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

S. Szklarek [a, *], I. Wagner [b], T. Jurczak [b], M. Zalewski [b]

[a] European Regional Centre for Ecohydrology of the Polish Academy of Sciences, Tylna 3, 90-364, Lodz, Poland
[b] Department of Applied Ecology, Faculty of Biology and Environmental Protection,University of Lodz, 90-237 Lodz, 12/16 Banacha str., Poland

A R T I C L E I N F O

Article history:
Received 30 May 2017
Received in revised form
17 September 2017
Accepted 23 September 2017

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

A B S T R A C T

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

* Corresponding author.
E-mail address: s.szklarek@erce.unesco.lodz.pl (S. Szklarek).

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

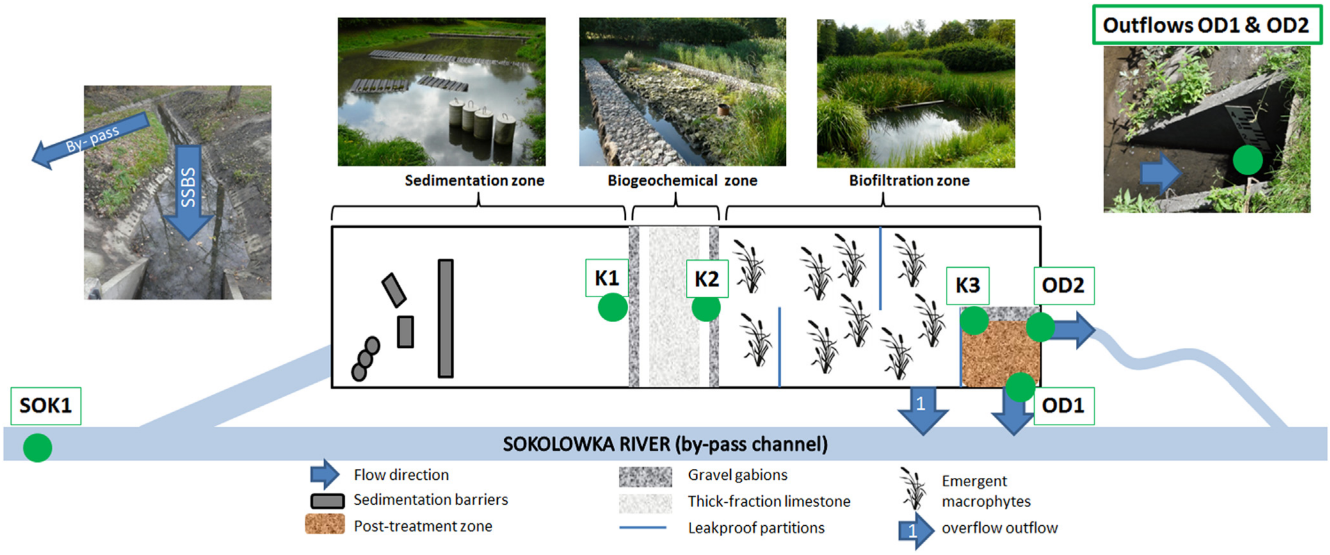

Fig. 1. Scheme of the seqentional sedimentation – biofiltration system on sokolowka river in Lodz, Poland.

- K1 – end of the sedimentation zone
- K2 – end of the biochemical zone
- K3 – end of the biofiltration zone
- OD1, OD2 – outflows from the system.

As the water leaves the SSBS via two different outflows, depending on the river discharge, the outflow in the analysis was presented as OD. The value for the OD point usually equaled the values for OD1 outflow. During periods of high or extremely high water level, OD values were calculated as the mean of all functioning outflows.

All water samples were collected manually for all sampling station during regular monitoring and high flow periods (during rainfall when SSBS was supplied with stormwater).

The following physical parameters were measured *in situ* by a YSI Professional Plus handheld multiparameter meter: water temperature (T), pH, dissolved oxygen (DO), conductivity (SPC) and water depth in the SSSB. YSI instrument was calibrated in laboratory before each sampling session. The collected water samples were analyzed for total nitrogen (TN) (Hach, 1997), total phosphorus (TP) (Golterman et al., 1978) and total suspended solids (TSS), by gravimetry. Ammonium, nitrates, phosphates and chloride ions were analyzed using a Dionex® ion chromatograph with a cation column (CG18, IonPac CS18, CSRS-ULTRA II) and an anion column (AG22, IonPac AS22, ASRS – ULTRA II). The systems were operated in isocratic elution at 30 °C at a flow rate of 1 ml/min. For ion identification, combined standards were used (Dionex Corporation).

The removal rate was calculated according below formulas:

$$R = (C_{n+1} - C_n)/C_n \times 100\%;$$

$$E = (C_{OD} - CS_{OK1})/C_{SOK1} \times 100\%;$$

where:

R - removal rate for each zone [%]
C – annual mean concentration of analyzed pollutant [mg L^{-1}],
n – sample points where 1 is SOK1, 2 is K1, 3 is K2, 4 is K3, and 5 is OD.
E - overall efficiency [%]

The efficiency of the sedimentation process was measured as the thickness of the sediment layer. Three sets of sediment samples were taken for further analysis in 2013: in June, August and October. The thickness of the deposits was measured manually, using a wooden pile with a scale, in a 2 m × 2 m grid. Sediment samples were taken in three transects: the first before the lamella line, the second in the middle of the sedimentation zone, and the last one - 2 m before the end of the zone (Fig. 2A). Three samples were taken in each transect: in the middle of zone, and 2 m from both shores, and a composite samples for analysis were prepared by mixing these three samples for each transect. The collected samples were dried and subjected to the following analyses: mineral and organic matter by gravimetry; sediment particle size (the areometric method according to Prószyński), TN (according to Klejdahl) and TP (colorimetry) were analyzed in an accredited laboratory. Sludge thickness maps were made in Surfer® version 8.

