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NbS – Nature based Solutions as part of the blue-green urban drainage infrastructure

Tatjana Uzelac,
Starum d.o.o. Pula, BSc., tanja@starum.hr

Abstract: We are witnessing a time when climate change necessitates adaptations and new approaches to solving urban drainage problems, which affect both ecosystems and the way people live in cities. One way to adapt is through nature-based solutions (NbS), especially in urban drainage. In urban areas, traditional drainage methods have proven insufficient, highly expensive, and often ineffective regarding runoff and flood control, as well as environmental and urban ecosystem preservation. In the Republic of Croatia, nature-based solutions have been implemented in urban drainage for a number of years, and recently these tools have also been used in other disciplines, especially green urban renewal strategies, and urban planning as inseparable parts, ultimately aiming for safer water, food, and energy management.

Key words: NbS, urban drainage, blue-green infrastructure, climate change, water management, energy

Rješenja temeljena na prirodi – Nature based Solutions kao dio plavo-zelene infrastrukture urbane odvodnje

Sažetak: Svjedoci smo vremena u kojem klimatske promjene uvjetuju prilagodbe i nove načine rješavanja problema urbane odvodnje a koji imaju utjecaj i na ekosustave i na način života ljudi u gradovima. Jedan od načina prilagodbe su i rješenja temeljena na prirodi (NbS sustavi) posebno u dijelu urbane odvodnje. Tradicionalni načini odvodnje u gradskim sredinama pokazali su se kao nedovoljni, te izrazito skupi a nerijetko i neučinkoviti u pogledu otjecanja i zaštite od poplava ali i zaštite okoliša te urbanih ekosustava. U Republici Hrvatskoj već se niz godina primjenjuju rješenja temeljena na prirodi u urbanoj odvodnji, a u posljednje vrijeme ti se alati koriste i u drugim disciplinama posebno strategija zelenih urbanih obnova i urbanog planiranja kao neodvojivih dijelova, a zbog, u konačnici, sigurnijeg upravljanja vodom, hranom i energijom.

Ključne riječi: NbS sustavi, urbana odvodnja, plavo-zelene infrastruktura, klimatske promjene, upravljanje vodom, energija

1. NATURE-BASED SOLUTIONS – NbS

The European Commission defines NbS as solutions that are “inspired by and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions", and the delivery of a range of ecosystem services.

The International Union for Conservation of Nature (IUCN) defines NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits" [1].

1.1 NbS for urban drainage

NbS can be categorized into three types [2]. Type 1 NbS consists of no or minimal intervention in ecosystems, with the objectives of maintaining or improving the delivery of ecosystem services both inside and outside of the preserved ecosystems. Type 2 NbS involves the extensive or intensive management approaches aimed at developing sustainable and multi-functional ecosystems and landscapes, to improve the delivery of ecosystem services compared to conventional interventions.
Type 3 NbS includes:

1. GREEN SPACE - multifunctional open space characterized by natural vegetation and permeable surfaces (urban parks and gardens of all sizes, heritage park, botanical garden, community garden, cemetery, schoolyards and sports fields, meadow, green strips, green transport track, "multifunctional" dry detention pond or vegetated drainage basin), trees and shrubs, forests (including afforestation), orchards, vineyards, hedges/shrubs/green fences, street trees.
2. SOIL CONSERVATION AND QUALITY MANAGEMENT – revegetation of slopes, cover crops, windbreaks, conservation tillage practices, permaculture, deep-rooted perennials, organic matter enrichment (manure, biosolids, green manure, compost, etc.), inorganic soil conditioners and amendments (biochar, vermiculite, etc.), blue-green space establishment or restoration, riparian buffer zones, mangroves (a group of trees and shrubs living in the coastal intertidal zone), salt marsh/seagrass, intertidal habitats, dune structures.
3. GREEN BUILT ENVIRONMENT - green roof, green-blue roof, green wall/facade, green alley, infiltration planters and tree boxes, temporary and/or small-scale interventions including green furniture, green living rooms, etc.
4. NATURAL OR SEMI-NATURAL WATER STORAGE AND TRANSPORT STRUCTURES - surface wetlands, floodplains, floodplain reconnection with rivers, restoration of degraded water bodies, restoration of degraded waterways, including stream re-meandering and river daylighting, retention pond/wet detention pond
5. INFILTRATION, FILTRATION AND BIOFILTRATION STRUCTURES - infiltration basin, vegetated filter strip, rain garden, wet/dry vegetated swale, with or without check dams, subsurface wetland or filtration system, bioretention basin/bioretention cell, lagoons

The third type of NbS is particularly used in urban drainage through the application of available mathematical modeling tools and GIS technology, all related to the new urban planning paradigm, the so-called KBUD (Knowledge Based Urban Development) method [3].

