 0.069 | 0.056 | 4445.1 | 5315.3 | 16.37 | 0.0186 | 834.48 |
| 09/07/2013 | 556 | 25.4 | 4.75 | 30.4 | <1 | 0.86 | 0.822 | 32403 | 35369 | 8.39 | 0.2271 | 3077.8 |
| 23/07/2013 | 570 | 18 | 9.3 | 12.8 | <1 | 0.532 | 0.499 | 19146 | 19508 | 1.86 | 0.043 | 527.72 |
| 31/07/2013 | 578 | 13 | 2.3 | 18.4 | <1 | 0.5 | 0.386 | 14803 | 14912 | 0.73 | 0.165 | 630.79 |
| 07/08/2013 | 585 | 58 | 20 | 32.8 | 1 | 1.062 | 1.189 | 77082 | 90989 | 15.28 | 0.4357 | 14201 |
| 13/08/2013 | 591 | 12.6 | 3.16 | 14.4 | <1 | 0.539 | 0.456 | 16974 | 18874 | 10.07 | 0.133 | 2022.9 |
| 03/09/2013 | 612 | 8.8 | 10.6 | 8.8 | <1 | 0.264 | 0.267 | 11049 | 14005 | 21.11 | 0.0532 | 2947.6 |
| 07/09/2013 | 616 | 3.8 | 1.83 | 4.8 | <1 | 0.136 | 0.123 | 56451 | 81663 | 30.87 | 0.0374 | 2403 |
| 13/09/2013 | 622 | 27.6 | | 14.4 | <1 | 0.47 | 0.582 | 30956 | 41297 | 25.04 | 0.1569 | 10899 |
| 22/09/2013 | 631 | 13.6 | 21.6 | 10.4 | <1 | 0.445 | 0.487 | 15344 | 20957 | 26.78 | 0.11 | 5534.2 |
| 29/09/2013 | 638 | 5.4 | 1.63 | 8 | <1 | 0.208 | 0.249 | 6529.8 | 14097 | 53.68 | 0.099 | 7537.6 |
| 05/10/2013 | 644 | 4.3 | 0.5 | 16.8 | <1 | 0.104 | 0.192 | 3641.1 | 12801 | 71.56 | 0.115 | 9054.3 |
| 08/10/2013 | 647 | 11.2 | 1.68 | 8 | <1 | 0.294 | 0.414 | 9551 | 20877 | 54.25 | 0.167 | 11311 |
| 19/10/2013 | 658 | 14.4 | 19.2 | 7.2 | <1 | 0.263 | 0.437 | 11143 | 28610 | 61.05 | 0.26 | 17452 |

***Note***: *Day of the year since January 1st 2012. Imax_15 indicates maximum rainfall intensity over 15 min intervals. ARI (Average Recurrence Interval) value corresponds to Imax_15 intensity values. Qp refers to instantaneous maximum discharge flow for the event. Vol is volume and VCUS refers to volumetric contribution of ungauged sources and Imax_15 refers to the maximum rainfall intensity over a 15 min period.*

# Results

### Routing parameters and lag computation for small events

Small rainfall events generating volumetric difference between outflow and inflow hydrographs of less than 10% (assuming conservation of mass) were first selected for the calibration of the routing parameters.

Figure 2 shows the inflow and outflow hydrographs for two rainfall events of similar magnitude but different characteristics: one with low intensity and long duration (9.5 mm over 24 hr) and the other with high intensity and short duration (7 mm over 1.9 hr period). The resulting hydrographs presented similar peak flows but different shape and duration as the discharge value for the second event returned to pre-event values within 12 hr. Both event hydrographs showed peak attenuation and resulted in a lag value of 1.2 hr (travel time for peak flow).

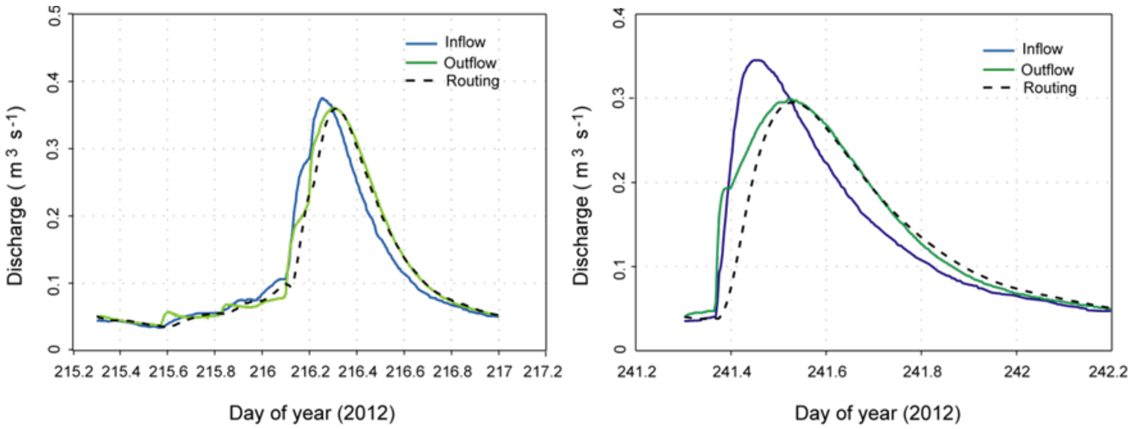


**Figure 2. Hydrographs of selected 2012 small rainfall events (including ungauged catchments), where volumetric differences between inflow and outflow were less than 10%. Events: 2/08/2012 (left) and 28/08/2012 (right). Lines correspond to observed inflow (blue), observed outflow (green), and routed inflow (dash-black). Time represents Julian day since 1/1/2012.**

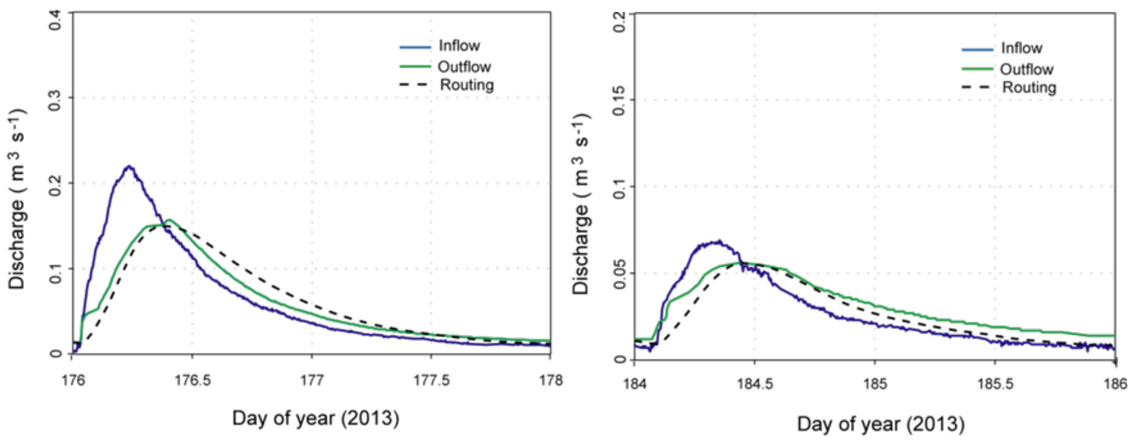


**Figure 3. Hydrographs of selected 2013 small rainfall events (including ungauged catchments), where volumetric differences between inflow and outflow were less than 10%. Events: 25/06/2013 (left) and 3/07/2013 (right). Lines correspond to observed inflow (blue), observed outflow (green), and routed inflow (dash-black). Time represents Julian day since 1/1/2012.**

Small event hydrographs recorded early in 2013 can be used to illustrate the effect of antecedent wetness condition on peak flow (Qp) and lag values.

Figure 3 shows two hydrographs that resulted from 7 mm (25/06/2013) and 3.6 mm (3/07/2013) of rain over a short period of time respectively. Catchment antecedent wetness conditions impacted in both peak flow generation (low) and peak lag values now resulting at 4.8 hr.

The routing parameters were selected by trial and error and they complied with conservation of mass and matching of the time to peak for the outflow hydrograph.

**Quantifying local water source contribution**

Small rainfall events with short duration (e.g. pulses) were used to highlight the role of local catchment areas contributing to the AWCB. Table 3 presents characteristics for selected rainfall events, maximum rainfall intensity over a 15 min (Imax_15) and peak flow discharge from ungauged areas.

**Table 3. Selected rainfall events for identification of local areas contributing to AWCB**

| Date | Total rain (mm) | Duration (hr) | Imax_15 (mm $hr^{-1}$) | Peak flow ($m^3$ $s^{-1}$) |
|---|---|---|---|---|
| 17/09/2012 | 9.3 | 1 | 23.7 | 0.264 |
| 22/10/2012 | 5 | 2.4 | 7 | 0.042 |
| 05/10/2013 | 4.6 | 0.5 | 16.8 | 0.160 |

The event hydrograph from ungauged areas rapidly responded to high rainfall intensity (first event in Table 3) with its peak discharge occurring prior to that of the observed inflow hydrograph (red line, Figure 4). Note that the peak discharges from ungauged areas were of similar magnitude to those observed for the (gauged) inflow.

The volumetric contributions to the outflow hydrograph from ungauged areas were 18.9%, 21% and 71% for the corresponding events in Table 3, respectively. The substantial increase for the later event indicated that at that time the water balance for AWCB was dominated by ungauged areas and water sources other than the measured inflow.

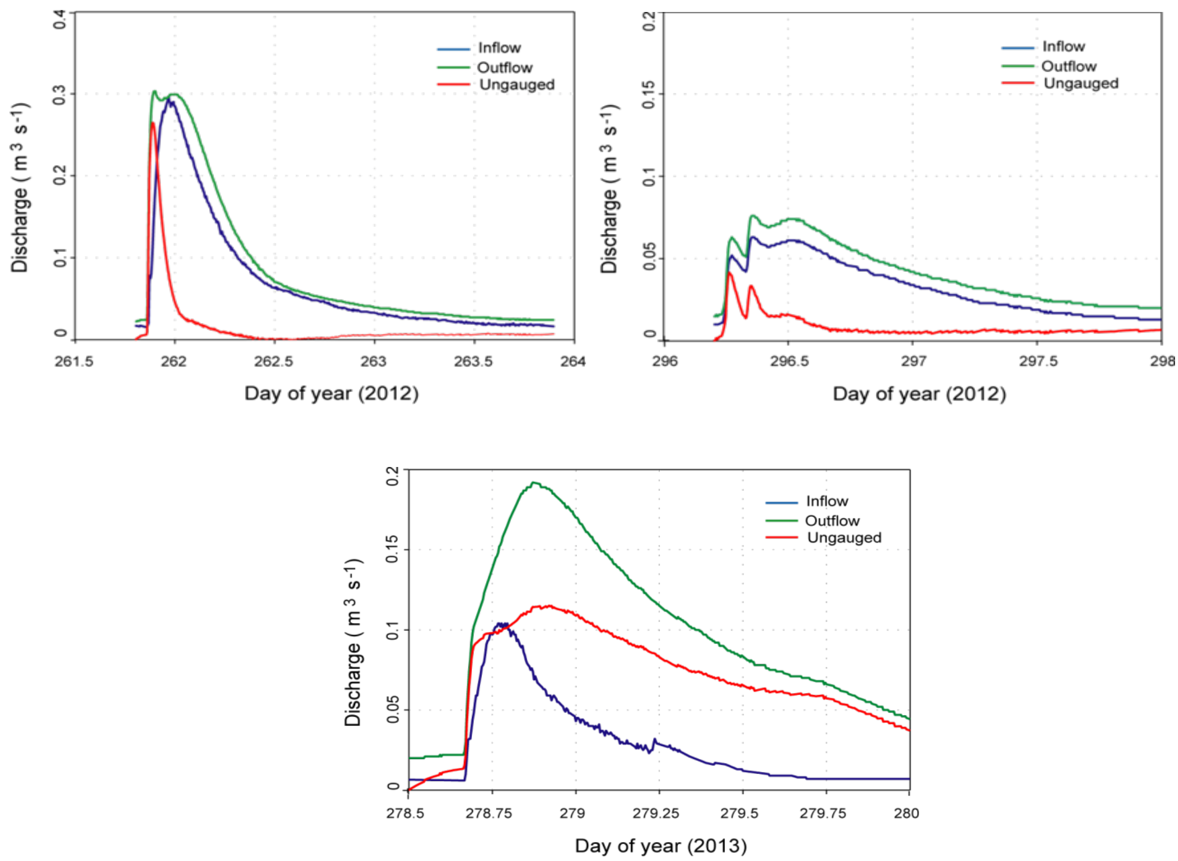


**Figure 4. Event hydrograph deconvolution to isolate ungauged areas contribution. Events: 17/09/2012 (left), 22/10/2012 (right), and 05/10/2013 (centre). Lines correspond to observed inflow (blue), observed outflow (green), and ungauged flow (red).**

### Quantifying water contribution from ungauged areas for large rainfall events

Large rainfall events (> 25 mm) with long duration (~ 24 hr) or event hydrographs presenting peak discharges above the 0.6 $m^3/s$ value, were used to highlight the potential maximum volumetric contribution and peak discharge values from ungauged areas. Since the rainfall duration exceeds the time of concentration for the contributing catchments, the volumetric contribution will be the direct result of the rainfall amount. It is expected that such rainfall events will allow the whole catchment area to contribute flow as direct runoff.

A total of 58 mm of rain fell over a 20 hr period starting on August 7th 2013, with a rainfall intensity (Imax_15) of 32 mm/hr. The event generated a peak discharge of 1.2 $m^3/s$ at the outflow station (Figure 5, right). The hydrograph corresponding to ungauged areas (red line in Figure 5) seems to sustain the outflow discharge for over a period of 9 hr after the first peak discharge (see Figure 5 right- panel between time 219.9 and 220.2) before responding to the second part of the rainfall event with a peak discharge of 0.437 $m^3/s$. The volumetric contribution from ungauged areas reached 16% of the outflow volume for the event.

A similar peak discharge value at the outflow station was generated by a high intensity rainfall event (18.5 mm in two hours) on 3 September 2012 (Figure 5, left). The resulting hydrograph for ungauged areas is consistent in relation to the magnitude of peak for the previous event (e.g. 10% reduction) but it showed a significant increase in volumetric contribution to 27% of the outflow.

As reported by DoW (2014), the inflow hydrograph for large events clearly showed the effect of water storage within the AWCB for discharge values larger than 0.6 $m^3/s$, which is indicated by the change in the slope of recession limb of the event hydrograph. The same response was also observable for the outflow hydrograph as the inflow dominates the volumetric contribution under high flow hydrological conditions.

Results from four rainfall events that resulted in peak discharge values larger than 0.6 $m^3/s$ also indicated an average volumetric contribution of 23% from ungauged areas to the outflow hydrograph.

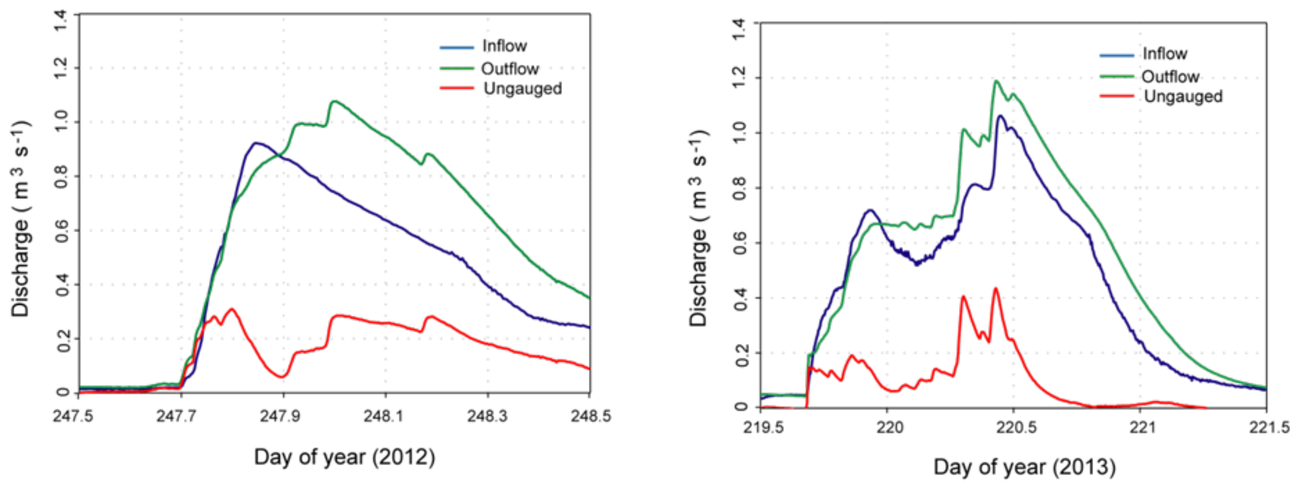


**Figure 5. Event hydrograph deconvolution to isolate ungauged areas contribution for large events. Events: 07/08/2013 (left), and 3/9/2012 (right). Lines correspond to observed inflow (blue), observed outflow (green), and ungauged flow (red).**

### Seasonal variability of volumetric contribution from ungauged areas

This analysis aims to identify seasonal changes for the volumetric contribution of ungauged sources (VCUS) to the AWCB as the catchment increases its wetness due to rainfall. The analysis should also highlight the effect of impervious areas directly connected and additional water sources that may not be explained by the catchment areas alone, such as for example water contribution by the shallow water table. The 28 rainfall events used in the analysis (from July 2012 to October 2013) are presented in Figure 6.

The analysis firstly focused on results from 2013 where individual events covered the winter and spring period from June to October. The relative contribution of ungauged water sources for each event as computed by (outflow-inflow)/outflow is presented in Figure 6 (right).

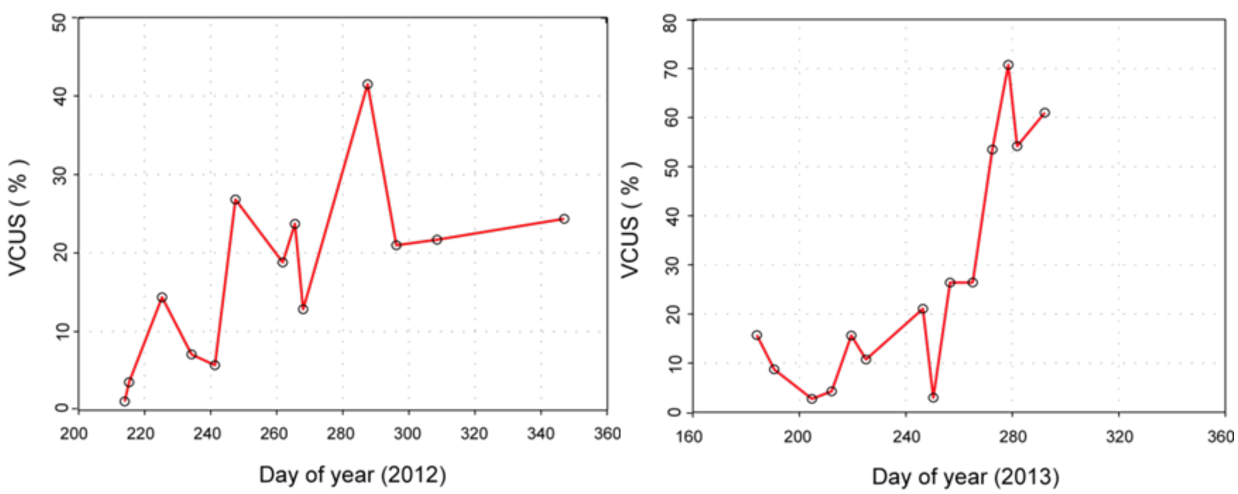


**Figure 6. Seasonal and inter-annual variation of volumetric contribution of ungauged sources (VCUS): 2012 (left), 2013 (right).**

The mass balance clearly indicated the impact of antecedent wetness condition and seasonality in rainfall inputs on the VCUS. Initially, VCUS values were below 20% until the occurrence of a large event by mid-August, but it moved then into a continued phase of increasing contribution with time. The VCUS values for the last four events were above 50% and those events occurred from the end of September to October 2013 coinciding with the increasing water level of the shallow water table (Figure 7).

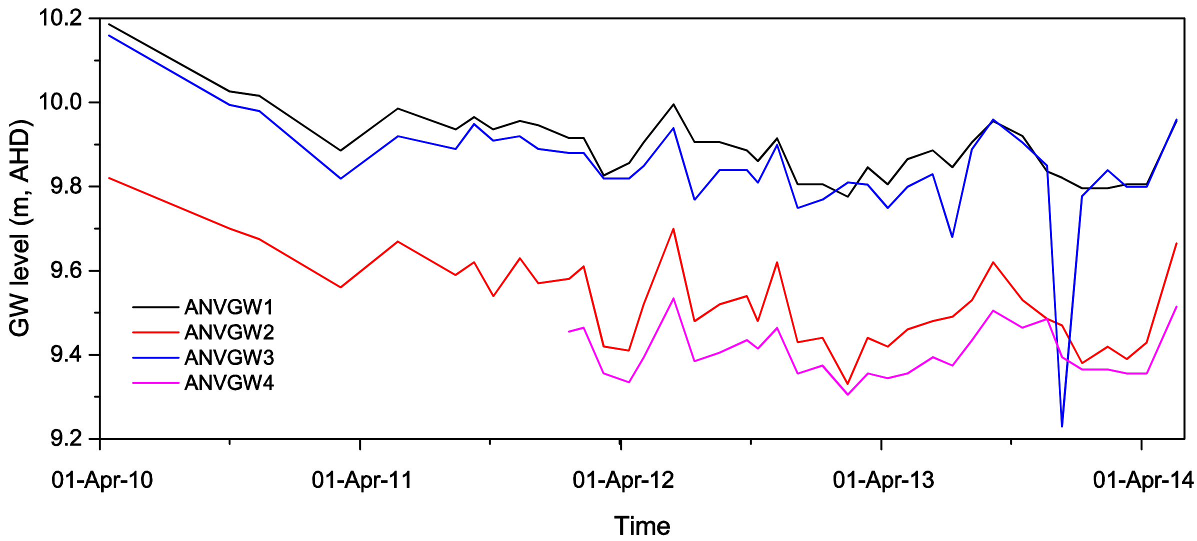


**Figure 7 Groundwater level from April 2010 to May 2014 at different bores of the AWCB and across seasons. ANVGW4 was installed in 2012.**

The VCUS value for events in 2012 also showed a trend of increasing contribution from ungauged areas but they were slightly above 20% (Figure 6, left). This value was exceeded by late August in agreement with the timing observed in 2013. A low VCUS value (13%) was observed in late September and it corresponded to a mid-size rainfall event (25 mm) generating substantial flow into the AWCB. Although the largest VCUS value (at 41%) was found for a small event (13/10/2012), high VCUS values (25%) were still observable at the end of the year even for very-high intensity events with a Imax_15 of 54.4 mm/h (20% Annual Exceedance Probability, AEP).

The seasonal variability of VCUS values shows significant differences in monthly rainfall distributions between 2012 and 2013. Both years present an atypically dry July followed by two remarkably different August and September rainfall totals, with the 2013 season up to 50% wetter. This resulted in significant differences in antecedent wetness conditions of the catchment that then impacted on the development of the shallow water table.

**Is there any indication for GW contribution?**

Unfortunately, water level records for low flow conditions (baseflow) were not of a suitable quality to assess the dynamics of low flow water stage for investigation of surface and groundwater interaction (see Appendix C). What follows simply aims to expose additional water sources that would be neither associated with nor generated by individual rainfall events from ungauged areas.

A preliminary estimation of the total catchment area contributing to VCUS can be computed under the following assumptions: 1) there are negligible initial water losses (interception and storage) for each rainfall event and 2) the VCUS hydrograph represents direct runoff from the event. The effective area contributing to runoff for each individual event can be computed as the ratio between the total volume of the VCUS hydrograph and the rainfall amount. The results are presented in Figure 8 in conjunction to total rainfall amount and Imax_15 values.

Contributing areas to direct runoff for each rainfall event clearly showed the effect of the antecedent wetness condition of the catchment on runoff sources. Small and large events occurring under low wetness condition seem to be mainly generated from impervious areas (lower line in Figure 8) or impervious areas directly connected (~10% of total catchment area) to the drainage network. More areas within the catchment progressively contributed towards runoff generation until it reached the total catchment area under high wetness condition. However, contributing area values larger than the total ungauged catchment area suggested that a different source of water (other than direct runoff from the particular event) was in fact contributing towards the AWCB. Although discharge from the shallow water table into the AWCB can be pointed as the possible source, further analysis and data is needed.

