Journal of Environmental Management 205 (2018) 201–208

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Sequential Sedimentation-Biofiltration System for the purification of a small urban river (the Sokolowka, Lodz) supplied by stormwater

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ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form
17 September 2017
Accepted 23 September 2017
Available online 4 October 2017

Keywords:
Multi-zone constructed wetland
Nutrients
Urban runoff
Water quality
Stormwater
Sediments

ABSTRACT

The study analyses the efficiency of a Sequential Sedimentation-Biofiltration System (SSBS) built on the Sokolowka river in Lodz (Poland). It was constructed to purify a small urban river whose hydrological regime is dominated by stormwater and meltwater. The SSBS was constructed on a limited area as multi-zone constructed wetlands. The SSBS consists of three zones: sedimentation zone with structures added to improve sedimentation, a geochemical barrier made of limestone deposit and biofiltration zone. The purification processes of total suspended solids (TSS), total phosphorus (TP), total nitrogen (TP) and other nutrients: phosphates (PO_4^{3-}), ammonium (NH_4^+) and nitrates (NO_3^-) of the SSBS were analyzed. Chloride (Cl^-) reduction was investigated. Monitoring conducted in the first two hydrological years after construction indicated that the SSBS removed 61.4% of TSS, 37.3% of TP, 30.4% of PO_4^{3-}, 46.1% of TN, 2.8% of NH4+, 44.8% of NO_3^- and 64.0% of Cl^-. The sedimentation zone played a key role in removing TSS and nutrients. The geochemical barrier and biofiltration zone each significantly improved overall efficiency by 4–10% for TSS, PO_4^{3-}, TN, NO_3^- and Cl^-. Although the system reduced the concentration of chloride, further studies are needed to determine the circulation of Cl^- in constructed wetlands (CWs), and to assess its impact on purification processes.

1. Introduction

Engineering has historically found a role in urban water management by assuring basic needs such as access to drinking water, providing a sewage system for preventing disease and controlling flooding (Brown et al., 2008). This approach, together with the overall trend to rely on engineered measures to meet environmental needs and solve environmental problems, has caused significant deregulation of natural processes, both as sources of ecosystem services, ecological safety and wellbeing for society, and as the basis for sustaining ecosystems and habitats (Grimm et al., 2008; Mass et al., 2016). Today, the aging technical (grey) infrastructure used for controlling the water cycle, together with high density development and climate change (Revi et al., 2014), are generally observed as being responsible for such problems as urban drought, the heat island effect (Gunawardena et al., 2017), hydraulic stress (Leitner et al., 2017) and intensified pollution transfer (Zhang et al., 2015) in urban areas.

Growing interest in green infrastructure in scientific research, policy and practice has driven the search for a solution to address these challenges. Such approaches as Blue-Green Infrastructure (European Commission, 2013) and Nature-Based Solutions (European Commission, 2015) are believed to provide more complex, multifunctional, benefits and be more cost-efficient than grey infrastructure. For example, the present value of the city-wide benefits of controlling combined sewer overflows in four Philadelphia's Watershed (Tacony-Frankford, Cobbs Creek, Lower Schuylkill River and Lower Delaware River Watersheds) using green infrastructure (Low Impact Development – LID) was estimated to be $2846.4 million over a 40-year study period (from 2010 to 2049); this is significantly greater than the estimated benefits of using grey infrastructure for the same purpose, which were found to total about $122.0 million (Stratus Consulting, 2009).

The use of constructed wetlands (CWs) is an example of a nature based-solution which has been successfully used for the retention and purification of stormwater runoff (Scholz, 2006; Mitsch and Gosselink, 2007; Vymazal, 2007; Dou et al., 2017). One of the fundamental parameters influencing the efficiency of the wetland is its size or physical dimension (Carleton et al., 2001; Johannesson

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https://doi.org/10.1016/j.jenvman.2017.09.066
0301-4797/

et al., 2011; Tanner and Kadlec, 2013; Wang et al., 2014; Vergeles et al., 2015). Maximum efficiency of the CW in this regard can hence be achieved by manipulating three key aspects: their area ratio (CWs area to drainage area), their hydraulic properties, which govern the retention time provided by CWs, and their kinetic properties, which determine the size and retention time requirements to achieve a certain target reduction (Mungasavalli and Viraraghavan, 2006). Although larger CWs can remove greater amounts of pollution, the spatial, infrastructural, social and economic circumstances of cities often preclude the construction CWs with a threshold size, which increases chances for efficient nutrient removal - recommended minimum of 2–5% of the drainage area (Schueler, 1992; Shutes et al., 2004; Bratieres et al., 2008), especially in high-density areas.

Pollutant removal in CWs depends also on several microbiological, biological, physical and chemical processes which occur sequentially or simultaneously (Scholz, 2006; Vymazal, 2007; Wang et al., 2017). The degree of nitrogen removal increases with temperature (Kadlec et al., 2012; Wang et al., 2017) and length of retention time (Kearney et al., 2013; Wang et al., 2014). Phosphate (PO_4^{3-}) removal typically occurs by biological activity and adsorption, while total phosphorus (TP) content is primarily influenced by the sedimentation efficiency and sediment retention capacity (Vymazal, 2007; Wang et al., 2017). The level of total suspended solids (TSS) is reduced by physical processes such as sedimentation, decantation and filtration (Kadlec and Wallace, 2009). Increasing the size of the CW should increase the efficiency of most of the nutrient removal processes, but traditional CWs are large-scale solutions that cannot be used in cities. Therefore, the integration of CW with sedimentation system and the biogeochemical structure the efficiency of water purification, even with much smaller area. An example of such measure is the is the multi-zone constructed wetland tested in this research.