Figure 1. Type 3 NbS – Rain garden, City of Pula (Starum) [4]

Figure 2. Type 3 NbS – King Tomislav Square, City of Pula (Starum) [5]

1.2. Blue-green infrastructure

Blue-green infrastructure (BGI) is an integrated system of natural and semi-natural elements that combines water and vegetation components to deliver multiple environmental, hydraulic engineering and social benefits. In the context of rapid urban development and climate change, traditional approaches to stormwater management based on centralized, so-called "gray" drainage systems, show limitations in terms of capacity, resilience and long-term sustainability.

Blue-green infrastructure introduces a water management paradigm based on the principles of retention, infiltration, evapotranspiration and natural filtration, thus reducing the hydraulic load on the system, improving water quality and enhancing the resilience of urban areas to extreme climate conditions.

1. The concept and components of blue-green infrastructure

BGI consists of interconnected elements that act as a functional network:

The blue component includes surface water and groundwater systems: rivers, streams, retention and detention ponds, artificial lagoons, infiltration systems, and constructed wetlands.

The green component includes vegetation systems: parks, urban forests, green corridors, green roofs and facades, and vegetation elements within stormwater drainage systems (e.g. rain gardens).

A key feature of BGI is its spatial and functional integration, where water is used as a resource within the landscape, rather than as waste to be removed as quickly as possible.

2. Hydrological and hydraulic function

The basic technical function of blue-green infrastructure is stormwater management through the processes of: retention and detention (temporary water storage), infiltration into the soil (provided adequate permeability and groundwater protection), slowing runoff (reducing peak flows), and extending retention time (typically 24–72 hours, depending on the system).

In this way, BGI helps reduce the risk of urban flooding, relieve sewage systems, and stabilize the hydrological regime within the catchment area.

3. Treatment function and water quality

Blue-green infrastructure systems act as natural biofilters in which various groups of pollutants are removed: suspended solids (TSS), heavy metals (Zn, Cu, Pb), hydrocarbons and oils, nutrients (N, P), and pathogens.

Removal processes include mechanical filtration, sedimentation, adsorption onto soil particles and biological degradation by microorganisms in the plant rhizosphere. Plants with developed aerenchyma play a particularly important role, enabling the supply of oxygen to saturated soil and thus stimulating aerobic decomposition processes.

4. Climatic and environmental role

Blue-green infrastructure plays a significant role in adapting to climate change: it reduces the urban heat island effect through evapotranspiration and shading, increases water retention capacity during intense precipitation, contributes to the preservation of biodiversity by creating habitats for different species, enables carbon sequestration through vegetation and soil.

In this way, these systems become key elements of nature-based solutions in urban environments.

5. Socio-economic aspects

In addition to technical and environmental functions, BGI also generates significant social and economic benefits:

increasing the quality of public spaces and the aesthetic value of the environment,

making a positive impact on the health and well-being of the population,

increasing the market value of real estate,

reducing construction and maintenance costs compared to conventional systems over the long term.

Cost-benefit analyses (CBA) show that, despite often higher initial investments, blue-green infrastructure achieves a more favorable cost-benefit ratio over the life cycle.

ROADS WITH STORMWATER DRAINAGE AND LANDSCAPING	SAVINGS IN RELATION TO A CONVENTIONAL PROJECT
Riva Street Pula	550.000,00 EUR
City Bypass 1 km, Pula	7.000.000,00 EUR
Industrial zone Štanga, Rovinj	660.000,00 EUR
Monsena – tourist resort, Rovinj	700.000,00 EUR
Nazorova Street, Pula	100.000,00 EUR
St. Benedict Street, Stupnik Municipality	200.000,00 EUR
"Viktor Lenac" shipyard, Kostrena Municipality	1.700.000,00 EUR