The significance of the changes of the concentrations of the analyzed compounds between sampling points were examined by the Wilcoxon signed-rank test.

3. Results and discussion

The pollutant concentration and pollutant concentration removal rate at each sample point in the SSBS are shown in Table 1 and Table 2, respectively. The changes in the mean values of the physicochemical parameters through the SSBS are shown in Supplement 1. The mean concentrations of pollutants and physicochemical parameters are given with reference to Polish Water Quality Standards (annual mean) (PWQS, 2014).

3.1. The key purification role of the sedimentation zone

The sedimentation zone is the first stage of water purification in the SSBS. It was found to provide the greatest reduction of analyzed pollutants (Tables 1 and 2). The zone reduced the mean concentration of TSS by 59.7% from 132.98 mg L^{-1} at the inflow (SOK1) to 53.63 mg L^{-1} at the end of the zone (K1) (see sample points on Fig. 1). Similar results were noted for the Imperial and Brawley multi-zone CWs, i.e. 94.3% and 88.8% respectively (Kadlec et al., 2010), both systems had pre-treatment zones with a mean depth

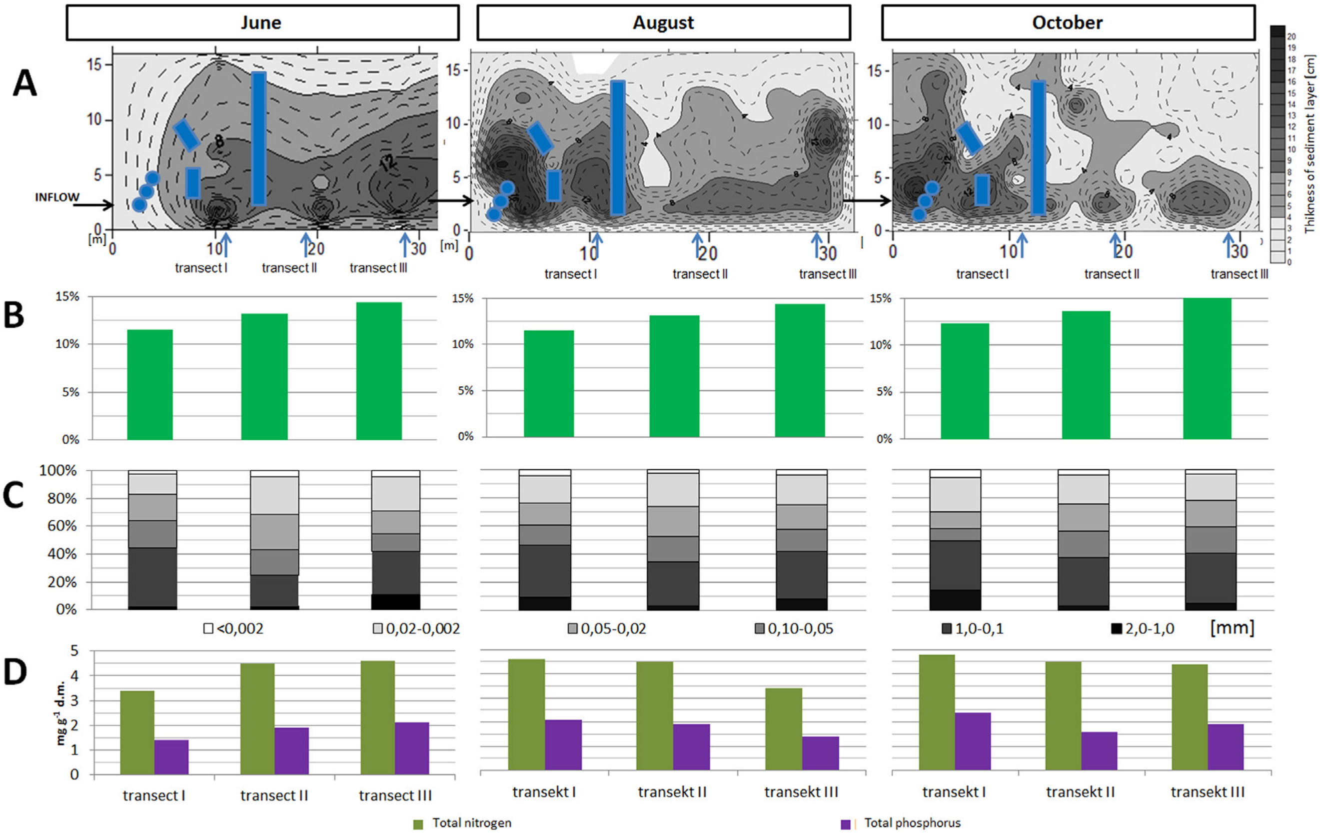

Fig. 2. Sediment analysis results in sedimentation zone in 2013 (A) sediment layer depth (blue circles - concrete columns, blue rectangles - lamels), (B) percent organic matter content in sediments, (C) particle size composition of sediments and (D) nitrogen concentration and total phosphorus in sediments.

Table 1
Annual mean concentration of analyzed compounds (with ± Standard Deviation - SD) at each sample point in Sequentionall Sedimentation-Biofiltration System, in reference to the Water Quality Standards (annual mean) (PWQS, 2014).