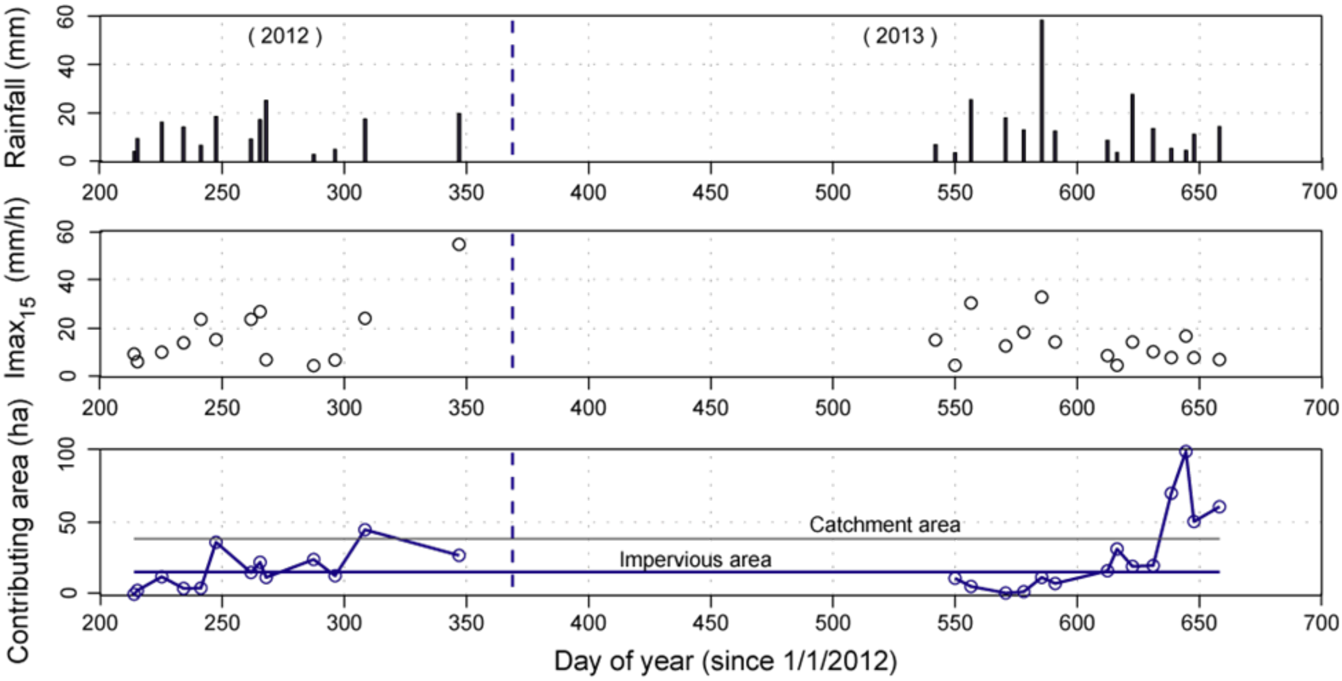


**Figure 8. Seasonal and inter-annual variation of contributing areas to VCUS based on rainfall event analysis: Rainfall (top), Imax15 (mid) and contributing area (bottom). Lines in bottom panel correspond to impervious areas (lower) and total catchment area (top) of ungauged areas contributing to VCUS.**

# Temporal trends in water and sediment quality

The objective of this section is to review and assess the water and sediment quality of the AWCB based on data collected over the period from 2004-2013. The analysis of the water quality data aims to evaluate the performance of the wetland in improving water quality of flow through the MSMD. The assessment has focused on four main aspects:

- Analysis of dissolved oxygen concentrations across the wetland;
- Analysis of spatial and temporal variability of the pollutants;
- Comparison of pollutant concentrations against HRAP targets and ANZECC guidelines; and
- Analysis of pollutant concentration levels under different hydrological conditions (dry and wet conditions).

Analysis of the effectiveness of the wetland in reducing concentrations of incoming pollutants by assessing differences in pollutant levels in the inlet and outlet is undertaken in the next Chapter.

## Dissolved oxygen concentrations

Over the 10 years of data, dissolved oxygen concentrations show clear seasonal trends, with maxima during winter months and minima during summer (Figure 9). In 2004, dissolved oxygen at the outlet (MSANVCBOUT) was typically around 5 mg/L, whereas in winter the dissolved oxygen appeared fully saturated, around 15 mg/L. Interestingly, a long term decrease in average dissolved oxygen concentrations (at both the inlet and outlet) was evident. From 2010 onwards, summertime dissolved oxygen concentrations reached zero; over the last few years anoxic water was measured (at both inlet and outlet) for several months over summer. The wintertime oxygen maximum has decreased over time to around 7 mg/L in 2014.

Dissolved oxygen concentrations were monitored in the groundwater via bores installed after the reconstruction of the living stream in 2010. The dissolved oxygen concentrations were consistently low, ranging from 0 to 2 mg/L, with no obvious seasonal trends.

Preliminary data collected in 2014/15 indicates that a strong diurnal oxygen signal occurs in the wetland surface waters, with night-time anoxia occurring for most of the summer (data not shown).

The oxygen status of a wetland has profound impacts on nutrient cycling, with both nitrogen and phosphorus typically responding to changing oxygen concentrations. The effect on nutrient transformations and wetland nutrient attenuation, of long-term decreases in surface water dissolved oxygen, inflowing groundwater anoxia, and seasonal and diurnal periods of anoxia must be investigated.

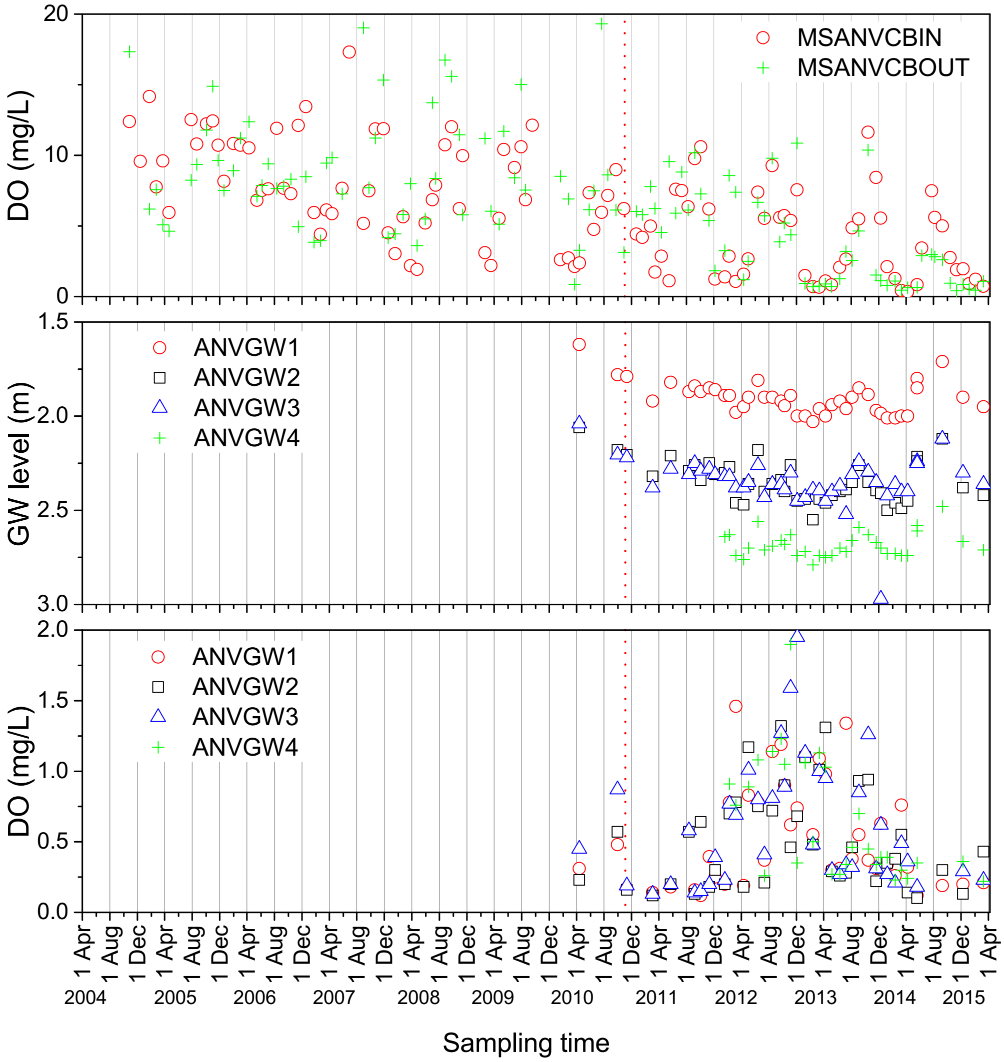


**Figure 9. Spatial and temporal variation of dissolved oxygen (DO) in Anvil Way Compensation Basin; in surface water at the main inlet (MSANVCBIN) and outlet (MSANVCBOUT) from 2004 - 2014 (top panel), and in the four groundwater monitoring bores from 2010 – 2015 (bottom panel). The depth to groundwater varies with season (middle panel).**

# Nutrient concentrations

### Surface water

*Comparison to targets and guidelines*

Nutrients in the surface water have been monitored over the ten-year period except for dissolved organic nitrogen (DON) and total kjeldahl nitrogen (TKN). Concentrations of nutrients at the outlet have varied considerably (Figure 10). The analysis shows that the total phosphorus (TP) and total nitrogen (TN) median concentrations do not pass HRAP target at the outlet of the AWCB, except during 2011 for TP and 2012 for TN. Differences between the total nutrients and their fractions are described below.

Median values of TN do not have large variations and they are close to the ANZECC guideline level for most years. In contrast, soluble inorganic fractions ($NH_3$ and NOx) show more variability and median values show an increase over time, especially NOx. In 2013, almost 100% of the measured values of NOx and $NH_3$ were above the guideline values. The organic fraction DON and TKN show a decreasing trend, though it should be noted that not as many samples have been collected in 2013 as in other years.

In contrast to TN, which has values that lay below HRAP and ANZECC values, TP concentrations are above the guidelines for all years except 2012. Filterable reactive phosphorus (FRP) shows more variability, and several years where the median concentration is above the guideline in 2005 and 2009, and years where the median concentration is below the target, such as 2006 and 2011.

Overall, in 2011, following the initial construction/restoration of the stream, a reduction in TP, FRP and $NH_3$ is observed. However, a notable increase in the TP, FRP and $NH_3$ concentrations is seen in the following years from 2011 to 2013, keeping these parameters above the target value. This is accompanied by a decline in DON concentration, however this is based on the single measurement of DON available in 2013.

The nature of the hydrological conditions can impact retention time and potential for nutrient processing. The levels of nutrient concentrations were therefore assessed for different hydrological conditions. However, due to limitations of the data set, it was not possible to assess the dynamics of nutrient concentrations during the baseflow, rising limb, and falling limb of various storm events. Instead, we explored the variability in nutrient concentrations under “low” and “high” flow pulses and how they varied between the dry and wet season.

High and low flow conditions were classified using the median value of daily outflows as the threshold. As the wetland changed from a fast high flow system into a slow low flow system after the reconstruction, the median values were calculated for conditions before and after the system restoration. The values 0.032 $m^3/s$ and 0.017 $m^3/s$ were considered the threshold values to classify low and high flows for conditions before and after respectively. The wet season was considered as the period from May to November and the dry season covered December to April (inclusive).

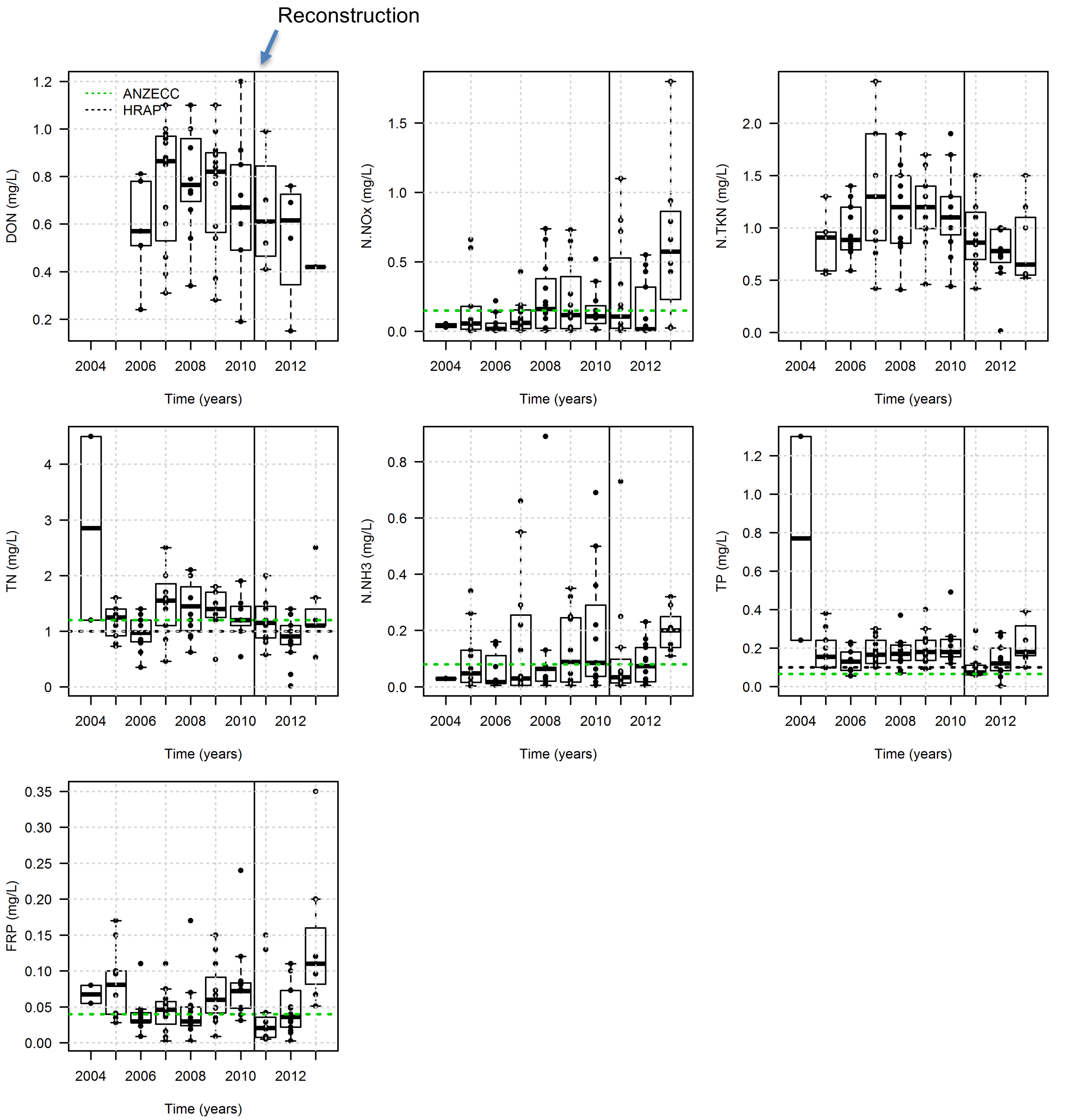


**Figure 10. Comparison of outflowing nutrient concentrations with HRAP target and ANZECC guidelines. Solid vertical line represents timing of the AWCB restoration works.**

For the period prior to the reconstruction of the AWCB, there were no significant differences between dry and wet season concentrations for either high or low flow conditions (Figure 11). All median values fall above ANZECC guidelines except for TN, which seems to display a different behaviour. For high flow events within the wet season the median concentration of TN falls below the guideline value. This may be the result of a dilution effect.

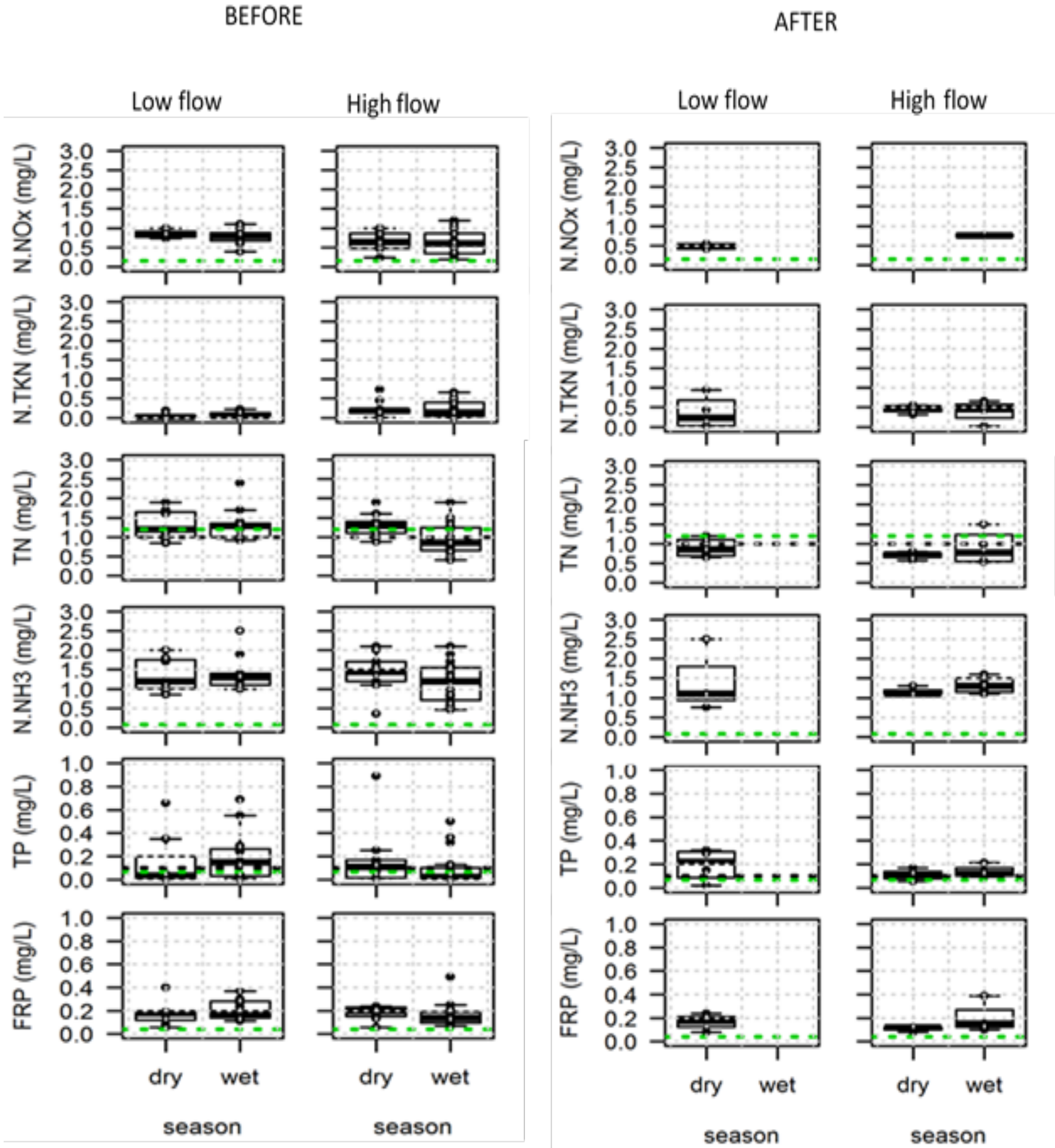


**Figure 11. Nutrient concentrations for different hydrological conditions for the period before and after the reconstruction of the AWCB (horizontal black dashed line=HRAP, horizontal green dashed line=ANZECC guideline).**

Unfortunately, for the period after the reconstruction, limited data is available to do a robust statistical test. However, as with the pre-reconstruction concentrations, it can be concluded that there are not important differences between pulses that occurred during the dry and wet seasons. Nonetheless, it should be noted that TN decreased to values below the guidelines for both high and low flows in both seasons.

**Groundwater**

*Comparison to ANZECC guidelines*

Nutrients in groundwater have been monitored since 2010 at four sites with no major change in the average concentration (Figure 12). ANZECC guidelines have been used for reference. TN concentrations were well above the guideline in 2011 and decreased below it in 2013. This was accompanied with a decrease in NOx. NOx seems to be the main portion of TN and therefore the reduction in TN might be associated with the reduction of NOx. NOx shows concentrations exceeding the ANZECC guidelines and also some values significantly higher than those in surface water. $NH_3$ concentrations were above the guideline values and showed no trend. Similarly, the TKN fraction remained stable over the four years. TP and FRP concentrations were mainly above the guideline levels. FRP concentrations in groundwater vary within the same range of those in the surface water.

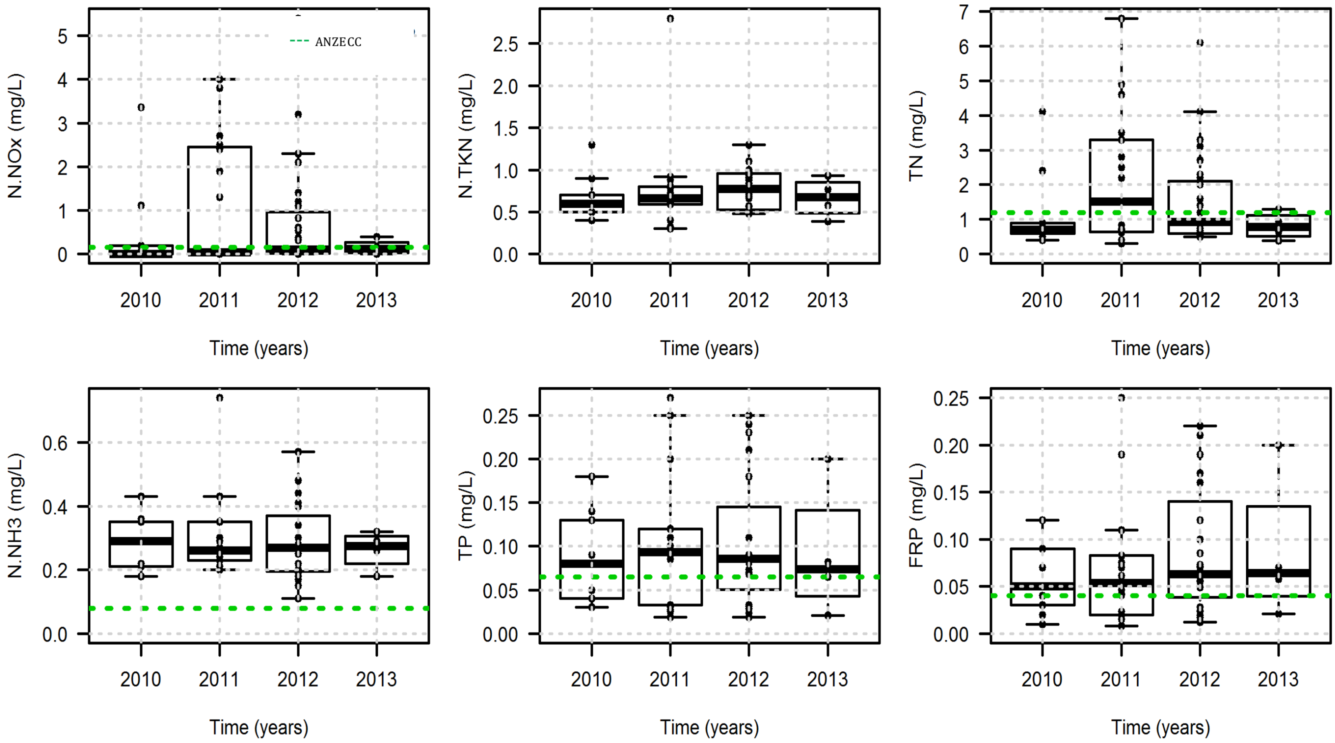


**Figure 12. Comparison of nutrient concentrations in groundwater with ANZECC targets (all stations considered).**

**Sediment**

Nutrients in the sediments have been monitored irregularly over the past ten years, except for TP. The comparison was also made difficult due to sites being sampled at a different frequency and at different locations. Before the reconstruction, sediment sampling sites varied because the aim was to collect base line data to characterise in-situ sediment and soil quality. From 2011, TN and TP have been monitored systematically at four stations (ANVSED1, ANVSED2, ANVSED3 and ANVSED4). ANVSED1 and ANVSED4 are located within the stream channel, and ANVSED2 and ANVSED3 are located on the wetland benches (Figure 1). For this analysis we have considered data collected since 2011. We expect that ANVSED1 and ANVSED4 to be affected by sediment-water interactions associated with water-borne nutrient loads, while ANVSED2 and ANVSED3 would be affected much more strongly by vegetation-soil dynamics, including possible seasonal dynamics associated with vegetation senescence.

In our first analysis, we averaged sediment nutrient concentrations across all four sites, to allow an overall assessment of concentrations. There was a change in TN and TP concentrations in 2011 that may respond to the removal of sediment during the reconstruction of the wetland. The spatially averaged TP concentrations continuously increased from 2007. TN concentrations were more variable but also displayed an increasing trend since 2010. As there are no guidelines for nutrient concentrations in sediments we have not compared concentrations to a target value. However, a guideline value for TP concentrations in soils was used for reference (DEC, 2010), with concentrations in the wetland soil/sediment below this guideline (2000 mg/kg).

There are marked differences in sediment phosphorus concentrations across the wetland with concentrations generally increasing with time (Figure 13–15). There appears to be no marked differences in sediment nutrient concentrations across the wetland.

