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Efficiency analysis of two sequential biofiltration systems in Poland and Ethiopia – the pilot study

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Abstract

The study presents the results of comparative analysis of sequential biofiltration systems (SBS) efficiency in Poland (SSBS) and Ethiopia (ASBS) constructed in order to purify urban storm- and waste water and mixed agricultural water, and treated sewage from a Water Treatment Plant, respectively.

The efficiency of SSBS (Poland) has been tested in different hydrological conditions prevailing during three storm events. The obtained results showed that the SSBS reduction efficiency reaches 95% for MM, 86% for TP and OM and 81% for TN. The results also demonstrated the enhanced reduction of analysed compounds in the diluted stage of storm events. The obtained data showed also that the SSBS purification rate is increasing with the flow up to 0.04 $m^3 s^{-1}$. Above this value the efficiency decreased and SSBS appears as the source of the analysed pollutants. For comparison, the effectiveness of ASBS (Ethiopia) which was examined when the sedimentation chamber was filled with sediments, showed the reduction of 8%, 78% and 65% for TP, OM and MM, respectively. Whereas TN was released from the system with a higher concentration in the ASBS outlet. The increased reduction in all the analysed compounds, amounted to 93% for TP, 73% for TN, 67% for MM and 36% for OM, was observed for samples collected after the sediment removal during proper maintenance of the system. The obtained results for both SBSs demonstrated the crucial role of monitoring and quantification of hydrological processes, especially transport of MM, OM and nutrients, for enhancement of the studied SBS efficiency.

Key words: sequential biofiltration system, urban stormwater, agricultural water pollution, water pollution, pollutants removal efficiency, ecohydrology.

1. Introduction

Urbanization not only alters the catchment hydrological regime, but also affects aquatic habitats by transporting a broad range of pollutants originating from different sources, including heavy metals, plant fertilizers and pesticides from lawns and gardens, oil from leaky cars, or pet waste deposited and accumulated during dry weather in the catchment (Marsalek *et al.* 2006; Wagner *et al.* 2008). Impervious areas, like rooftops, paved roads, sidewalks, etc. which can increase the concentration of various pollutants, are a special case (Yisa *et al.* 2011). Cities also import food and other materials which results in elevated amounts of nutrients and carbon in urban catchments (Walsh *et al.* 2004). In consequence, the runoff from urbanised surfaces leads to increased loads of nutrients, metals, pesticides, and other contaminants to streams and rivers (Gebre, Van Rooijen 2009; Tromp *et al.* 2012). This in turn can pose a risk to humans and other living organisms and, in consequence, affects the economy and social well-being (Luna 1968; Walsh *et al.* 2004; Wildi *et al.* 2004; Christensen *et al.* 2006; Wagner *et al.* 2007). Such situation is observed in the case of the City of Lodz – the third largest city in Poland with 800 000 inhabitants. The city area is divided between the catchments of 18 small streams. During the industrial revolution in the early 1930s, the main river-beds were channelized by concrete slabs to straighten the course and deepen the bed for the purpose of stormwater detention (Jokiel, Maksymiuk 2002; Biezanowski 2003; Kujawa, Kujawa 2003; Wagner, Zalewski 2009). This, together with the imperviousness of the city catchment, has reduced the water retention in the landscape and streams and has led to increased river flow peaks during storm events (Wagner *et al.* 2007). Such problem has occurred in the case of the Sokolowka River (Wagner *et al.* 2007). The main channel of this river was regulated and converted into a collector for 50 stormwater outlets. Consequently, the reservoirs situated along the Sokolowka River continuum have received nutrient-enriched stormwater, which increased their trophic status and stimulated the phytoplankton growth and appearance of cyanobacterial blooms that reduce the ecosystem services.

As evidenced by the field research, the highest input of pollutants comes from the upper, most urbanized and thus most densely populated part of the Sokolowka River basin (Urbaniak *et al.* 2012a; 2012c). As confirmed by field observations, the majority of stormwater outlets are located within this stretch, and consequently, large amounts of stormwater are discharged, polluted by domestic sewage infiltrated from the septic tanks. Thus, to reduce the input of pollutants from the upper part of the Sokolowka River catchment and to improve the quality of the whole river system and its reservoirs, the ecohydrological regulations within the designed Sokolowka Sequential Biofiltration System (SSBS) were implemented (Zalewski *et al.* 2012).

Outside of the urban area, the contamination of water bodies is mostly connected with agriculture. This kind of human activity releases sediments, pesticides, animal manures, fertilizers and other kinds of inorganic and organic pollutants into the receiving water ecosystems. The associated food-processing industries are also significant sources of pollution. Many of these pollutants find the way to the surface and groundwater resources through widespread runoff and percolation (Ongley 1996). Moreover, agriculture is known as a major cause of erosion and sedimentation. Erosion leads to the increased siltation and sedimentation rate in rivers, lakes, reservoirs and wetlands. Adsorption of some chemicals, like phosphorus, chlorinated pesticides and most metals, on the surface of the silt and clay fraction, results in the pollution problem in the downstream parts of the aquatic system (Ongley 1996). Such problems are especially important for African countries where the rate of erosion is higher compared to other parts of the world due to intensive precipitation, land deforestation and overgrazing. One of such endangered counties is Ethiopia. The economy of this country is mostly based on agriculture, which occupies 90% of the mountainous area and thus contributes to the fact that Ethiopia is one of the world's most vulnerable biogeographic regions susceptible to land degradation. The major cause of land degradation in Ethiopia is deforestation (Amede, Nigatu 2001; Berry 2003; Asres, Awulachew 2010; EPA 2012), which together with unsustainable agricultural practices and intensive rain cause a progressive erosion (Jiru 2010). This in turn creates pollution, siltation an eutrophication of water bodies (Amare 2005; Endalew, Tollner 2009) and leads to the development of toxic cyanobacterial blooms (Tesfay 2007; Willén *et al.* 2011) and accumulation of micropollutants, like heavy metals and dioxins in sediments and aquatic organisms (Urbaniak, Zalewski 2011; Urbaniak *et al.* 2010; Zalewski *et al.* 2010).

Such problems were observed in the case of the Asella River valley (Negussie *et al.* 2011; Zalewski *et al.* 2010). In the 1970s, 3 km from the city, a reservoir (Burkitu Reservoir, called also Asella Lake) was constructed for the purpose of supplying drinking water to the population of the city. However, it has been abandoned since the time it was perceived to have caused the disease among people. The research done by Zalewski *et al.* (2010) also demonstrated strong sediment contamination in a reservoir by toxic dioxins, which exceeded the permitted sediment quality limit of 0.85 ng TEQ kg^{-1} d.w., whereas samples collected below the reservoir have values below this limit (Zalewski *et al.* 2010; Urbaniak *et al.* 2012b). The main cause of above water quality problems is soil erosion, and thus lake siltation, due to deforestation and land overgrazing and overload of pollutants coming from livestock and Asella Water Treatment Plant.

