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Nature-based Solutions for Integrated Local Water Management

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Abstract

Nature-based solutions (NBS) imitate natural processes and serve to generate multi-benefit values and services to the local communities. Sustainable solutions are multi-purpose measures implemented at the site, and offer communities targeted environmental water-related solutions in wastewater treatment, water retention, and pollution mitigation that result in a climate-resilient landscape.

Numerous good cases combine NBS for environmental pollution mitigation, prevention, and management. They can be implemented and managed locally, and are stimulated as zero-emission and climate-resilient technology. The main areas of intervention where NBS is best applied are agricultural run-off mitigation (constructed ecosystems), wastewater and leachate treatment (constructed wetlands), revitalisation of standing water bodies (floating wetlands), stormwater retention measures (rain gardens), and nutrient reuse (sludge drying reed beds).

A new report by the *Sustainable sanitation Task Force* (active in Global Water Partnership Central and Eastern Europe) on NBS in wastewater treatment indicates a moderate improvement in NBS application, but also relevant progress in engineering knowledge and innovation. It also estimates the application of several NBS treatment technologies for rural sanitation improvement and water reuse potentials.

Keywords

Nature-based solutions, wastewater treatment, leachate treatment, sludge treatment, urban drainage, landscape water management, constructed wetlands, floating treatment wetland, sludge drying reed beds, urban rain garden

1 Introduction

Freshwater ecosystems (rivers, lakes, ponds, and wetlands) provide essential ecosystem services and benefits our society receives from nature.[1,2] Their functioning has been heavily impacted by human activities, poor water management, and climate change.

Nature-based solutions (NBS)[1] are identified as interventions that address these challenges or resolve problems.[3] Planned actions imitate natural processes and serve to generate multi-benefit value and services to the local communities. All the NBS have many social, economic, and environmental effects. The main benefits beside their positive effects on the local water cycle in the catchment are:

- Water purification – increasing the natural capacity of water bodies for self-purification,
- Water retention – restoring the natural water retention capacity of catchments,
- Biodiversity conservation – supporting numerous habitats.

Their impact is beneficial under conditions of climate change adaptation, as they are a part of natural, climate-proof solutions that are adapted to changed water levels and pollution loads. Despite the growing recognisability of NBS, current water management practices remain largely under the influence of traditional (also called conventional or grey) solutions, and as such mostly provide primary water management benefits (*e.g.*, stream channelization to reduce flooding) without delivering other secondary ecosystem services (*e.g.*, flood plains designed synergistically to provide aesthetics, wildlife habitat, carbon sequestration, *etc.*). However, combining NBS with grey elements can provide important co-benefits[4] beyond mitigation of natural hazards. A new generation of infrastructure projects, integrating green and grey,[5] seeks a more holistic and integrated local water management that considers different sectors, stakeholders, and needs.

2 NBS and their multi-beneficial targets

A selection of NBS addressing water-related problems will be described here. They represent a selection of planned techniques that are based on ecosystem services to improve water quantity and quality, as well as improve the resilience to climate change. Firstly, NBS are mostly connected to decentralised systems for wastewater treatment (constructed wetlands) and sewage sludge management (sludge drying reed beds). Their contribution to landscape water management can: 1) minimise the pollution loads thus contributing to the environmental resilience and habitat stability of rivers, streams, and lakes (recipients), and 2) enable uptake of nutrient (nitrogen, phosphorus) and water reuse thus reducing water consumption and use of additional fertilisers.

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Secondly, water retention under the climate adaptation needs (water retention and quality improvement for agriculture) will be discussed. Results of flood management planning of the past decades are water retention bodies of different sizes. In Slovenia, a comprehensive strategy for the management of freshwater (flood prevention) reservoirs has not been established; their condition is deteriorating day by day. Most of the reservoirs are in a eutrophic state, as can be seen from the datasets observing cyanobacteria presence in the water bodies, and are closely linked to eutrophication.[6] In the past decades, many reservoirs have developed secondary uses and activities that significantly limit the effective implementation of their primary purpose. The main reasons for their poor ecological state are scattered pollution from the hinterland, *i.e.*, non-point and point pollution, unauthorised secondary and tertiary uses, and uncoordinated management.

