Avtorici prispevka:
1. Darja Istenič, LIMNOS Podjetje za aplikativno ekologijo d.o.o., Slovenija, darja@limnos.si
2. Maja Zupančič Justin, LIMNOS Podjetje za aplikativno ekologijo d.o.o., Slovenija, maja@limnos.si

Trajnostni načini reševanja problematike padavinskih vod

Odtok padavinske vode iz neprepustnih površin predstavlja kvantitativno in kvalitativno obremenjevanje površinskih stoječih in tekočih voda. Različni trajnostni pristopi, kot so suhi in mokri zadrževalniki, deževni vrtovi, ponikovalnice itd., omogočajo zadrževanje in čiščenje padavinskega odtoka. Najpogosteje se uporabljajo mokri zadrževalni bazeni, ki omogočajo učinkovito odstranjevanje suspendiranih snovi in vezanih onesnažil. Za odstranjevanje raztopljenih onesnažil (hranila, težke kovine) pa je potrebna nadgradnja zadrževalnikov z dodatnimi tehnologijami, kot so peščeni in adsorpcijski filtri, zasaditev z ustreznimi močvirskimi rastlinami ter dodajanje flokulantov. Nadgrajeni zadrževalniki so bolj učinkoviti pri odstranjevanju raztopljenih kovin in hranil. Poleg tega rastlinska vegetacija, ustrezno razmerje med dolžino in širino zadrževalnika ter razmerje med površino prispevnega območja in prostornino zadrževalnika odločilno vplivajo na učinkovitost čiščenja. Poleg samočistilne sposobnosti sistemi za upravljanje meteornih vod zagotavljajo tudi povečanje biodiverzitete v lokalnem okolju, uravnavajo mikroklimo, omogočajo recikliranje vode, predstavljajo prostor za oddih, rekreacijo in izobraževanje v naravi. Njihova aplikacija je možna tako v urbanem in ruralnem okolju kot tudi v sklopu hišnih vrtov.

Ključne besede: zadrževalnik, deževni vrt, peščeni filter, *Phragmites australis*

Sustainable methods for solution of stormwater problem

Stormwater runoff from impermeable surfaces presents quantitative and qualitative loading of surface standing and running waters. Different sustainable methods such as dry and wet detention ponds, rain gardens, swales etc. enable retention and treatment of stormwater runoff. Most commonly used are wet detention ponds which enable efficient elimination of suspended solids and bound pollutants. For elimination of dissolved pollutants (nutrients, heavy metals) an enhancement of detention ponds with additional technologies, such as sand and sorption filters, plantation with appropriate wetland plants and addition of flocculants, is needed. Upgraded detention ponds are more efficient in elimination of dissolved metals and nutrients. Besides this, vegetation, suitable length to width ratio and ratio between catchment area and pond volume have significant impact on the treatment performance. Along self-treatment capacity, systems for stormwater treatment enable an increase of biodiversity in local environment, mitigate microclimatic conditions, enable water recycling, they present an area for relaxation, recreation and education in nature. Application of the systems is possible in urban and rural environment as well as in individual house gardens.

Key words: Detention pond, rain garden, sand filter, Phragmites australis*, pollutants, treatment, ecosystem services*

1 Introduction

Stormwater runoff is a consequence of precipitation on impermeable surfaces such as asphalt and paved areas, roofs, nailed soil and rocks. The increased surface runoff might cause flooding in the cities, in downstream water bodies and wastewater treatment plants. It also flushes numerous pollutants, which accumulate on urban surfaces as a result of different human activities. Stormwater runoff from urban areas therefore presents a quantitative and qualitative loading for natural water bodies, including groundwater, which is the main drinking water source in many countries. Therefore stormwater runoff has to be retained and treated.

Stormwater characteristics:

- In general stormwater runoff contains low but not insignificant pollutant concentrations; however in the short period of first flush event high concentrations of pollutants can occur.
- The occurrence of runoff depends on precipitation pattern which is determined by climatic, orographic and other specific conditions of the local area. Inter-event dry periods, when accumulation of pollutants in urban surfaces takes place are also important.
- Therefore there is also a time dependant variability of runoff volume and pollutant loads within each single event as well as among the events.
- Pollutant loads depend also on the type of the catchment (industrial, rural, residential) and the dynamics of the activities in the catchment.
- The most common pollutants in stormwater runoff are suspended solids, heavy metals, nutrients, organic micro-pollutants and pathogens.