To solve the above problems, the reduction of organic and mineral matter input as well as contamination with pollutants in the upper part of the river catchment was needed. This was achieved by the implementation of the Asella Sequential Biofiltration System (Zalewski *et al.* 2010). The implementation of this system was done on the basis of the constructed prototype in Poland – Sokolowka Sequential Biofiltration System – used for purification of urban storm- and wastewater (Zalewski *et al.* 2012).

Following the above described problems occurred in the urban (Sokolowka) and agricultural (Asella) catchment, the presented study was focused on the analysis of the performance of the sequential biofiltration systems in Poland and Ethiopia for the treatment of urban and agricultural water pollution. Since the systems were newly constructed, their functioning had to be monitored and evaluated in order to optimize their working. In the case of the urban system, the efficiency of removal of total nitrogen, total phosphorus, organic and mineral matter was determined. The analysis was performed during three storm events occurred in 2012 in order to determine the impact of rain and consequently the flow intensity on the efficiency of removal of the above-mentioned parameters by the system. In the case of Asella, the study was focused on the assessment of system efficiency in the removal of total nitrogen, total phosphorus, organic and mineral matter and ions in two periods: before and after sediment dreading from the sedimentation chamber (with improper and proper maintenance of the system). Additionally, in order to assess the frequency of sediment removal, which is needed for proper functioning of the system, the rate of sedimentation was calculated.

2. Study area

2.1. The Sokolowka Sequential Biofiltration System (SSBS)

The Sokolowka River cuts through the north-western part of the City of Lodz, Poland, with catchment area of 44.5 km^2 (Fig. 1).

The Sokolowka River represents a typical urban stormwater receiver supplied mostly by ca. 50 stormwater outlets. The main channel was regulated by concrete slabs to straighten the course and deepen the bed for the purpose of runoff detention. These changes in the river bed resulted in the loss of its self-purification capacity. Consequently, the river as well as reservoirs situated along the Sokolowka River continuum receive nutrient-enriched stormwater stimulating the phytoplankton growth and the development of toxic cyanobacterial blooms, and thus limiting their ecosystem services and causing the health problems among people. To mitigate these environmental problems, the ecohydrological systemic solutions have been applied and the Sokolowka Sequential Biofiltration System (Fig. 1) was constructed within the framework of the SWITCH Project „Sustainable Water Management Improves Tomorrow's Cities' Health" (http://www.switch.unesco.lodz.pl; Zalewski *et al.* 2012).

The main purpose of the constructed SSBS was to remove sediments, suspended solids, particulate

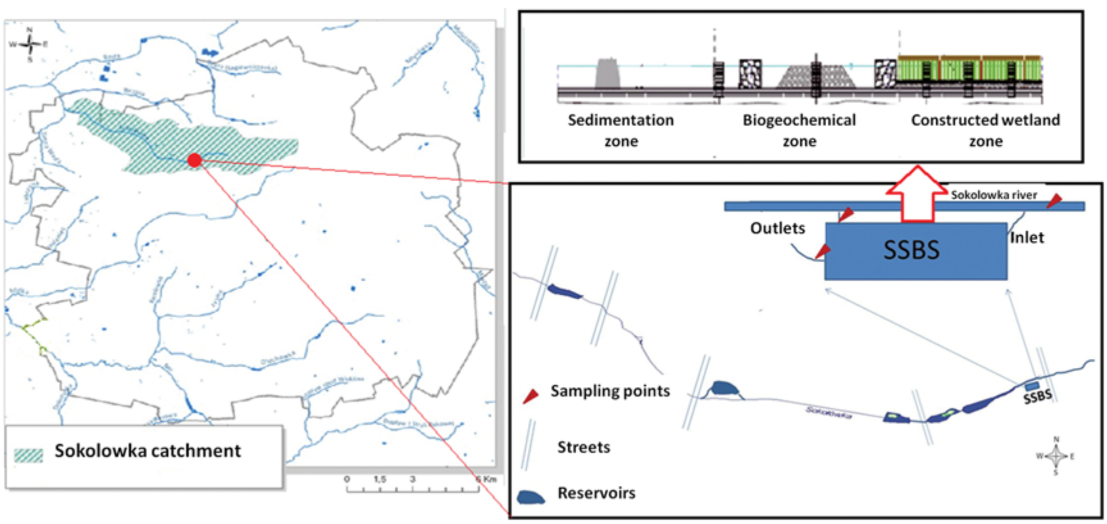

Fig. 1. Location of the Sokolowka River catchment and the SSBS against a background of the city of Łódź.

pollutants, petroleum hydrocarbons, heavy metals, nutrients and bacterial contamination from stormwater runoff through sedimentation and filtration mechanisms (Zalewski *et al.* 2012).

The system consists of three different zones:

– the zone of hydrodynamically intensified sedimentation – where the runoff is conveyed by a diversion channel to a sedimentation chamber with a surface area of 344 m^2. Its main function is pre-treatment of the inflowing stormwater runoff via sedimentation of suspended particulate matter, phosphorus and other pollutants bound to suspended particles.
– the zone of intensive biogeochemical processes − where the runoff first flows through a geotextile installed at the internal wall of the limestone gabion in order to sieve out fine particles. The geochemical barrier built of limestone is used for improvement of biological parameters through reduction of nitrogen and phosphorus compounds in the water leaving the sedimentation chamber.
– the zone of intensive biofiltration – where the runoff is treated in the vegetation chamber with a surface of 325 m^2. This section is responsible for removing biogenic compounds. The flora includes *Phragmites australis, Typha latifolia* and *Acorus calamus,* set zonally one by another (Fig. 1).

2.2. The Assela Sequential Biofiltration System (ASBS)

The Assela town is situated at an average elevation of 2300 m a.s.l., about 175 km south-east of Addis Ababa on a sloping plateau between Mt. Chilalo and the Rift Valley escarpment. Geographically, the town is located at the longitude of 39°08′E and the latitude of 7°57′N . The total population of the city is 84 645 (CSA 2005).

Some 1970 km south of the Assela town, the earthen dam was constructed to supply the town with water. The dam was constructed at a small tributary of the Combolcha River − the Burkitu River. At present the system is not functioning. The use of the Burkitu Reservoir (called also Asella Lake) as a source of water for the Assela town was banned as a result of its contamination and risk to human health. Therefore, since 1990, the source has been shifted to the Ashebeka River from which the water is supplied to the Assela Water Treatment Plant (AWTP) (Fig. 2). Regarding the high siltation and contamination of the Burkitu Reservoir by dioxins (Zalewski *et al.* 2010) and nutrients, with higher concentrations in the inlet and smaller concentrations at the outlet of the reservoir, the construction of the sequential biofiltration system was proposed in order to mitigate the pollutants accumulation in the reservoir's ecosystem (Zalewski *et al.* 2010).