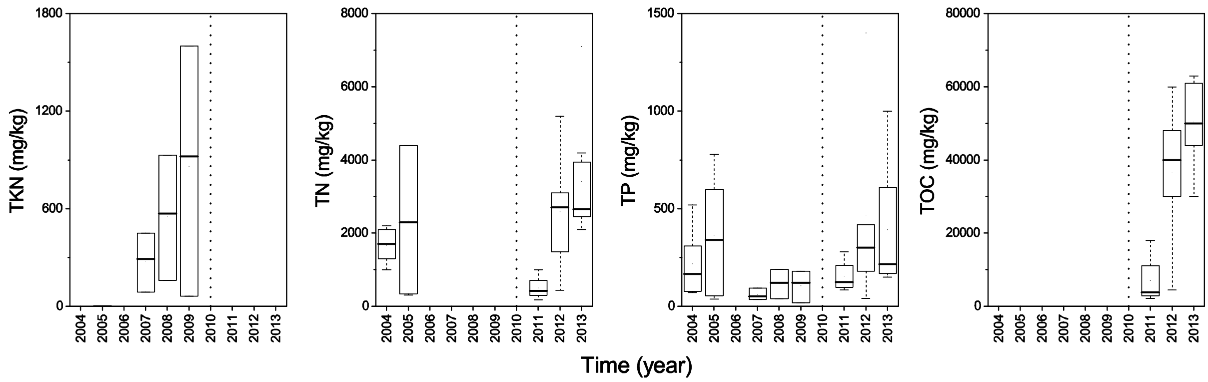


**Figure 13. Concentration of nutrients in sediments (average of all stations). Dotted vertical line indicates basin restoration.**

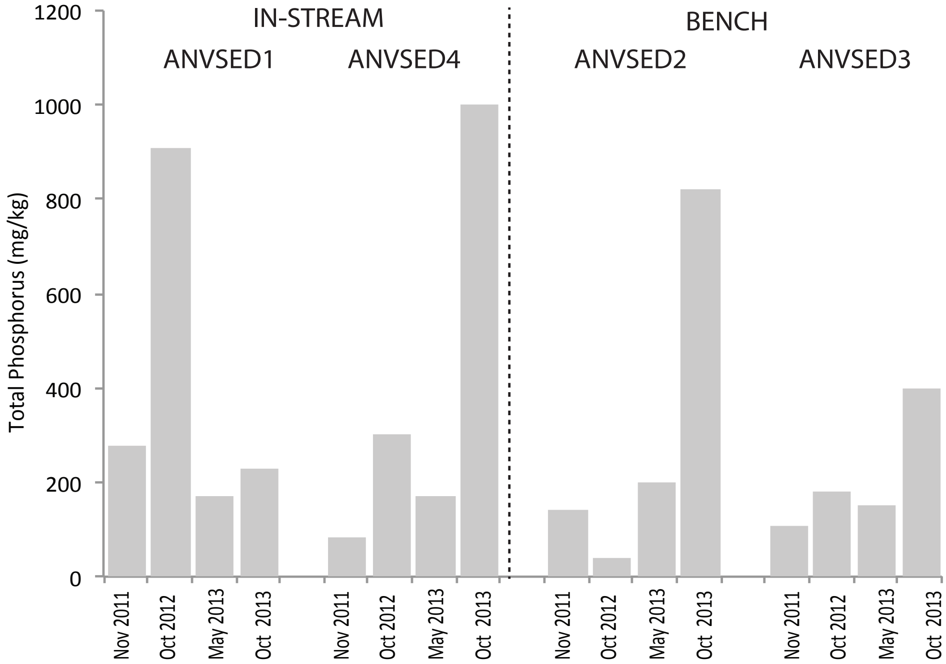


**Figure 14. Total phosphorus concentrations in sediments across the four sites and four sampling dates.**

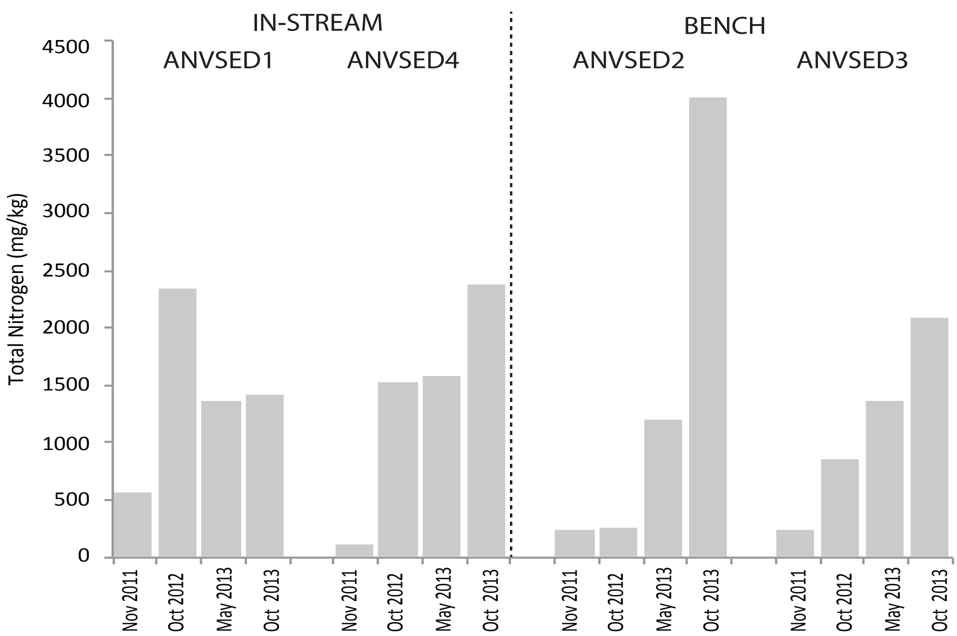


**Figure 15. Total nitrogen concentrations in sediments across the four sites and the four sampling dates.**

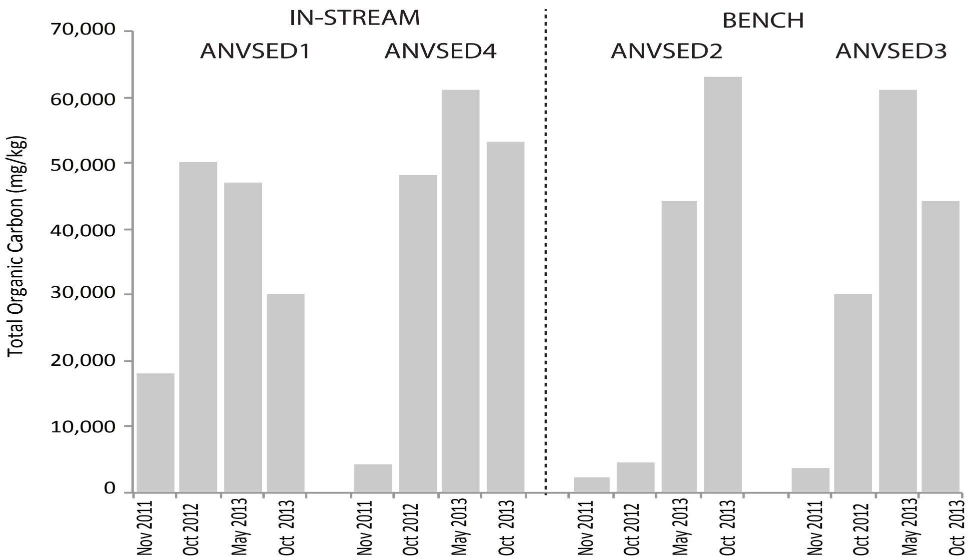


**Figure 16. Total organic carbon concentrations in sediments across the four sites and the four sampling dates.**

The total mass of nutrients in the sediment was estimated by assuming that the sediment nutrient concentration at each site was representative of specific areas of inundated wetland (Figure 17). Therefore a relevant area could be attributed to each nutrient concentration such that:

*Sediment-N (kg) = Sediment-N (mg/kg) x Sediment Bulk Density (kg/m$^3$) x Sediment Area (m$^2$) x Sediment Depth (m)*

where N represents the nutrient, 0.25 m was used for the Sediment Depth, and the soil was assumed to be dominated by sand, with an average Bulk Density of 1300 kg/m$^3$ assumed.

The area of benches (AREA2 and AREA3) contains a greater volume of sediment, and therefore it is these areas that appear to accumulate more mass of nutrients (Figure 18 – 19). There has been a continuous increase in the total mass of nutrients (nitrogen, phosphorus and organic carbon) contained in the sediments across the site (Table 4).

We note that these results must be treated with caution due to the very low spatial resolution of the sediment data sampling and the subsequent assumptions made about representative area of sediment for each sampling site. However, there appears to be clear evidence of accumulation of both organic carbon and nitrogen in the wetland sediments. Interestingly the evidence is less clear for phosphorus, suggesting other mechanisms are controlling the accumulation and possible release of phosphorus from the wetland sediments.

**Table 4. Total sediment nutrients across the four sampling periods. Note that “x” in the trendlines are the days since November 11 2011.**

| Date | Days | Total P (kg) | Total N (kg) | Total OC (kg) |
|---|---|---|---|---|
| Nov 11 2011 | 0 | 384 | 1260 | 11,000 |
| Oct 9 2012 | 335 | 511 | 4853 | 73,267 |
| May 5 2013 | 545 | 542 | 7372 | 170,298 |
| Oct 16 2013 | 707 | 2015 | 15846 | 164,065 |
| **Trendline (x=days)** | | TP=1.866x+122.6 | TN=18.64x-62.67 | TOC=240.7x+9163 |
| **$R^2$** | | 0.55 | 0.84 | 0.92 |

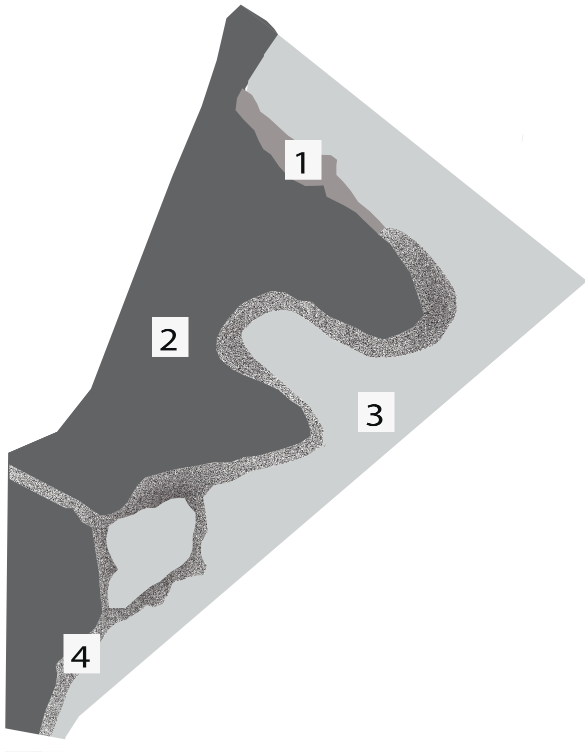


**Figure 17. Sediment/soil regions used for estimation of total nutrient mass stored in sediments. Sediment/soil nutrient concentrations measured at ANVSED1, ANVSED2, ANVSED3 and ANVSED4 were considered representative of Region 1, 2, 3 and 4 respectively.**

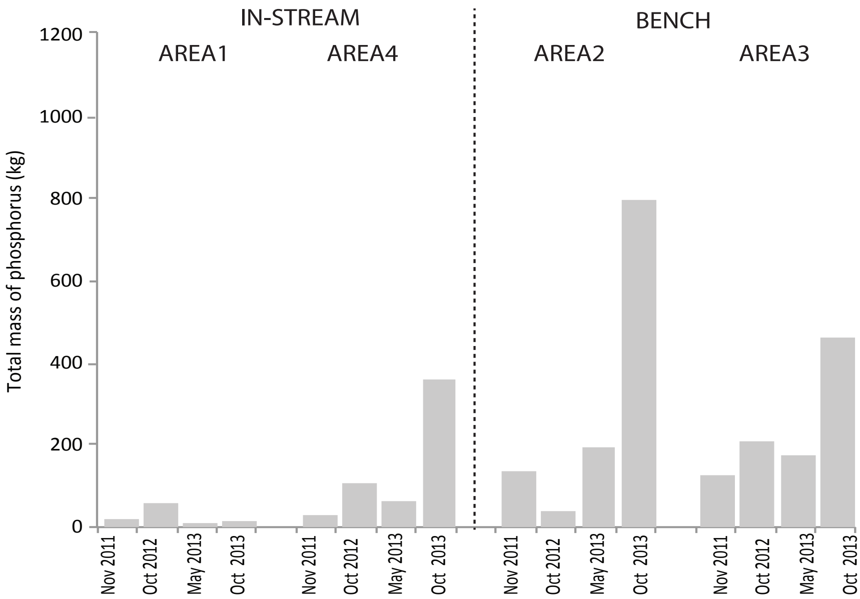


**Figure 18. Total mass of phosphorus in the sediments.**

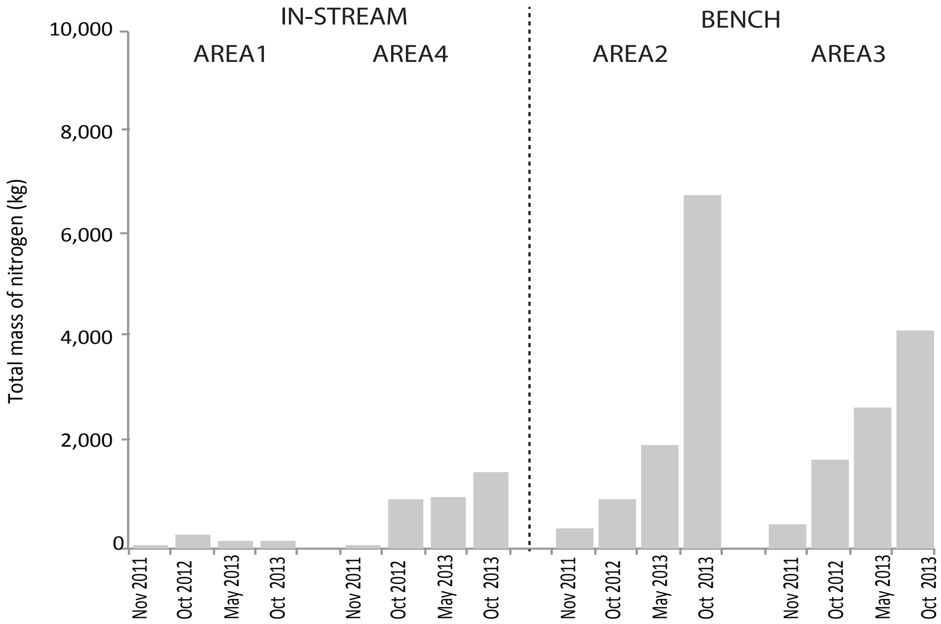


**Figure 19. Total mass of nitrogen in the sediments.**

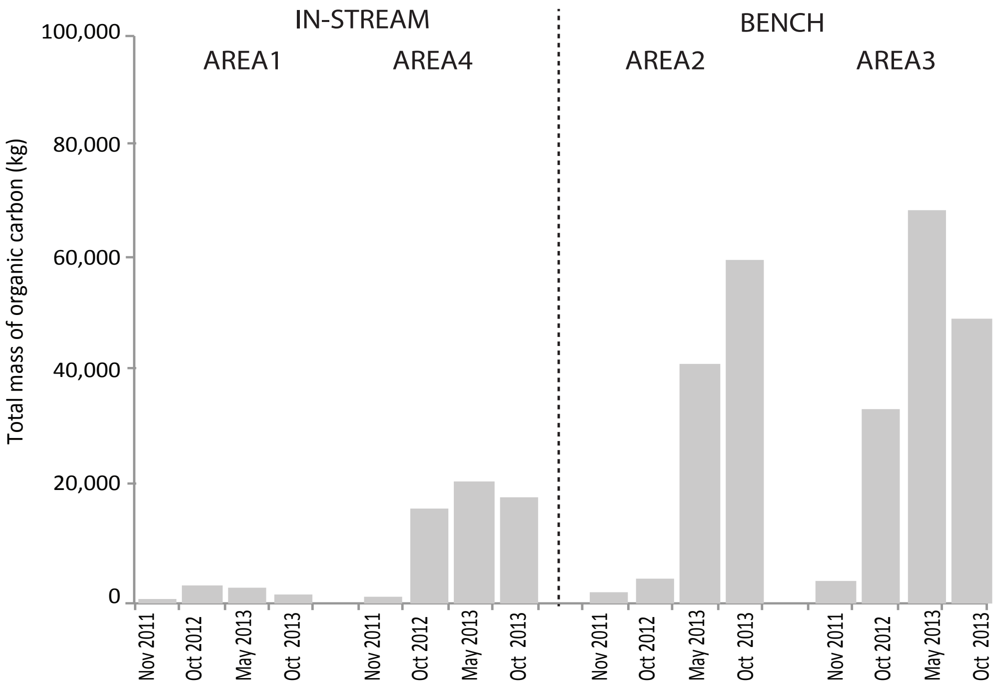


**Figure 20. Total mass of organic carbon in the sediments.**

# Soluble and total metal concentrations

### Surface water

*Comparison to ANZECC guidelines*

The soluble fractions of metals have been monitored only until 2008 in the outlet (Figure 21), after which total metals (Figure 22) were monitored (with some also collected in 2004). At the outlet, both the soluble and total fractions of Al, Cr, Cu and Zn exceeded ANZECC guidelines. For Fe, only the total fraction exceeded the guidelines. As, Ni, and Pb only occasionally exceeded the guideline values. Note that the reduction in concentration of metals as they pass through the wetland is described in the next Chapter.

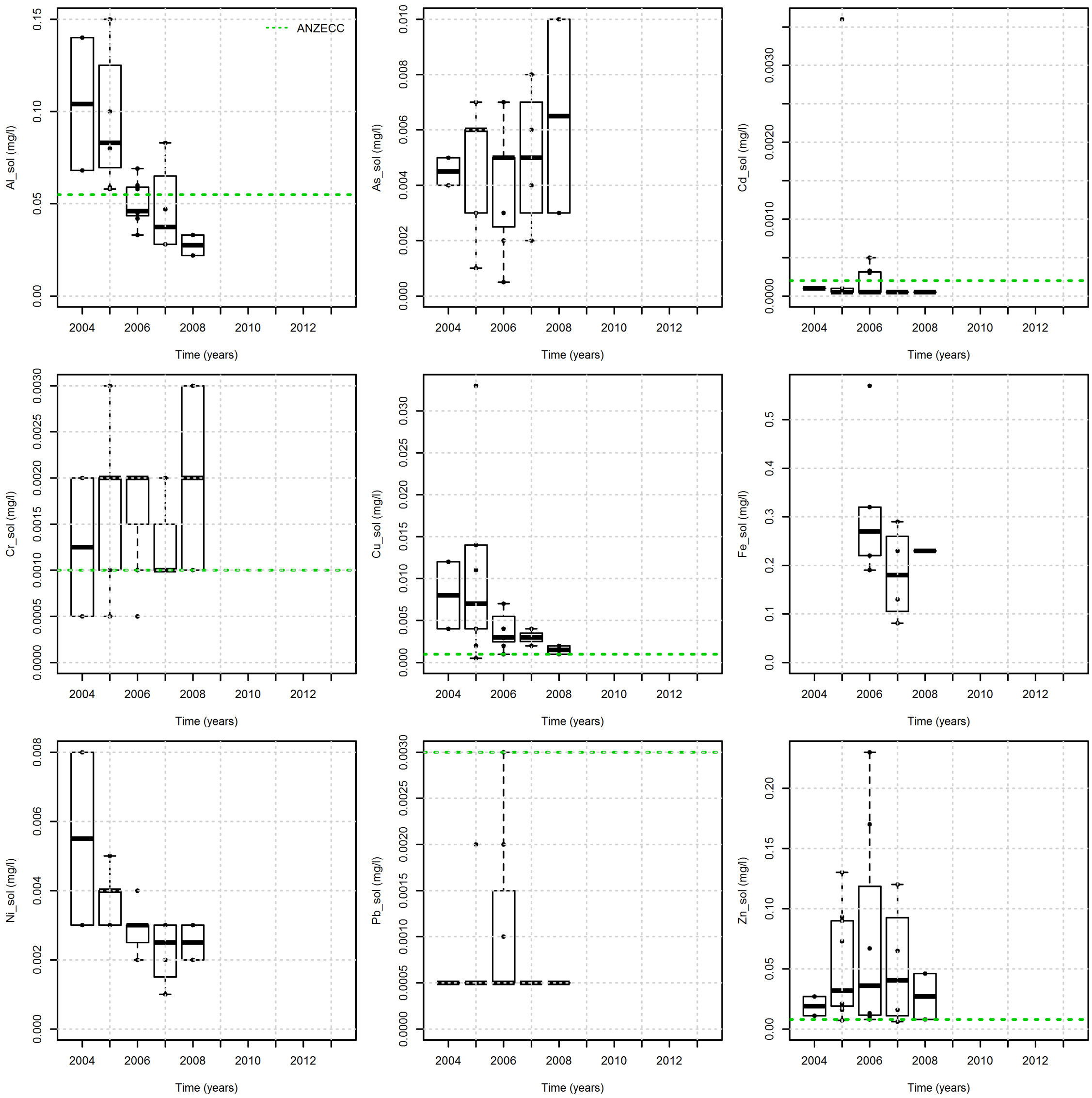


**Figure 21. Concentration of soluble metals in the wetland outlet. Compared with ANZECC guidelines. Note: Nickel and arsenic guideline values are 0.011 mg/L and 0.013mg/L respectively; they are not shown in the graphs. There is no guideline value for soluble iron.**

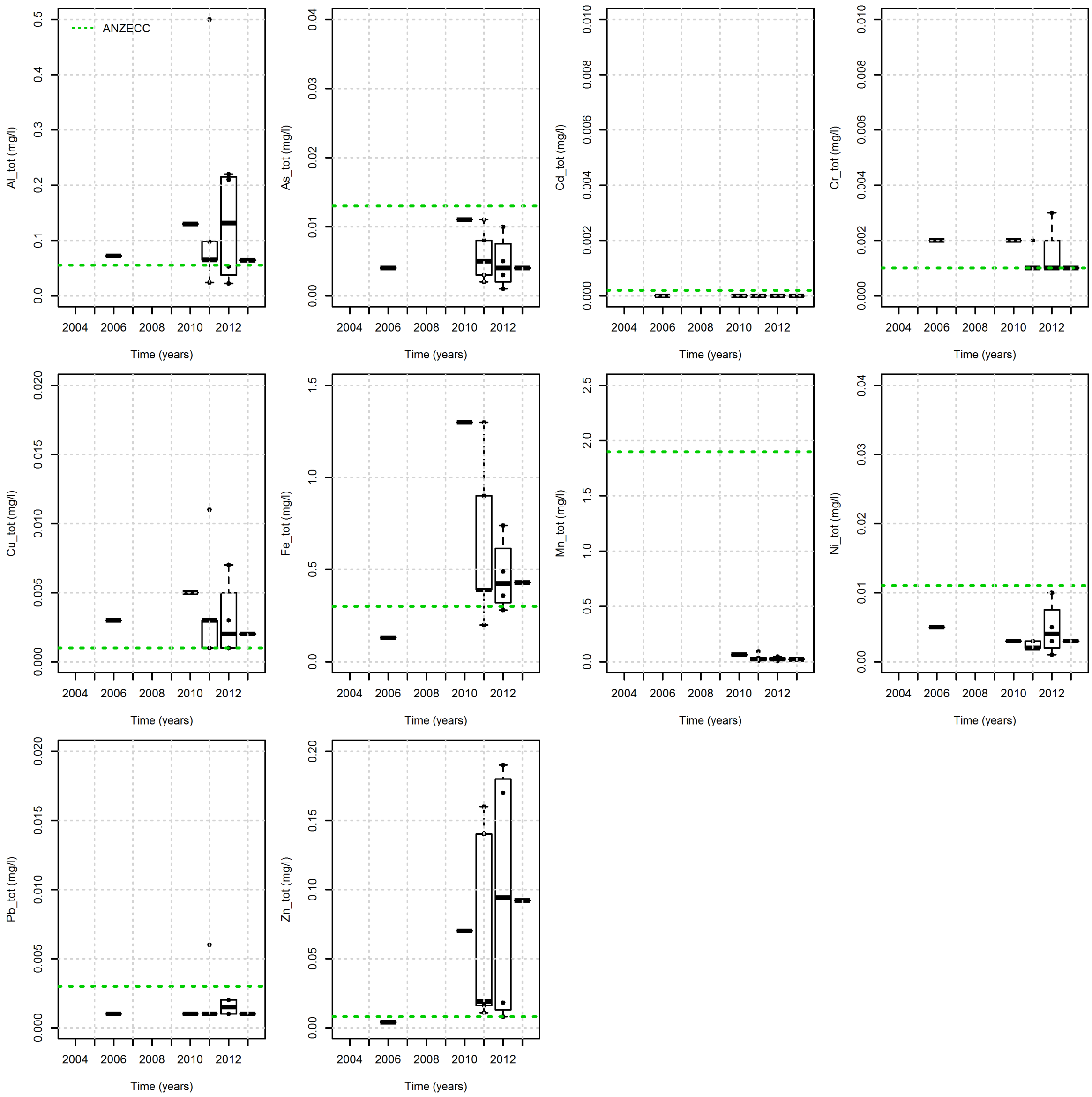


**Figure 22. Concentration of total metals in the wetland outlet compared with ANZECC guidelines.**

## Groundwater

*Comparison to ANZECC guidelines*

Monitoring of soluble metals in groundwater occurred only in 2010 and 2011. Soluble Al concentrations were well above the guideline and Cr and Zn occasionally exceeded the guideline (Figure 23). The range of soluble Al concentrations in the groundwater were similar to the range of concentrations observed in the surface water for the monitoring stations in the wetland other than the outlet (not shown). Cr and Zn concentrations were higher in surface waters. A reduction in soluble metal concentrations was observed in 2011; however, it is difficult to associate this only to the reconstruction effort undertaken within the wetland.

