Journal of Environmental Management 226 (2018) 120–130

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Assessment of the treatment efficiency of an urban stormwater pond and its impact on the natural downstream watercourse

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ARTICLE INFO

Keywords:
Stormwater pond
Runoff
Wastewater
Nutrient
Micropollutants
Treatment

ABSTRACT

During the last few decades, stormwater ponds have become an alternative management practice in order to avoid flooding and to contain rainwater and runoff in urban areas where impervious land cover has increased. A second purpose of stormwater ponds is to improve the quality of runoff water that is usually contaminated with nitrogen, phosphorus, metals and organic micropollutants. Processes used are based on natural methods such as settlement and contribute to minimize the impact of these inputs to the natural aquatic system. This study aims to better understand the behavior of a wet stormwater pond, Heron Lake (33 ha) located in the city of Villeneuve d'Ascq in northern France through various indicators [trace metals, PAHs, PCBs, caffeine (CAF), carbamazepine (CBZ), nutrients and pathogens]. For that purpose, water quality was monitored for 1 year, mainly at the entrance and at the outlet of the lake. Sampling have also been done in the downstream aquatic environment, the Marque River. Sediments were sampled in the lake to evaluate the pollution trapped during sedimentation. Our results of both water and sediment sampling highlight: (i) the wastewater input into the Heron Lake is estimated to be equivalent to that of roughly 3800 inhabitants; (ii) the removal rates observed at the outlet, relative to concentrations at the entrance channel, vary as follows for these dissolved species: 24% for NO_3^- and PO_4^{3-}, 28% for CBZ, 35% for Cu, 63% for Pb, 78% for CAF, 84% for Zn and up to 93% for NH_4^+; (iii) there are high levels of sediment contamination with metals, PAHs and PCBs at the entrance channel; (iv) the eutrophication of this pond is attributed to persistent high nutrient concentrations in both water and sediment, and has contributed to the development of an invasive macrophyte, the *Elodea nuttallii*; and (v) there appears to be only a negligible impact of the discharge from the lake to the natural watercourse, contributing annual loads of < 2 up to 6% of the total amount of Cu, Pb, Zn, CAF, CBZ and nutrients measured in the Marque River, and having a slight diluting effect on concentrations in the Marque River.

1. Introduction

The large increase of impervious land cover in urban areas during the last few decades has led to the construction of many stormwater ponds. The primary purpose of these ponds is to prevent flooding and/or to drain neighboring wetlands. Their functions have been broadened to include the treatment of stormwater runoff in order to protect downstream natural ecosystems from pollution. Treatment is generally based on settling processes (Marsalek et al., 2005) since runoff pollution is mainly bound to particles (Gaspéri et al., 2009; Rule et al., 2006; Pitt et al., 2004; Gromaire-Mertz et al., 1999). Additionally, bacterial activity and upper plant uptake can also occur in these engineered systems and can potentially contribute to self-purification (Tixier et al., 2011). The water quality of the runoff depends on local factors, including runoff from roofs versus pavement, type and degree of road traffic, and agricultural practices. The water can also be highly contaminated by Suspended Particulate Matter (SPM) (Athayde et al., 1983), trace metals (Gromaire-Mertz et al., 1999; Huber et al., 2016; Robert-Sainte et al., 2009; Davis et al., 2001), Polycyclic Aromatic Hydrocarbons (PAHs) (Krein and Schorer, 2000), pesticides (Richards et al., 2016), nitrogen and phosphorus species (Islam and Tanaka, 2004; Chambers et al., 2016) and bacteria (Paule-Mercado et al., 2016; Paule et al., 2015). In addition, stormwater ponds can also receive untreated wastewater related to the management of sewage overflow during storm events or leakage of the sewer system. Untreated wastewater contributes to increased input of nitrogen, phosphorus, biodegradable

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https://doi.org/10.1016/j.jenvman.2018.08.015
Received 27 November 2017; Received in revised form 30 July 2018; Accepted 4 August 2018

organic matter, and microorganisms, as well as inorganic and organic micropollutants into the stormwater ponds (Pitt et al., 2004; Chambers et al., 2016). In the case study presented, an additional challenge for the management of such ponds is controlling the enrichment of nutrients in order to limit eutrophication. In fact, eutrophication can substantially degrade the aquatic system and lead to the development of invasive species. In particular, the macrophyte *Elodea nuttallii*, is a nuisance species that has impaired the management of flooding risk by clogging outflow pumps. Another management challenge, when the pond is also used for recreational activities, is to limit cyanobacterial blooms that can release toxins in the water.

In order to address the various management objectives, two main types of basins exist (Marsalek et al., 2005; Tixier et al., 2011): (i) ponds that are partly or completely empty between two storm events and (ii) wet ponds that are permanently maintained at a certain level of water storage allowing the existence of aquatic habitats. The pond dimensions are also an important factor, and will vary in order to accommodate the inflows and the residence time of the water with a basin of sufficient size to avoid the transport and/or the release of polluted suspended matter during extreme weather events.

This study focuses on understanding the behavior of a large artificially constructed wet stormwater pond (Heron Lake in Northern France) in order to first assess the contamination through targeted substances (*i.e.* nutrients, dissolved fraction of trace metals, and organic micropollutants: PAHs, PCB, caffeine and carbamazepine), secondly to quantify the effect of treated water on the aquatic ecosystems downstream, and finally, to evaluate the treatment performance of the pond through the reduction of the various pollutants. This study brings new insights in the evaluation of the pond performance in several ways. First, it evaluates the contribution of dissolved fractions of metal pollutants, corresponding to the most mobile and bioavailable fraction, whereas most previous studies look at the combined particulate and dissolved fraction. Secondly, we evaluate the effectiveness of additional loads of wastewater into a system designed principally to handle stormwater runoff, as well as the limitations of using this system as a recreational area. Finally, through the calculation of discharge loads and examination of spatial pollutant gradients, we can assess the effectiveness of removal rates and in lake processes, as well as the specific role and function of the last downstream pond, in mitigating discharge of pollutants into the downstream environment. Thus, this study serves as a useful example to inform management agencies on best practices when engineering and adjusting stormwater pond systems in comparable municipal regions.