Considering the above, the Assela Sequential Biofiltration System (ASBS) was constructed in 2010 as part of the Ecohydrological Systemic Solution (Fig. 2) (Zalewski *et al.* 2010) implemented for the restoration of the Burkitu Reservoir. The implementation of such solutions have been done within the framework of the Polish-Ethiopian project "Ecohydrology – a transdisciplinary science – for integrated water management and sustainable development in Ethiopia" (project no. 1280/2008, 1018/2009, 944/2010, 23/2011, 62/2012).

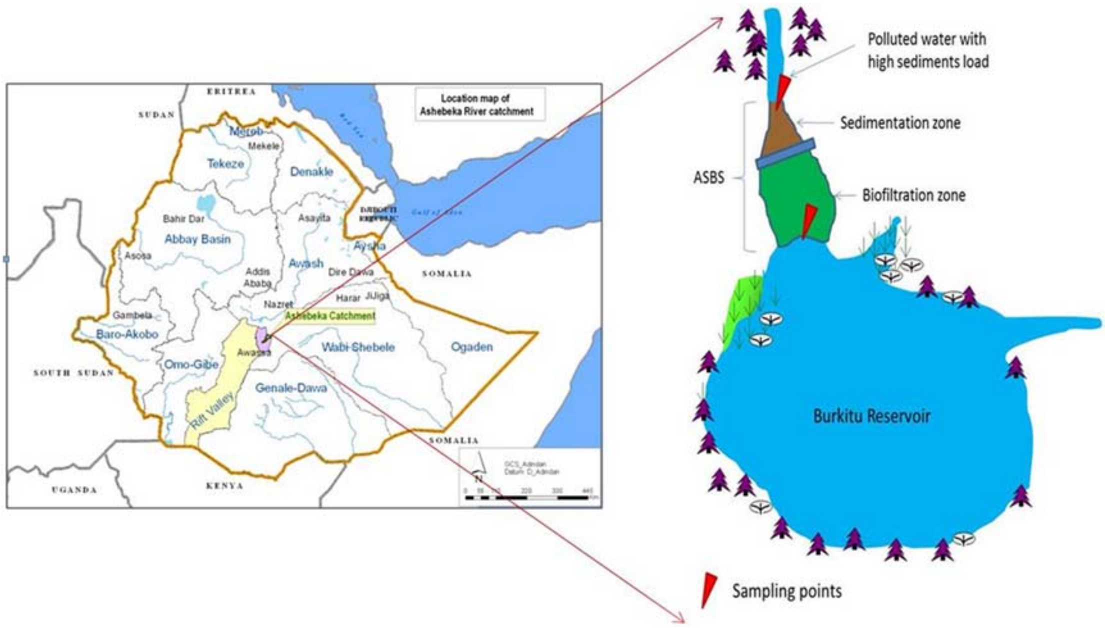

Fig. 2. Ashebeka river basin and the location of the ASBS.

The ASBS consists of an infiltration dam, which enhances the sedimentation in an impoundment. Its main function is the pre-treatment of the inflowing water via sedimentation of the suspended particulate matter, phosphorus and other pollutants bound to suspended particles. Construction of this type of dam was based on a slow water flow through the gravel foundation to supply the vetiver grass (*Chrysopogon zizanioides*) wetland and gradually reduce the nitrogen and phosphorus concentration. Sediments deposited in the sedimentation zone, which are supposed to contain a high level of micropollutants, are recommended for bioenergy production (Fig. 2).

3. Materials and methods

3.1. SSBS

3.1.1. Sampling

In the case of SSBS, a total of 3 storm events (30.03.2012, 31.03.2012 and 12.05.2012) were sampled. To assess the pollutants removal efficiency for SSBS during a storm, samples were collected throughout the storm event from the river above the SSBS (referred to as an inlet) and outlets of the SSBS. Samples were collected in 5 minute intervals when the conductivity was changing more than 100 µS cm^{-1} and in 15 minute intervals when the conductivity was changing less than 100 µS cm^{-1}. The collected samples were further analysed in order to determine Total Nitrogen (TN), Total Phosphorus (TP), organic matter (OM) and mineral matter (MM) (Fig. 3).

3.1.3. TP and TN analysis

Analysis of Total Nitrogen (TN) concentration was done using the persulfate digestion method (method no. 10071; HACH 1997). Samples for Total Phosphorus (TP) analysis were digested with the addition of Oxisolve® Merck reagent (Merck, Darmstadt, Germany) using the Merck MV 500 Microwave Digestion System and determined with the ascorbic acid method according to Golterman *et al.* (1978).