Total metals in groundwater were only monitored in 2011 and 2012 (Figure 24**Error! Reference source not found.**). Al, Cr, Fe and Zn exceeded guideline values. Concentrations of these metals in groundwater were in general lower than in the wetland surface water.

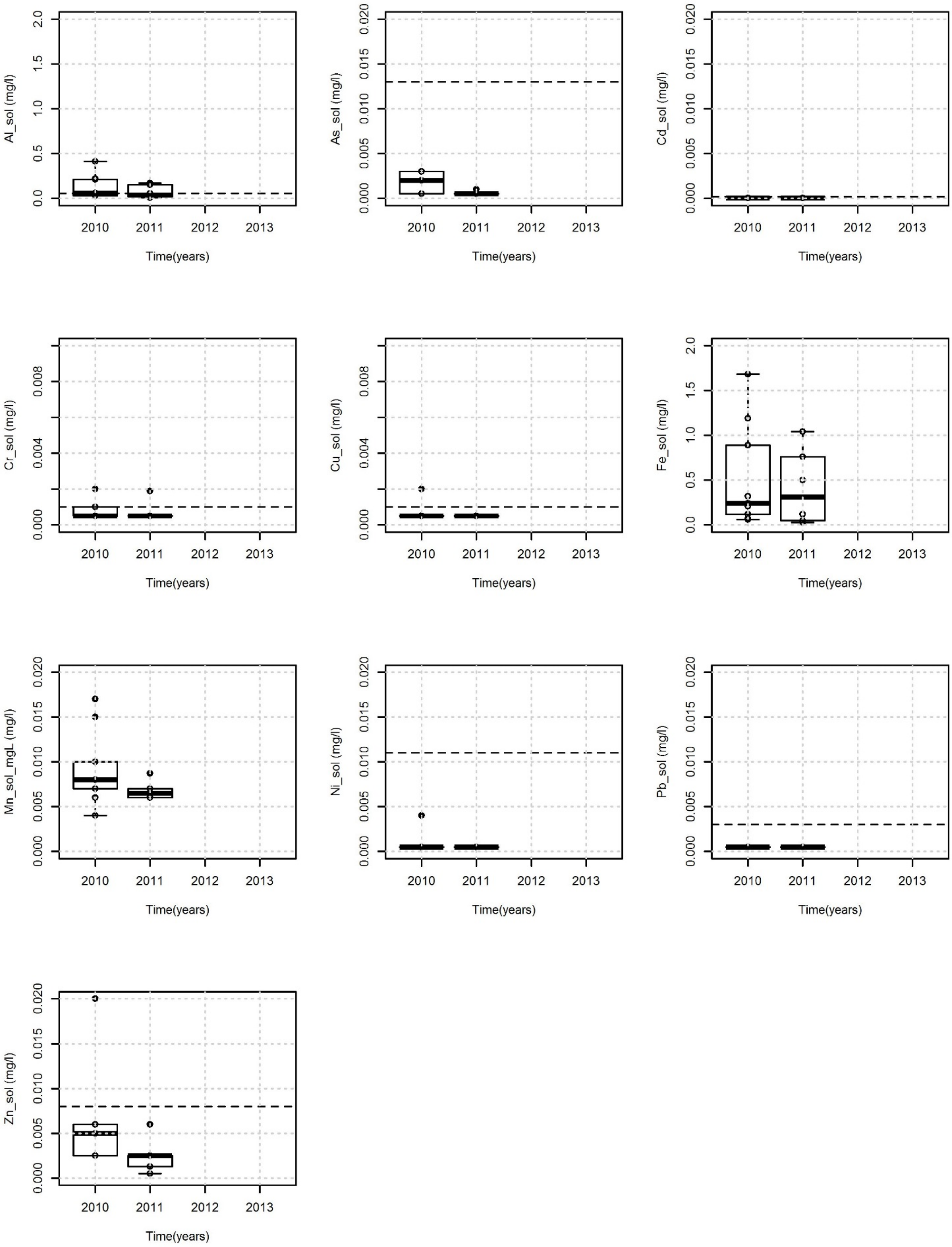


**Figure 23. Concentrations of soluble metals in groundwater compared with ANZECC guidelines (all stations included).**

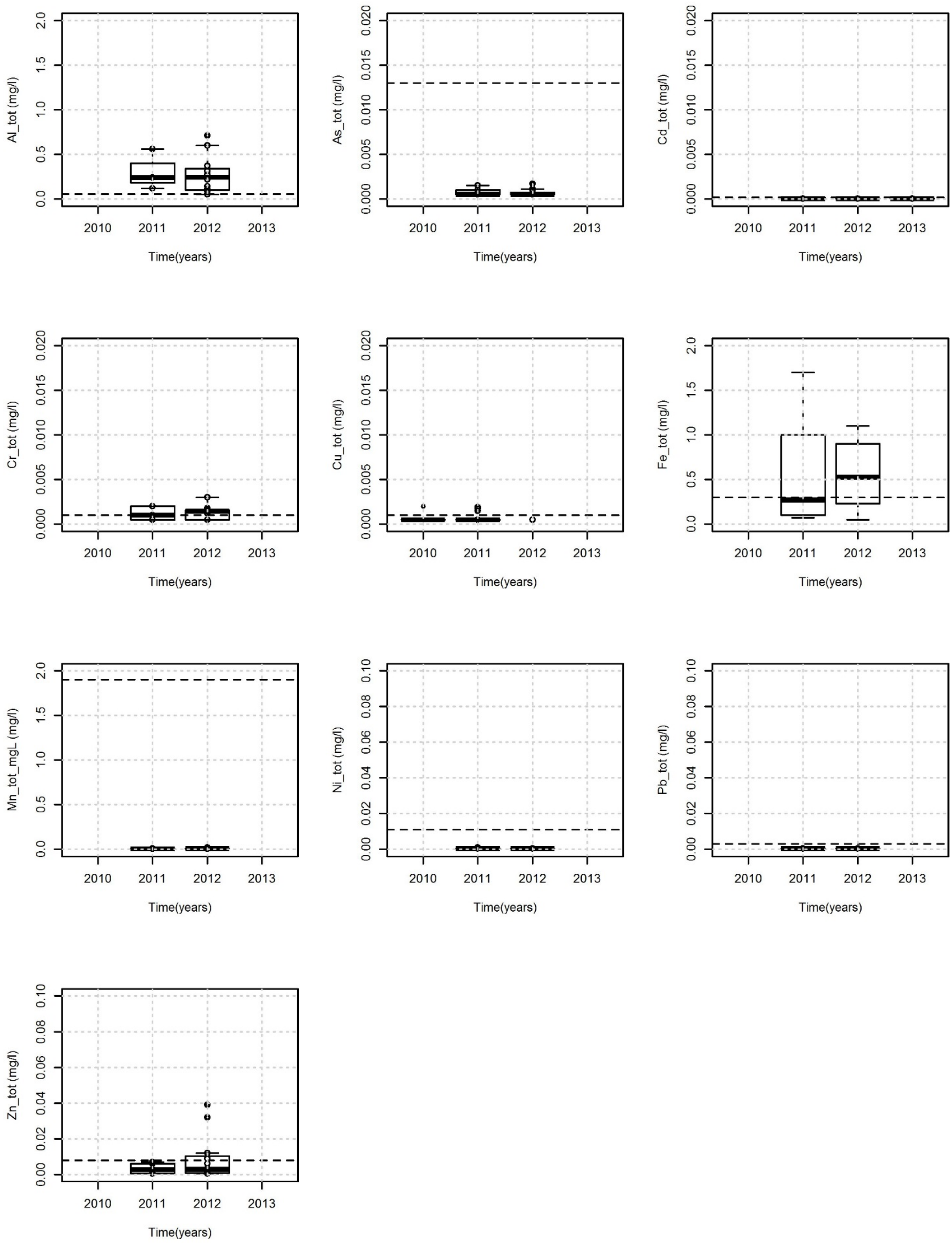


**Figure 24. Concentration of total metals in groundwater compared against ANZECC guidelines.**

## Sediment

*Comparison to ANZECC guidelines*

Extractable metals have only been measured in 2005 and therefore are excluded from this analysis. Total metal concentrations are presented and compared against the low and high guideline values (Figure 25) highlighting that the most critical metal in the AWCB sediments is Zn, with concentrations well above the high guideline value. Other metals, such as Cu, Hg, Ni, Pb and non-metals such as As also represent a concern for the environment, with concentrations of these metals occuring below the high limit but above the lower guideline value. Overall, there was a decrease in metal concentrations from 2004 until 2010 when the reconstruction of the wetland was undertaken. Concentrations of metals were low in 2011 and possibly in response to the AWCB reconstruction efforts (all sulfidic sediment was removed from the basin in 2010). They increased again from 2012

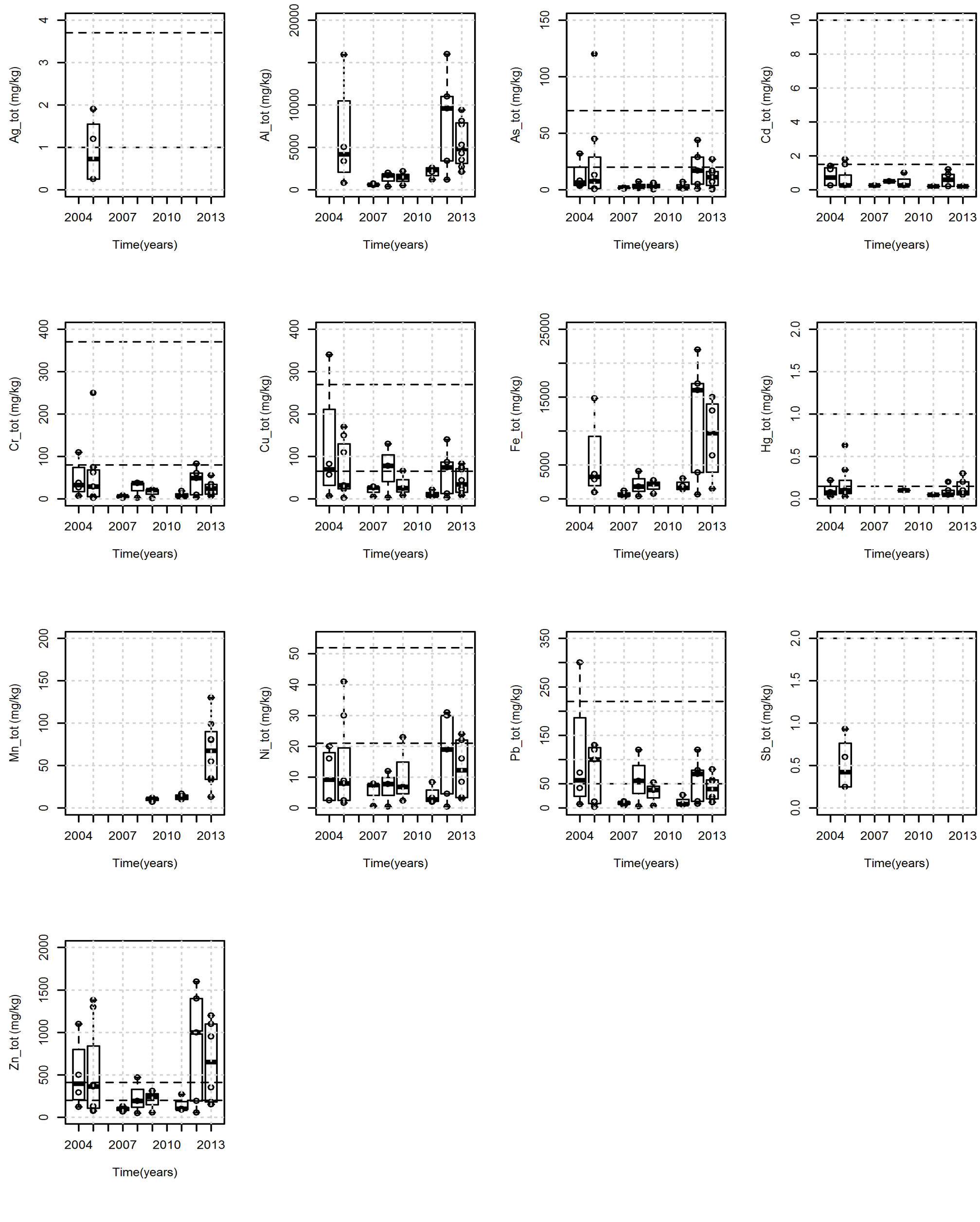


**Figure 25. Concentration of total metals in sediment compared with sediment guidelines (all stations included). Horizontal dashed lines represent high and low interim ANZECC & ARMCANZ guidelines.**

# Wetland treatment performance

This section presents two types of analysis that aim to assess the performance of the wetland at removing nutrients and metals.

The first analysis compares the spatio-temporal variability of pollutant concentrations in the surface water. The second analysis aims to quantify the reduction of pollutants during their passage through the AWCB. The last analysis has been approached in two ways: (a) by estimating the reduction in concentrations (calculation of standardised delta concentration) and (b) by calculating the pollutant load reduction. Strengths and weaknesses in these two approaches are explained below.

## Spatio-temporal variability of pollutant concentrations within the wetland

The variability of the pollutant concentration is compared in time and among four main monitoring stations:

- Wetland inlet (**MSANVCBIN**)
- Middle (**MSANVCBMID**)
- Mars Street Drain inlet (**MSMA1**)
- Wetland outlet (**MSANVCBOUT**)

In addition, concentrations of nutrients at the outlet were statistically analysed for comparison between concentrations before and after reconstruction of AWCB.

### Nutrients

The differences in nutrient levels between different monitoring stations of the wetland are shown in Figure 26. For much of the time, the wetland outflow has the lowest nutrient concentrations of the four sites. Overall, nitrogen concentrations are reduced to a greater extent than phosphorus concentrations. Most nitrogen species concentrations at the outlet are lower than concentrations at both the main inlet and the Mars Street Drain inlet. In contrast, phosphorus concentrations at the outlet are lower than at Mars Street Drain inlet, but close to or above the concentrations at the main inlet.

Dissolved organic nitrogen (DON) is quite stable while NOx shows an overall increase over the analysed period for all the monitoring sites. The limited dissolved organic carbon (DOC) data indicates higher concentrations at the drain outlet than at the other monitoring stations. On an annual basis there seems not to be an important difference between before and after the reconstruction of the AWCB. Only DON and NOx seem to have a decreasing and increasing trend, respectively, after the reconstruction of the AWCB and the mean annual concentrations in the outlet are similar or less than the wetland inlet.

Table 5 displays the p-values for the comparison of nutrient concentrations in the wetland outlet before and after the reconstruction of the AWCB.

**Table 5. Statistical comparison of the outflowing nutrient concentrations before and after the construction of the living stream.**

| | Parametric paired t-test (95%) p-value | Non-parametric paired t-test (95%) p-value | Difference in concentrations before and after the wetland modification |
|---|---|---|---|
| TN | 0.04 | | **significant** |
| TKN | | 0.01 | **significant** |
| NOx | | 0.05 | borderline |
| $NH_3$ | 0.63 | | not significant |
| TP | | 0.24 | not significant |
| FRP | | 0.17 | not significant |

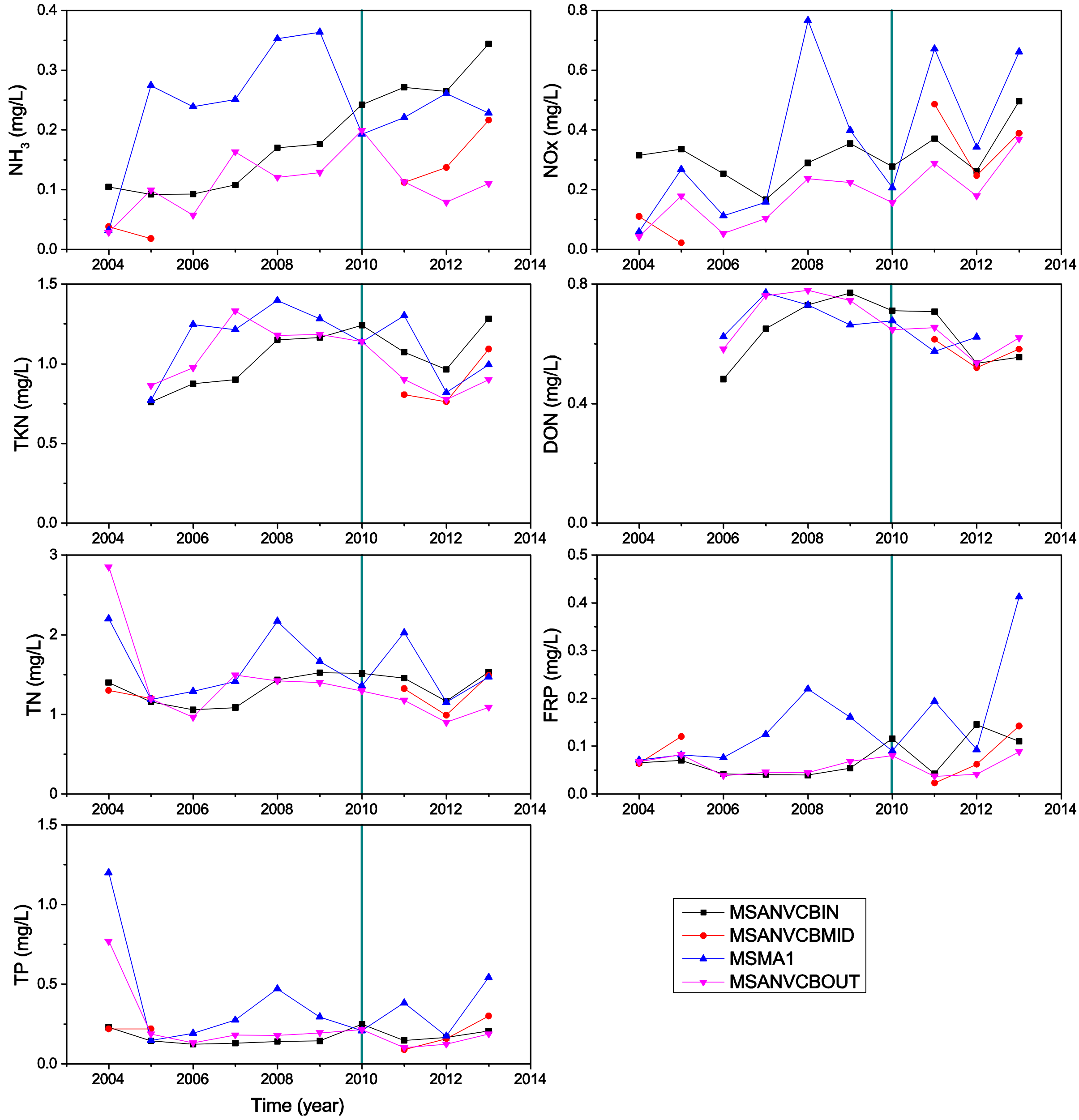


**Figure 26. Temporal variability of annual average nutrient concentrations at four different locations within the AWCB. Blue vertical line indicates the basin restoration.**

### Metals

For this analysis two outliers were not considered: 18/01/2011 and 7/03/2012. Concentrations of total metals for these days ranged between 85 and 112 mg/L.

The concentrations of metals are higher at the Mars Street drain inlet (MSMA1), except for As (Figure 27). In general, it seems that the wetland is capable of reducing the concentration of metals as the concentrations at the outlet are below the concentrations at the inflows.

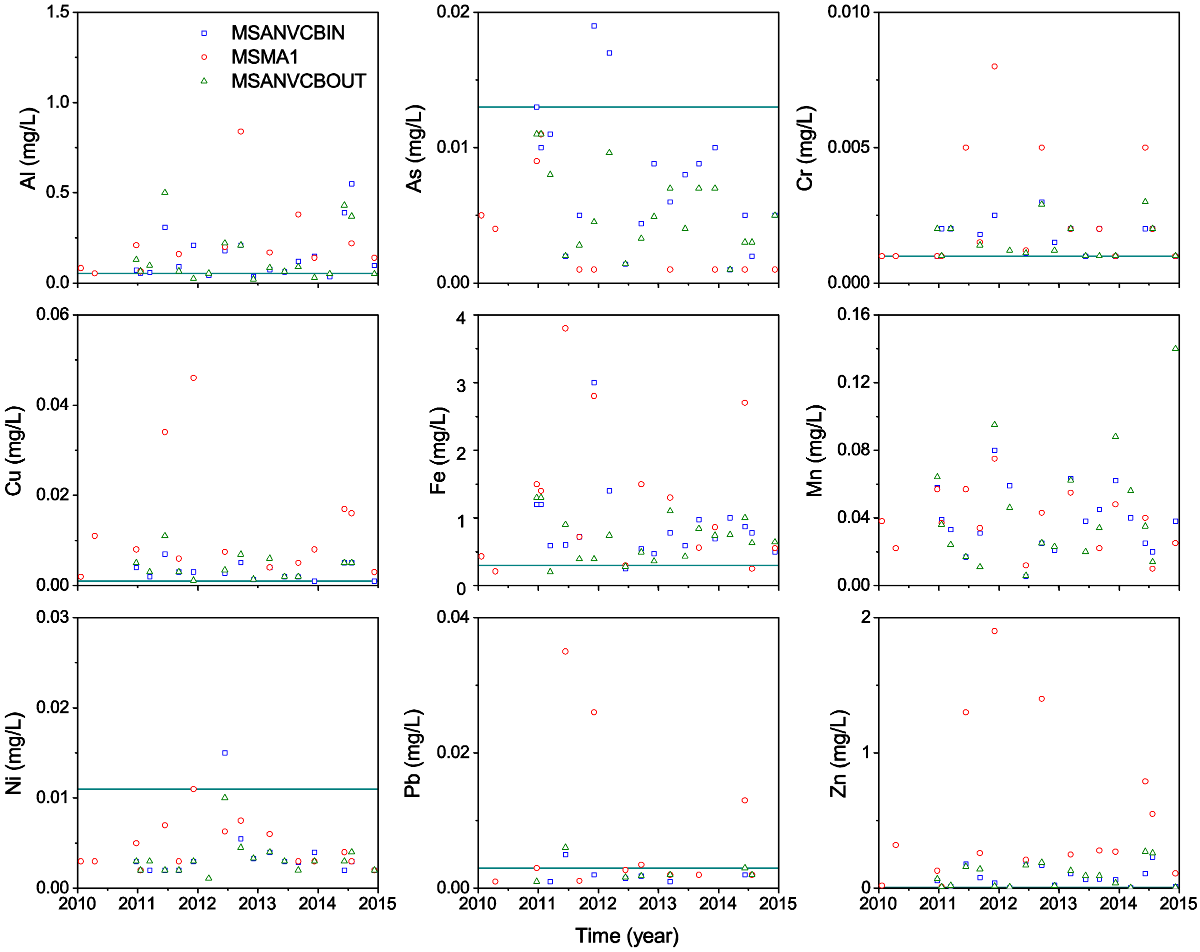


**Figure 27. Temporal variability of average total metal concentration at three different locations within the wetland. Horizontal blue line represents the ANZECC guideline for that metal.**

## Reduction of pollutant concentrations across the wetland

Wetland efficiency is typically calculated as the difference between pollutant load in the influent ($L_{in}$) and effluent ($L_{out}$). For the computation of the load, pollutant concentration and water flow should be monitored simultaneously at the inlet and outlet. In the AWCB, there are two main inlets: (1) MSANVCBIN and (2) MSMA1.

Unfortunately, since flow records in the inlet are restricted to only two years (2012 and 2013) and only one of the inlets (MSANVCBIN), the calculation of "wetland efficiency", and how it has changed with time, was not always possible. The estimation in the reduction of the nutrients was therefore approached in two ways:

(1) Estimation of standardised delta concentration (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 caused by dilution processes driven by ungauged sources rather than an actual biogeochemical reduction of nutrient loads.
(2) Estimation of loads after the reconstruction. This was calculated on occasions where there was simultaneous records of nutrients and flow in the main inlet and the outlet and when there was no recorded data MSMA1 (and therefore assumed that there was no contribution from this source).

