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Temporal dynamics of stormwater nutrient attenuation of an urban constructed wetland experiencing summer low flows and macrophyte senescence

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ABSTRACT

The attenuation of urban stormwater nutrient is essential for maintaining ecological health of downstream waterways. Constructed wetlands (CWs) are widely used for stormwater management due to the economic and environmental benefits they create by attenuating nutrients. This research assessed stormwater nutrient attenuation in a surface flow CW located in Western Australia, by assessing data spanning decadal, seasonal and diurnal time-scales. The study site was built in 2004 and restored in 2010, and the significance of such restoration was also assessed in this research. The CW designed to minimize nutrient loads to downstream sensitive waterways despite experiencing Mediterranean climates with strong hydrological seasonality including prolonged low or no flow conditions during the dry summer periods and nutrient-rich pulses during the wet winter periods. Furthermore, seasonal ungauged water inputs and macrophytes senescence made the system complex to optimize nutrient attenuation. The annual average attenuation of nitrogen (N) and phosphorus (P) based nutrients were 2–4 times higher during the post-restoration periods than that observed during the pre-restoration periods. The attenuation of inorganic, organic, dissolved and total N was higher during the dry periods of the post-restoration regimes, while P species showed higher attenuation during the wet periods of the post-restoration regimes. Inorganic N showed greater attenuation than attenuation of inorganic P throughout the year. *Baumea articulata* and *Schoenoplectus validus* were the dominant macrophyte species across the site; *B. articulata* was estimated to store about 3 and 2 times higher N and P pools, respectively than that stored in *S. validus*. Low dissolved oxygen (DO) occurred in the site and DO showed a decreasing trend over the decade and a distinct diurnal signature of day-time peaks and night-time anoxia. Diurnal pattern in aquatic metabolism, defined as the daily fluctuation of DO levels within the water column of CW, was related to solar radiation and nutrient concentrations, and could be considered as a proxy of CW function.

1. Introduction

Water quality is declining in many urban areas due to non-point source nutrients, typically delivered via stormwater (Roy et al., 2008; Wong et al., 2012), leading to nuisance algal blooms and eutrophication in downstream waterways (Taylor et al., 2004; Hathaway et al., 2012). Stormwater and/or associated nutrient can also lead to habitat fragmentation, biodiversity loss and changes in the morphological and hydrological characteristics of the watercourses (Taylor et al., 2004; Walsh et al., 2005; Francey et al., 2010; Zgheib et al., 2012). As a result, management of stormwater quality has become an essential strategy to improve ecological integrity of drainage systems, and as a means to improve urban sustainability and liveability (Hatt et al., 2007; Wong et al., 2012; Deletic et al., 2013).

A paradigm shift in stormwater management has therefore been taking place in many cities around the world based on Integrated Stormwater Management System (ISWMS) and through adoption of Best Management Practices (BMPs). Such initiatives have been referred as Low Impact Development (LID) in the USA (Hinman, 2005), Sustainable Urban Drainage Systems (SUDS) in the UK (CIRIA, 2000) and Water Sensitive Urban Design (WSUD)

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Nomenclature

General

AHD	Australian Height Datum
AGB	Above ground biomass
ANZECC	Australian and New Zealand Environment and Conservation Council
AWCB	Anvil Way Compensation Basin
BGB	Below ground biomass
BMPs	Best Management Practices
BOD	Biochemical oxygen demand
BoM	Bureau of Meteorology
COD	Chemical oxygen demand
CW	Constructed wetland
DAFWA	Department of Agriculture and Food
DEM	Digital Elevation Model
DNRA	Dissimilatory nitrate reduction
DO	Dissolved oxygen
DoW	Department of Water
Eh	Oxidation-reduction potential
HRAP	Healthy River Action Plan
HRT	Hydraulic retention time
ISWMS	Integrated Stormwater Management System
LID	Low Impact Development
MSMD	Mills Street Main Drain
SCP	Swan Coastal Plain
SDC	Standardised delta concentration
SDC_ave	Standardised delta concentration_averaged
SERCUL	South East Regional Centre for Urban Landcare
SOD	Sediment oxygen demand
SOD	Sediment oxygen demand
SUDS	Sustainable Urban Drainage Systems
WA	Western Australia
WSUD	Water Sensitive Urban Design