Sampling points	TSS (mg L^{-1})	TP (mg L^{-1})	PO_4^{3-} (mg L^{-1})	TN (mg L^{-1})	NH_4^+ (mg L^{-1})	NO_3^- (mg L^{-1})	Cl^- (mg L^{-1})
SOK1	132.98 ± 231.11	0.67 ± 0.68	0.46 ± 0.78	6.14 ± 4.39	1.09 ± 1.62	10.52 ± 6.57	1280.1 ± 2475.8
K1	53.63 ± 72.59	0.35 ± 0.29	0.28 ± 0.46	3.94 ± 2.51	1.57 ± 2.19	7.54 ± 7.69	241.5 ± 528.6
K2	47.25 ± 75.92	0.33 ± 0.24	0.26 ± 0.41	3.52 ± 2.43	1.41 ± 2.17	6.93 ± 7.22	182.7 ± 386.6
K3	34.68 ± 60.40	0.31 ± 0.27	0.24 ± 0.38	3.29 ± 2.71	0.90 ± 1.30	5.90 ± 7.62	166.3 ± 325.5
OD	51.37 ± 76.19	0.42 ± 0.41	0.32 ± 0.48	3.31 ± 2.32	1.06 ± 1.69	5.81 ± 6.94	460.9 ± 978.4
Water quality standard (II class)	≤50	≤0.40	≤0.31	≤10	≤2	≤22.5	≤300

of 2 m, while that of the SSBS was only 0.4 m. Although, as noted by Kadlec and Wallace (2009), SSBS systems with shallow sedimentation zones should be less effective at TSS reduction. Walker (2001) indicates that additional structures such as islands promote particle sedimentation, even in CWs with a mean depth of 0.77 m. High reduction of TSS (84.4%) was noted in the first zone (cell) of the Dye branch stormwater wetland in Piedmont, where water depth was less than 30 cm over 79% of the total wetland area (Hathaway and Hunt, 2010).

The role of the sedimentation structure could be seen in the results of sediment thickness analyses (Fig. 2A). Sediments accumulating in the first zone were removed by excavator from the shore after winter when the ice and snow cover melted (March–April, each year). For ease of operation, the structures were moved to the distal part of the sedimentation zone. One month after sediment removal (June 2013), the greatest thickness of sludge ranged from 6 cm to 12 cm at the end of the zone, and below 8 cm near the inlet part. In August and October, the deepest sedimentation layer, ranging from 6 cm to 18 cm, was found in the inlet, while it remained at the same level (6–14 cm) at the end of the zone. The sedimentation structure facilitated strong TSS reduction by slowing the inlet flow velocity, which promoted particle sedimentation (Kadlec and Wallace, 2009).

The sedimentation zone played a key role in the process of phosphorus reduction. The mean concentration of TP in the

Table 2
Overall and each zone removal rates in the Sequentional Sedimentation-Biofiltration System.

	TSS (%)	TP (%)	PO_4^{3-} (%)	TN (%)	NH_4^+ (%)	NO_3^- (%)	Cl^- (%)
removal rate for each zone of SSBS							
SOK1-K1	59.7	47.8	39.1	35.8*	−44.0*	28.3*	81.1
K1-K2	4.8*	2.9	4.4	6.9*	14.6	5.8*	4.6*
K2-K3	9.4*	3.0	4.3*	3.7*	47.1	9.8*	1.3*
K3-OD	−12.5*	−16.4*	−17.4	−0.3*	−14.9	0.9*	−23.0
overall removal rate in relation to inflow concentration							
SOK1-OD	61.4*	37.3*	30.4	46.1*	2.8	44.8*	64.0

* Significant results with $p < 0.05$.

sedimentation zone fell from 0.67 mg L^{-1} to 0.35 mg L^{-1} (Table 1): a 47.8% reduction (Table 2). The importance of the first zone of purification systems in P reduction was also confirmed by Johannesson et al. (2011), who found that 80% of the incoming phosphorus sediments were retained in the initial part of a Swedish CW. Hathaway and Hunt (2010) noted 61.3% reduction of TP in first wetland cell. Andersson et al. (2005) observed that efficiency reduction of TSS could increase the removal rate of TP. Also Kadlec et al. (2010) found particulate P to be the major phosphorus form retained in the Imperial and Brawley CWs in the USA.

The observed decrease in mean TP concentration in the sedimentation zone of the SSBS might be also a result of phosphate removal. The mean concentration of PO_4^{3-} fell from 0.46 mg L^{-1} to 0.28 mg L^{-1} (Table 1): a 39.1% removal rate (Table 2). Phosphates can be removed from water by physicochemical processes and biological uptake (Fisher and Acreman, 2004; Vymazal, 2007). The occurrence of calcium, aluminum and iron ions in the water and the suspension flowing into the SSBS might enhance PO_4^{3-} binding in sediments (Moore and Miller, 1994; House and Denison, 2000; Wang et al., 2009), particularly the sediments in the first zone of the SSBS whose mineral fraction content was above 85% (Fig. 2B). Phosphates might also accumulate in biomass. Kadlec et al. (2010) noted that the sedimentation basin might function as algal ponds, which provide for PO_4^{3-} removal. Zhimiao et al. (2016) report that incorporating an algal pond in a CW results in phosphate levels being reduced by 86.4–88.7%, while traditional CWs remove PO_4^{3-} in the range 60.1–75.0% during a three-day retention period. Microbiological activity could be also responsible for phosphate reduction (Truu et al., 2009).