Climate change is causing both extreme precipitation events and agricultural drought in the region[7]. This comes as a result of seasonal change in precipitation, increasing winter precipitation, and summer temperature heat peaks.[8] Water reservoirs thus take on a new role of supplying water since existing water supplies are becoming insufficient. At the same time, some of these water sources also need to be used for new development activities in the region. It should be emphasised that the water in all reservoirs is of poor quality, and in some places, potentially health-threatening cyanobacteria are even present.

Therefore, thirdly, revitalisation of standing water bodies (local ponds, lakes, and water accumulations) by floating treatment islands, constructed wetlands, and other NBS should be considered to reverse the declining ecological state of the water bodies. Buffer systems that protect water from agricultural run-off are often-neglected solutions that are being reused under the climate change threats (erosion, droughts, and floods). The fact that this type of pollution is nonpoint source calls for the development of simple and resilient constructed ecosystems.

Lastly, sustainable urban drainage systems. They reduce pressure on existing water treatment infrastructure through bioretention and infiltration. It includes building green infrastructure to capture and treat stormwater for a range of co-benefits. This also supports groundwater recharge.[9]

3 Selection and effects of landscape NBS

The most frequent NBS are constructed wetlands (CWs), which are biologically engineered wastewater treatment systems that rely on the presence of plants and microorganisms, the interaction of physical, chemical, and biological processes, as well as different removal mechanisms.[10,11] CWs can treat different types of wastewaters: municipal and industrial wastewater, pre-treated wastewater, landfill leachate, stormwater, agricultural runoff, *etc*. They efficiently remove suspended solids, organic matter, and nutrients.[10] However, the removal of heavy metals is not frequent.[12]

In addition to treating wastewater, CWs have several ancillary benefits, such as wildlife habitat provision,[13] possibilities for effluent reuse, and nutrient recovery, and carbon sequestration. These benefits may be considered equally important as water purification when making future cities sustainable and resilient.

Each CW consists of a pre-treatment step (septic tank or sedimentation basin) followed by one or more interconnected beds. Most CWs in Europe are subsurface vertical or horizontal flow wetlands. The latest trend that is transforming perception of CWs as land consuming technology enables the required efficiency on a much smaller surface with the use of active aeration. This type of system is extremely efficient in the removal of organic matter (BOD > 99 %)[14], and also has a longer life span since oxygen supply conditions are better.

CWs are isolated with impermeable PEHD foil and filled with filter media (most often gravel) planted with macrophytes. The majority of CWs are planted with common reed (*Phragmites australis*) that is found in abundance in the region.[10] The biodegradation of wastewater pollutants is mainly achieved by microorganisms attached to wetland roots and filter media.

The disposal of sludge is a growing challenge not only for the wastewater industry, but also for all involved stakeholders (public utilities, municipalities, ministries, *etc.*). To ensure the circular approach that has lately been developed and stimulated to deliver value from a waste, wastewater treatment plants can be paired with sludge treatment drying reed beds (SDRB). This generally ensures the position of the wastewater treatment process as a generator of nutrients available for reuse.

SDRBs dehydrate, mineralise, and stabilise sewage sludge using only natural processes. Chemical coagulation/flocculation is not required since reed bed technology is based on a passive dewatering process. In the process, sludge is distributed on the planted bed of gravel and sand, after which drying takes place by a combination of evapotranspiration, filtration, and gravity drainage through the filter layer.[15] The technology enables long-term storage and sustainable reuse of sludge with low operating and maintenance costs. This represents significant savings in operating costs. SDRBs can completely replace mechanical dehydration (*e.g.*, belt presses, centrifuges), but this nature-based technology often does not come into consideration because of a rather large footprint. They require a much larger area than mechanical dewatering, which means that SDRB technology appears most practical for smaller and medium-sized wastewater treatment plants (WWTPs) where land is not expensive or is state-owned.