The search for cost-effective solutions and optimization of these processes led to the design of the Sequentional Sedimentation-Biofiltration System (SSBS), based on the principles defined by Ecohydrology (Zalewski et al., 1997; 2000, 2002). Optimization of SSBS operation was based on the relationship between nutrient supply, the system hydrological parameters, the function of its biotic structure and its biogeochemical processes (Zalewski, 2014; Palmer et al., 2015). The SSBS differs from traditional CWs in having separate zones (sedimentation and geochemical barrier), which increase the pollution removal rate. Only the last biofiltration zone of the SSBS exists as a traditional CW – a treatment system with wetland plants and soil media.

The present study was conducted to determine the nutrient removal rate in each of the three zones of the SSBS, with particular emphasis on the influence of the structures used in the sedimentation zone and limestone deposits on the purification processes, and the overall efficiency of the system. The SSBS is a constructed wetland for purifying water in a small urban river, whose hydrological regime is determined by stormwater and meltwater, with a limited surface area comparing to the recommended minimum of 2–5% of the drainage area (Schueler, 1992; Shutes et al., 2004; Bratieres et al., 2008). A review by Carleton et al. (2001) and Kadlec and Wallace (2009), found the SSBS to have the smallest area ratio (0.02%) of CWs, i.e. the ratio of purification system surface area to contributing watershed area.

2. Materials and methods

2.1. Study site

The study was conducted in the city of Lodz, central Poland, whose hydrographic network consists of several small streams or rivers. One of these waterways is the Sokolowka river, flowing in the north-western part of the city. The Sokolowka river catchment area is 45.95 km^2, and the total length of the watercourse is 12.8 km. The total length of the separated stormwater drain system connected to the river is three times that of the river itself, with over 50 outlets.

The upper part of the catchment which supplies the SSBS is covered by high density single-housing with a high proportion (more than 47%) of impermeable surface (Bartnik and Moniewski, 2013). The river below the SSBS is tamed with a cascade of six recreational reservoirs. The cascade of reservoirs used to be protected from the stormwater pollution by a sedimentation tank located on the bank of the river (km 9 + 537). In 2011, the sedimentation tank was replaced by the SSBS as part of the EU SWITCH project (6 FP EU, GOCE 018530), in close cooperation with the Lodz City Office. Additionally, two dry ponds were constructed above the SSBS in 2009 and in 2012 to purify the water and mitigate the flow volume propagating downstream. Sokolowka River became a demonstration project for testing ecohydrological approaches and system solutions to enhance city sustainability based on water resources management (Wagner and Zalewski, 2011).

The catchment area above the SSBS is 5.72 km^2. The SSBS is 65 m long and 16 m wide, with an area of 1040 m^2, which represents 0.02% of the catchment area. The mean depth of the SSBS is 0.35 m with a maximum of 0.5 m. The SSBS is divided into three zones (Fig. 1.):

- An intensified hydrodynamic sedimentation zone (with surface flow): an area with concrete and lamellar structures which reduce the energy of the inflow and enhance sedimentation. The zone is 32 m long and is closed with a rock gabion, which was covered by geotextile coconut mat.
- An intensified biogeochemical processes zone (with subsurface flow) made of limestone: an area which increases the intensity of biological processes, has an additional filtration function and adsorbs PO_4^{3-}. The zone is 5 m long and ends with a rock gabion.
- A biofiltration zone (with surface flow): a wetland zone with *Phragmites australi, Typha latifolia, Acorus calamus* planted in rows next to each other (in 6 m, 10 m and 8 m-long strips, respectively) in 0.35 m-deep sand-gravel subsoil. At the end of each plant zone, PVC sheet piles 8 m long were installed, set perpendicularly to the flow direction, which increase the length of the water flow path by about 25–30%.
- A post-treatment zone: an 8 m × 8 m area behind the final sheet piles, without subsoil material. Separated from the biofiltration zone by a concrete curb measuring about 100 × 30 × 15 cm.

The SSBS is located of the left bank of the Sokolowka river, and connected by a side channel; the main channel of the river still operates as a “bypass channel” to prevent hydraulic overload and erosion damage, and to prevent flushing out pollutants stored in the SSBS during periods of high flow (Fig. 1). During normal and high-flow periods, the SSBS system works as a free water surface wetland (FWS CW), while during winter, when ice covers the system, it acts as a horizontal sub-surface flow wetland (HSSF CW).

2.2. Sampling and analyses

The research was conducted during two consecutive hydrological years after SSSB construction (2011/2012 and 2012/2013). Water samples were taken twice a month (every two weeks) with additional samples taken during rainfall periods at five sampling stations:

- SOK1 – inflow of the Sokolowka river above the system