1.1 Stormwater retention and treatment

The facility for stormwater detention and treatment must handle the runoff characteristics. Best management practices differ in their purpose – some enable only mitigation of hydraulic loads, while others enable also different treatment processes to occur. The most common best management practices are described below.

- Filter drains or sand filters are areas with gravel, where rainwater drains through and is collected in a perforated pipe.
- Porous asphalt and paving are water permeable surfaces with high void content. An adjacent reservoir provides temporary water storage and mitigates runoff.
- Sedimentation tanks, silt traps, oil and grit separators etc. are technical practices, usually used as pre-treatment structures.
- Swales are vegetated broad and shallow channels mainly used for transportation of stormwater; however, some water quality improvement can also occur through settling and infiltration into the soil.
- Filter strips are grassed or vegetated strips of land where stormwater flows across. They are similar to swales, but have flatter banks.
- Soakaways are underground chambers or rock-filled volumes where stormwater soaks into and slowly infiltrates into the surrounding soil.
- Infiltration trenches are long and thin soakaways filled with stones or rubbles. The infiltration surface area is enlarged thus enabling better treatment performance compared to soakaways.
- Infiltration ponds/basins are designed to retain stormwater runoff at the surface and allow it to slowly soak to the underground through the base of the pond.
- Wet detention ponds or retention ponds have a permanent water volume and temporary storage volume above it. They are designed like small and shallow natural lakes with sufficient water residence time to enable numerous treatment processes to occur.

- Detention basins are dry most of the time but provide stormwater storage during rainfall to attenuate peak runoff flows for the protection of downstream facilities and receiving water bodies. Due to not having permanent water storage, these ponds are also named dry ponds.
- Combined systems are combinations of two or more previously described systems.
- For local runoff management so called rain gardens are in use. They are created as ornamental parts of private gardens or parks. Stormwater is retained after rainfall and then percolated to the underground.

Treatment performance of different stormwater treatment and retention facilities (Table 1) varies greatly according to the type of facility as well as according to the pollutant concentrations of the inflow water (Deutsch, 2003).

Table 1: Treatment performance of different stormwater best management practices

	% removal efficiency				
	TSS	**Tot N**	**Bacteria**	**Hydrocarbons**	**Metals (total)**
Filter	60-90	20-30	20-40	70-90	70-90
Infiltration trench/basin	60-90	20-50	70-80	70-90	70-90
Swales	10-40	10-35	30-60	60-75	70-90
Lagoon	50-85	10-20	45-80	60-90	60-90
Dry detention basin	60-80	20-40	20-40	-	40-55
Extended detention basin	30-60	5-20	10-35	30-50	20-50
6-10 hour detention	40-80	20-40	40-50	30-60	30-60
16-24 hour detention	50-90	20-40	60-75	50-75	45-85
Retention basin	80-90	20-40	40-60	30-40	35-50
Wetland	70-95	30-50	75-95	50-85	40-75

Source: Deutsch, 2003

Besides treatment efficiency and stormwater retention, an important characteristic of stormwater facilities is also providing additional ecosystem services such as providing recreational and park areas, habitats for wildlife, mitigation of local clime, possibilities for water reuse and similar. When deciding for a specific stormwater management facility also available space, urban characteristics, vulnerability of receiving water body and price are important factors.

Wet detention ponds (WDP) are among the most reliable and commonly established system used to mitigate the impact of stormwater runoff. They are easy to construct and enable additional ecosystem services.

2 Materials and methods

Seven stormwater WDP were compared according to their structure, treatment efficiency and additional ecosystem services. The most important factors affecting treatment efficiency were pointed out. Four of the WDP were traditional WDP, designed as simple water bodies, while the other three WDP were upgraded with additional treatment technologies in order to improve the removal of pollutants.

WDP mimic natural wetlands and small lakes. They have a permanent water volume and a temporary storage above it. The permanent volume is 1-1.5 m deep and during wet periods the water level can rise up to 2 m. This level is secured with overflow structures. During the inflow, the incoming water first exchanges the permanent water volume. During dry period, there is no outflow.