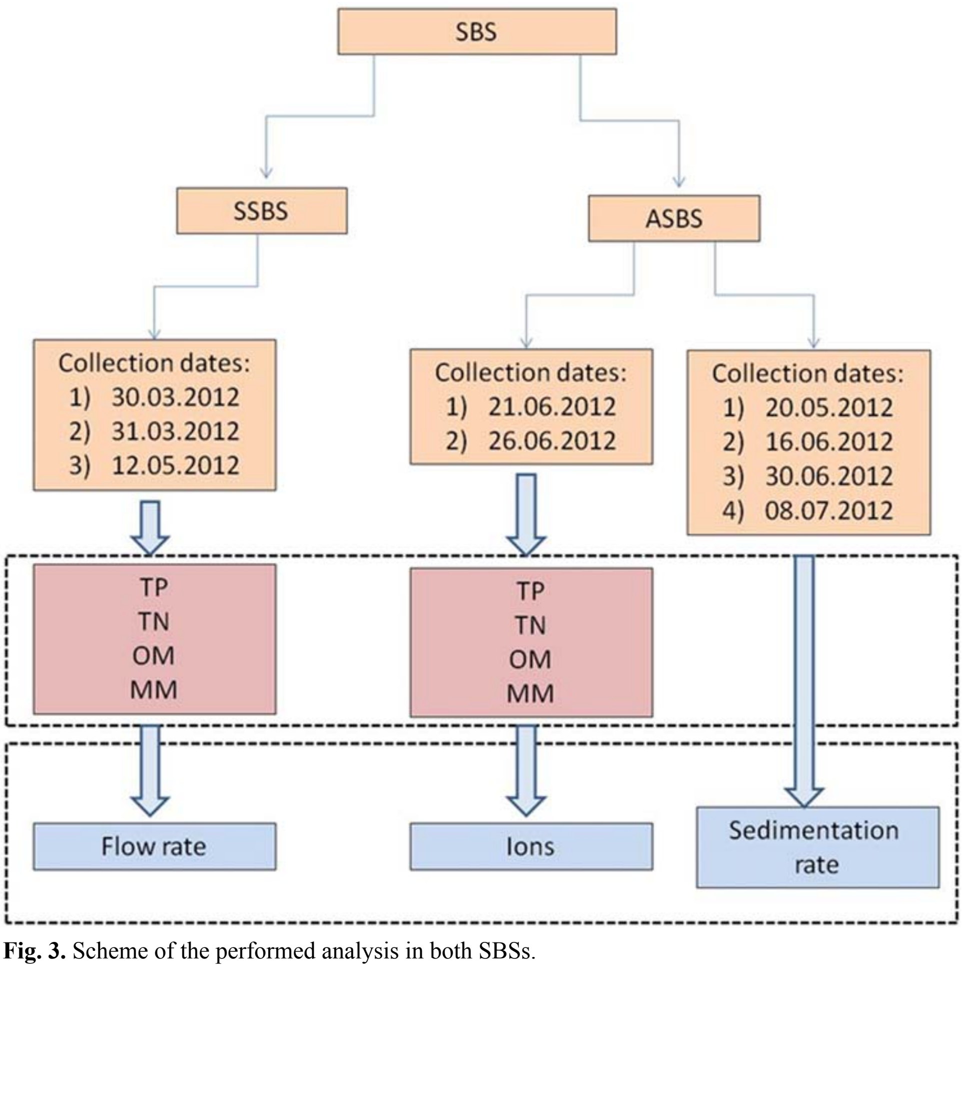

Fig. 3. Scheme of the performed analysis in both SBSs.

3.1.4. Organic matter (OM) and mineral matter (MM) analysis

The water samples were filtered through GF/C filters (pore size 45μm). To determine the organic matter (OM) by the gravimetrical method, the filters were placed in crucibles in a drying oven at 105°C for 24 hours. Then, the weight of sediments was determined and dried in a muffle furnace at 500°C for 24 hours.

The OM content was calculated according to the following formula:

$$M_{om} = (M_{105} - M_{500}) / V_f \quad (1)$$

where:
M_{om} – mass of organic matter,
M_{105} – mass of a sample after drying at 105°C,
M_{500} – mass of samples after drying at 500°C,
V_f – volume of a filtered water sample.

The MM was calculated according to the following formula::

$$M_{mm} = (M_f - M_{500}) / V_f \quad (2)$$

where:
M_f – mass of filters,
M_{500} – mass of samples after drying at 500°C,
V_f – volume of a filtered water sample.

3.1.5. Flow rates

The flow rates were read from the automatic flow recorder (Isco 2150 Area Velocity Flow Module). The applied flow module uses the continuous wave Doppler technology to measure the mean velocity. The sensor transmits a continuous ultrasonic wave, and then measures the frequency shift of returned echoes reflected by air bubbles or particles in the flow (Urbaniak *et al.* 2012a).

3.1.6. Efficiency determination

Efficiency of the systems was calculated as a percent reduction (*R)* for each pollutant concentration as follows:

$$\% \, Reduction = (1 - Co) / Ci \times 100 \quad (3)$$

where:
Ci – the inflow concentration in mg L^{-1};
Co – the outflow concentration in mg L^{-1}.

3.2. ASBS

3.2.1. Sampling

Water samples were collected two times in July 2012 from the inlet and the outlet of the system. The samples were collected before and after the removal of sediments from the sedimentation zone of ASBS which was done on 21 June 2012 (Fig. 2).

Plastic bottles (2 L) were used to collect water samples. After the collection, the samples were filtered on GF/C filters (pore size 0.45 μm). The filters were open-air dried and kept with aluminium foil until the analysis of organic/mineral matter. Filtered and unfiltered water was kept in 50 ml plastic containers in -20°C until further analysis of Total Nitrogen (TN) and Total Phosphorus (TP) (unfiltered water), organic matter (OM) and mineral matter (MM) and ions (filtered water) (Fig. 3).

3.2.2. TP and TN analysis

The TP and TN analysis was described in section 3.1.3.

3.2.3. Organic matter (OM) and mineral matter (MM) analysis

The organic matter (OM) and mineral matter (MM) analysis was described in section 3.1.4.

3.2.4. Ions analysis

Filtrated water samples were analysed using the ion chromatography system (Dionex Corporation, ICS-1000) separately for anions (fluorides, chlorides, nitrites, bromides, nitrates, phosphates and sulphates) and cations (lithium, sodium, ammonium, potassium, magnesium and calcium). Each system consisted of a guard column (CG18 for cations and AG22 for anions), an analytical column (IonPac CS18 for cation, IonPac AS22 for anion) and an electrolytic suppressor (CSRS-ULTRA II cation electrolytic suppressor and ASRS – ULTRA II anion electrolytic suppressor) to stabilize the baseline. 16 mM methanesulphonic acid (Fluka) for the cation analysis and a mixture of 4.5 mM sodium carbonate and 1.4 mM sodium bicarbonate prepared from the AS22 Eluent Concentrate (produced by Dionex Corporation) for the anion were used as eluent. Systems were operated in isocratic elution in 30°C at a flow rate of 1 ml/min. Measurements were performed using a 25 μl injection loop. For ion identification, combined standards were used (Dionex Corporation).

3.2.5. Determination of the sedimentation rate

The rate of sedimentation was measured by using circular plastic sediment traps four times in 2012: on 20th May; 16th June, 30th June and 8th July. The traps were attached to a wooden peg with a nail and put at three different points in the sedimentation chamber in order to obtain a representative value.

4. Results

4.1. The Sokolowka Sequential Biofiltration System (SSBS)

4.1.1. The distribution of pollutants' concentration vs. storm duration and flow volume

Characteristics of the three measured storm events including the amount of precipitated water per hour and the river flow at the same time are presented in Fig. 4.

The results for TN, TP, MM and OM distribution in time (storm duration) are presented in Fig. 5. During the first storm event (30.03.2012), the concentration of TN increased from 5 mg L^{-1} at the beginning of the storm (0 minutes) to the maximum value of 6.6 mg L^{-1} in the first 30 minutes after the storm commencement and rapidly declined to 3.5 mg L^{-1} at the time of the maximum flow at the 115th min of the storm duration. However, when the runoff started to recede from its peak (from 0.037 m^3 s^{-1} to 0.017 m^3 s^{-1}), the TN concentration began to rise in the last 36 minutes. The time interval between the two peaks was 85 minutes (Fig. 5A).

The peak value of TP also preceded the runoff peak. The TP concentration was 0.36 mg L^{-1} and it reached the maximum value (1.01 mg L^{-1}) in the first 30 minutes of the storm duration. TP concentration then started to increase while the flow declined (Fig. 5B).

The MM and OM concentrations rapidly increased during the first 40 minutes of the storm duration exceeding 0.65 g L^{-1} and 0.22 g L^{-1}, respectively (Fig. 5C, D).