### Standardised delta concentration (SDC)

In this section we approximate the wetland efficiency by calculating the concentration difference between the influent ($\mathrm{C_{in}}$) and effluent ($\mathrm{C_{out}}$), normalised by the influent ($\mathrm{C_{in}}$). We define this estimation as the standardised delta concentration (SDC) and it is expressed as:

$$SDC = \frac{C_{in} - C_{out}}{C_{in}}$$

where $\mathrm{C_{in}}$ is the pollutant concentration at MSANVCBIN and $\mathrm{C_{out}}$ is the pollutant concentration at MSANVCBOUT.

The estimation of the efficiency using the difference in concentrations between the influent and effluent works well for closed systems. Unfortunately, the system cannot be considered a closed system due to the unknown contribution of MSMA1 and groundwater. However, from the water balance analysis we can expect the Mars Street drain to contribute between 20 and 70% depending the time of the year (Figure 6). Consequently, we have considered two scenarios. The first scenario considers the main wetland inlet (MSANVCBIN) as the only contribution and the SDC is calculated as above. The second scenario considers a 50% contribution of MSMA1. In this situation SDC is calculated considering $^{*}\mathrm{C_{in}}$ as the arithmetic average of pollutant concentration at MSANVCBIN and MSMA1, denoted SDC_ave:

$$SDC\_ave = \frac{^{*}C_{in} - C_{out}}{^{*}C_{in}}$$

where $^{*}\mathrm{C_{in}}$ is the averaged pollutant concentration at MSANVCBIN and MSMA1 and $\mathrm{C_{out}}$ is the pollutant concentration at MSANVCBOUT.

The change in the SDC over time is presented below expressed as percentage for the different pollutants, with 100% meaning complete reduction of inlet nutrient concentration. Both, the annual and seasonal changes are analysed below.

### Nutrient reduction: average annual changes

The annual average SDC change over time is shown in Figure 28. For N, the relative reduction in inorganic dissolved fractions (NOx and $NH_3$) is higher than total and organic fractions. There are relatively few episodes of increased concentrations at the outflow (indicated by negative SDC). The reduction of $NH_3$ does not change importantly after the reconstruction of the wetland, however the reduction of NOx seems to be affected by the reconstruction. This is also supported by the statistical analysis (see Table 6 and Table 7).

Unlike dissolved inorganic N fractions, DON and TN reduction seem to be stable i.e. without large losses or gains neither before nor after the reconstruction of the AWCB (however, TN shows greater variability than DON due to the inorganic component). For both, the reduction in concentrations seems to improve after the reconstruction.

The reduction of P, either as TP or FRP, presents high variability. Some positive change is observed after reconstruction of the AWCB, especially in 2011 and 2012.

On average the reduction of inorganic N fractions seems to be greater than the removal of the inorganic P fraction.

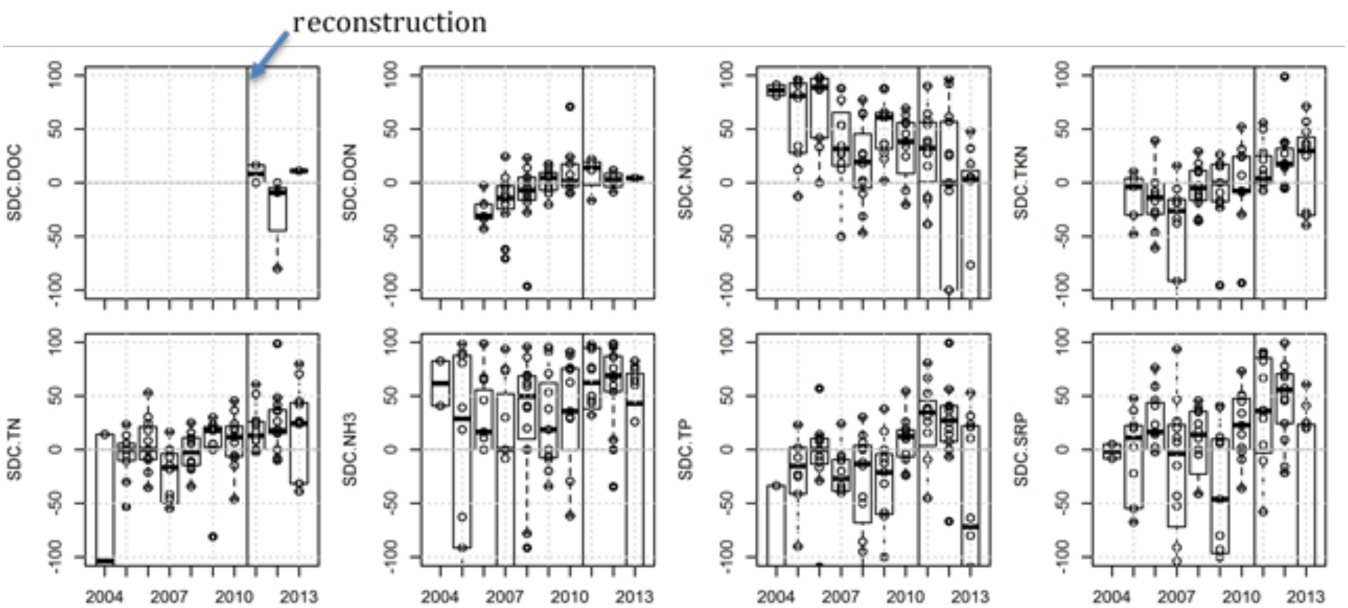


**Figure 28. Annual changes in the standardised delta concentration of nutrients (%). Positive values indicate a reduction in nutrient concentration (SDC = Standardised Delta Concentration)**

### Nutrient reduction: seasonal differences

The SDC was also computed using all available monthly data to demonstrate the large seasonal variation in the wetland operation. As it is not possible to accurately compute the reduction of nutrients due to the lack of information on the Mars Street drain, two scenarios are presented: the first considers SDC with no influence of the Mars Street drain; the second considers a 50% contribution from the Mars Street drain and 50% from the inflow. Whilst we cannot ascertain exactly the reduction due to uncertainty in the data, the range between the values gives an estimate of the variability in the SDC that is caused by the Mars Street drain influence. Figure 29 shows that if we consider the influence of Mars Street drain flows as being equal to the main inlet, the wetland would efficiently remove pollutants most of the time (green line consistently above zero), except for some occasional negative peaks. Similarly to the annual changes, the inorganic fractions of N were observed to vary more than DON and TN.

In terms of seasonality, the wetland seems to reduce nutrient concentrations more effectively in summer, and in particular, this is observed for the inorganic fractions of N. DON is quite stable and is only varying slightly due to seasonal changes.

TP seems to be reduced more effectively during winter. FRP is more variable with decreased SDC in summer. Overall, the reduction percentage of TP and FRP appears to have improved after reconstruction of the AWCB in late 2010, though no statistically significant difference was observed for FRP (Table 6).

From the data presented, it is difficult to definitively assert that the new wetland design has been beneficial in removing dissolved nutrients. Statistical comparison of nutrient reductions before and after the construction of the living stream shows different results for SDC and SDC_ave (Table 6 and Table 7). NOx seems to be more affected as in both cases the statistical tests were significant. However, this result may be biased by two samples in November and December in 2013. In these two occasions, while the concentration of NOx in the outlet ranged from 0.97 to 1.8 mg/L), the concentrations in both inlets were below the detection limit. As a consequence, the calculation of SDC and SDC_ave turned out in large negative values that may have biased the statistical tests. Further analysis is required to understand the reason for these large negative values and increase in NOx, and to understand whether it is contributed to from groundwater seepage, or potentially from biogeochemical transformations occurring within the system.

**Table 6. Statistical comparison of SDC (not accounting for Mars Street drain) before and after the construction of the living stream.**

| | Parametric paired t-test (95%) p-value | Non-parametric paired t-test (95%) p-value | Difference in SDC before and after the wetland modification |
|---|---|---|---|
| SDC DON | | 0.16 | not significant |
| SDC TN | | 0.01 | **significant** |
| SDC TKN | | 0.06 | not significant |
| SDC NOx | 0.03 | | **significant** |
| SDC $NH_3$ | | 0.73 | not significant |
| SDC TP | | 0.03 | **significant** |
| SDC FRP | | 0.09 | not significant |

**Table 7. Statistical comparison of SDC_ave (accounting for Mars Street drain) before and after the construction of the living stream.**

| | Parametric paired t-test (95%) p-value | Non-parametric paired t-test (95%) p-value | Difference in SDC_ave before and after the wetland modification |
|---|---|---|---|
| SDC_ave DON | | 0.500 | not significant |
| SDC_ave TN | | 0.064 | not significant |
| SDC_ave TKN | | 0.013 | **significant** |
| SDC_ave NOx | | 0.037 | **significant** |
| SDC_ave $NH_3$ | | 0.695 | not significant |
| SDC_ave TP | 0.533 | 0.556 | not significant |
| SDC_ave FRP | | 0.556 | not significant |

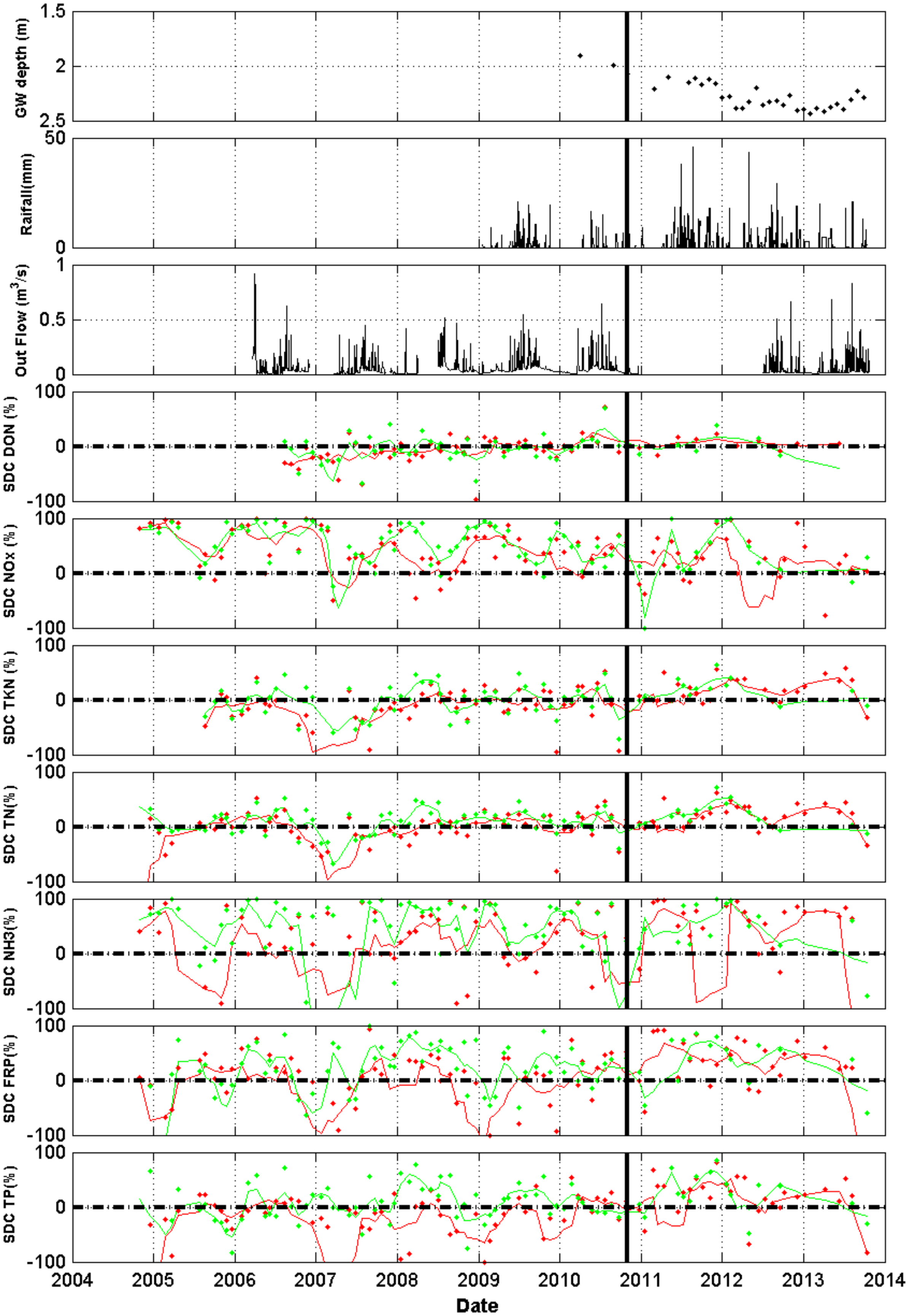


**Figure 29. Temporal variability of groundwater level, rainfall, outlet flow and the SDC of nutrients at AWCB (Red points: *SDC*; Green points: *SDC_ave*; Red line=five point moving average *SDC*; Green line=five points moving average *SDC_ave*). Vertical black line indicates time of the reconstruction. Negative values indicate increase in nutrient concentration at the outlet. Gap between the red and green line indicates the likely level of uncertainty due to lack of gauged data for Mars Street drain.**

### Metal reduction: average annual changes

The reduction in metal concentrations across the wetland is variable (Figure 30 and Figure 31) and also depends on whether one (main) or two (main and Mars Street drain) inlets are considered. When both inlets were given equal weighting then Al, Cu, Fe, Pb and Zn were reduced on average by 50%.

The elements As and Cd seem to be removed only when the main inlet was considered in the SDC calculation. When both inlets were accounted for in the calculation, SDC_ave was negative. This could indicate that these elements may be increased by the system. However, this could also indicate that for these metals, the Mars Street drain may act as a dilution source. This was supported by the fact that the concentration of As and Cd in the Mars Street drain have typically been very low compared to values from the main inlet (Figure 31).

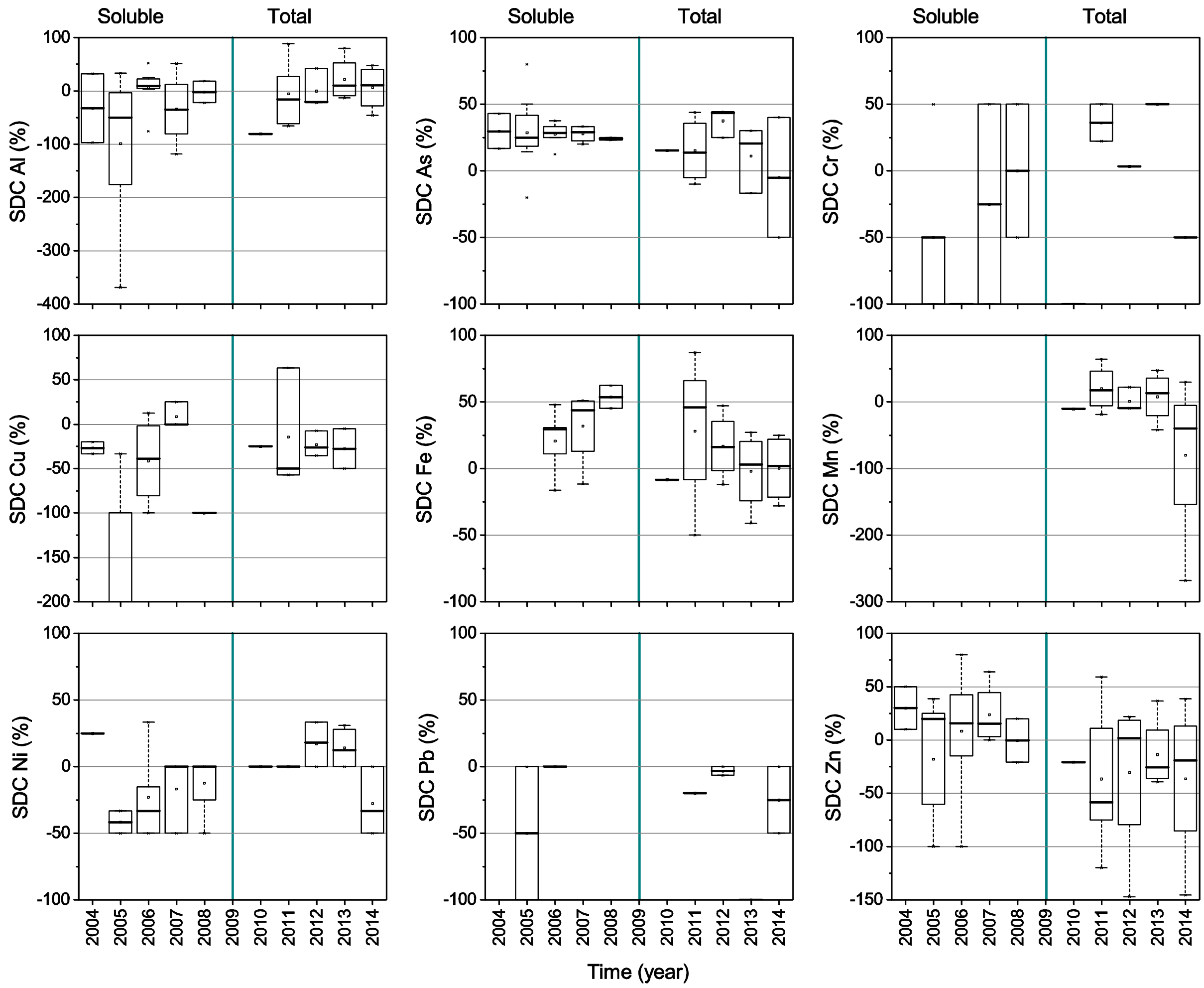


**Figure 30. Annual variability of soluble and total metal attenuation (as SDC). SDC used MSANVCBIN and MSANVCBOUT data. Soluble metal data were available from 2004-2008 and total metal data from 2010 to 2014. Vertical blue line indicates this analytical transition. No data from the main inlet and outlet were available for 2009.**

### Metal reduction: seasonal differences

The analysis of the seasonality in the capacity of the wetland to reduce soluble metals was hampered by the fact that only patchy data was available and in many cases concentrations of metals were very low (Figure 32). There seems to be some seasonality in the removal of Zn and Pb with higher removal during dry months. When only the main inlet was considered in the calculation of SDC, the removal of metals was mostly negative (except for As) indicating low removal or the presence of another unmonitored source. When the effect of the Mars Street drain was taken into account the wetland showed positive SDC indicating removal of the metals.

Arsenic was the exception to this since it displayed a persistently negative value for SDC_ave. However, this does not necessarily indicate an increase in As. Due to the low concentration of As measured in the Mars Street Drain, it was likely contributing to the dilution of As in the main inlet. It was therefore not possible to distinguish between a removal or dilution effect.

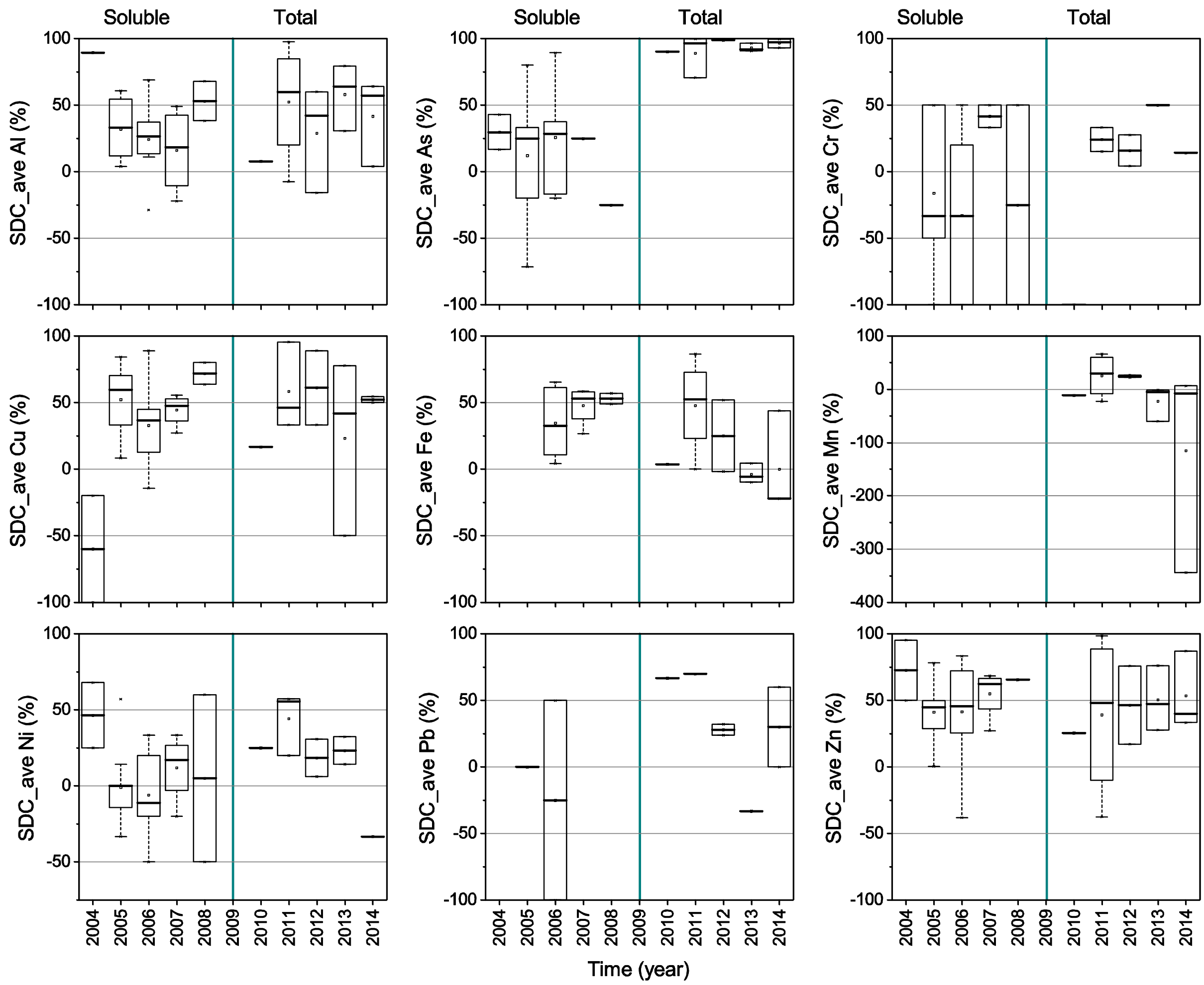


**Figure 31. Annual variability of soluble and total metal attenuation (as SDC_ave). SDC_ave uses the arithmetic mean of MSANVCBIN and MSMA1 data as inlet, and MSANVCBOUT data as outlet. SDC_ave was calculated when data from these three locations were available. Soluble metal data were available from 2004-2008 and total metal data from 2010 to 2014. Vertical blue line indicates this analytical transition. Soluble metal data was available from MSMA1 in 2009, but was not used above as data was not available from the other sites.**

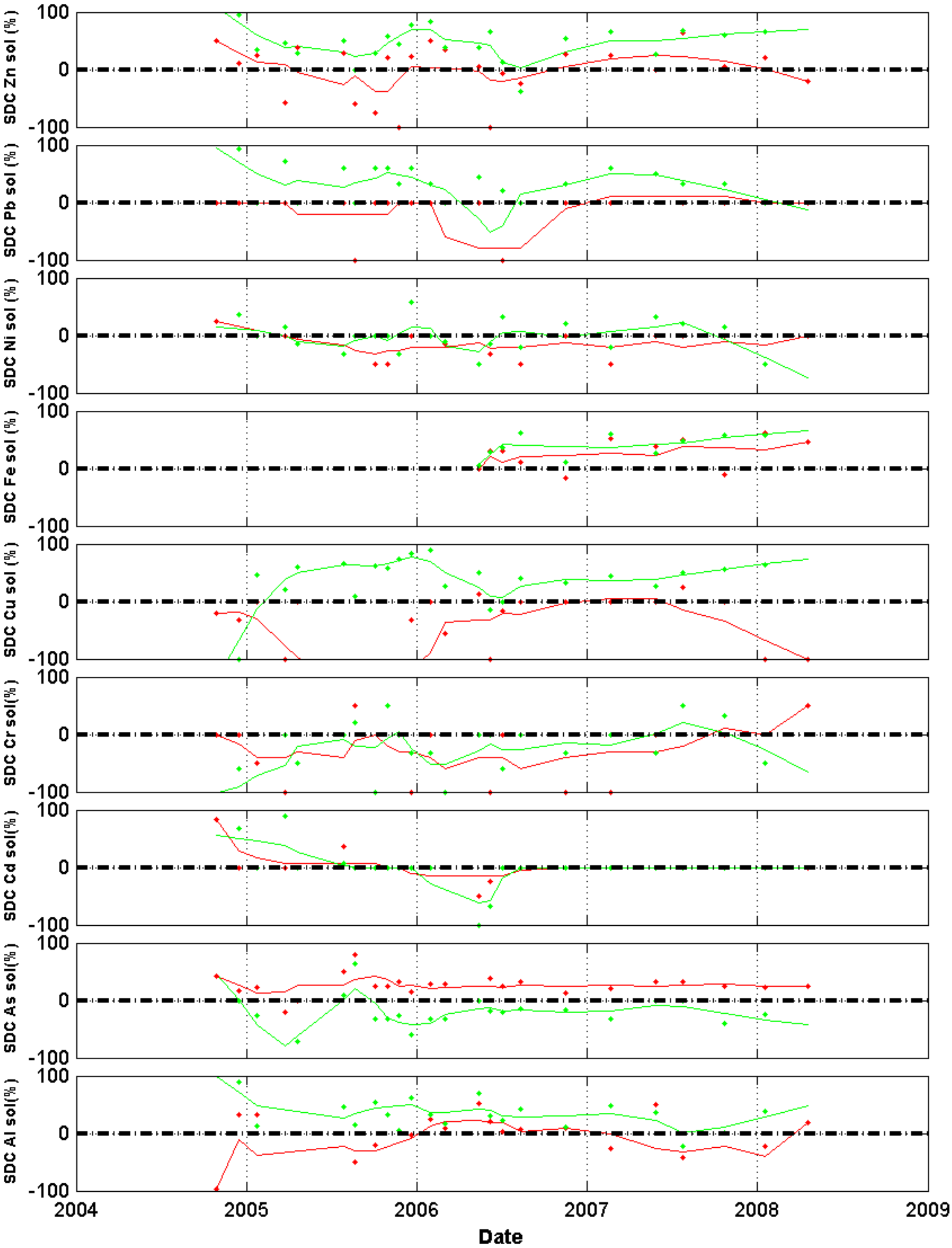


**Figure 32. Temporal variability of the SDC of soluble metals for AWCB (Red points: *SDC*; Green points: *SDC_ave*; Red line=five point moving average *SDC*; Green line=five points moving average *SDC_ave*). Note that the data presented was collected prior to basin re-configuration and soluble metal data was available up to 2008. Negative values indicate increase in nutrient concentration at the outlet. The gap between the red and green lines indicates the likely level of uncertainty due to the lack of flow data from the Mars Street drain.**

## Reduction of pollutant load across the wetland

This section shows the removal efficiency of the wetland expressed as the difference between the pollutant load in and out the system (Figure 33). This could only be calculated for those occasions in which the concentration of pollutant and flow in the inlet and outlet was simultaneously known, and at the same time there was considered to be a relatively small influence of the Mars Street drain. This occurred at eight times between 2012 and 2013.