2.1 Traditional wet detention ponds

The traditional (classic) WDP were built in the suburbs of the city of Aarhus in Denmark (Figure 1). The WDP have had inflow (orange circles in Figure 1) and outflow structures (green triangles in Figure 1) and an open water body. Plants vegetated the ponds by natural colonization. The systems were included in a network of 130 WDP build in the city of Aarhus, which has 250.000 inhabitants. The investigated WDP were constructed in 2003 and lie next to each other in forested surroundings, creating park-like area that attracts people and wildlife. The ponds have different capacities and shapes and treat runoff from different catchments, from residential areas to local roads and industrial areas.

Figure 1: Four traditional wet detention ponds (A, B, C and D) in the city of Aarhus (orange circle – inlet, green triangle – outlet)

These diverse systems have high buffering capacity that can face hydraulic and pollutant fluctuations in stormwater runoff. Because sedimentation is the main removal process in WDP, they are highly efficient in removal of suspended solids. This was shown by numerous authors, e.g. Terzakis et al. (2008), Bratieres et al. (2008), Hossain et al. (2008). However different studies show significantly different efficiency of WDP in removal of nutrients (Carleton et al., 2001, Hvitved-Jacobsen et al., 1984). The dissolved fraction of nutrients cannot be removed by sedimentation as the main treatment process in WDP (Vaze et al., 2004).

2.2 Upgraded wet detention ponds

Literature overview indicates that WDP are efficient in removal of suspended solids and associated pollutants, but the removal of soluble and colloidal pollutants is relatively low, because these pollutants cannot be removed via sedimentation. Therefore there is an increased need for additional treatment of stormwater after passing WDP or in the pond itself, i.e. upgrading of WDP.

In presented research three systems were upgraded with additional technologies in order to enhance elimination of soluble and colloidal pollutants. The systems were constructed in three Danish cities (Aarhus, Silkeborg and Odense) in the framework of European LIFE project TREASURE in 2007. Each pond consists of a sand trap at the inlet and open water area with wetland vegetation. Plants enhance sedimentation, provide surfaces for attached organisms like algae and bacteria that carry out major pollutant transformations; they accumulate heavy metals in the roots and uptake nutrients.

All three ponds were amended with sand filters. Sand filters were positioned at the outflow from the systems and were planted with common reeds. Besides this, each of the WDP was upgraded with an additional technology specific for each system:

The specific additional technology of the system at Aarhus is enrichment of bottom sediments with iron salts. The iron chloride/sulphate solution was added to the pond after approximately one year of operation. Enrichment of bottom sediments with iron salts is in use for rehabilitation of eutrophic lakes. The iron in the sediment increases sorption sites for

P and heavy metals.

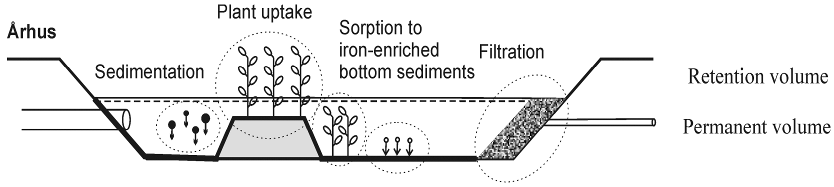

Figure 2: Scheme of wet detention pond in Aarhus with iron enriched bottom sediments

The specific additional technology of the system at Odense was sorption filter. It was positioned after the sand filters in order to prevent clogging. The filter was filled with a natural product obtained from fossil oysters that consists of 96 % of $CaCO_3$ and $MgCO_3$. It has been found that materials that contain a lot of calcite and dolomite are efficient in P adsorption and materials containing iron and aluminum are efficient in sorption of heavy metals.