2. Material and methods

2.1. Study area

Heron Lake is the last of 6 ponds in a stormwater management system constructed in the 1970s (Fig. 1), with an area of 33 ha and an estimate volume of 634,000 m^3. Overall, this 6 pond system drains runoff from a 1449 ha watershed housing 33,000 inhabitants that is mostly covered by impervious surfaces (mainly pavement, streets, carparks and highways). The runoff coefficient is estimated at 0.47 (internal report of the Water Division of Lille Metropolis), corresponding to the coefficient for residential and industrial surfaces (Mark and Marek, 2011). The ratio of the stormwater area to the catchment area is about 3% in total. The average and maximum depths of Heron Lake are 1.5 m and 2.5 m, respectively, and the residence time of the water is estimated around 2–3 months (Lafforgue and Vieillard, 2016). The water level in Heron Lake is controlled by three automatic pumps, and each of them has a capacity of 750 $L\,s^{-1}$. The pumping system is located at the outlet and ensures the discharge of the water into a natural watercourse, the Marque River, which has a water level that is slightly higher (2 m) than the elevation of the lake surface. During the sampling period in 2014, a total discharge of 2,737,500 m^3 to the river was recorded.

Heron Lake receives runoff and untreated wastewater (sewage) from residential sources in the city of Villeneuve d'Ascq (64,000 inhabitants). The incoming water is pretreated through desilting as it passes through the 5 successive smaller upstream ponds over a distance of approximately 2 km before entering Heron Lake. The upstream ponds have a total area of 14 ha and a total volume of 168,000 m^3, which corresponds to 1% of their catchment area (Fig. S1). In addition to the inflows from the upstream ponds, Heron Lake also receives 475,000 m^3 of direct inputs of runoff and untreated urban sewage water annually at its channel entrance (Lafforgue and Vieillard, 2016) (Fig. 1). The inputs of untreated urban wastewater are due to either leakage or breaks in the sewer system, which is separate from the stormwater system.

In addition to their purpose as a stormwater management system, these lakes have been converted into a public recreational area with many walking and running paths, are a draw for water sports (fishing and sailing), and serve as a bird sanctuary. In 2013, sailing stopped on the Heron Lake due to the presence of a high density of macrophytes (principally *Elodea nuttallii*) within the lake. Since then, this macrophyte growth has reoccurred each year, mainly from April to September depending on the meteorological conditions and also probably on the water quality. Additionally, the senescence of the macrophytes in the middle of summer induces visual and odor nuisances and causes recurrent clogging of the outflow pumps.

2.2. Targeted compounds

The monitoring of Heron Lake was carried out using several tracers, which represent the possible pressures of pollution found in urban and peri-urban areas (Zgheib et al., 2012; Gaspéri et al., 2012; Tixier et al., 2012; Gallagher et al., 2011). Urban aquatic systems are often polluted by metals and those generally studied are Cu, Pb, and Zn because of their widespread uses (Bradl, 2005). As no industry is located surrounding our study area, trace metals originate mostly from the road traffic, roofs or pipes (Bradl, 2005; Göbel et al., 2007).

Concerning organic pollutants, PAHs are also widespread in urban areas because their origins are related to incomplete combustion of wood and coal, and from vehicular and industrial emissions (Wang et al., 2007; Yunker et al., 2002; Net et al., 2015). We analyzed 16 PAHs, which are listed in the Water Framework Directive (WFD) because of their toxicity, carcinogenic and mutagenic effects (Net et al., 2015; Mitchell, 2010; Straif et al., 2005). These 16 PAHs include 6 light PAHs (*i.e.* ≤ to 3 cycles) [naphthalene (Nap), acenaphtylene (Acy), acenaphtene (Ace), fluorene (Flo), phenanthrene (Phe), anthracene (Ant)] and 10 heavy PAHs (*i.e.* > 3 cycles) [fluoranthene (Fla), pyrene (Pyr), chrysene (Chr), benzo[*a*]anthracene (BaA), benzo[*k*]fluoranthene and benzo[*f*]fluoranthene] (Bb + kF), benzo[*a*]pyrene (BaP), dibenzo[*a,h*]anthracene (DBA), indeno[*1,2,3-c,d*]pyrene (IP), benzo [*g,h,i*]perylene (BP)]. Polychlorobiphenyls (PCBs) are organic compounds nowadays banned in many countries because of their persistent and toxic behavior (WHO, 1993). They originate from leakage of dielectric fluids, transformers or capacitors but also from paints or pesticides (Net et al., 2015). Overall, 8 PCBs (28, 31, 52, 101, 118, 138, 153, 180) were investigated in both aqueous phase and surface sediments of the lake for a single sampling period (the spatial survey of January 2015).

Caffeine (CAF) and Carbamazepine (CBZ) are good indicators of wastewater discharge according to several studies (Panasiuk et al., 2015; Daneshvar et al., 2012; Buerge et al., 2003). CBZ is used by humans specifically as an anticonvulsant drug and mood stabilizer (Panasiuk et al., 2015). The low degradability of CBZ in the Waste Water Treatment Plant (WWTP) makes this compound a good indicator of anthropogenic impact (Sauvé et al., 2012). In contrast, CAF is largely removed during the conventional biological treatment in the WWTP. The presence of CAF in the aquatic system indicates recent discharge of untreated wastewater into the system, whereas CBZ is a good indicator