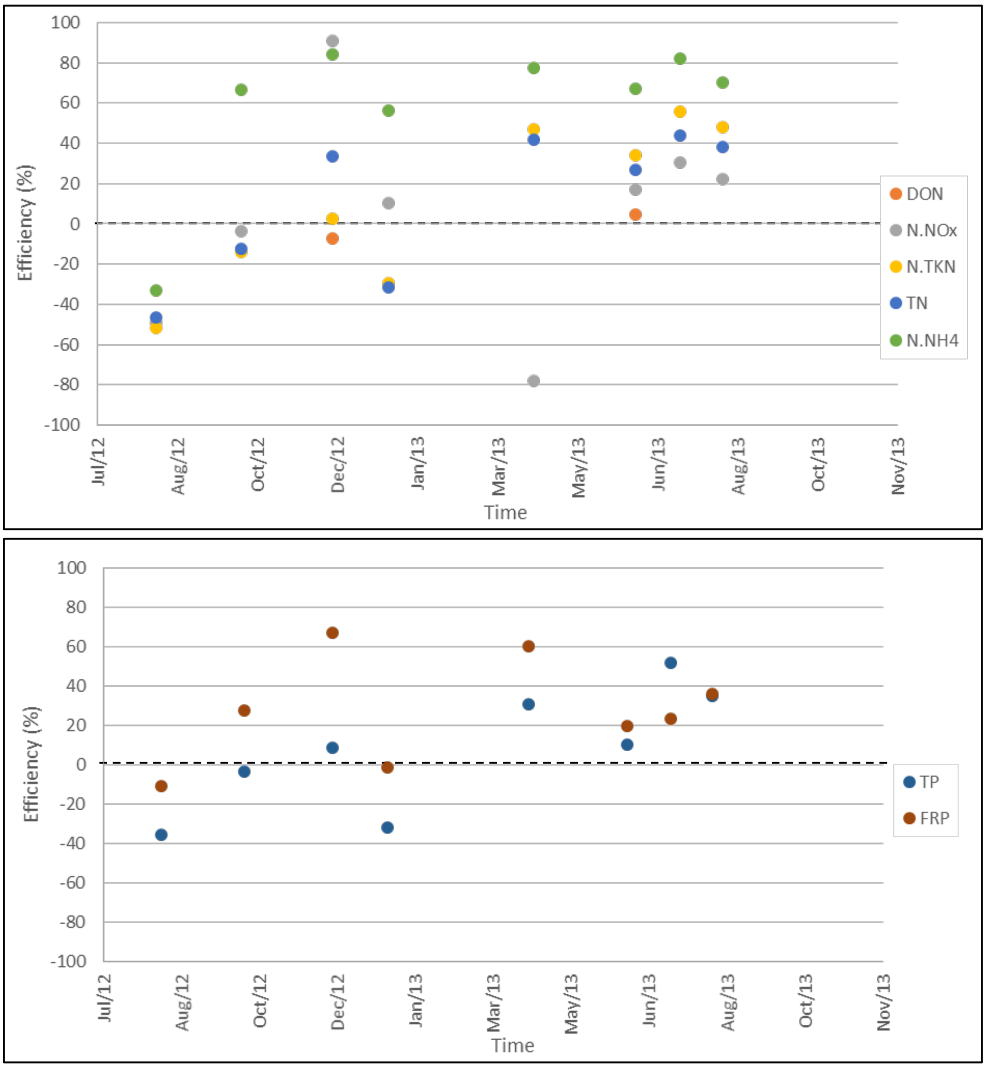


**Figure 33. Wetland efficiency for nutrient removal for N fractions (top) and P fractions (bottom).**

The wetland is highly efficient at removing N as $NH_3$, with the removal efficiency being above 50% (since October 2012). This is equivalent to a mass removal between 0.1 and 11 kg/day (data in kg/day not shown). TKN, TN and NOx are the N species subsequently removed with less efficiency. Although there is only limited data on dissolved organic nitrogen (DON), that data suggests that this fraction is hardly removed. This is consistent with the observation above that the SDC for DON (see Figure 29 in the above section) was generally low.

Similar to N, the efficiency of phosphorus removal improves from October 2012. Phosphorus is removed with an efficiency of up to ~70% for the soluble fraction (FRP), which seems to be removed with more efficiency than TP.

# Vegetation dynamics

The macrophyte monitoring program aimed to monitor spatial variation in nutrient concentrations across the vegetated stands of AWCB in different hydrological zones. 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 nutrient and contaminant can be estimated from repeated harvesting and analysis of macrophyte tissues.

AWCB was re-vegetated five years ago, and annual growth and senescence processes have facilitated macrophyte establishment. *Baumea articulata* (jointed twig-rush) and *Schoenoplectus validus* (lake club rush) represent the most widely dispersed macrophytes across the flats of AWCB. *B. articulata* is a perennial rush native to Australia that can reach heights of 2.5 m (Vymazal & Kröpfelová 2008). It exhibits slow establishment and may remain inconspicuous in its initial growth seasons (Tanner 1996; Vymazal & Kröpfelová 2008). Once established, dense stems are formed with minimal seasonal senescence, with rooting depths of 30-40 cm (Vymazal & Kröpfelová 2008). *S. validus* is a perennial rush with 10-30 cm rooting depths. In mature strands, it exhibits seasonal variations in above-ground biomass (Vymazal & Kröpfelová 2008).

While AWCB was initially planted with five different macrophyte species, in 2012 ground–truthing of only the two dominant species (*B. articulata* and *S. validus)* was conducted (Figure 34). This is the only time species coverage has been determined, despite species coverage and biomass changing significantly during the macrophyte establishment period, and also on a seasonal basis (Figure 35). So while the monitoring program was designed to estimate nutrient removal by plants across the site, the lack of recent ground-truthed species coverage data prevents meaningful estimation of nutrient pools and also nutrient removal by wetland vegetation.

It is important to note that *S. validus* was sampled at all four macrophyte sampling sites on all three samplings dates (October 2012, May 2013 and October 2013). However *B. articulata* was only sampled at ANVMAC1 and ANVMAC2 (due to minimal coverage at ANVMAC3 and ANVMAC4). Also, *B. articulata* was not sampled at all on October 2013 (due to minimal coverage at ANVMAC1 and ANVMAC2). *S. validus* was opportunistic and quickly grew into any gaps, especially in the areas where *B. articulata* was sampled. While *B. articulata* has good longevity, *S. validus* demonstrated effective recruitment and has dominated the site.

Total TKN concentrations in *S. validus* were approximately the same in above and below ground tissue. However, the significantly higher below ground *S. validus* biomass again ensured the below ground total TKN content per unit area was higher.

Total above ground phosphorus concentrations were similar to below ground phosphorus concentrations in *B. articulata* across all sites. However due to the significantly higher below ground biomass, the P content per unit area was higher in below ground *B. articulata*.

Total TKN concentrations in below ground *B. articulata* tissue were significantly higher than in above ground tissue. The significantly higher biomass and the higher TKN concentrations in below ground *B. articulata* tissue ensured the below ground total TKN content per unit area was higher.

In summary, below ground biomass provided significantly more nutrient storage that above ground biomass. In addition, below ground *S. validus* exhibited a seasonal trend, with maximum biomass and nutrient content (per unit area) in May. Nutrient content per unit area was significantly greater for *B. articulata* than *S. validus*. This suggests that wetland management to promote establishment and increased coverage of *B. articulata* would improve nutrient retention across the wetland. We note that with the minimal vegetation management currently in place, *S. validus* has out-competed *B. articulata.* The suggested seasonal dynamics of *S. validus* also suggests that nutrients would be transferred to other pools within the wetland in summer, including possible release to the soil and wetland waters.

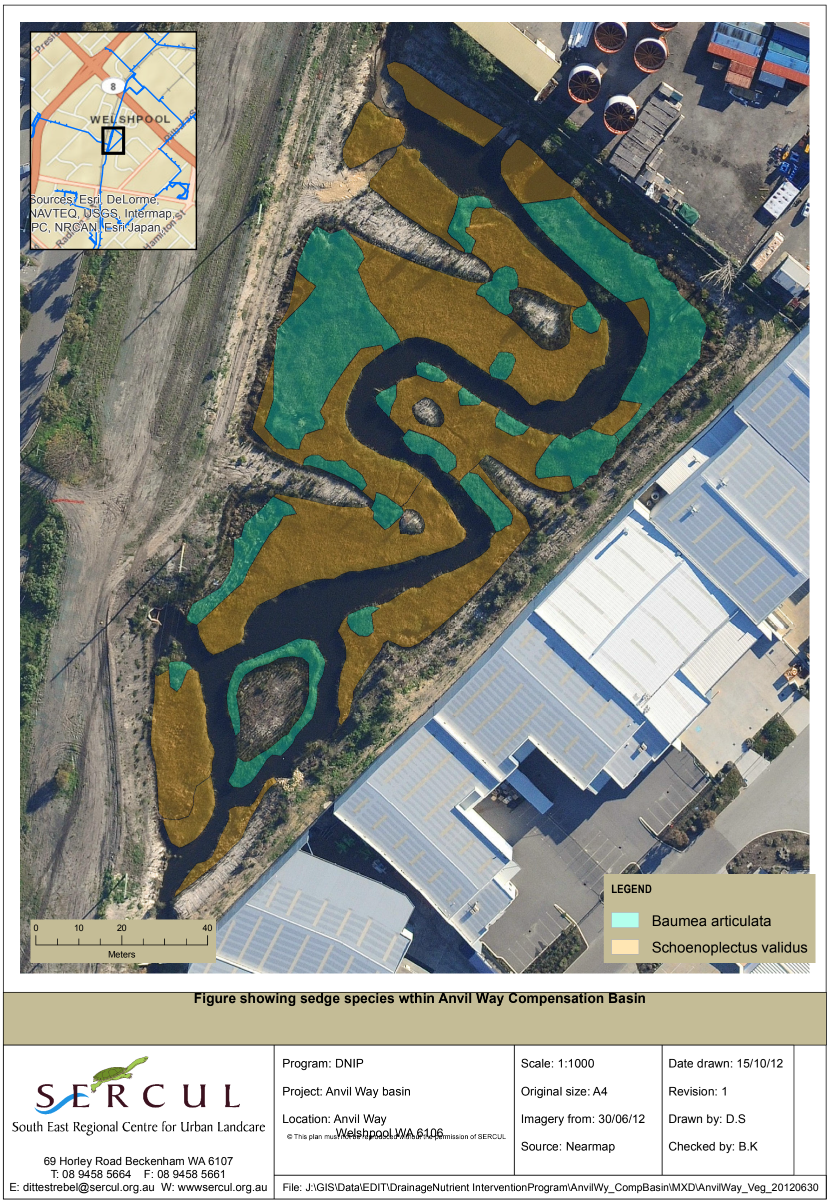


**Figure 34. Ground-truthing of species coverage at June 30, 2012.**


**Figure 35. Comparison of vegetation coverage across the upper part of AWCB. A) June 2012: the date of the ground-truthing of species coverage. B-D) macrophyte tissue sampling dates October 2012, May 2013 and October 2013 respectively.**

Total below ground biomass and biomass per unit area were both significantly higher than above ground biomass (and biomass per unit area), in both *S. validus* and *B. articulata* and across all sites (see Figure 36 to Figure 45). *S. validus* above ground biomass varied significantly across seasons and sites, with no clear seasonal trends. *S. validus* below ground biomass showed district seasonal variation, peaking in May 2013 (we note that the scarcity of seasonal data makes trend analysis challenging). No seasonal trend in biomass was obvious for *B. articulata*.

Total above ground phosphorus concentrations were significantly higher than below ground phosphorus concentrations in *S. validus* across all sites. However due to the significantly higher below ground biomass, the P content per unit area was higher in below ground *S. validus*.

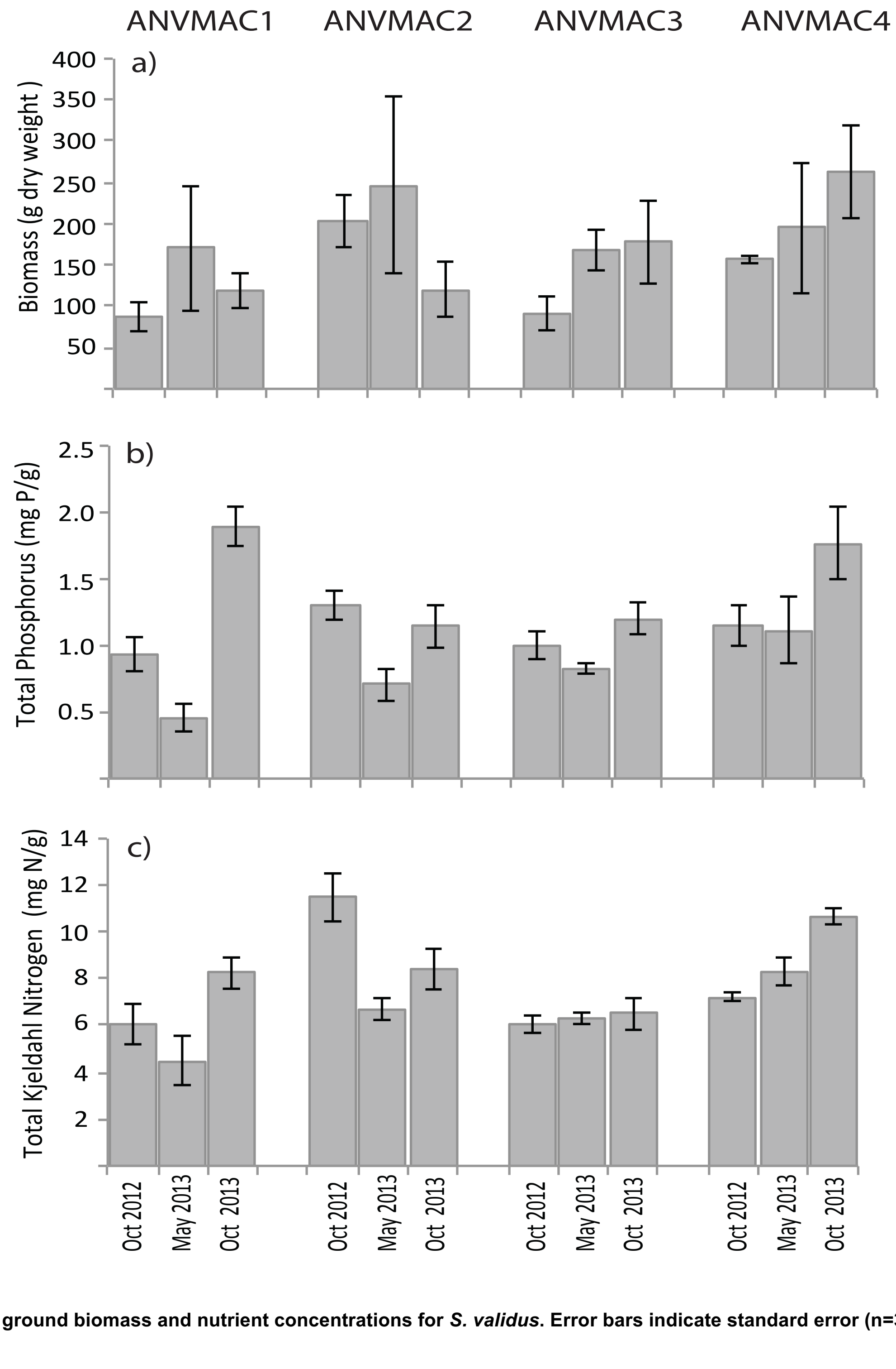


**Figure 36. Above ground biomass and nutrient concentrations for *S. validus*. Error bars indicate standard error (n=3).**

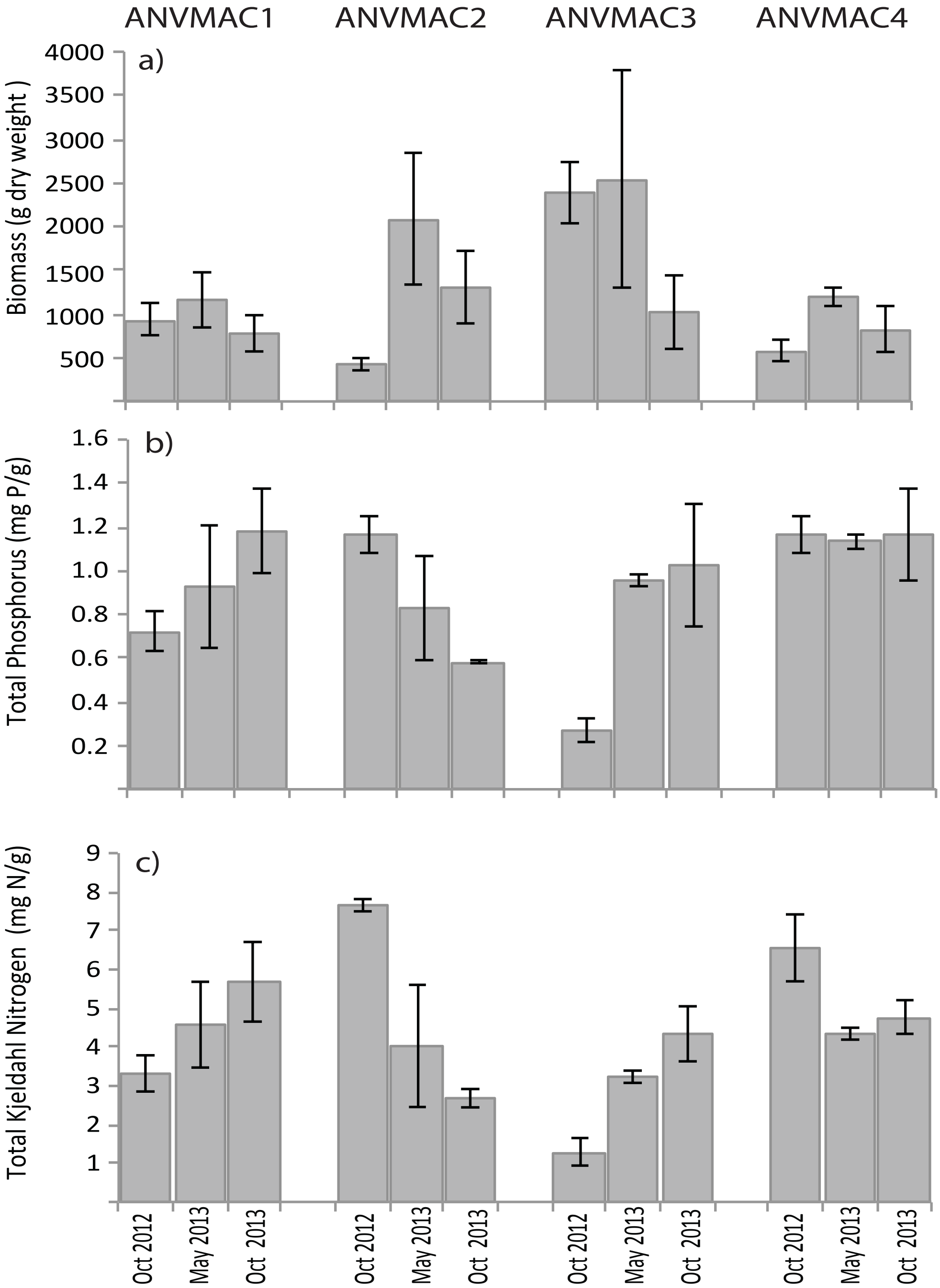


**Figure 37. Below ground biomass and nutrient concentrations for *S. validus*. Error bars indicate standard error (n=3).**

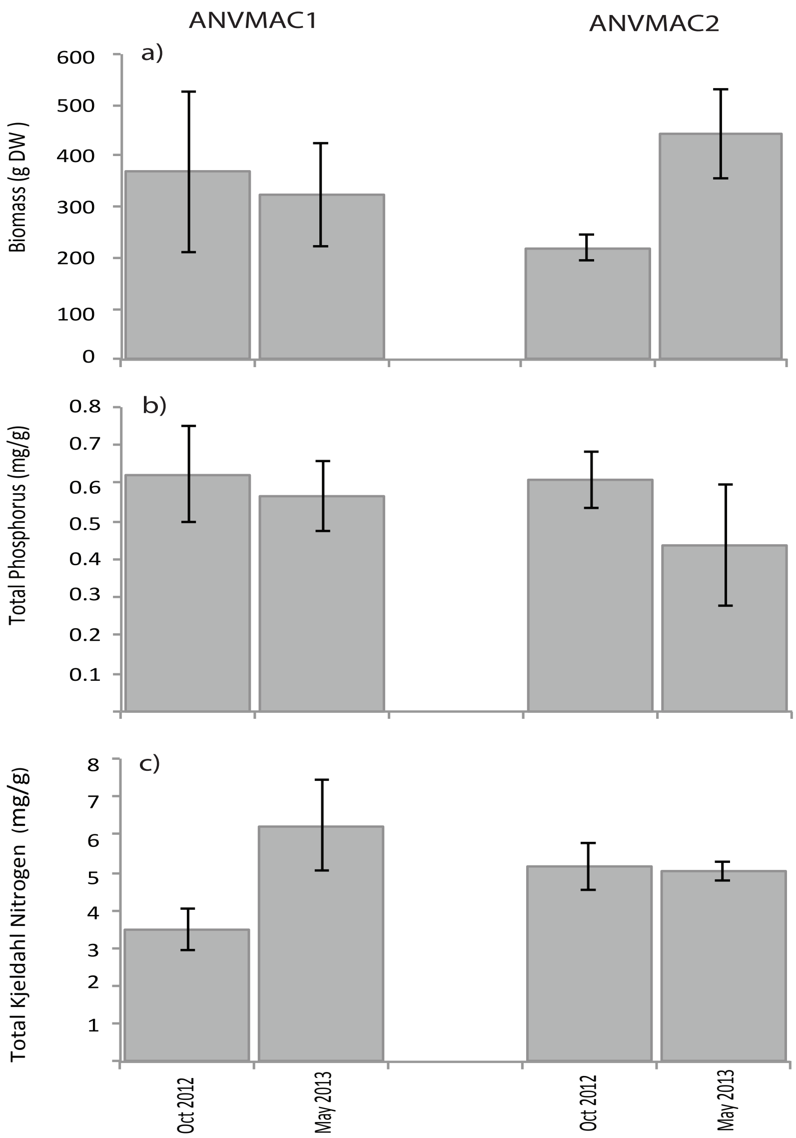


**Figure 38. Above ground biomass and nutrient concentrations for *B. articulata*. Error bars indicate standard error (n=3).**