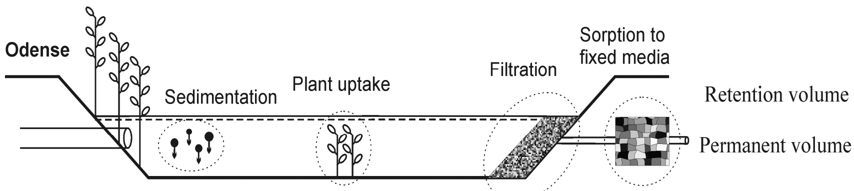

Figure 3: Scheme of wet detention pond in Odense with sorption filter

The additional technology implemented in the pond at Silkeborg was a flow proportional injection of aluminium hydroxide to promote the formation of flocks with high sorption capacity for dissolved pollutants. The sedimentation of the flocks was enhanced by 2 flow perpendicular sand dikes planted with reed. Addition of flocculants like Al and Fe salts form insoluble flocks in the bulk water. The flocks have good settling properties and high sorption capacity for P, heavy metals, organic micropollutants and algae.

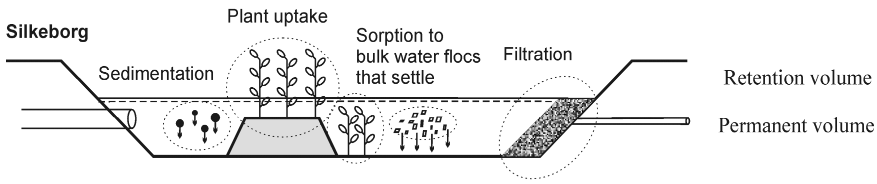

Figure 4: Scheme of wet detention pond in Silkeborg with addition of aluminium flocculant at the inlet

2.3 Monitoring

Water was sampled at the inlets, middle of the ponds and at the outlets. Samples were analysed for total suspended solids (TSS), ammonia nitrogen, total nitrogen (TN), orthophosphate, total phosphorous (TP), chemical oxygen demand (COD), Na, Ca, Fe, Cu, Zn, Ni, Cr, Cd and polycyclic aromatic hydrocarbons (PAH), pH, temperature, O_2 and turbidity.

Sediments were sampled along the flow and analysed for P, Fe, Mn, Ca, Na, K, Al, Pb, Zn, Cd, Ni, Cr, Cu and PAH.

At the traditional wet ponds plants were sampled at the inlet, middle and outlet. In the upgraded systems plants were sampled according to the planting scheme. Plant tissues were analysed for P, Fe, Mn, Ca, Na, K, Al, Pb, Zn, Cd, Ni, Cr, Cu.

3 Results and discussion

The analyses of water quality parameters showed that all ponds were efficient in removal of

TSS and TP (Figure 5). Upgraded WDP received higher loads of PO_4-P and heavy metals and enabled significant removal of these pollutants. Efficient removal of Zn, Cu, Cr and Pb in stormwater treatment wetlands was reported also by other studies, e.g. Bulc and Vrhovšek (2003) and Scholes et al. (1999). The majority of heavy metal concentrations referred to Zn and Cu, which were especially high at the Odense pond. The additional technologies in the upgraded WDP enhanced the removal of soluble pollutants, especially phosphorous and heavy metals.

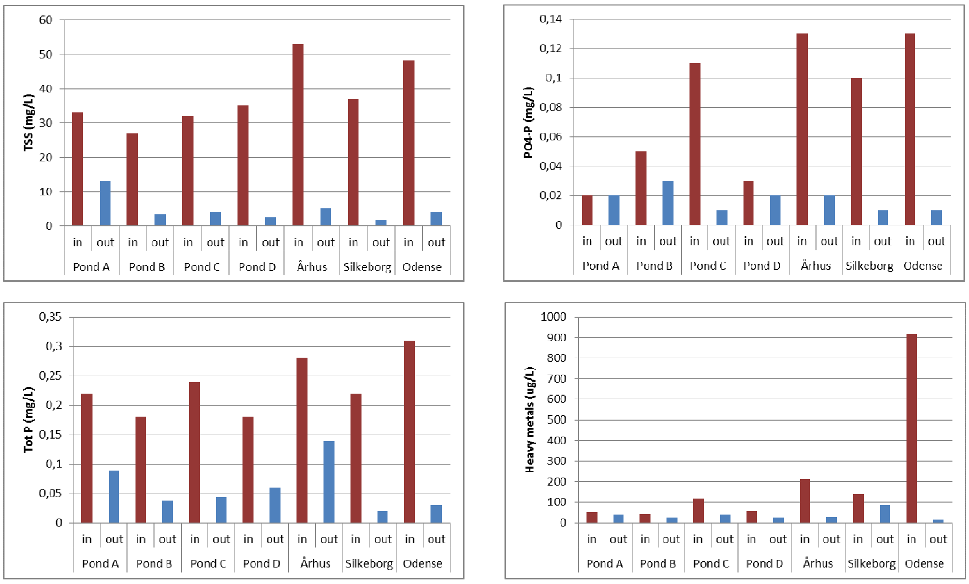

Figure 5: Water treatment performance of four traditional (A, B, C, D) and three upgraded wet detention ponds (Aarhus, Silkeborg, Odense)