The sedimentation zone provided a significant reduction of TN and NO_3^-: 35.8% and 28.3%, respectively (Table 2). The mean concentration of TN decreased from 6.14 mg L^{-1} to 3.94 mg L^{-1}, and the mean NO_3^- concentration fell from 10.52 mg L^{-1} to 7.54 mg L^{-1} (Table 1). A significant increase of mean NH_4^+ concentration from 1.09 mg L^{-1} to 1.57 mg L^{-1} (a 44% rise) was noted (Tables 1 and 2). Hathaway and Hunt (2010) observed 51.7% reduction of TN and 68.2% for NO_x in first wetland cell.

The first SSBS zone provided 81.1% reduction of chlorides, whose concentration changed from a mean of 1280.1 mg L^{-1} at SOK1 to the 241.5 mg L^{-1} at the end of the sedimentation zone. Little knowledge exists concerning the degree of chloride reduction provided by CWs, therefore further analysis is needed to investigate this observed reduction of Cl^-, especially since some of the stormwater control measures, such as permeable pavements, have been found to release chloride in spring, after winter salt application (Borst and Brown, 2014; Winston et al., 2016).

3.2. Complementary role of the geochemical barrier

The geochemical barrier further increased the removal rate of all analyzed pollutants in the SSBS by 2.9–6.9% (Table 2). Higher values were recorded for NH_4^+ with a reduction of 14.6%.

The mean concentration of TSS fell from 53.63 mg L^{-1} to 47.25 mg L^{-1} between K1 and K2 (Table 1), corresponding to a 4.8% reduction. The observed reduction of TSS is likely due to a result of the existence of a rock and limestone barrier which stopped pollution in the sedimentation zone and acted as a filter. Studies conducted in China (Zhang et al., 2010) note that sedimentation and filtration may remove 89–97% of the initial TSS concentration of urban runoff.

The geochemical barrier increased the reduction of phosphorus by 2.9% for TP and 4.4% for PO_4^{3-} (Table 2), but neither result was statistically significant. The mean concentration decreased from 0.35 mg L^{-1} to 0.33 mg L^{-1} for TP and from 0.28 mg L^{-1} to 0.26 mg L^{-1} for PO_4^{3-} (Table 1). Low reduction rate, not in the line with the design assumptions, might be caused by high reduction observed in the sedimentation zone. It also could be attributed to variation in hydrological conditions (Lu et al., 2016), as well as physicochemical conditions such as pH (Dittrich et al., 2011), water temperature and dissolved oxygen (Zhang et al., 2008; Herrmann et al., 2014), which affected the phosphate purification processes. Further investigation is need to determine the rather low reduction of phosphates in this zone.

Nitrogen compounds were also reduced in the geochemical barrier. The mean TN concentration decreased from 3.94 mg L^{-1} to 3.52 mg L^{-1} (Table 1), which increased the removal rate by 6.9% (Table 2). The mean concentration of NH_4^+ fell from 1.57 mg L^{-1} to 1.41 mg L^{-1}, (Table 2), representing a 14.6% reduction in the geochemical barrier (Table 2). The mean NO_3^- concentration fell from 7.54 mg L^{-1} to 6.93 mg L^{-1} (Table 1), corresponding to a 5.8% reduction (Table 2). The reductions of TN and NO_3^- were statistically significant. The reduction of nitrogen compounds observed in the geochemical barrier in the SSBS might also be a result of physicochemical purification processes (Vymazal, 2007; Lee et al., 2009).

The mean chloride concentration decreased from 241.5 mg L^{-1} to 182.7 mg L^{-1} in the geochemical barrier (Table 1), which provided 4.6% significant reduction in this zone (Table 2). An investigation of four different materials acting as reactive media for deicing salt removal from urban runoff by de Santiago-Martin et al. (2016) found that limestone provided a 5% removal rate of Cl^- at an inflow concentration about 150 mg L^{-1}.

3.3. Efficiency of the biofiltration zone

Biofiltration zone of the SSBS increased removal efficiency of all analyzed pollutants (Tables 1 and 2). Mean TSS concentration decreased from 47.25 mg L^{-1} to 34.68 mg L^{-1}. The biofiltration zone provided a 9.4% significant reduction of TSS. The mean TP concentration changed from 0.33 mg L^{-1} to 0.31 mg L^{-1}, a 3% reduction, in this zone. The observed mean concentration of PO_4^{3-} decreased from 0.26 mg L^{-1} to 0.24 mg L^{-1}, which corresponded to 4.3% significant removal provided by this zone. The zone provided significant reductions in TN (3.7%) and NO_3^- (9.8%), and an insignificant reduction of NH_4^+ (47.1%). The mean concentration of nitrogen compounds decreased from 3.52 mg L^{-1} to 3.29 mg L^{-1} for TN, from 1.41 mg L^{-1} to 0.90 mg L^{-1} for NH_4^+ and from 6.93 mg L^{-1} to 5.90 mg L^{-1} for NO_3^-.

The small increase of removal rate seen for the pollutants, except for ammonium, might be due to the high level of removal observed in the sedimentation zone, creating diminishing returns for pollutant removal. Hathaway and Hunt (2010) also noted less reduction of TSS, TN and TP (18%, 16% and 3%, respectively) in the last wetland zone. In addition, other studies have shown that macrophytes play a complementary role in water purification to nutrients and suspended matter in FWS CWs (Vymazal, 2007; Lee et al., 2009; Jia et al., 2014).

The mean chloride concentration fell from 182.7 mg L^{-1} to 166.3 mg L^{-1} (a 2.7% reduction) across the biofiltration zone. According to Chairawiwut et al. (2016), Cl^- could be retained by absorption and creation of salts in sand-gravel soil. Also, some plant species, such as *Typha angustifolia*, *Juncus maritimus* and *Eleocharis palustris*, have phytodesalinization potential (Guesdon et al., 2016).