On the next day of the storm event (31.03.2012), TN had the same distribution pattern. The TN concentration ranged from 3.7 mg L^{-1} to the maximum value of 10.2 mg L^{-1} within 45 minutes after the beginning of the storm runoff. The TN concentration then declined sharply until the minimum value of 4 mg L^{-1}, which occurred at the time of the maximum flow at the 145th minute of the storm duration. However, when the runoff started to recede from its maximum value of 0.108 m^3 s^{-1}, the TN concentration was increasing. The time interval between the two peaks was 100 minutes. Whereas TP was distributed uniformly with the storm runoff volume. It increased, however, from the lowest value of 0.138 mg L^{-1} to the maximum value of 1.178 mg L^{-1}. At the beginning of the storm event, the flow was 0.007 m^3 s^{-1} and the maximum value recorded was three times higher than the storm event on the previous day (30.03.2012) (0.108 m^3 s^{-1}). The MM and OM concentrations had about two times lower values compared to the previous storm and amounted to 0.32 g L^{-1} and 0.12 g L^{-1}, respectively (Fig. 5).

During the storm event on 12.05.2012, both TN and TP peaks preceded the flow peak. The TN increased from 4.4 mg L^{-1} at the beginning of the storm (0 minute) to the maximum value of 12.2 mg L^{-1} and TP also increased from 0.15 mg L^{-1} to 2.3 mg L^{-1} within 45 minutes from the beginning of the storm runoff. The TN concentration then declined sharply until the constant value of 5.7 mg L^{-1} reached at the time of the maximum flow at the 75th minute of the storm duration. TP had a uniform distribution in the runoff volume starting from the 70th minute of the storm event (Fig. 5).

In both events, the TN, MM and OM peaks preceded the maximum flow, which means that a large portion of the TN, MM and OM load was transported in the early portion of the stormwater

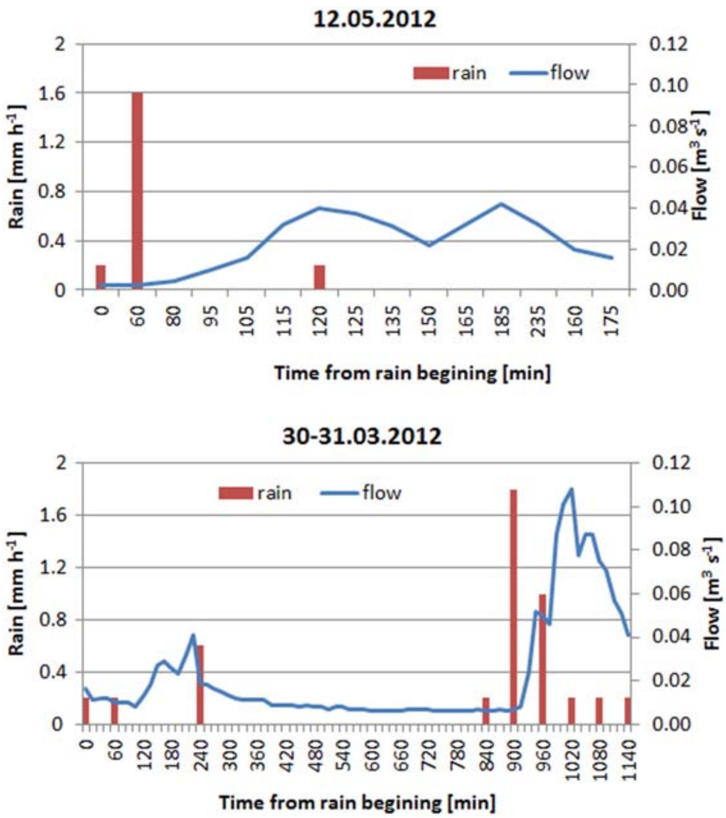

Fig. 4. Rain and flow comparison on SSBS for three analyzed storm events.