The majority of pollutant removal in all WDP took place in the open water area, indicating that sedimentation is the most important treatment process. Heavy metals and other pollutants that are sorbed to different substances are subdued to sedimentation which results in accumulation of pollutants in the sediment. Concentrations of heavy metals in the sediment were significantly higher compared to heavy metal concentrations in natural lakes reported by Samecka-Cymerman and Kempers (2001). The concentrations were decreasing from the inlet to the outlet in the systems with high length to width ratio and rich vegetation of submerged plants. The reduction of heavy metal concentration along the water flow was reported by many authors, e.g. Walker and Hurl (2002), Sriyaraj and Shutes (2001), Hares and Ward (2004).

The upgraded WDP were carefully planted with selected wetland plant species. In total there were 14 native plant species planted along the banks of the ponds and in the open water area or islands, creating a rich wetland biodiversity. Traditional WDP were vegetated by natural colonization which resulted in predominance of *Typha latifolia* along the banks of all systems, while in open water area there was mainly *Potamogeton* sp., while pond B was extensively vegetated with invasive *Elodea canadensis*.

The main role of plants in WDP was to enable a natural and aesthetic appearance of the systems, increasing biodiversity and enhancing sedimentation. Besides this, plants also accumulated certain amounts of heavy metals and nutrients. Heavy metals were accumulated in the roots and rhizomes and were not transported into aboveground tissues. Heavy metal concentrations in the plants were correlated with concentrations of heavy metals in the water and sediment.

3.1 Factors affecting treatment efficiency

The results on treatment efficiency in different systems have pointed out the most important

factors affecting treatment performance. The results are important for further development design and dimensioning of WDP. Due to sedimentation is the most important treatment process in WDP (including in the upgraded systems), the factors that enhance sedimentation also enhance total treatment performance. The systems with higher length to width ratio enabled water flow to slow down more and reached better sedimentation compared to more rounded systems. In pond B there was extensive growth of invasive submerged wetland plant *Elodea canadensis*. Despite its negative impacts as invasive species it enhanced sedimentation significantly. One of the upgraded systems also had transversal sand dikes which divided a pond into three compartments. The dikes reduced the water flow and improved sedimentation of flocks. For elimination of dissolved pollutants implementation of additional technologies is crucial.
The treatment performance of WDP depends also on hydraulic and pollutant loading of the system. The loadings are expresses as the ratio between pond volume and catchment area (cubic meters of pond per hectare of catchment). The lower the ratio the higher the loading of the system. Upgraded WDP received significantly higher loads compared to traditional WDP, however the outflow pollutant concentrations were the same of even lower compared to the traditional WDP (Figure 5). This can indicate that the traditional WDP were over dimensioned.

3.2 Ecosystem services of wet detention ponds

Ecosystem services are everything that we can get or benefit from natural ecosystems. They are divided in supporting, provisioning, regulating and cultural services. Due to their treatment abilities, most obvious ecosystem service of WDP is regulating service, namely purification of water. However, WDP also have other ecosystem services which are as well of significant importance (Table 2). The investigated WDP in Denmark had emphasised cultural service, since there was an educational path created around the four traditional WDP. The path was equipped with information boards and banks. The path was soon adopted also by local visitors for jogging and walking the dogs.