An aerial shot of an example of the best practice for integration of two NBS (CW and SDRB) into a rural environment is shown in the following figure. The figure shows WWTP in Kaštelir in Croatia, where treated wastewater is available to farmers for irrigation of olive groves and vineyards, while the harvested biosolids (product of sludge drying reed beds) can be used as soil amendment. Biosolids analysis confirmed the safety of application on agricultural land.

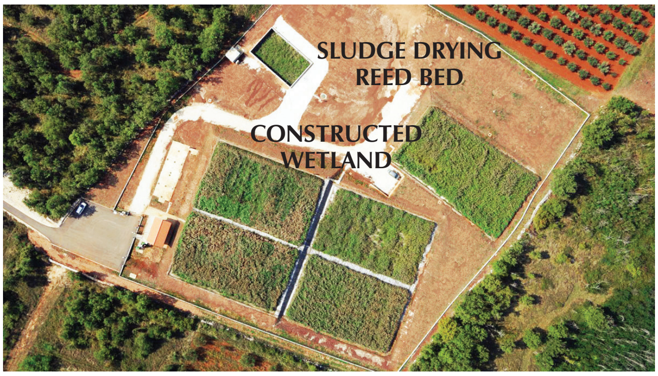

Fig. 1 – Constructed wetland for wastewater treatment along with a planted drying bed for sludge treatment at Kaštelir in Croatia (1.900 PE) (source: LIMNOS Ltd).

With SDRB technology, different types of sewage and industrial sludge can be treated. Sludge is normally stored in the SDRB between 8 and 10 years. Due to the parallel occurrence of several processes (dehydration, drying, and mineralisation), sludge volume is significantly reduced. The sludge no longer contains pathogen organisms, and is therefore stabilised. The result of the process is compost-like soil that can be reused as fertiliser in agriculture, cover layer for landfills or as construction material.

SDRB are constructed in rectangular concrete basins or soil excavated basins. The bottom of the basins is impermeabilised with a waterproof membrane to protect groundwater and/or to prevent water gains. The drained water from the sludge is collected through perforated pipes placed on the bottom of beds, and returned to a wastewater treatment plant. The bed hosts a filter with layers of gravel and sand. Reeds (*Phragmites australis*) are planted[10] in the top layer of sand.

The number of beds and the surface area vary and depend on the amount of sludge to be treated and the local climate. Sludge is distributed homogeneously on the surface of the bed in loading calculated batches. Each feeding period is followed by a resting period that can last several weeks.

Fig. 2 – Sludge drying reed beds at the finalisation of construction works (left), and after the first year of operation (right) (source: LIMNOS Ltd.)

Rural areas, prone to scarce settlements that cause costly centralised sewage network construction, are particularly suitable for NBS application. A recent report by the Sustainable Sanitation Task Force of Global Water Partnership[16] gives an overall estimation of the application of several NBS treatment technologies for rural sanitation improvement and water reuse potentials in the region of Central and Eastern Europe. It has been discovered that, in the past 10 years, the technical knowledge of NBS for wastewater treatment has increased significantly. This is partly the result of EU support to research and innovation projects in NBS. The feedback of respondents displayed an improved knowledge on available types of NBS for rural (dispersed) wastewater treatment; however, they have not gained widespread establishment. The reasons for the modest use of NBS are mainly the lack of awareness of these solutions, some negative experiences of early trial attempts, and lack of available surfaces, predominantly on the settlement scale. The use of NBS in wastewater treatment has improved in most of the surveyed countries, particularly in Slovakia, Poland, Estonia, and Slovenia, where the offer and demand for treatment wetland technologies is readily available and applied.[16] Another reason is that, in engineering culture, conventional approaches (technical solutions) have traditionally been more favoured and respected. In addition, lower operating costs are often neglected when deciding on the technology because of unfamiliarity with the NBS.

A particular type of wastewater, the treatment of which is often energy-intensive, is landfill leachate. Uncollected and untreated leachate poses a serious threat to groundwater and surface water sources, as well as public health.