3.4. Overall efficiency of the SSBS

The monitoring data revealed that the concentrations of all analyzed pollutants decreased along the flow path of the SSBS (Table 1).

The mean concentration of TSS fell from 132.98 mg L^{-1} at the SSBS inlet to 51.37 mg L^{-1} at the outlet, a 61.4% reduction, which almost met Polish Water Quality Standards (PWQS, 2014). This reduction was statistically significant. The presence of an uncontrolled and rapidly changing flow across the SSBS, combined with a small SSBS surface area in relation to the total catchment area, might influence TSS reduction. CWs with a controlled (pumped) water inflow, ensures a constant retention time, provided higher efficiency, of around 94%–97% with a TSS concentration of 200–330 mg L^{-1} at the inflow (Kadlec et al., 2010; Zheng et al., 2016).

The removal rate of TP and PO_4^{3-} also almost met PWQS at the outflow, with their concentrations decreasing from 0.67 mg/l to 0.40 mg/l for TP (37.3%; significant) and 0.46 mg/l to 0.32 mg/l for PO_4^{3-} (30.4%; not significant).

The observed overall reduction rates of TSS and TP were below the removal rates of 68–89% (TSS) and 34–59% (TP) noted in reviews of wastewater treatment in other types of CW (Vymazal, 2007, 2010). Carleton et al. (2001) report that TSS and TP reduction in stormwater CWs depends on the area ratio and detention time.

The observed levels of nitrogen compounds at the inflow and at the outflow from the SSBS were below PWQS values. The mean concentration of TN decreased from 6.14 mg/l to 3.31 mg/l, and mean concentration of NO_3^- fell from 10.52 mg/l to 5.81 mg/l. Both compounds demonstrated statistically significant rates of reduction: 46.1% for TN and 44.8% for NO_3^-. The removal rate of NH_4^+ was only 2.8% (not significant), with 1.09 mg/l mean concentration at the SSBS inlet and 1.06 mg/l at the outlet.

The reductions in the levels of nitrogen compounds indicate that SSBS provides the conditions for the transformation of nitrogen to gaseous form via the denitrification process. Chen et al. (2014) report that denitrification contributed to 54%–94% of TN reduction, while sedimentation was responsible for 1%–46% and plant uptake for 7.5%–14.3%.

The mean concentration of chlorides decreased from 1280.1 mg/l to 460.9 mg/l through the SSBS; however, both values exceeded the level of 300 mg/l specified by the PWQS. The observed 64% reduction of Cl^- was not significant. Coenen (2004) regards chloride as a forgotten part of the overall circulation of elements in the environment. Few studies have examined the removal of chlorine by CWs. Further research about chloride circulation in CWs is important, particularly in the light of their possible toxic impact on water ecosystems (Tixier et al., 2012; Szklarek et al., 2015) and negative impact on the efficiency of purification processes (Scholz, 2006; Zhang et al., 2008).

The concentration of all analyzed compounds, beside nitrates, increased across the post-treatment part of the SSBS (zone K3-OD) (Table 2). This could suggest that some pollutant might have been flushed out from previous zones during high flows and stored in the last part of the SSBS. The post-treatment part was not maintained, so the sediment retention capacity was exhausted. Moreover, the SSBS was a young system, so some erosion from soil-gravel subsoil in biofiltration zone could have also occurred. The increased concentration of pollutants in this part of the SSBS needs further investigation, as it is known that post-treatment structures play an important role in CW design, thus improving the efficiency of pollutant removal and extending the operating time of the system without the need for costly and disruptive maintenance (Mungasavalli and Viraraghavan, 2006).

Research has shown that multi-zone constructed wetlands such the SSBS, whose total surface area is 0.02% of the catchment area, could facilitate pollutant removal, even on a small area which was below the recommended minimum 2–5% of the CWs drainage area (Schueler, 1992; Shutes et al., 2004; Bratieres et al., 2008). The findings confirm that area ratio is not the only parameter which should be considered when designing CWs: Tanner and Kadlec (2013) demonstrated that an increase in the CW surface area to basin area ratio from 1% to 2% results in a 75% improvement in overall nitrogen removal efficiency, while an increase of 2%–4% increases the efficiency by only a further 43%.

4. Conclusions

This study assesses the pollutant removal efficiency of a multi-zone constructed wetland (Sequential Sedimentation-Biofiltration System) intended for the purification of a small urban river supplied by stormwater (The Sokolowka river, Lodz, Poland).

The study demonstrated that the SSBS provided high pollutant removal rate, especially while considering its relatively small surface area to the total catchment area. According to Carleton et al. (2001) and Kadlec and Wallace (2009), the removal efficiency of the SSBS was comparable or even higher than that of systems with higher area ratio (Supplement 2).

The results indicate that the sedimentation zone played a fundamental role in the removal of TSS and nutrients. Its performance can be improved by the implementation of structures such as concrete and lamellar systems, which support the sedimentation process and lower the inlet flow velocity. Post-investment management of this zone, including regular monitoring and removal of excess of the sediments, should provide high efficiency and extend the operating time of the system.

The SSBS ensured efficient nitrogen transformation, resulting in significant reduction of TN and NO_3^-. The inflow concentrations of N compounds were below the Polish Water Quality Standards (2014), so the system could be adjusted to improve the reduction of the main pollutants (TSS and phosphorus), which were exceeded at the inflow.

The system reduced chloride concentration, but further studies are needed to understand its circulation in CWs and to assess the impact of Cl^- on purification processes.

The results indicate that it possible to create efficient working multi-zone CWs such as monitored SSBS based on ecohydrological principles for removing pollutants in urban areas with limited space.