Table 2: Ecosystem services of wet detention ponds and their impact to the environment

	Impact		
	Low	**Medium**	**High**
Supporting services			
Oxygen production	X		
Nutrient and water cycling			X
Soil production	X		
Habitat assurance			X
Provisioning services			
Water			X
Bio-chemicals and pharmaceuticals	X		
Decoration			X
Regulating services			
Purification of water, air and soil			X
Climate regulation and carbon sequestration		X	
Erosion prevention			X
Mitigation of draughts and floods			X
Cultural services			
Recreational			X
Cultural and spiritual inspiration		X	
Education			X
Aesthetic function			X

Ecosystem services including efficient water treatment and reuse can also be reached in rain gardens which are best management stormwater practice suitable for private gardens and farms. Rain gardens can be designed as percolation systems which enable percolation of rainwater on site or can detain rainwater and enable their further use in watering the gardens, irrigation, toilet flushing etc. which is an important feature in times of water shortages.

4 Conclusions

The results on treatment performance and ecosystem services in four traditional and three upgraded stormwater detention ponds have shown that all systems can eliminate suspended solids and associated pollutants while removal of soluble pollutants is improved by additional technologies implemented in upgraded wet detention ponds. Ecosystem services provided by stormwater wet detention ponds are similar in both type of the systems and are important for good acceptance of those systems by local population and improvement of the environment in general.

Literature

Bratieres, K., Fletcher, T.D., Deletic, A., Zinger, Y. Nutrient and sediment removal by stormwater biofilters: A large-scale design optimization study. *Water Research*, 2008, vol. 42, no. 14, pp. 3930-3940.

Bulc, T., Vrhovsek, D. Highway runoff treatment in the city of Celje in Slovenia. *Suvremeni promet*, 2003, vol. 23, no. 1-2, pp. 79-83.

Carleton, J.N., Grizzard, T.J., Godrej, A.N., Post, H.E. Factors affecting the performance of stormwater treatment wetlands. *Water Research*, 2001, vol. 35, no. 6, pp. 1552-1562.

Deutsch, J.C. Review of the Use of stormwater BMPs in EuropeProject under EU RTD 5th Framework Programme, Contract No EVK1-CT-2002-00111, Report 5.1., Adaptive Decision Support System (ADSS) for the Integration of Stormwater Source Control into Sustainable Urban Water Management Strategies. London, Middlesex University, 2003.

Hares, R.J., Ward, N.I. Sediment accumulation in newly constructed vegetative treatment facilities along a new major road. *Science of total environment*, 2004, vol. 334-335, pp. 473-479.

Hossain, M.A., Alam, M., Yonge, D.R., Dutta, P. Efficiency and flow regime of a highway stormwater detention pond in Washington, USA. *Water, Air, and Soil Pollution*, 2005, vol. 164, no. 1-4, pp. 79-89.

Hvitved-Jacobsen, T., Yousef, Y.A., Wanielista, M.P., Pearce, D.B. Fate of phosphorous and nitrogen in ponds receiving highway runoff. *The Science of the Total Environment*, 1984, vol. 33, pp. 259-270.

Samecka-Cymerman, A., Kempers, A.J. Concentrations of heavy metals and plant nutrients in water, sediments and aquatic macrophytes of anthropogenic lakes (former open cut brown coal mines) differing in stage of acidification. *The Science of the Total Environment*, 2001 vol. 281, no. 1-3, 87-98.

Scholes, L.N.L., Shutes, R.B.E., Revitt, D.M., Purchase, D., Forshaw, M. The removal of urban pollutants by constructed wetlands during wet weather. *Water Science and Technology*, 1999, vol. 40, no. 3, pp. 333-340.

Sriyaraj, K., Shutes, R.B.E. An assessment of the impact of motorway runoff on a pond, wetland and stream. *Environment International*, 2001, vol. 26, no. 5-6, pp. 433-439.

Terzakis, S., Fountoulakisa, M.S., Georgaki, I., Albantakis, D., Sabathianakis, I., Karathanasis, A.D., Kalogerakis N., Manios, T. Constructed wetlands treating highway runoff in the central Mediterranean region. *Chemosphere*, 2008, vol. 72, no. 2, pp. 141-149.

Vaze, J., Chiew, F.H.S. Nutrient loads associated with different sediment sizes in urban stormwater and surface pollutants. ASCE *Journal of Environmental Engineering,* 2004, vol. 130, no. 4, pp. 391-396.

Walker, D.J., Hurl, S. The reduction of heavy metals in a stormwater wetland. *Ecological Engineering*, 2002, vol. 18, no. 4, pp. 407-414.