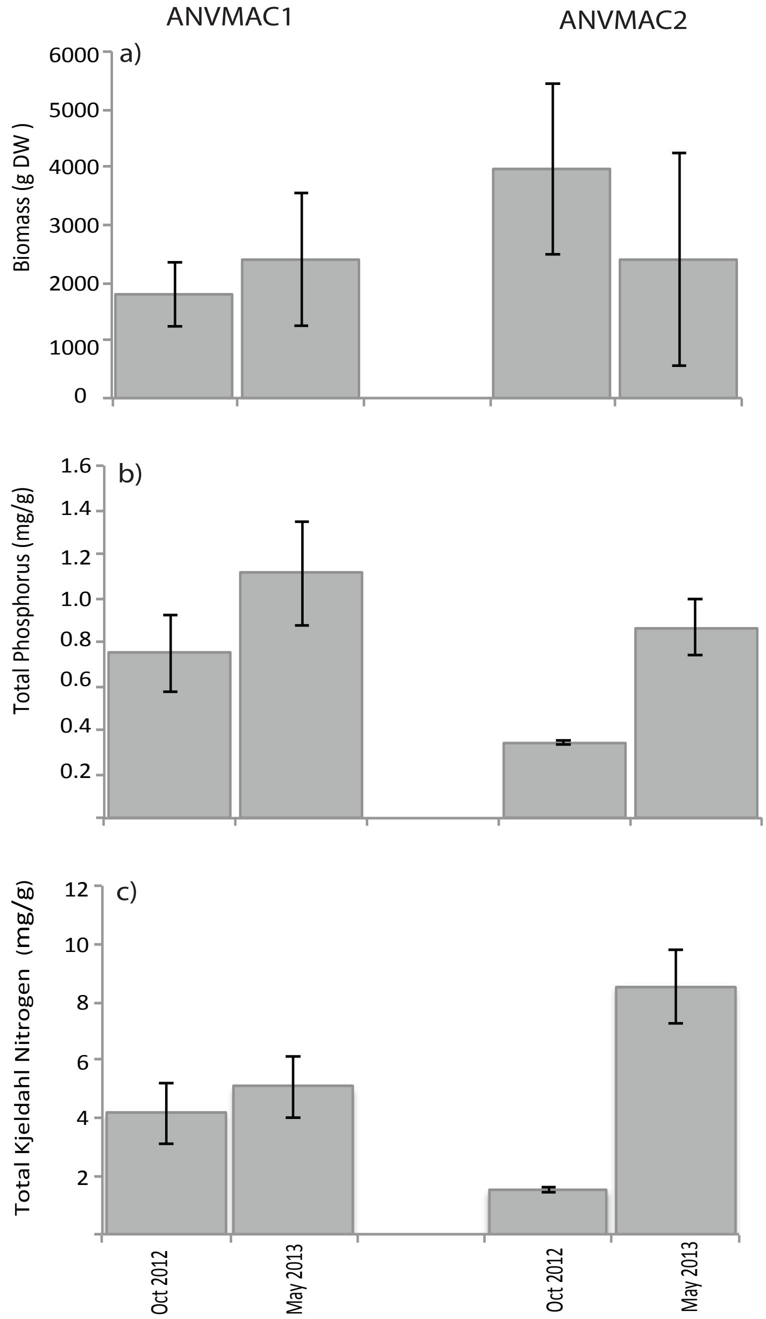


**Figure 39. Below ground biomass and nutrient concentrations for *B. articulata*. Error bars indicate standard error (n=3).**

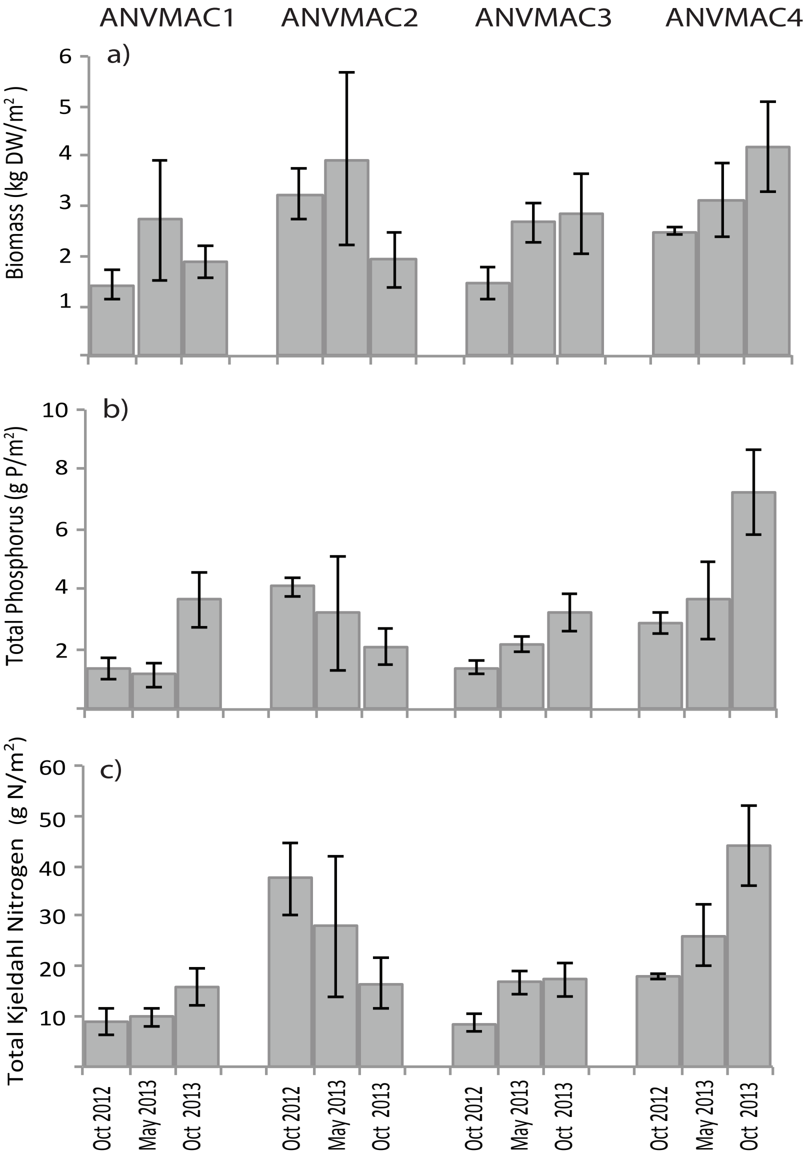


**Figure 40. Above ground biomass and nutrient concentrations per unit area for *S. validus*. Error bars indicate standard error (n=3).**

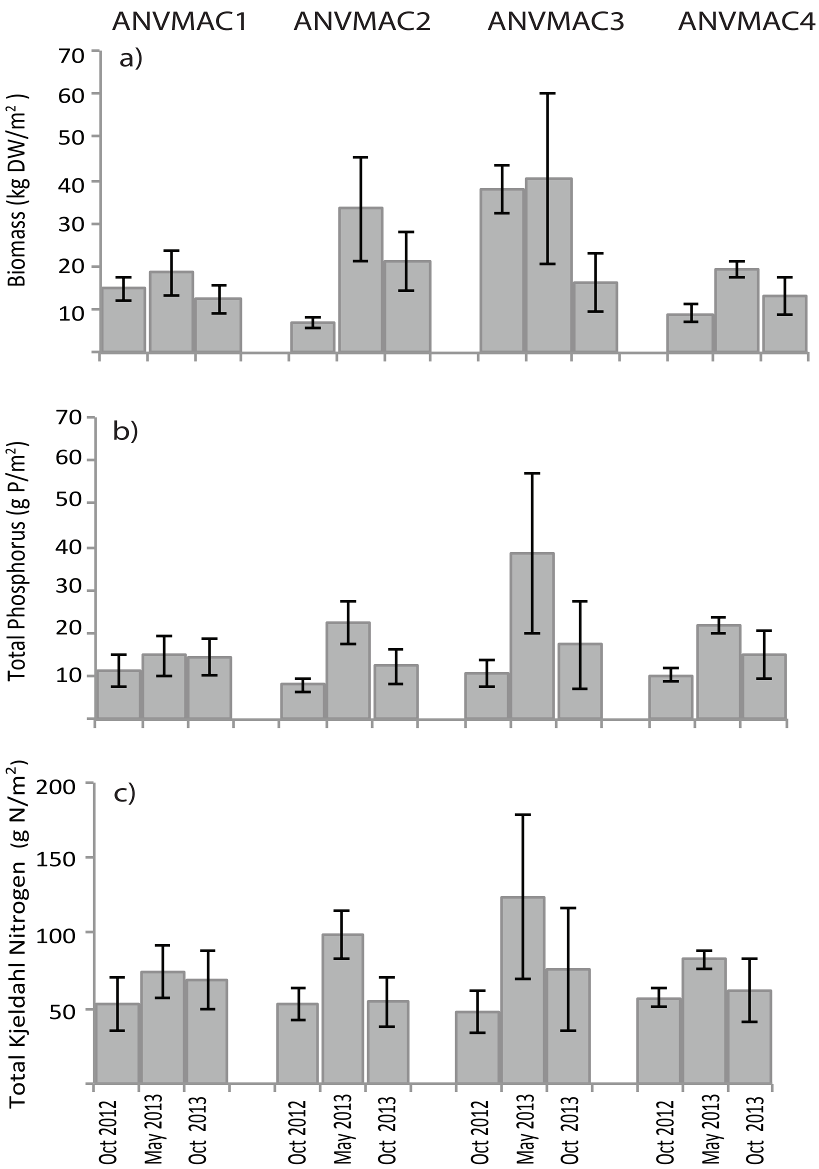


**Figure 41. Below ground biomass and nutrient concentrations per unit area for *S. validus*. Error bars indicate standard error (n=3).**

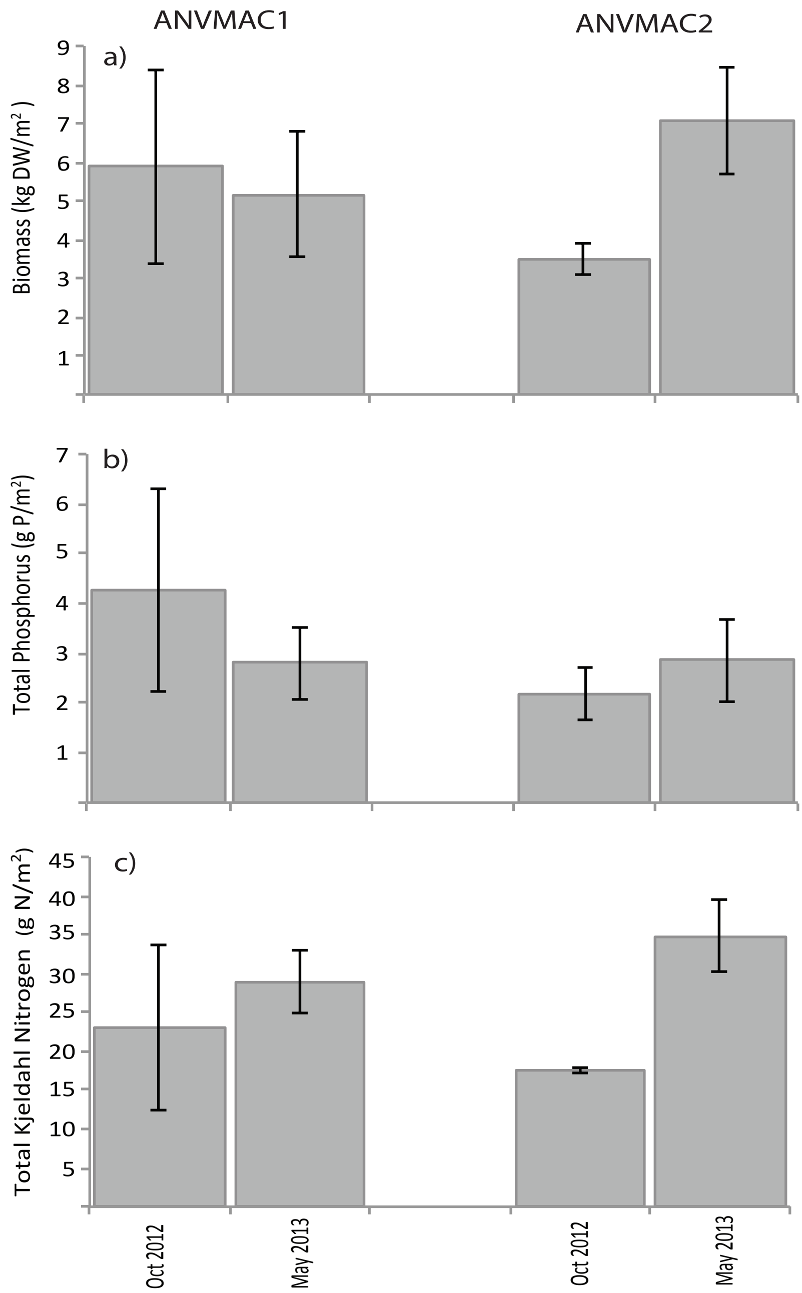


**Figure 42. Above ground biomass and nutrient concentrations per unit area for *B. articulata*. Error bars indicate standard error (n=3).**

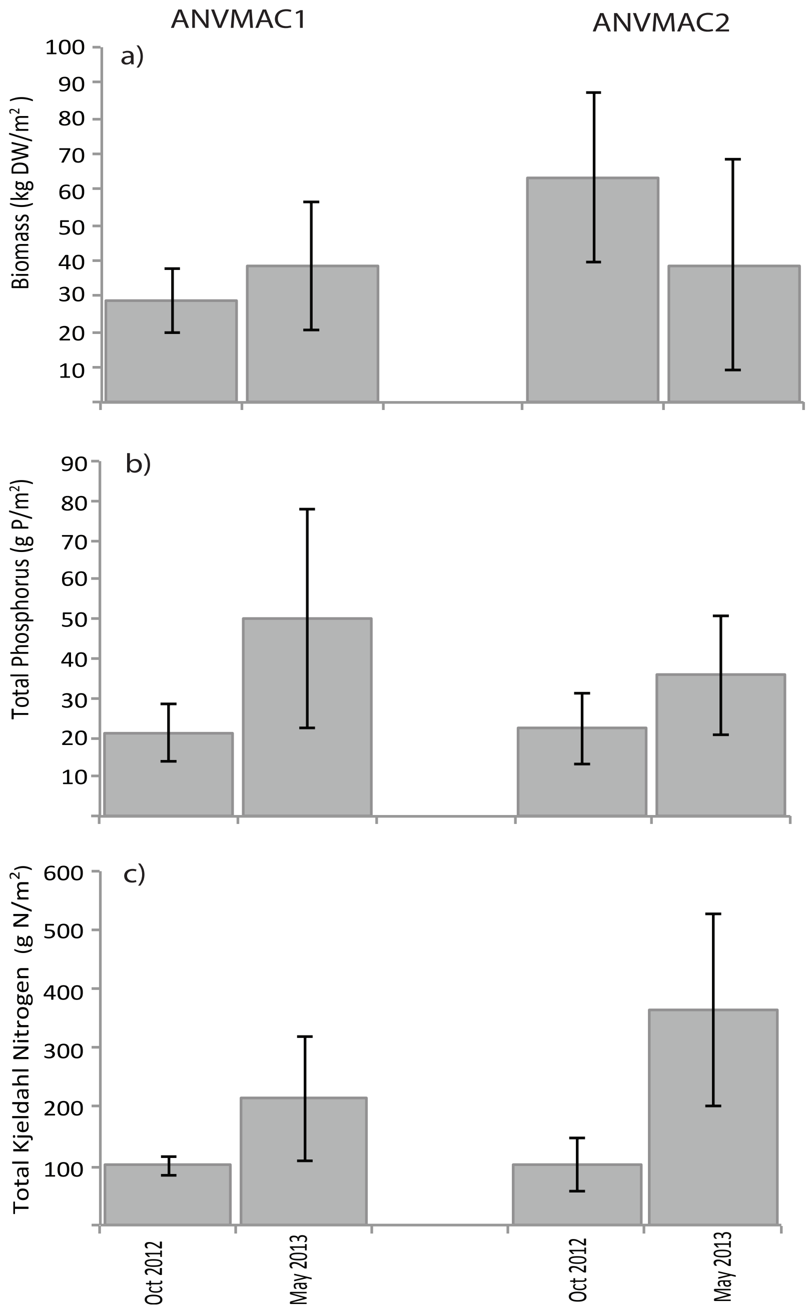


**Figure 43. Below ground biomass and nutrient concentrations per unit area for *B. articulata*. Error bars indicate standard error (n=3).**

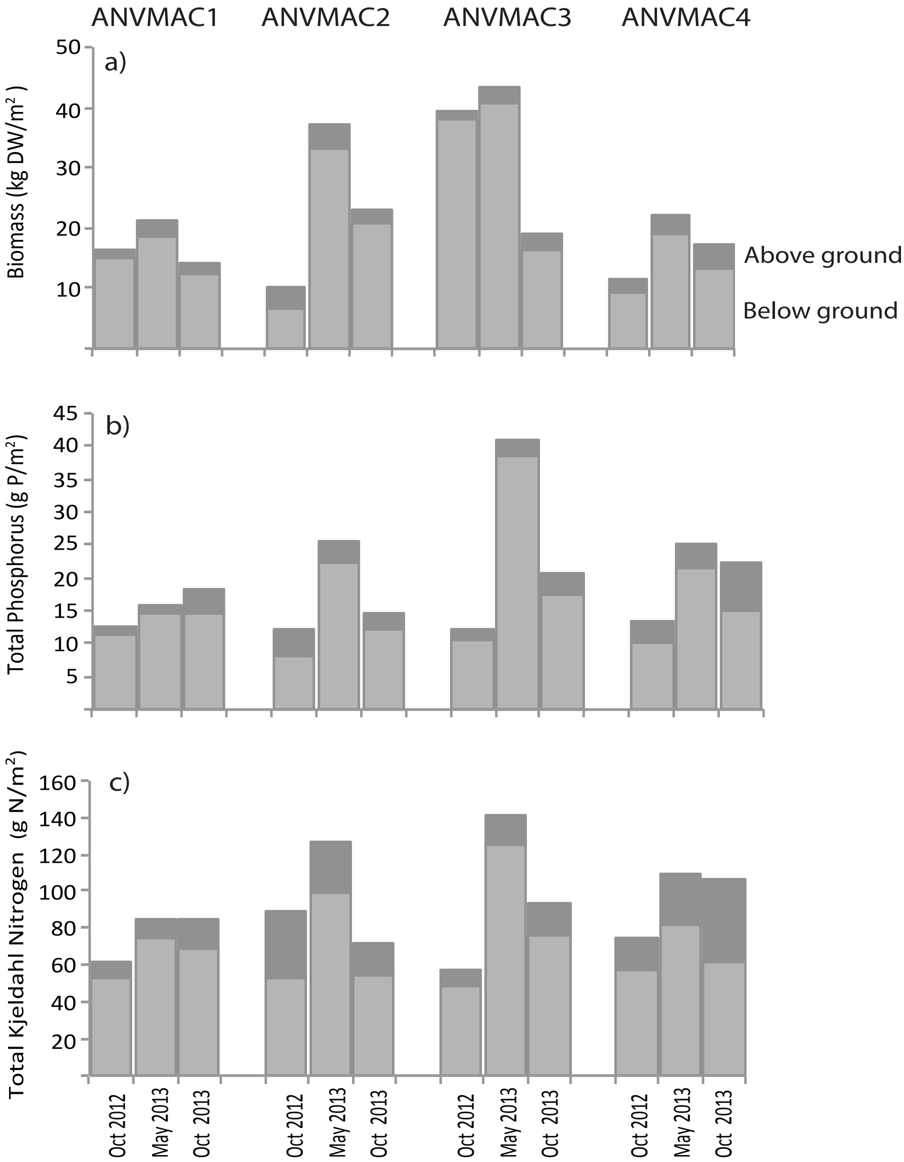


**Figure 44. Comparison of above and below ground biomass and nutrient content per unit area for *S. validus*.**

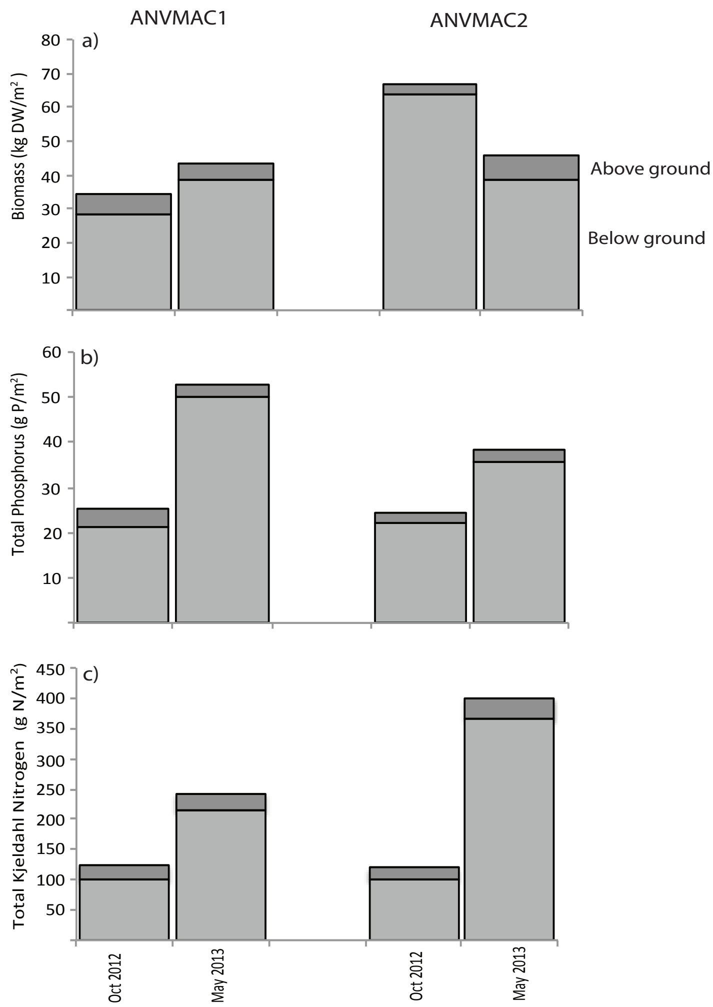


**Figure 45. Comparison of above and below ground biomass and nutrient content per unit area for *B. articulata*.**

We note that without species coverage data collected at the same time as vegetation tissue sampling, we are unable to compare total nutrient in the vegetation pool compared to the sediment pool. We can however run two different scenarios: a) if the whole wetland was dominated by *S. validus*; and b) if the whole wetland was dominated by *B. articulata*.

Under these scenarios the nutrient pool would be estimated by multiplying the nutrient content per area for each species by the total area of vegetation in the wetland (7,260 $m^2$). If the wetland was 100% *S. validus*, the total vegetation nutrient pool would be 141 kg P and 665 kg N. If the wetland was 100% *B. articulata* the total vegetation nutrient pool would be 256 kg P and 1605 kg N.

The aerial photographs (Figure 35) indicate that the wetland in 2012 was indeed dominated by *S. validus*, thus the total N value assuming 100% *S. validus* should be considered a conservative estimate of the vegetation N pool. This total N pool are similar in magnitude to the sediment/soil total N pool in 2011, although almost an order of magnitude lower than sediment/soil total N pool in 2013 (Table 4). We also note that sediment total nutrient pools are increasing steadily with time and do not display seasonal trends, suggesting that nutrients are more permanently bound in the sediments.

Finally, the increase with time in total sediment nutrients is larger than the seasonal loss from the vegetation nutrient pools. This suggests the sediments are capturing more nutrients than are released on a seasonal basis from vegetation. Possible sources of these nutrients are wetland water, both storm events and base flow, and also the superficial groundwater that may intersect the wetland sediments and soils on a seasonal basis. These results highlight the importance of understanding nutrient cycling and transfers between the soil/sediments, wetland water and vegetation.

# Summary and recommendations

This report reviewed and assessed the performance of the AWCB project over the period 2004-2013. The analysis of hydrological, water and sediment quality, and macrophyte attributes has been aimed at developing a better understanding of the system's ability to effectively treat stormwater, and also to compare conditions before and after the reconstruction and revegetation of the AWCB.

An overview of the data collection and monitoring is presented in the monitoring program summary section. The quality of the analysis of the wetland performance is dependent on the quality and consistency of the monitoring. Changes in the location of the monitoring stations and sampling frequency, has introduced some uncertainty into the analysis, especially for the comparison between conditions before and after the construction of the living stream. A first recommendation, as has been the case since reconstruction of the AWCB, is to continue a relatively simple monitoring program as permanently as possible and address specific issues with intensive sampling events as outlined specifically below.

The analysis of the data allowed us to provide answers to several of the most important questions addressed 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.

Overall, it is highlighted that the system is still in transition from a high flow low retention time system into a low flow dominated meandering system, and it may take several years until the system stabilises and differences can be observed clearly. It is important to undertake improvements in flow gauging at Mars Street drain as well as a simultaneous monitoring of flow and water quality where possible since this will allow more accurate calculation of the efficiency of the wetland. Similarly, improvements in gauging base flow conditions are necessary to better understand the contribution of groundwater.