Numerical

A_b	Biomass area (m^2)
A_s	Sediment area (m^2)
B_s	Sediment bulk density (kg/m^3)
C_i	Nutrient concentration at *ith* timestep (mg/L)
C_{inlet}	Nutrient concentration at the inlet (mg/L)
C_{outlet}	Nutrient concentration at the outlet (mg/L)
C^*	Average nutrient concentration at the inlet and MSD (mg/L)
DO_{max}	Maximum DO saturation during the afternoon (%)
DO_{min}	Minimum DO saturation during the morning (%)
D_s	Sediment depth (m)
DW_b	Dry weight of the biomass (kg)
EC	Electric conductivity (μS/cm)
L	Nutrient load (mg/s)
L_A	Nutrient load attenuation (%)
L_i	Load at the inlet (mg/s)
L_o	Load at the outlet (mg/s)
NC_b	Biomass nutrient concentration (mg/kg)
NC_s	Sediment nutrient concentration (mg/kg)
NM_b	Biomass nutrient mass (kg)
NM_s	Sediment nutrient mass (kg)
Q_b	Quadrat area as 0.0625 m^2
Q_i	Flow rate at *ith* timestep (m^3/s)
$Q_{outflow}$	Discharge rate at the outflow (m^3/s)
V	Volume of the AWCB (m^3)
ΔDO_{sat}	Delta DO saturation (%)

Nutrients and chemicals

Al	Aluminium
C	Carbon
Ca	Calcium
DIC	Dissolved inorganic carbon
DIN	Dissolved inorganic nitrogen
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
Fe	Iron
FRP	Filtered reactive phosphorus
FTN	Filtered total nitrogen
FTP	Filtered total phosphorus
Mn	Manganese
N	Nitrogen
NH_3	Filtered ammonia
NO_2	Filtered nitrite
NO_3	Filtered nitrate
NOx	Filtered total oxidised nitrogen
NUON	Filtered non-urea organic nitrogen
P	Phosphorus
PN	Particulate nitrogen
PP	Particulate phosphorus
TDC	Total dissolved carbon
TKN	Total Kjeldahl nitrogen
TN	Unfiltered total nitrogen
TOC	Total organic carbon
TP	Unfiltered total phosphorus
UreaN	Filtered urea nitrogen

in Australia (Lloyd, 2001). In general, WSUD are based on the idea that the management, protection and conservation of the urban water cycle must take place to ensure that the urban water environment is sensitive to natural hydrological, economic and ecological processes (Deletic et al., 2013), and that the ecological services of urban waterways are maintained (Brown et al., 2009). There are different WSUD elements are in practice for stormwater nutrient attenuation, and constructed wetland (CW) is one of them.

CWs have found widespread adoption over the past few decades due to their ability to treat and transform stormwater nutrient by utilizing different hydrological and biogeochemical processes. These processes take place within the water, soils/sediments, aquatic macrophytes and microbial assemblages of CWs (Carleton et al., 2000, 2001; Kivaisi, 2001; Mitsch and Gosselink, 2007; Vymazal, 2007). CWs vary widely in their performance ranging from 10 to 90% for nitrogen (N) and phosphorus (P), and in some cases they may increase nutrient levels (Malaviya and Singh, 2012; Saeed and Sun, 2012). The performance depends on numerous factors including the area and land use of the catchment, nutrient loading rate, hydro-climatological variability, macrophyte biomass, hydraulic retention time (HRT), groundwater connectivity and specific sediment/soil properties (Hamilton et al., 1993; Carleton et al., 2001; Gasperi et al., 2011; Zgheib et al., 2011, 2012; Tang et al., 2013). The degree of nutrient attenuation in CWs is controlled biogeochemically and/or hydrologically (Fink and Mitsch, 2007; Huang et al., 2011; Chang et al., 2013; Jahangir et al., 2016). N and P of stormwater experience different transformations depending on the CW's biogeochemical conditions. These conditions include oxygen concentrations, availability of a carbon (C) source, macrophytes and microorganism abundance, soil/sediment properties and degree catchment-riparian-hyporheic exchange (Kadlec and Knight, 1996). For example, a lack of oxygen supresses nitrifica-