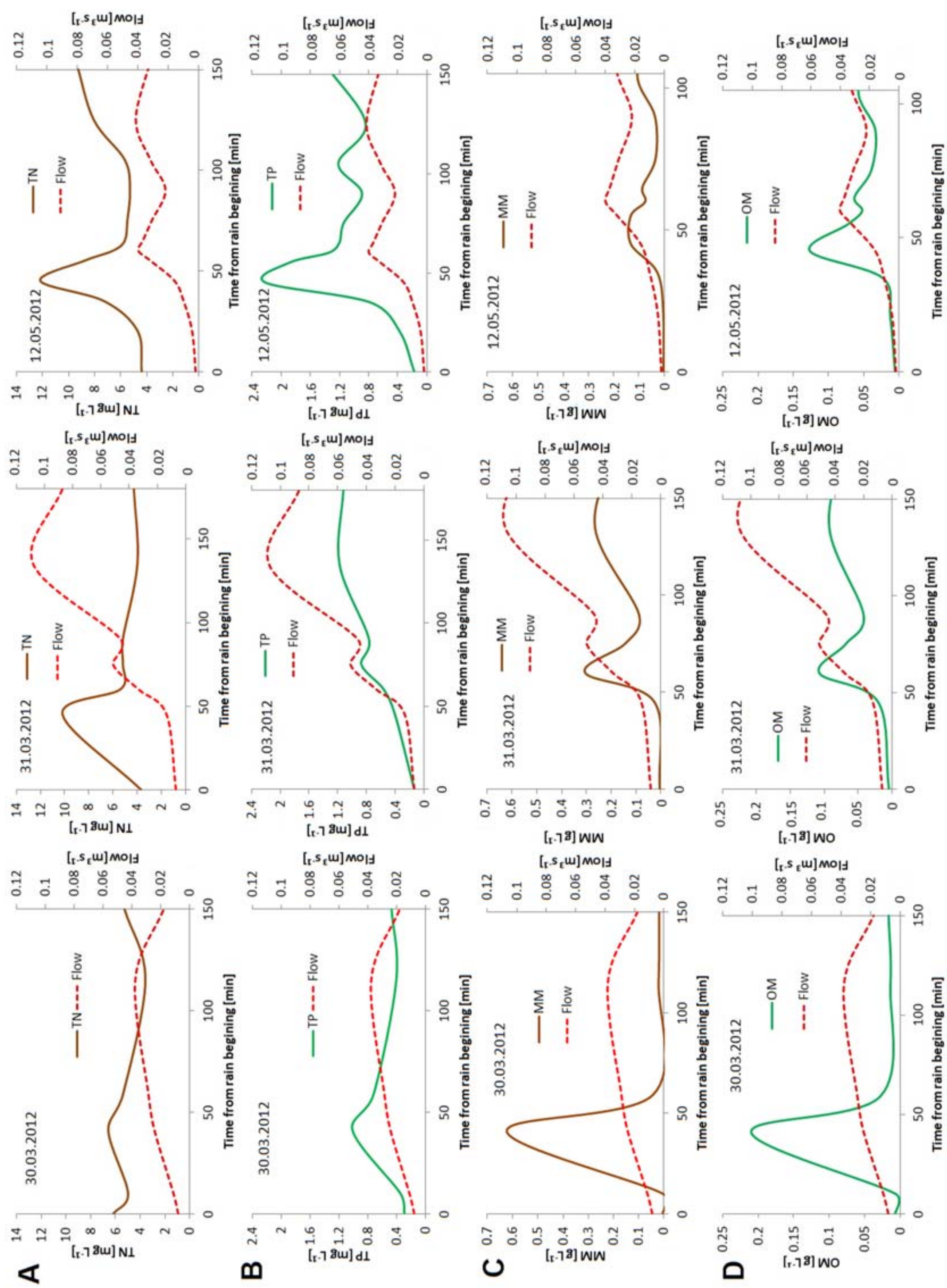

Fig. 5. The distribution of (A) TN, (B) TP, (C) MM and (D) OM with storm time and flow volume.

runoff volume. Whereas, the TP peak preceded the maximum flow in the first and third storm event (30.03.2012 and 12.05.2012) and was evenly distributed throughout the runoff volume in the storm event of 31.03.2012 (Fig. 5).

As presented in Fig. 6, the lowest and the highest monitored flow were 0.009 $m^3 s^{-1}$ and 0.038 $m^3 s^{-1}$ on the storm event occurred on 30.03.2012. The purification efficiency of the SSBS observed on the same date was about 50%. On the next day (31.03.2012), however, the maximum flow was 0.150 m^3/s and SSBS became a source of the analysed compounds (Fig. 6).

The efficiency of SSBS was increasing with the flow rate until it reached 0.021 $m^3 s^{-1}$ and it decreased as the flow increased. It indicates that the system has a certain flow threshold at which it performs efficiently.

4.1.2. The pollutants reduction by SSBS

The obtained results for the reduction of TN, TP, MM and OM in the condensed and diluted stage of storm are presented in Table I. The results showed higher % reduction of the analysed compounds in the diluted phase of the storm. The TN concentration recorded on 30.03.2012 was an exception – the largest reduction occurred in the initial phase of the storm.

The highest reduction of 95% during the study period was observed for MM in the diluted stage of the storm on 12.05.2012. The next high reduction value was noted for TP and was observed during the diluted stage of the storm on 12.05.2012.

Whereas the lowest reduction rate (21%) was observed for MM in the condensed phase of the storm event on 12.05.2012 and in the diluted phase of the storm event on 31.03.2012 (22%) and for TN (28%) in the diluted stage of the storm occurred on 30 and 31.03.2012.

4.2. The Assela Sequential Biofiltration System (ASBS)

4.2.1. Reduction of pollutants by the ASBS

Water samples from ASBS were collected two times: before (21.06.2012) and after the removal of sediments from the sedimentation chamber (26.06.2012) in order to analyse the reduction of TN, TP, OM and MM and ions. The obtained results are presented in Table II and Table III.

As indicated in Table II, before the removal of trapped sediments on 21.06.2012, TP was reduced by 8%, OM by 78% and MM by 65%. Only in the case of TN, its concentration increased of about 24% (from 0.07 to 0.096 mg L^{-1}).

The samples collected after the sediment removal on 26.06.2012 were characterised by the reduction of all analysed compounds up to 93% for TP, 73% for TN, 36% for OM and 67% for MM (Table II). Regarding the reduction observed for samples collected before the sediment removal, ASBS reduction efficiency rapidly increased in the case of TN and TP, whereas reduction of MM decreased to about 32%.

In the case of ions analysis before sediment dredging, the considerable reductions were noted for bromides, phosphates, sulphates, potassium and magnesium. As evidenced by the results obtained for samples collected after the sediment removal, also the significant reduction of nitrates was observed, in addition to the above listed ions (Table III).

4.3. Sedimentation process

The rate of sedimentation measured during the dry and wet period are presented in Table IV. The average sedimentation rate was 0.5 cm day^{-1} (ranged from 0.45 to 0.65 cm day^{-1}) and 1.5 cm day^{-1} (ranged from 1.50 to 1.60 cm day^{-1}) during the dry and wet season, respectively.

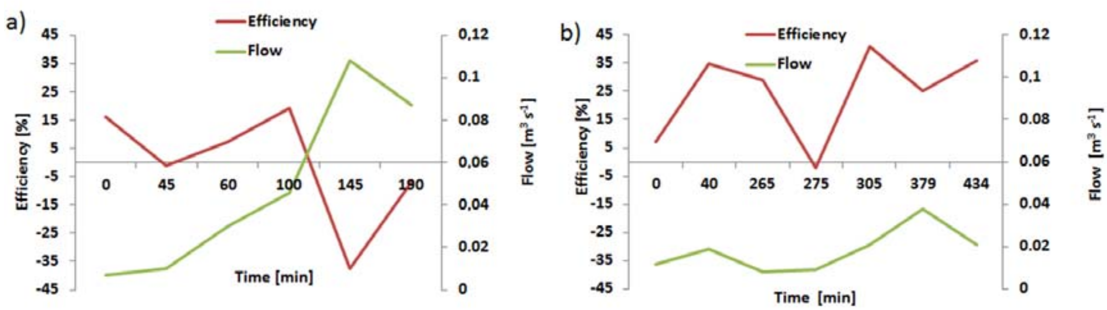

Fig. 6. The impact of flow volume on SSBS purification efficiency; a) storm event on 30.03.2012; b) storm event on 31.03.2012.

Table I. The TN, TP, MM and OM concentration and reduction by the SSBS during three storm events in 2012.

Parameter	Phase of the storm	Sampling site		Reduction	
		Inlet	Outlet	Reduction	Reduction %
Sampling date 30.03.2012					
TN [mg L^{-1}]	Condensed	7.5	4.15	3.35	45
	Diluted	5.3	3.8	1.5	28
TP [mg L^{-1}]	Condensed	0.639	0.248	0.391	61
	Diluted	0.477	0.159	0.318	67
MM [g L^{-1}]	Condensed	0.023	0.01	0.013	57
	Diluted	0.02	0.004	0.015	78
OM [g L^{-1}]	Condensed	0.016	0.011	0.005	30
	Diluted	0.017	0.005	0.012	70
Sampling date 31.03.2012					
TN [mg L^{-1}]	Condensed	3.7	-	-	-
	Diluted	7.9	5.65	2.25	28
TP [mg L^{-1}]	Condensed	0.138	-	-	-
	Diluted	2.058	0.635	1.423	69
MM [mg L^{-1}]	Condensed	0.003	-	-	-
	Diluted	0.624	0.485	0.139	22
OM [mg L^{-1}]	Condensed	0.004	-	-	-
	Diluted	0.184	0.026	0.158	86
Sampling date 12.05.2012					
TN [mg L^{-1}]	Condensed	4.6	2.3	2.3	50
	Diluted	8.1	1.5	6.6	81
TP [mg L^{-1}]	Condensed	0.245	0.131	0.114	47
	Diluted	0.842	0.118	0.724	86
MM [mg L^{-1}]	Condensed	0.009	0.007	0.002	21
	Diluted	0.026	0.001	0.025	95
OM [mg L^{-1}]	Condensed	0.014	0.004	0.01	70
	Diluted	0.026	0.004	0.022	84

Table II. The TN, TP ,OM and MM concentration before (21.06.2012) and after removal of accumulated sediment from the sedimentation area of ASBS (26.06.2012).