Co-natural reclamation of landfills by biotechnologies made of landfill wastes can be used to stabilise and recover soil by improving its structure, as well as increase soil quality by regulating nutrient supply.[17] New innovative treatment wetland (ITW), namely, floating treatment wetland (FTW), aerated vertical wetland with geopolymers (GP – ATW), and electroactive biofilm-based treatment wetland (EAB – TW) are being engineered to address polluted landfill leachate and run-off, aiming to deliver a 95 % reduction in heavy metals, and a 99 % reduction in ammonium and BOD_5 compounds.[17] Use of geopolymers instead of gravel in ATW improves efficiency in removal of some specific pollutants (e.g. heavy metals), while the presence of electroactive bacteria in the TW has the potential of generating added value by-products (*i.e.* electricity and useful compounds),[18] assuring costly remediation of the landfill.

NBS in this case aims to increase the resilience of EU waste infrastructures against climate change since they manage flush flooding and run-off caused by heavy rainfall, and prevent fires and explosions caused by droughts and unusual heatwaves (treated water reuse).

FTW is a type of NBS dependent on a buoyant structure where macrophytes are grown. The fundamental features of FTW are stability and buoyancy. Stability of the structure is necessary for the plants to anchor their roots, while buoyancy positions the plants at the water level. This phytotechnology keeps the plant roots permanently in contact with water, which enables the removal of pollutants. In FTWs, plant roots provide an active settling medium and surface area for essential attachment, and food for microbial population[19,20] needed for the removal of pollutants. FTWs have mainly been adopted for the treatment of stormwater, wastewater, and as an intervention tool to improve water quality (Fig. 3) and reduce harmful algal blooms in standing water bodies. FTWs treat water as well as provide multi-beneficial impacts (littoral zone protection, landscape and tourism reinforcement.[21] They revive water bodies by introducing an additional structure into the water environment, which creates a habitat for various organisms, from plants, microorganisms, invertebrates to fish and birds. This enables more types of organisms to live, the formation of more varied food webs, and a more productive aquatic environment.

Fig. 3 – Floating islands for water body revitalisation (Velenje Lake (left), Kamešnica pond (right), Slovenia); (source: LIMNOS Ltd.)

FTWs have been tested for the treatment of landfill leachate at the mesocosms scale, achieving removal efficiencies of 97 % for ammonium, and organic matter above 87 %.[22] The evidence available confirms the long-term performance of FTWs, as there is plenty of evidence of their ability for treating organic matter nutrients and suspended solids (*e.g.*, conventional ponds). FTWs provide comparable performance as another type of treatment wetlands, especially due to their capacity to withstand water level fluctuations.[23] The area of an FTW required to enhance water quality of surface bodies is not well documented, and the coverage used varies greatly, from less than 20 %[24] to 50 %[25] and even 100 %.[26] Fig. 4 presents FTW, which will be applied and tested on XILOGA landfill in Spain.[17]

NBS can also treat agricultural runoff, which contains excess quantities of diverse pollutants, such as sediments, nutrients, pathogens, veterinary medicines, pesticides, and metals.[27] Mitigating agricultural run-off by constructed ecosystems[28] that remove nutrients and other pollutants from drainage ditches, has proved to be a relevant and efficient solution.[29] Constructed ecosystems (Fig. 5) are various but simple structures of natural materials that are applied in drainage ditches. They create conditions for the development of biologically active surfaces where microorganisms increase nature's self-cleansing capacities, and represent a sustainable approach to reducing the pollution load to water resources. Their multi-benefit effect is realised in development or preservation of habitats.

Fig. 5 – Different designs of constructed ecosystems (2-level ditch on the left; meandering outline on the right) (source: LIMNOS Ltd)

The effectiveness of constructed ecosystems was monitored on four (4) field locations (Fig. 6) treating various agricultural runoff, and resulted in average 56 % reduction in COD, 50 % reduction in TSS, 67 % reduction in nitrates.[30] The solution was most efficient for the treatment of livestock farm run-off achieving 96 % removal of organic matter, over 70 % reduction in $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$, 77 % reduction in TSS, and 70 % reduction in $P\text{-}PO_4^{3}$.