Acknowledgments

The project was carried out as a part of the “Innovative recourses and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development project financed by the European Union from the European Fund of Regional Development based on the Operational Program of the Innovative Economy, POIG.01.01.02-10-106/09. This study follows on from research performed as a part of the EU Project “SWITCH” (IP 6 PR UE, GOCE 018530 2006–2011).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.09.066.

References

Andersson, J.L., Bastviken, S.K., Tonderski, K.S., 2005. Free water surface wetlands for wastewater treatment in Sweden – nitrogen and phosphorus removal. Water Sci. Technol. 51 (9), 39–46.

Bartnik, A., Moniewski, P., 2013. Changes of the basic physico-chemical characteristics of small rivers influenced by anthropogenic elements in the area of Łódź, Poland. Understanding Freshwater Quality Problems in a Changing World. In: Proceedings of H04, IAHS-iapso-IASPEI Assembly, Gothenburg, Sweden, July 2013, pp. 336–344 (IAHS Publ. 361, 2013) ss.

Borst, M., Brown, R.A., 2014. Chloride released from three permeable pavement surfaces after winter salt application. J. Am. Water Resour. Assoc. 50 (1), 29–41.

https://doi.org/10.1111/jawr.12132.

Bratieres, K., Fletcher, T.D., Deletic, A., Zinger, Y., 2008. Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. Water Res. 42, 3930–3940. https://doi.org/10.1016/j.watres.2008.06.009.

Brown, R., Keath, N., Wong, T., 2008. Transitioning to water sensitive cities: historical, current and future transition states. In: 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.

Carleton, J.N., Grizzard, T.J., Godrej, A.N., Post, H.E., 2001. Factors affecting the performance of stormwater treatment wetlands. Water Res. 35 (6), 1522–1562. https://doi.org/10.1016/S0043-1354(00)00416-4.

Chairawiwut, W., McMartin, D.W., Azam, S., 2016. Salts removal from synthetic solution-potash brine by non-planted constructed wetlands. Water 8, 113. https://doi.org/10.3390/w8040113.

Chen, Y., Wen, Y., Zhou, Q., Vymazal, J., 2014. Effects of plant biomass on nitrogen transformation in subsurface-batch constructed wetlands: a stable isotope and mass balance assessment. Water Res. 63, 158–167. https://doi.org/10.1016/j.watres.2014.06.015.

Coenen, M., 2004. Chlorine. In: Merian, E., Anke, M., Ihnat, M., Stoeppler, M. (Eds.), Elements and Their Compounds in the Environment. WILEY-VCH, pp. 1423–1443. ISBN: 978-3-527-30459-2.

de Santiago-Martin, A., Michaux, A., Guesdon, G., Constantin, B., Despréaux, M., Galvez-Cloutier, R., 2016. Potential of anthracite, dolomite, limestone and pozzolan as reactive media for de-icing salt removal from road runoff. Int. J. Environ. Sci. Technol. 13 (10), 2313–2324. https://doi.org/10.1007/s13762-016-1085-1.

Dittrich, M., Gabriel, O., Rutzen, Ch, Koschel, R., 2011. Lake restoration by hypolimnetic $Ca(OH)_2$ treatment: impact on phosphorus sedimentation and release from sediment. Sci. Total Environ. 409, 1504–1515. https://doi.org/10.1016/j.scitotenv.2011.01.006.

Dou, T., Troesch, S., Petitjean, A., Gábor, P.T., Esser, D., 2017. Wastewater and rainwater management in urban areas: a role for constructed wetlands. Proced. Environ. Sci. 37, 535–541. https://doi.org/10.1016/j.proenv.2017.03.036.

European Commission, 2013. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Green Infrastructure (GI) — Enhancing Europe's Natural Capital. Brussels. COM/2013/0249 Final.

European Commission, 2015. Towards an EU Research and Innovation Policy Agenda for Nature-based Solutions & Re-naturing Cities. https://doi.org/10.2777/765301. Final report of the Horizon 2020. ISBN: 978-92-79-46051-7.

Fisher, J., Acreman, M.C., 2004. Wetland nutrient removal: a review of the evidence. Hydrol. Earth Syst. Sci. 8 (4), 673–685. https://doi.org/10.5194/hess-8-673-2004.

Golterman, H.L., Clymo, R.S., Ohnstad, M.A.M., 1978. Methods for Physical and Chemical Analysis of Fresh Waters. Blackwell Scientific, Oxford.

Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, Ch.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global change and the ecology of cities. Science 319 (5864), 756–760. https://doi.org/10.1126/science.1150195.

Guesdon, G., de Santiago-Martin, A., Galvez-Cloutier, R., 2016. Phytodesalinization potential of Typha angustifolia, Juncus maritimus, and Eleocharis palustris for removal of de-icing salts from runoff water. Environ. Sci. Pollut. Res. 23 (19), 19634–19644. https://doi.org/10.1007/s11356-016-7176-1.

Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising green and bluesspace to mitigate urban heat island intensity. Sci. Total Environ. 584–585, 1040–1055. https://doi.org/10.1016/j.scitotenv.2017.01.158.

Hach, 1997. Water Analysis Handbook, third ed. HACH Company, Loveland, Colorado, U.S.A., p. 1309

Hathaway, J.M., Hunt, W.F., 2010. Evaluation of storm-water wetlands in series in Piedmont North Carolina. J. Environ. Eng. 136 (1), 140–146. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000130.

Herrmann, I., Nordqvist, K., Hedström, A., Viklander, M., 2014. Effect of temperature on the performance of laboratory-scale phosphorus-removing filter beds in on-site wastewater treatment. Chemosphere 117, 360–366. https://doi.org/10.1016/j.chemosphere.2014.07.069.