	21.06.2012				26.06.2012			
	Inlet	Outlet	Reduction	% reduction	Inlet	Outlet	Reduction	% reduction
TN [mg L^{-1}]	0.07	0.096	-0.068	**-24**	1.249	0.294	0.955	**76**
TP [mg L^{-1}]	0.012	0.011	0.001	**8**	0.473	0.028	0.445	**93**
OM [g L^{-1}]	0.067	0.014	0.053	**78**	0.239	0.151	0.088	**36**
MM [g L^{-1}]	2.6	0.9	1.7	**65**	7.7	2.5	5.2	**67**

5. Discussion

Reversing the degradation of the water ecosystems requires solutions based on integrative problem-solving science, such as ecological engineering and ecohydrology (Zalewski 2010; 2011).

In order to mitigate the water pollution, the first principle of ecohydrology required quantification of processes at the catchment scale, including monitoring of threats (Zalewski 2010; 2011). This was reflected in the first part of the work focused on the analysis of the occurrence and rate of pollution transferred into two different catchments: urban and agricultural in different hydrological conditions.

The latter part of the presented work reflects the second and the third principle of ecohydrology concerning the possibility of increasing the resilience and enhancing the absorption capacity of environment for pollutants (Zalewski 2010; 2011) through optimization of sequential biofiltration systems (SBS) functioning and efficiency. This will lead to optimal conditions for removal of pollutants by such systems and consequently the quality improvement in downstream ecosystems.

5.1. *Optimization of sequential biofiltration systems efficiency in Poland and Ethiopia*

5.1.1. *The case of Sokolowka Sequential Biofiltration System*

The problem of flooding in urban areas occurs due to conversion of natural grounds into impervious areas. Until the 1990s, the flood prevention had been the main objective of the stormwater management (Roy-Poirier 2010). The increasing adverse impact of stormwater pollution on the urban environment results in seeking new solutions for their purification. The promising results are related to small-scale use of wetlands and sedimentation ponds (Persson, Wittgren 2003). Several scholars have demonstrated the successful use of constructed wetlands for the treatment of urban stormwater runoff (Fenta 2007) and domestic wastewater (Koukia *et al.* 2009). Díaz *et al.* (2012) reported the removal of nitrate and total suspended solids ranging from 22% to 99% and from 31% to 96%, respectively. Randall (2011) showed the reduction of TN and TP concentrations up to 53% and 79%, respectively. The TP removal efficiency of 59% in constructed wetlands has also been reported by Lu *et al.* (2009). On the other hand, significant phosphorus leaching from bioretention systems has also been observed in a number of studies (Dietz, Clausen 2005; Hunt *et al.* 2006). Moreover, it was reported that flood-pulse wetlands are much less effective compared to continuous flow-through wetlands (Díaz *et al.* 2012). Unfortunately, urban catchments are usually affected by stormwater runoff peaks which negatively impact the purification efficiency due to excessive load of pollutants compared to wetland/biofilter removal capacity. Therefore, the analysis of contaminants transported during a storm is crucial for optimisation of biofilters/wetlands, or as in our case – for the efficiency of pollutants' removal by sequential biofiltration systems.

Our study analysed three storm events. The obtained results showed that the TN peak preceded the maximum flow. This means that a large portion of the TN load was transported in the early portion of the runoff volume. Also the OM and MM peaks preceded the maximum flow during all storms. The highest OM and MM peaks were observed on 30.03.2012, probably as a result of a dry period lasting for a month that occurred before the rain. The organic and mineral matter deposited during the dry period was therefore washed out from the catchment surface at the first intensive rain. This thesis is confirmed by the study of Gunawardena *et al.* (2013) who demonstrated that dry deposition in

Table III. The ions concentration before (21.06.2012) and after removal of accumulated sediment from the sedimentation area of ASBS (26.06.2012).

	21.06.2012				26.06.2012			
	Inlet	Outlet	Reduction	% reduction	Inlet	Outlet	Reduction	% reduction
Fluorides [mg L^{-1}]	0.33	0.42	-0.09	-27	0.3	0.33	-0.03	-10
Chlorides [mg L^{-1}]	4.49	4.73	-0.24	-5	2.18	3.71	-1.53	-70
Nitrites [mg L^{-1}]	0	0	0	**0**	0.01	0	0.01	100
Bromides [mg L^{-1}]	0.07	0.05	0.02	**29**	0.01	0.03	-0.02	-200
Nitrates [mg L^{-1}]	0.21	0.31	-0.1	-48	1.53	0.32	1.21	**79**
Phosphates [mg L^{-1}]	0.17	0.04	0.13	**76**	0.04	0.01	0.03	**75**
Sulphates [mg L^{-1}]	3.58	2.76	0.82	**23**	10.66	3.57	7.09	**67**
Sodium [mg L^{-1}]	5.62	5.56	0.06	**1**	3.54	4.67	-1.13	-32
Amonium [mg L^{-1}]	0.04	0.05	-0.01	-25	0.15	0.4	-0.25	-167
Potasium [mg L^{-1}]	4.97	3.97	1	**20**	4.04	4	0.04	**1**
Magnezium [mg L^{-1}]	0.79	0.72	0.07	**9**	0.67	0.53	0.14	**21**
Calcium [mg L^{-1}]	13.66	13.4	0.26	**2**	11.41	10.92	0.49	**4**

Table IV. The rate of sedimentation in the sediment area of ASBS.

Season	Collection date	Sedimentation Rate [cm day^{-1}]
Dry season	20.05.2012	0.45
	16.06.2012	0.65
Wet season	30.06.2012	1.5
	08.07.2012	1.6

urban areas occurred with a higher rate due to traffic and industrial emissions. The TP peak preceded the maximum flow in two of the three analysed storm events (30.03.2012 and 12.05.2012) and had an even distribution throughout the runoff volume during the storm of 31.03.2012. This uniform TP distribution could be attributed to dilution of stormwater runoff during the second day of rain and discharges of domestic wastewater directly into the Sokolowka River during the storm, as this kind of practice was observed during the field visits and sampling.