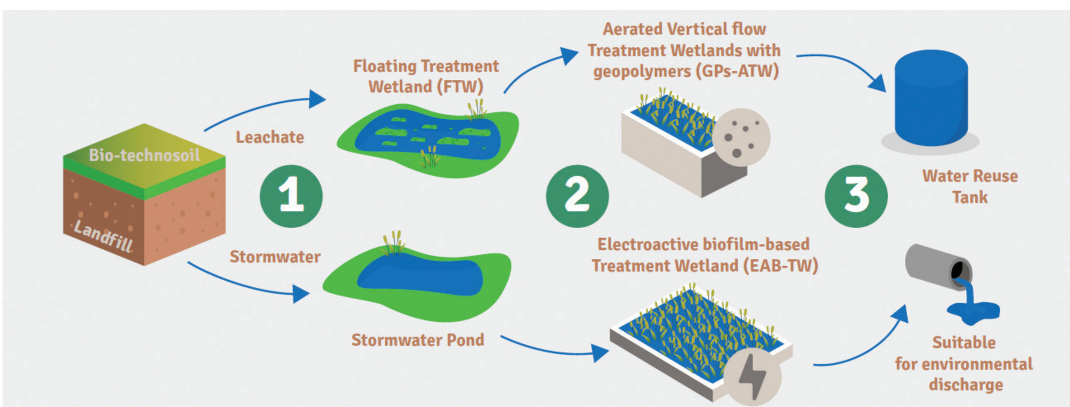

Fig. 4 – Different nature-based solutions applied on a landfill in Spain[17]

Fig. 6 – Constructed ecosystems in the landscape (Trzin (left) and Tešanovci (right); Slovenia) (source: LIMNOS Ltd.)

Sustainable drainage systems (SUDS) are designed to manage stormwater locally (as close to its source as possible), to mimic natural drainage and encourage its infiltration, attenuation, and passive treatment.[31] One multifunctional NBS are urban rain gardens (Fig. 7). They are usually designed as a shallow area in the flood-prone urban area intended to retain stormwater. It is an urban blue-green infrastructure with relevant landscape features. Due to increasing heat waves and summer droughts, urban rain gardens have the potential to be designed as water-retaining, purifying, and shadow-providing green spaces. Rain gardens can thus not only contribute to stormwater management but also perform a range of other functions (water treatment, biodiversity support, and heat reduction).

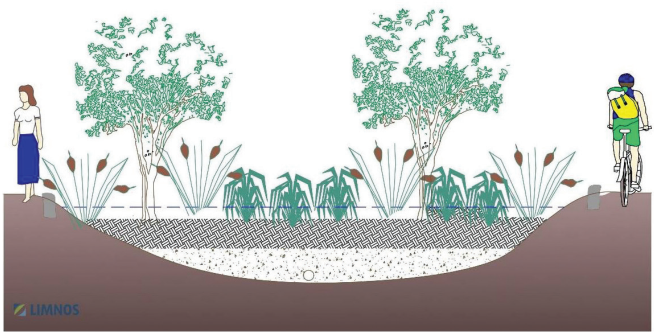

Fig. 7 – An urban rain garden design indicating multipurpose use of this NBS (source: LIMNOS Ltd.)

In Ljubljana (Slovenia), such a rain garden is being designed in order to treat polluted stormwater from the 400 m^2 surface area of a parking lot. According to the size of the catchment area, the required surface area for the rain garden is 40 m^2. It will be constructed as a shallow depression for potential water storage. At the bottom, the garden will be filled with a layer of gravel to filter pollutants and provide additional storage capacity for rainwater, thus preventing summer drought for growing plants. The surface area will be covered with a layer of a mixture of soil, sand, and compost to grow various attractive and low maintenance plants, such as shrubs, perennial flowering plants, and grasses.

After treatment and retention in the rain garden, the water will be used for watering the green areas around the building. Employees of two neighbouring public buildings will be able to enjoy the shade and nature of the rain garden.

4 Benefits of NBS for water management and the community

From the following table, one can estimate multi-beneficial effects on water management, mainly on water quality, availability, biodiversity but also on enhancement of climate resilience in general.