House, W.A., Denison, F.H., 2000. Factors influencing the measurement of equilibrium phosphate concentrations in river sediments. Water Resour. 34 (4), 1187–1200. https://doi.org/10.1016/S0043-1354(99)00249-3.

Jia, H., Sun, Z., Li, G., 2014. A four-stage constructed wetland system for treating polluted water from an urban river. Ecol. Eng. 71, 48–55. https://doi.org/10.1016/j.ecoleng.2014.07.013.

Johannesson, K., Andersson, J., Sundblad-Tonderski, K., 2011. Efficiency of a constructed wetland for retention of sediment associated phosphorus. Hydrobiologia 674 (1), 179–190. https://doi.org/10.1007/s10750-011-0728-y.

Kadlec, R.H., Wallace, S.D., 2009. Treatment Wetlands. CRC Press, Boca Raton. ISBN: 978-1-56670-526-4.

Kadlec, R.H., Roy, S.B., Munson, R.K., Charlton, S., Brownlie, W., 2010. Water quality performance of treatment wetlands in the Imperial Valley, California. Ecol. Eng. 36, 1093–1107. https://doi.org/10.1016/j.ecoleng.2010.04.028.

Kadlec, R.H., Pries, J., Lee, K., 2012. The Brighton treatment wetlands. Ecol. Eng. 47, 56–70. https://doi.org/10.1016/j.ecoleng.2012.06.042.

Kearney, M.A., Zhu, W., Graney, J., 2013. Inorganic nitrogen dynamics in an urban constructed wetland under base-flow and storm-flow conditions. Ecol. Eng. 60, 183–191. https://doi.org/10.1016/j.ecoleng.2013.07.038.

Lee, C.-G., Fletcher, T.D., Sun, G., 2009. Nitrogen removal in constructed wetland systems. Eng. Life Sci. 9 (1), 11–22. https://doi.org/10.1002/elsc.200800049.

Leitner, P., Hauer, C., Graf, W., 2017. Habitat use and tolerance levels of macroinvertebrates concerning hydraulic stress in hydropeaking rivers – a case study at the Ziller River in Austria. Sci. Total Environ. 575, 112–118. https://doi.org/10.1016/j.scitotenv.2016.10.011.

Lu, S., Zhang, X., Wang, J., Pei, L., 2016. Impacts of different media on constructed wetlands for rural household sewage treatment. J. Clean. Prod. 127, 325–330. https://doi.org/10.1016/j.jclepro.2016.03.166.

Mass, M., Balvanera, P., Bourgeron, P., Equihua, M., Baudry, J., Dick, J., Forsius, M., Halada, L., Krauze, K., Nakaoka, M., Orenstein, D.E., Parr, T.W., Redman, C.L., Rozzi, R., Santos-Reis, M., Swemmer, A.M., Vădineanu, A., 2016. Changes in biodiversity and trade-offs among ecosystem services, stakeholders, and components of well-being: the contribution of the International Long-Term Ecological Research network (ILTER) to Programme on Ecosystem Change and Society (PECS). Ecol. Soc. 21 (3), 31. https://doi.org/10.5751/ES-08587-210331.

Mitsch, W.J., Gosselink, J.G., 2007. Wetlands, fourth ed. John Wiley & Sons, Inc., Canada. ISBN13: 978–0471699675.

Moore Jr., P.A., Miller, D.M., 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium, and iron amendments. J. Environ. Qual. 23, 325–330. https://doi.org/10.2134/jeq1994.00472425002300020016x.

Mungasavalli, D.P., Viraraghavan, T., 2006. Constructed wetlands for stormwater management: a review. Fresenius Environ. Bull. 15 (11), 1363–1372.

Palmer, M.A., Liu, J., Matthews, J.H., Mumba, M., D'Odorico, P., 2015. Water security: gray or green? Science 349 (6248), 584–585. https://doi.org/10.1126/science.349.6248.584-a.

Polish Water Quality Standards, 2014. Regulation of the Minister of the Environment of 22 October 2014 on the Classification of the Condition of Surface Water Bodies and Environmental Quality Standards for Priority Substances.

Revi, A., Satterthwaite, D.E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R.B.R., Pelling, M., Roberts, D.C., Solecki, W., 2014. Urban areas. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part a: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535–612. ISBN: 9781107641655.

Scholz, M., 2006. Wetland Systems to Control Urban Runoff. Elsevier, Oxford, UK. ISBN: 978-0-444-52734-9.

Schueler, T.R., 1992. Design of Stormwater Wetland Systems: Guidelines for Creating Diverse and Effective Stormwater Wetlands in the Mid-Altantic Region. Metropolitan Washington Council of Governments, Washington. D. C, U.S.A.

Shutes, R.B.E., Ellis, J.B., Revitt, D.M., Forshaw, M., Winter, W., 2004. Urban and highway runoff treatment by constructed wetlands. Develop. Ecosyst. 1, 361–382. https://doi.org/10.1016/B978-044451691-6/50023-5.

Stratus Consulting, 2009. A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds. Stratus Consulting, Boulder. https://www.michigan.gov/documents/dnr/TBL.AssessmentGreenVsTraditionalStormwaterMgt_293337_7.pdf.

Szklarek, S., Stolarska, M., Wagner, I., Mankiewicz-Boczek, J., 2015. The microbiotest battery as an important component in the assessment of snowmelt toxicity in urban watercourses - preliminary studies. Environ. Monit. Assess. 187, 16. https://doi.org/10.1007/s10661-014-4252-1.