## Water balance and hydrological dynamics

The following concluding remarks result from the hydrological analysis:

1. Previous comparisons of inflow vs outflow daily volumes has suggested that the inflow station accounts for 90% of the incoming water into AWCB, however, the detailed water balance analysis for individual events indicated that that contribution of ungauged inputs can be substantially higher than this.
2. Water contribution from ungauged areas at event scale was significant and varied in a predictable way consistent with rainfall event characteristics (amount and duration) and antecedent wetness conditions.
3. Volumetric contribution from ungauged areas was large (40-80%) for small and frequent rainfall events (< 1 ARI), particularly between the spring and summer season.
4. Volumetric contribution from ungauged areas was consistently smaller (13-27%) for mid-size to large rainfall events when runoff volume was dominated by 75% of the catchment area accounted for by the inflow station.
5. Peak flow discharge from the ungauged areas reached 0.45 $m^3/s$. Rating strategies should be planned to properly address this discharge value.
6. Volumetric contributions from ungauged areas and areas generating runoff varied over the season in accordance with antecedent wetness conditions.
7. Transit times for the inflow hydrograph into AWCB varied from 4.8 to 1.2 hr for early flows (autumn) and wet winter conditions respectively. No differences were found for transit time value for mid-size or large events with a 1.2 hr value being suitable for both hydrological conditions.

## 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. It was not possible to undertake a full mass balance analysis of the wetland, however, attempts to quantify the sediment and vegetation stores were made. Based on this, the original questions raised at the beginning of the report are repeated here, clustered under similar topics, with responses based on the findings.

***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)?***

Pollutant concentrations in the wetland outflow were compared with HRAP targets and ANZECC guidelines. Compliance was found to be variable and different for each nutrient species assessed. In general, the variability of total fractions such as TN and TP was less than the variability of soluble fractions. Differences in TN and TP were observed, and while TN complies on most sampling occasions, the wetland was not able to reduce TP concentrations below the values. DON was noted to be a very stable fraction of N with limited reduction across the wetland.

Median values for nutrients in groundwater hardly varied over the years where there was available data. Concentrations of nutrients were compared with ANZECC guidelines for reference. Concentrations of TN and NOx exceeded the guidelines and were significantly higher than in surface water.

Al, Cu, Cr, and Zn are critical metals. They were above the guideline level both in surface and groundwater (except for Cu in groundwater). For Fe, only the total fraction exceeds the guidelines in surface and groundwater. As, Ni, and Pb only occasionally exceeded the guideline values in surface water. Zn was also enriched within the sediments, with concentrations consistently above the high guideline value.

***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?***

The difference between inlet and outlet nutrient concentrations was approximated by computing SDC and SDC_ave with the reality somewhere between these two values. Overall the SDC values reported indicate an overall reduction in pollutants due to the presence of the system, however the potential role of dilution from ungauged sources makes it difficult to isolate the role of the wetland in actively removing N and P that would otherwise be delivered to downstream water bodies. The analysis of the data indicates that TN and TP are reduced under low to medium flow conditions, however, there also appears to be discharge of OC and organic-N from the wetland. Overall, the reduction in dissolved inorganic nutrients (particularly $NH_3$ and FRP) has positive implications for waterway ecological integrity, but there appears to be substantial variability in performance.

***Q. What is the wetland treatment efficiency for a range of different parameters under different hydrological conditions?***

***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?***

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

The analysis of the pollutant removal capacity was restricted due to the lack of information of ungauged sources. An approximation of pollutant removal efficiency was done by calculating the standardised difference in pollutant concentration between the wetland inlet and outlet. Although this analysis was not able to provide an accurate value for the wetland efficiency it provided a range of values that highlighted the importance of the impact of ungauged sources. It also highlighted the effect of seasonality in the removal capacity. For nutrients, different fractions were assessed and the reduction percentage was evaluated separately for dissolved organic and inorganic fractions. The SDC was also computed for soluble metals.

The wetland seems to reduce nutrient concentrations more effectively in summer, and in particular, this is observed for the inorganic fractions of N. DON is quite stable and is only varying slightly due to seasonal changes. TP seems to be reduced more effectively during winter. FRP is more variable with decreased SDC in summer. No difference in the compliance of guideline values was observed between low and high flows whether they occurred within the wet season, or the dry season.

During some occasions after the reconstruction, it was possible to calculate the efficiency of the wetland as the reduction in loads. The reduction in dissolved and total nutrients based on event analysis indicated substantial reduction of $NH_3$ (~70%; equivalent to a mass removal between 0.1 and 11 kg/day) and modest reductions in $NO_3$ and FRP (~20-40%) and TN and TP. The soluble fraction of P seems to be removed with more efficiency than TP.

### *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 TP are increasing, although not higher than the concentration suggested as a guideline for soils. The TP concentration was highest at ANVSED1, at the main inlet. Net assimilation of nitrogen was observed in sediments with time (TN=18.64t+62.67, p=0.84), where t the number of days since November 11 2011. Net assimilation of organic carbon was also observed in sediments with time (TOC=240.7t+9163, p=0.92). The temporal trend for P assimilation was less obvious (TP=1.866t+122.6, p=0.55). Concentrations of metals in sediment decreased after the reconstruction of the wetland due to the removal of sediment, but have been increasing since then.

The sediments were a significantly greater store of nutrients than the macrophytes. A key finding is that TP content is an order of magnitude higher in sediments than in macrophyte biomass. TN content was double in the sediments than the macrophyte biomass.

Nonetheless it was apparent that the below ground biomass provided significantly more nutrient storage than the above ground biomass. In addition below ground *S. validus* exhibited a seasonal trend, with maximum biomass and nutrient content (per unit area) in May. Nutrient content per unit area was significantly greater for *B. articulata* than *S. validus*. This suggests that wetland management to promote establishment and increased coverage of *B. articulata* would improve nutrient retention across the wetland. We note that within the minimal vegetation management currently in place, *S. validus* has out-competed *B. articulata*. The seasonal dynamics of *S. validus* also suggests that nutrients would be transferred to other pools within the wetland in summer, including possible release to the soil and wetland waters.

Scenarios were used to estimate the total nutrient pool in vegetation. The vegetation total P pool was similar in magnitude to the sediment/soil total P pool in 2011, though almost an order of magnitude lower than sediment total P pool in 2013. The vegetation total N pool was also similar in magnitude to the sediment/soil total N pool in 2011, and again an order of magnitude lower than sediment/soil total N pool in 2013. We also note that sediment total nutrient pools are increasing steadily with time and do not display seasonal trends, suggesting that nutrients are more permanently bound in the sediments.

Finally, the increase with time in total sediment nutrients is larger than the seasonal loss from the vegetation nutrient pools. This suggests the sediments are capturing more nutrients than are released on a seasonal basis from vegetation. Possibly sources of these nutrients are wetland water, both storm events and base flow, and also the superficial groundwater that may intersect the wetland sediments and soils on a seasonal basis. These results highlight the importance of understanding nutrient cycling and transfers between the soil/sediments, wetland water and vegetation. These investigations are part of ongoing work being undertaken by CRC Project B2.4 and C4.1.

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

The low spatial resolution of data made it to difficult to accurately answer this question. However, given the TN and TP SDC value were improved following restoration, it suggests the meandering path and increase in low flow retention time is useful at reducing the concentration of particulate organic matter.

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

Given the sediments appear to be the main sinks of nutrients, it appears that water-sediment processes are likely the main reduction processes within the wetland, and in particular the sedimentation of particulate material. The role of sediment nutrient fluxes to the water during low flow conditions may be significant and the role of denitrification remains unclear given the largely anaerobic conditions that occur in the wetland. This is being further explored by CRC Projects C4.1 and B2.4.

***Q. Does the wetland improve waterway ecological integrity?***

The substantial increase in vegetation biomass across the entire domain since the restoration has provided new habitat that would not have otherwise been available. Whilst not reviewed here, monitoring undertaken by SERCUL has indicated the nature of the macroinvertebrate community.

***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?***

***Q. Could the wetland be manipulated/managed differently to be more effective?***

This can only be determined via modelling of the entire wetland system and assessing different management options. This will be investigated as part of the CRC Project C4.1.

## Recommendations

There are several challenges regarding optimization of treatment performance of the basin in the sandy coastal plain environments. Based on the synthesis of the available data, the following recommendations are made. Where these recommendations are being tackled as part of on-going CRC Projects, this is indicated.

- Track the water flow regime through the Mars Street outflow.
- Strengthen water quality monitoring at Mars Street outflow during the dry season.
- Monitor soil nutrients (as well as in-stream sediment nutrients), to determine if macrophyte nutrients are being transferred to the underlying soils. (Project B2.4)
- Monitor metal content (particularly Al, Cr, Cu, Zn and Fe) in surface water and sediment.
- Vegetation species mapping should be repeated at the time of vegetation tissue sampling.

- Explore initiatives to improve P attenuation within the basin.
- Understand the potential for hypoxia and P release from the sediment (Project C4.1)
- Analyse organic species of nutrients, and inorganic and organic carbon in surface water, groundwater and sediment (Project B2.4)
- Remove nutrient rich and sludgy sediments and dead macrophytes periodically from the basin as these may be a source of nutrient and contaminants, if feasible to do so.

The understanding and quantification of the nutrient removal processes during seasonal saturation of the riparian zone is necessary. Sediment saturation can trigger intense biogeochemical processing and impact the effectiveness of riparian nutrient attenuation. Examination of these zones can provide insights into wetland function and contribute to explaining aspects of the variability described above. Comparison of nutrient species and concentrations within the surface water, groundwater and soil pore water can also be used to inform water quality model setup and operation, to facilitate 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 (as aquatic productivity or respiration) may serve as a simple indicator of wetland function. The linkage between wetland metabolism and seasonal flow, sediment saturation, oxic and anoxic condition and nutrient attenuation still requires improved understanding. Preliminary dissolved oxygen data has highlighted diurnal shifts from 0-10 mg/L over the course of several hours when flow is low, and this has particular implications for nutrient transformations, the wetland water quality and the nutrients delivered downstream on the first flush after a period of no flow.

Groundwater - surface water interactions and their contribution to the overall nutrient budget of the basin need to be investigated. Monitoring of groundwater bores, tracer/isotopic test or modelling could be used to investigate the issue.

Nutrient release from the sediments to the overlying water column needs to be investigated as occasionally the basin acts as a "source of nutrients". As identified above, the overall contributions of macrophytes to nutrient attenuation remains uncertain but potentially significant and should be further investigated.

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# Acronyms and glossary

**AEP:** Annual Exceedance Probability

**AHD**: Australian Height Datum

**ANZECC**: Australian and New Zealand Environment Conservation Council

**ARI**: Average Recurrence Interval

**ARMCANZ**: Agriculture and Resource Management Council of Australia and New Zealand

**AWCB**: Anvil Way Compensation Basin

**AWP**: Anvil Way Project

**CRC**: Cooperative Research Centre

**DOC:** Dissolved Organic Carbon

**DM**: Discharge Measurement

**DoW**: Department of Water

**HRAP**: Healthy Rivers Action Plan

**MSMD**: Mills Street Main Drain

**OC**: Organic Carbon

**SDC**: Standardised Delta Concentration

**SERCUL**: South East Regional Centre for Urban Landcare

**TKN:** Total Kjeldahl Nitrogen

**TN:** Total Nitrogen

**TP:** Total Phosphorus

**TOC**: Top of Casing

**TOC**: Total Organic Carbon

**VCUS**: Volumetric Contribution of Ungauged Sources

**WIN**: Water Information Network (sites)

**WIR**: Water Information Reporting

**WSUD**: Water Sensitive Urban Design

**Routing parameters**: A standard set of parameters for a flood hydrograph routing using a linear reservoir model. Parameter values include a weighting coefficient (X) and a time of travel (K) of the flood.

# Appendix A

# Sites and locations of monitoring stations

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

| WIN site ID | Variable | First measurement | Status | Equipment | Known issues |
|---|---|---|---|---|---|
| 509369 | Rainfall/ Meteorology | 06/10/2008 | Operating | Tipping bucket | N/A |
| 6162964 | Inflow (Orrong Rd) | 18/07/2012 | Operating | Starflow (water level and velocity) | Vegetation growth, drift in transducer records, turbulence affecting Doppler |
| 6162796 | Outflow (adjustable weir) | 22/07/2011<br>25/02/2012 | 25/02/2012<br>Operating | Oddysey Probe(water level)<br>Float well sensor | Increase in water level from October (debris/ vegetation growth)<br>Vegetation growth, sedimentation, weir operation, tail water effect for high flow conditions |

**Table A 2. Groundwater sampling bores, site and locations at Anvil Way Compensation Basin.**

| Bore | Site code | WIN site ID | Location | Latitude | Longitude | m, AHD | Time of installation |
|---|---|---|---|---|---|---|---|
| 1 | ANVGW 1 | 23041042 | Approx half way along the north-west side of the basin | -31°59'26.94" | 115°56'13.44" | 11.80575 | March 2010 |
| 2 | ANVGW 2 | 23041043 | Lower end of the south-west side of the basin | -31°59'31.02" | 115°56'11.28" | 11.87998 | March 2010 |
| 3 | ANVGW 3 | 23041044 | North of the main basin inlet on the eastern side of the drain | -31° 59'25.44" | 115°56'11.10" | 12.19941 | March 2010 |
| 4 | ANVGW 4 | 23044836 | Near Mills Street main outlet | -31°59'29.53" | 115°56'9.27" | 12.09476 | January 2012 |

**Table A 3. Surface water sampling sites and locations at Anvil Way Compensation Basin (this table does not include all sampling sites, only the four that have been monitored consistently over the years).**

| Site code | AWRC Code | WIN site ID | Latitude | Longitude | Comments |
|---|---|---|---|---|---|
| MSANVCBIN | 6162797 | 23002242 | -31°59'26.46296" | 115°56'11.81783" | Represents the main inlet of the basin |
| MSANVCBMID | 6162795 | 23002240 | -31°59'29.43266" | 115°56'11.20815" | Middle point of the basin along main flow path |
| MSANVCBOUT | 6162796 | 23002241 | -31°59'32.09793" | 115°56'9.92367" | Site close to main outlet of the basin |
| MSMA1 | 6162962 | 23001158 | -31°59'30.30552" | 115°56'9.18222" | Mars Street Drain Inlet to the basin |

**Table A 4. Sites codes of sediment sampling zone of the AWCB with their geographic location and short description.**

| Site code | WIN Site ID | Latitude | Longitude | Description |
|---|---|---|---|---|
| ANVSED1 | 230438338 | -31°59'26.51564" | 115°56'11.51619" | Near the main inlet (sedimentation area) representing major inflow |
| ANVSED2 | 230438339 | -31°59'27.82900" | 115°56'10.89894" | Site on densely vegetated area. Major macrophyte species includes *Baumea articulata* and *Schoenoplectus validus* |
| ANVSED3 | 230438340 | -31°59'30.01148" | 115°56'11.29674" | Site on vegetated and flood plain area. Major macrophyte species includes *Baumea articulata* and *Schoenoplectus validus* |
| ANVSED4 | 230438341 | -31°59'31.28724" | 115°56'9.68152" | Site near the main outlet (also represents the quality of the sediment coming from the Mars Street drain.) |

**Table A 5. Vegetation sampling locations.**

| Site Code | AWRC code | Easting | Northing | Description |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| ANVMAC1 | 6164605 | -31°59'27.07899" | 115°56'11.69641" | Site close to the main inlet of the basin which has contact with water throughout the year |
| ANVMAC2 | 6164606 | -31°59'27.91626" | 115°56'10.84840" | Site close to first sand bund, polishing water during wet seasonal flow. No contact with water during hot summer season |
| ANVMAC3 | 6164607 | -31°59'30.19256" | 115°56'11.20320" | Site close to midpoint, on flow path of the basin |
| ANVMAC4 | 6164608 | -31°59'31.47774" | 115°56'9.54976" | Site close to main outlet, on flow path of the basin |

# Appendix B

# Sample frequency for water and sediment quality assessment

**Table B 1. Sample frequency and number of samples collected for each surface water monitoring site (part 1).**

| | 2004 | | 2005 | | | | | | | | | 2006 | | | | | | | | | | | 2007 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site ID /Months** | **10** | **12** | **1** | **2** | **3** | **4** | **7** | **8** | **10** | **11** | **12** | **1** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| 616125 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6162665 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ANVCBIN2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCB1 | | 3 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCBIN | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| MSANVCBMID | | 3 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCBOUT | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| MSDIVCBOUT | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSMA1 | 1 | 3 | 3 | | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| MSMA2 | 3 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**Table B 2. continued (part 2).**

| | 2008 | | | | | | | | | 2009 | | | | | | | | | | | 2010 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site ID /Months** | **1** | **2** | **3** | **4** | **7** | **8** | **10** | **11** | **12** | **1** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| 616125 | | | | | | | | | | | | | | | | | | | | | | | 2 | | | | | | | | | |
| 6162665 | | | | | | | | | | | | | | | 3 | 3 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | | | | | | 2 |
| ANVCBIN2 | | | | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | | |
| MSANVCB1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MSANVCBIN | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MSANVCBMID | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCBOUT | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| MSDIVCBOUT | | | | | | | | | | | | | | | | 3 | 3 | 2 | 1 | | | | | | | | | | | | | |
| MSMA1 | 3 | 3 | 3 | 3 | 3 | 6 | 3 | 3 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| MSMA2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**Table B 3. continued (part 3).**

| | 2011 | | | | | | | | | 2012 | | | | | | | | | | | 2013 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site ID /Months** | **1** | **2** | **3** | **4** | **7** | **8** | **10** | **11** | **12** | **1** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| 616125 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6162665 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ANVCBIN2 | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCB1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSANVCBIN | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 4 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 7 | 3 | 2 |
| MSANVCBMID | | | | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 6 | 3 | 3 | 3 | 2 | 4 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 |
| MSANVCBOUT | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 5 | 2 | 2 | 3 | 3 | 3 | 3 | 2 | 4 | 2 | 2 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 2 |
| MSDIVCBOUT | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MSMA1 | 2 | | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | 2 | 2 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 3 | 2 | 3 | 3 | 2 |
| MSMA2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

**Table B 4. Sample frequency and number of samples collected at each groundwater monitoring site.**

| Year | 2010 | | | 2011 | | | | | | 2012 | | | | | | | | 2013 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Months | 4 | 9 | 11 | 3 | 8 | 9 | 10 | 11 | 12 | 2 | 3 | 4 | 7 | 8 | 9 | 10 | 12 | 1 | 2 |
| Site ID | | | | | | | | | | | | | | | | | | | |
| ANVGW1 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 2 |
| ANVGW2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 2 |
| ANVGW3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 2 |
| ANVGW4 | | | | | | | | | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 2 |

**Table B 5. Sample frequency and number of samples collected at each sediment monitoring site.**

| Year | **2004** | | **2005** | | **2006** | **2007** | **2008** | **2009** | | **2010** | **2011** | **2012** | **2013** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Month*<br>Site | *10* | *12* | *01* | *06* | | *01* | *03* | *03* | *06* | | *11* | *10* | *05* | *10* |
| ANVCB10 | | | | | | | | | 2 (d=25cm) | | | | | |
| ANVCB6 | | | | | | | | | 2 (d=7cm) | | | | | |
| ANVCB7 | | | | | | | | | 2 (d=38cm) | | | | | |
| ANVCB8 | | | | | | | | | 2 (d=26cm) | | | | | |
| ANVCB9 | | | | | | | | | 2 (d=13cm) | | | | | |
| MSANVCB1 | | 1 | 1 | 2 | | | | | 2 (d=40cm) | | | | | |
| MSANVCB2 | | | | 2 | | | | | 2 (d=25cm) | | | | | |
| MSANVCBIN | | 1 | 1 | 2 | | 1 (d=20cm) | 1 (d=30cm) | 1 (d=20cm) | | | | | | |
| MSANVCBMID | | 1 | 1 | | | | | | 2 (d=25cm) | | | | | |
| MSANVCBOUT | 1 | 1 | 1 | 2 | | 1 (d=20cm) | 1 (d=30cm) | 1 (d=20cm) | | | | | | |
| MSMA1 | | 1 | 1 | | | 1 (d=20cm) | 1 (d=30cm) | 1 (d=20cm) | | | | | | |
| ANVSED1 | | | | | | | | | | | 1 (d=13cm) | 1 (d=13cm)<br>1 (in situ, no data)<br>1 (d=20cm) | 1 (d=na)<br>1 (in situ, no data) | 1 (d=0cm)<br>1 (in situ, no data) |
| ANVSED2 | | | | | | | | | | | 1 (d=10cm) | 1 (d=10cm)<br>1 (in situ, no data) | 1 (d=na)<br>1 (in situ, no data) | 1 (d=0cm)<br>1 (in situ, no data) |
| ANVSED3 | | | | | | | | | | | 1 (d=8cm) | 1 (d=10cm)<br>1 (in situ, no data) | 1 (d=na)<br>1 (in situ, no data) | 1 (d=0cm)<br>1 (in situ, no data) |
| ANVSED4 | | | | | | | | | | | 1 (d=17cm) | 1 (d=20cm)<br>1 (in situ, no data) | 1 (d=10cm)<br>1 (in situ, no data) | 1 (d=0cm)<br>1 (in situ, no data) |
| ANVSED1US | | | | | | | | | | | | | 1 (d=na)<br>1 (in situ, no data) | |
| ANVSED4DS | | | | | | | | | | | | | 1 (d=10cm)<br>1 (in situ, no data) | |

d= sample depth; na= information not available

# Appendix C

# Caveats related to quality of the hydrological data

The raw water stage data at the inflow station presented two issues: a) a trend of increasing water level from December 2012 to February 2013 during baseflow conditions, and b) a trend of decreasing water levels from July 13th 2013 due to a drift in the pressure transducer sensor (estimated to be 1 mm/day). There was no correction of the first error in the data. The second systematic error of the sensor was corrected using water stage readings during field visits by field staff but cause for the drift is not clear.

The use of the Starflow for flow discharge computation requires two additional steps to provide reliable information: 1) point velocity measurements with an independent current meter in the proximity of the Starflow, and 2) finding conversion coefficients to relate velocity measurements by Starflow to the “flow mean velocity in the section” via independent flow discharge measurements (DMs). Although the latter activity has been undertaken by DoW, no field check on the performance of the Starflow acoustic current meter has been reported and the “raw velocity” data was used for flow discharge computation.

It was observed that the raw data for velocity over 2012 consistently showed low velocity values inside the pipe during inter-event periods (in the order of 0.1 m/s) and no abrupt change in velocity values other than those responding to rainfall events. The same values were observed for a period of three weeks after the redeployment of the equipment in mid-June 2013. Subsequently, velocities under baseflow conditions jumped to a new higher level (around 0.5 m/s) for the rest of 2013. It was also documented that during high flow conditions, the turbulence generated near the Doppler affected velocity measurements due to the flow regime transitioning from free surface to surcharge conditions in the culvert. Such conditions seem to occur when the inflow discharge is greater than 0.6 $m^3$/s. This effect only lasts for approximately 2 hr and the flow discharge hydrograph was manually edited to remove this effect.

The use of this “raw data for velocity” for indexing (correlation to obtain mean flow velocity for the station) poses a critical restriction for discharge estimates and could provide an explanation for the high values for the mean velocity factor ($V_m$) for the station. Raw data from the station would benefit from a more robust analysis and corroboration (verification using theoretical rating and/or hydraulic modelling) prior its use for discharge computation.

Water levels at the outflow station during baseflow conditions in 2012, were considered to be stable and controlled by two logs at the weir, but in 2013 were influenced by channel accretion and vegetation growth and showed a steady increase. A correction to the water stage for baseflow conditions in 2013 was applied by DoW to decrease and align the records with water levels recorded during 2012. Of particular interest is the large correction applied to baseflow conditions for the period September-October 2013. Two rating curves (“Tables” in Hydstra database) have been based on flow condition and water stages for this site. As pointed out by DoW (2014), the concrete structure (weir) at the outlet station presented partial control on flow discharge for high flow conditions. Two discharge measurements for high flow ($Q > 0.5$ $m^3$/s) have been successfully undertaken by DoW and used to constrain the rating curve for this station.

The construction of the rating tables for both sites can be considered as provisional due to the limited amount of flow measurements (eight), uncertainties in flow velocity measurements by the Starflow (no independent verification conducted in the field), and lack of documentation of the weir log operation and maintenance activities both affecting water level for low flow conditions.

The raw data for velocity collected by the Starflow needs further investigation using hydraulic modelling and theoretical rating (e.g., flow discharge computation in pipes) to assess if any correction needs to be applied prior to its use in flow discharge calculation. An inexpensive Doppler technology (Incoherent) has been chosen for monitoring the site without an independent check, resulting in large uncertainties for flow discharge estimates. Even with the use of new Coherent Doppler technology, independent field measurements using traditional methods will still be required.

Finally, manipulation and editing of water stage for low flow conditions from September to December jeopardized the opportunity to identify shallow groundwater discharge into the AWCB.

More independent discharge measurements for low, intermediate and large flow hydrological conditions are needed to overcome the above issues.

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