A climate-resilient infrastructure relies on the following characteristics: 1) it is adapted to weather extremes with a combination of NBS (buffer) and grey engineering solutions, 2) it is tailor-made to local and context-specific risks, such as flooding, landslides; and 3) it is another occurrence that combines the effects of local geospecificities. It is a continuing process and is linked to Integrated Water Resources Management.[1] This process promotes coordinated and inclusive management of water issues, to maximise the environmental, economic, and social impact on the landscape/basin by providing a holistic communication approach.

Water in the 20^{th} century has been treated as the driver of large infrastructure projects, and therefore management

Table 1 – Effect of NBS on water management

	Effect on water management			
Nature-based solution type	Purification	Habitat	Retention	Climate resilience
CW	xxx		x	xxx
SDRB	xxx		x	xx
ITW for leachate treatment	xxx		x	xx
FTW for surface water body revitalisation	x	xxx		x
Urban rain gardens (SUDS)	xx	x	xxx	x

x – low impact; xx – medium impact; xxx – high impact and communication has been decidedly shaped by water infrastructure (drinking water, dams, energy, and irrigation). In this context, there are many stakeholder interests and conflicts to be resolved. Integrated management is in fact an agreement between stakeholders, but it does not include natural, ecosystem, aesthetic, and other aspects. In this regard, NBS is an opportunity (and condition) for truly integrated landscape (basin) water management.

Presented in this work are different instances of decentralised water-related examples that provide multiple benefits, combine different approaches, and thus consider wider areas of water as an element of our nature/landscape/basin. The key units are watersheds that go beyond the borders of political/policy and do not only emphasise economic development potentials.

List of abbreviations

COD	– chemical oxygen demand
CW	– constructed wetland
EAB – TW	– electroactive biofilm-based treatment wetland
FTW	– floating treatment wetlands
GP – ATW	– aerated treated wetland with geopolymers
ITW	– innovative treatment wetlands
NBS	– nature-based solutions
SDRB	– sludge drying reed beds
SUDS	– sustainable drainage systems
TSS	– total suspended solids

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SAŽETAK

Prirodna rješenja za integrirano lokalno upravljanje vodama

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Rješenja temeljena na prirodi (NBS) oponašaju prirodne procese i služe stvaranju višestruko korisnih vrijednosti i usluga lokalnim zajednicama. Održiva rješenja su višenamjenske mjere koje se provode na samoj lokaciji, a zajednicama nude ciljana ekološka rješenja vezana uz pročišćavanje otpadnih voda, retenciju voda i ublažavanje onečišćenja koja doprinose postizanju klimatski otpornih krajobraza.
Postoje brojni pozitivnih slučajevi primjena NBS-a za ublažavanje, prevenciju i upravljanje onečišćenjem okoliša. Ta se rješenja mogu implementirati i upravljati lokalno, imaju nultu stopu emisije i doprinose klimatskoj otpornosti. Područja u kojima se NBS rješenja najbolje primjenjuju su ublažavanje poljoprivrednog otjecanja (izgrađeni ekosustavi), obrada otpadnih i procjednih voda (izgrađena močvarna područja), revitalizacija stajaćih vodnih tijela (plutajuće močvare), mjere zadržavanja oborinskih voda (kišni vrtovi) i ponovna uporaba hranjivih tvari (sušenje mulja na trski). Novo izvješće organizacije *Global Water Partnership* o primjeni NBS-a ukazuje na umjereno poboljšanje primjene NBS-a u pročišćavanju otpadnih voda uz znatan napredak u inženjerskom znanju i inovacijama. Također procjenjuje primjenu potencijala nekoliko NBS tehnologija za poboljšanje sanitarnih uvjeta u ruralnim sredinama i ponovljenu uporabu voda.

Ključne riječi
Rješenja temeljena na prirodi, pročišćavanje otpadnih voda, pročišćavanje procjednih voda, obrada mulja, urbana odvodnja, upravljanje krajobraznim vodama, izgrađeni biljni uređaji, plutajući biljni uređaj za pročišćavanje, sušenje mulja na trski, urbani kišni vrt

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