The obtained results demonstrated also that the analysed parameters were usually higher in the condensed phase of storm, except for the storm on 30.03.2012 characterised by higher pollution concentration in its diluted phase. Despite this difference, the reduction occurred in all cases for all parameters. SSBS reduced the concentration of MM and OM during the three storm events up to 70-95% (only MM on 31.03.2012 had lower reduction), similarly to results obtained by other researchers worldwide, e.g. Higgins *et al.* (2006) showed the reduction of 95%, Kadlec and Knight (1996) over 80% and Obarska-Pempkowiak *et al.* (2010) over 90%.

It should also be emphasised that biotic communities and biogeochemical processes in biofilters are strongly influenced by hydraulic and hydrologic conditions. Therefore, changes in the flow rate and storm duration are reported also as factors influencing the removal of nutrients in biofilters (Davis *et al.* 2006; Persson, Wittgren 2003; Mitsch, Gosselink 2007; Kadlec, Wallace 2009). Bratieres *et al.* (2008) observed that higher stormwater inflow volumes resulted in outflows containing a higher proportion of less treated stormwater, due to a shorter detention time. Similarly, during the storm event on 31.03.2012, the pollutant reduction efficiency of SSBS dropped to a negative value turning the system into the source of TN. It was estimated that SSBS appears to be efficient at a flow between 0.02 $m^3 s^{-1}$ and 0.04 $m^3 s^{-1}$. This finding supports the already postulated necessity of constructing the detention pond in the upper Sokolwka River section, above SSBS. The implementation of such detention pond will help the proper functioning and pollutants removal efficiency of SSBS. The further investigations are required to determine the quantity of flow which can be absorbed by SSBS and the quantity above which the system release accumulated pollutants.

5.1.2. The case of Assela Sequential Biofiltration System

The effectiveness of constructed wetlands/biofilters for the treatment of agricultural wastewater has also been explained in worldwide research (Peterson 1998; Koskiaho *et al.* 2003; Healy *et al.* 2007; Lu *et al.* 2009; Vymazal 2009; Díaz *et al.* 2012).

In the case of ASBS, the pollutants were leaching as a result of the exceedingly large loads of sediments and nutrients from the catchment due to its deforestation and thus progressive soil erosion, as well as due to the input of nutrients via livestock and the Water Treatment Plant discharges. The obtained results for nutrients reduction by ASBS presented in Table II showed a significant decrease in the analysed compounds with the exception of one parameter – TN. The obtained results indicated that prior to removal of accumulated sediments, the TN concentration at the outflow was higher than that noted in the incoming sediments (Table II). This may be attributed to the following two main reasons: 1) the incoming water was flowing out of the sediment trap without any treatment as the sediment trap was full of trapped sediment up to its capacity; or 2) release of the internal TN load which had been accumulated during the proper functioning of ASBS. However, after removal of the trapped sediment, the pollutant reduction efficiency of ASBS significantly increased for three parameters TN, TP, and MM (Table II). In the case of ions, the sediments removal led to an increase in the removal of nitrates (from 48 to 79%) (Table III). This result may indicate that the sediment trap was not functioning properly due to high thickness of accumulated sediments and thus lack of trapping capacity for inflowing suspended matter and nutrients.

It should also be emphasized that the ASBS is monitored and maintained only one/two times per year. This resulted in improper efficiency of the system. To mitigate this problem, a sediment removal schedule is being developed based on the result of this study. According to the result of the sedimentation rate (Table IV), the trapped sediment needs to be removed at least once every 2-3 months. This is also important for enhancement of the removal of highly toxic dioxins, as the majority of them are bound to sediment particulates. The previous research showed that during the first year of the ASBS operation, the toxicity of dioxins was reduced by about 70% (Urbaniak *et al.* 2012b). Therefore, further proper maintenance of ASBS is crucial to retain the appropriate conditions for conversion of dioxins into less toxic forms.

The other important issue is to maintain the wetland area below the sediment trap. The removal of pollutants is often accomplished by manipulating the system's hydraulic and hydrologic conditions and by selecting the type of dominant vegetation accordingly (Kadlec, Wallace 2009). The wetland vegetation of ASBS retards and distributes the flow leading to the increased pollutant contact with plant surfaces and hence maximizes the removal of finely graded particles (Wong *et al.* 1999). Koskiaho *et al.* (2003) and Elsaesser (2011) observed the best performance of the wetland with the longest water residence time (WRT) retaining annually about 25 kg of TP and 300 kg of TN per hectare. High WRT promotes biodegradation and photodegradation processes that are involved in the removal of emerging contaminants (Yeh *et al.* 2009). As evidenced by Elsaesser *et al.* (2011), the vegetated wetland system reduced the toxicity generated by pesticides by 95%, whereas the non-vegetated wetland – by 79%. Many studies have demonstrated that plants contribute to water treatment through both direct and indirect mechanisms (Brix 1994; Tanner 1996; Gottschall *et al.* 2007; Cheng *et al.* 2011). However, the selection of plant species is crucial (Tanner 1996). In addition, the pollutant removal efficiency of wetlands increases with the establishment and maturation of wetland vegetation (Tanner *et al.* 2005). In the case of ASBS, the field observation demonstrated that wetland plants (vetiver grass) were permanently grazed by cattle and removed by local people. Therefore, for further optimization of the ASBS efficiency, its proper maintenance and protection against grazing and cutting is needed.

The above results and field observation showed that the potential for water purification in ASBS can be enhanced through proper maintenance of the system and application of nutrients and flow pattern analysis.

Conclusions and recommendations

The obtained results led to the following conclusions and recommendation:

1. In the case of SSBS, the obtained results on the distribution of pollutants vs. flow volume and flow duration support the already existing idea of constructing the detention pond upstream of SSBS (due to a small size of SSBS compared to the entire Sokolowka River catchment) in order to stabilize the flow peaks and thus optimize the purification performance of SSBS;
2. In the case of SSBS, the analysis of nutrients vs. flow pattern plays the key role in the optimization of its construction and operation; this kind of analysis should also be applied in the Adaptive Assessment and Management of ASBS;
3. Proper maintenance of ASBS (e.g. periodic removal of accumulated sediments, vegetation maintenance) is essential for increasing its purification efficiency.
4. The further studies should be focused on more detailed analysis not only of nutrients and organic and mineral matter but also other pollutants related to the urban catchment like heavy metals, PAH, dioxins etc. Moreover the research need to be performed for a longer period (e.g. hydrological year) in order to analyze the systems efficiency in different hydrological and temperature conditions. At the same time the analysis of wetland plants biomass should be also conducted.

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