Tanner, C.C., Kadlec, R.H., 2013. Influence of hydrological regime on wetland attenuation of diffuse agricultural nitrate losses. Ecol. Eng. 56, 79–88. https://doi.org/10.1016/j.ecoleng.2012.08.043.

Tixier, G., Rochfort, Q., Grapentine, L., Marsalek, J., Lafont, M., 2012. Spatial and seasonal toxicity in a stormwater management facility: evidence obtained by adapting an integrated sediment quality assessment approach. Water Res. 46, 6671–6682. https://doi.org/10.1016/j.watres.2011.12.031.

Truu, M., Juhanson, J., Truu, J., 2009. Microbial biomass, activity and community composition in constructed wetlands. Sci. Total Environ. 407, 3958–3971. https://doi.org/10.1016/j.scitotenv.2016.08.148.

Vergeles, Y., Vystavna, Y., Ishchenko, A., Rybalka, I., Marchand, L., Stolberg, F., 2015. Assessment of treatment efficiency of constructed wetlands in East Ukraine. Ecol. Eng. 83, 159–168. https://doi.org/10.1016/j.ecoleng.2015.06.020.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. Sci. Total Environ. 380, 48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014.

Vymazal, J., 2010. Constructed wetlands for wastewater treatment. Water 2, 530–549. https://doi.org/10.1016/j.ecoleng.2005.07.002.

Wagner, I., Zalewski, M., 2011. System solutions in urban water management: the Lodz (Poland) perspective. In: Howe, C., Mitchell, C. (Eds.), Water Sensitive Cities. IWA Publishing, London, pp. 231–245.

Walker, D.J., 2001. Modelling sedimentation processes in a constructed stormwater wetland. Sci. Total Environ. 266, 61–68. https://doi.org/10.1016/S0048-9697(00)00730-0.

Wang, Y., Shen, Z., Niu, J., Liu, R., 2009. Adsorption of phosphorus on sediments from the Three-Gorges Reservoir (China) and relation with sediment compositions. J. Hazard Mater. 162, 92–98. https://doi.org/10.1016/j.jhazmat.2008.05.013.

Wang, H., Huang, C.-C., Ge, Y., Wu, J., Chang, J., 2014. The performance of species mixtures in nitrogen and phosphorus removal at different hydraulic retention times. Pol. J. Environ. Stud. 23 (3), 917–922.

Wang, M., Zhang, D.Q., Dong, J.W., Tan, S.K., 2017. Constructed wetlands for wastewater treatment in cold climate — a review. J. Environ. Sci. https://doi.org/10.1016/j.jes.2016.12.019 (in press), Corrected Proof.

Winston, R.J., Davidson-Bennet, K.M., Buccier, K.M., Hunt, W.F., 2016. Seasonal

Variability in stormwater quality treatment of permeable pavements situated over heavy clay and in a cold climate. Water Air Soil Pollut. 227, 140. https://doi.org/10.1007/s11270-016-2839-6.

Zalewski, M., 2000. Ecohydrology – the scientific background to use ecosystem properties as management tools toward sustainability of water resources. Ecol. Eng. J. Ecohydrol. 16 (1), 1–8. https://doi.org/10.1016/S0925-8574(00)00071-9.

Zalewski, M., 2002. Ecohydrology – the use of ecological and hydrological processes for sustainable management of water resources. Hydrol. Sci.–J. Sci. Hydrol. 47 (5), 825–834. https://doi.org/10.1080/02626660209492986.

Zalewski, M., 2014. Ecohydrology, biotechnology and engineering for cost efficiency in reaching the sustainability of biogeosphere. Ecohydrol. Hydrobiol. 14, 14–20. https://doi.org/10.1016/j.ecohyd.2014.01.006.

Zalewski, M., Janauer, G.A., Jolánkai, G., 1997. Ecohydrology. A New Paradigm for the Sustainable Use of Acquatic Resources. Conceptual Background, Working Hypothesis, Rationale and Scientific Guidelines for the Implementation of the IHP-v Projects 2.3/2.4. IHP-V Technical Documents in Hydrology No. 7, UNESCO, Paris, p. 58.

Zhang, L., Scholz, M., Mustafa, A., Harrington, R., 2008. Assessment of the nutrient removal performance in integrated constructed wetlands with the self-organizing map. Water Res. 42, 3519–3527. https://doi.org/10.1016/j.watres.2008.04.027.

Zhang, M., Chen, H., Wang, J., Pan, G., 2010. Rainwater utilization and storm pollution control based on urban runoff characterization. Journal of Environ. Sci. 22 (1), 40–46. https://doi.org/10.1016/S1001-0742(09)60072-3.

Zhang, X., Wu, Y., Gu, B., 2015. Urban rivers as hotspots of regional nitrogen pollution. Environ. Pollut. 205, 139–144. https://doi.org/10.1016/j.envpol.2015.05.031.

Zheng, Y., Wang, X.C., Dzakpasu, M., Ge, Y., Zhao, Y., Xiong, J., 2016. Performance of a pilot demonstration-scale hybrid constructed wetland system for on-site treatment of polluted urban river water in Northwestern China. Environ. Sci. Pollut. Res. 23, 447–454. https://doi.org/10.1007/s11356-015-5207-y.

Zhimiao, Z., Xinshan, S., Yanping, X., Yufend, Z., Zhijie, G., Fanda, L., Yi, D., Wei, W., Tianling, Q., 2016. Influences of seasons, N/P ratios and chemical compounds on phosphorus removal performance in algal pond combined with constructed wetlands. Sci. Total Environ. 573, 906–914. https://doi.org/10.1016/j.scitotenv.2016.08.148.