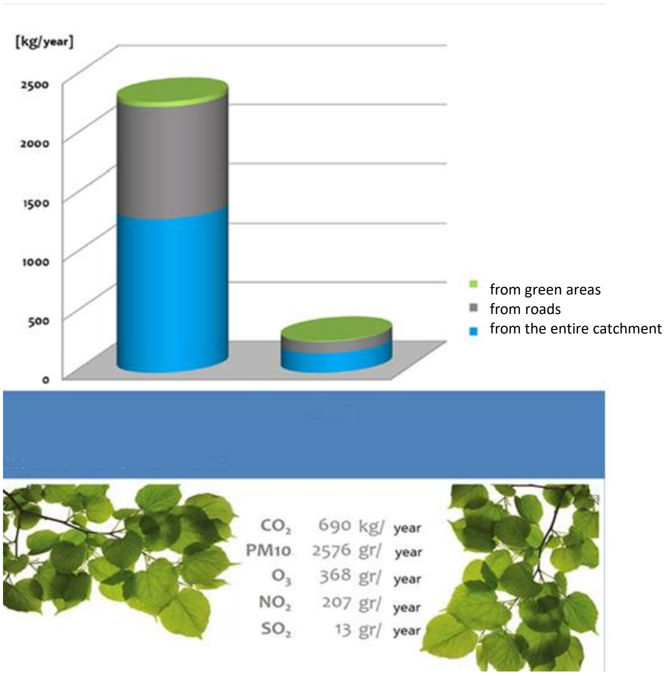

Figure 3. Savings of blue-green infrastructure compared to the conventional system and reduction of the pollution load of Nazorova Street in Pula (Starum) [6]

2. EXAMPLES OF IMPLEMENTING NbS DRAINAGE SYSTEMS IN THE CITY OF PULA

The City of Pula faced major flooding problems due to the following reasons: topography (in the very south of the Istrian peninsula), old sewerage channels (combined sanitary and storm water), rapid urban development and spatial plans that failed to account for changes in runoff and additionally expensive stormwater drainage unable to keep up with rapid urban development, short heavy rain (related to climate change), subsurface (impermeable clay soil)

The city area is characterized by terra rossa of varying depths from zero to several tens of meters on a limestone bedrock. As for the soil types in the immediate area of the City of Pula, we can say that they have been greatly changed by human influence, so instead of a specific soil type, we deal with anthropogenized soils.

In relation to the relief and topographic characteristics of the city, the sewage system of the City of Pula can be defined as the sewage system of the high and low zones of the city. In the lower parts of the city, the sewage system is laid at a small depth, with small gradients, and is influenced by the sea and groundwater in places where anthropogenic and natural fill materials, as well as terra rossa soil, have been registered. In the higher parts of the city, the sewage system is installed at greater depths, in a cascaded manner and with steeper gradients. In the higher parts of the city, the sewage system fails to operate during rainfall, resulting in surface runoff along the steep streets of the city, while in the lowest parts of the city the sewerage is affected by the sea and groundwater.

In addition, surface water from the higher parts of the city is retained in the lower parts, on the main city squares. The problems are greater because the part of the surface water that does not gravitate to the city (the Pragrande valley) is artificially introduced into the inner city core.

With the increase in construction in the steeper parts of the city, erosion and surface runoff have intensified, and the problems of stormwater and surface water drainage have also become more severe. Following the 2007 pilot project of introducing NbS, a conceptual design for citywide drainage was developed on Nazorova Street and as such incorporated into the General Urban Plan (GUP) of the City of Pula.

2.1. Nazorova Street

Nazorova Street is part of the central city catchment area of approximately six hectares, exceptionally steep in the higher parts and with no longitudinal gradient in the lower parts.

The applied NbS drainage systems consist of three rain garden retentions, differing from each other in several characteristics, with a geomembrane installed in the lowest part to prevent groundwater intrusion into the rain garden, a central rain garden retention with drainage layers, and an upper-zone rain garden retention where the street stormwater pipe is directed into underground retentions and, after retention, returned to the stormwater drainage system.

Figure 4. Construction of rain garden retentions of Nazorova Street [6]

The calculation was carried out using the rational method for a return period of 100 years and a duration of 24 hours. It should be noted that the design rainfall for pipelines, overflows and gully gratings refers to the maximum peak flow, while retention facilities are dimensioned according to the rainfall volume of a hundred-year return period and a duration of 24 hours. Hydrological data were obtained for the City of Pula from the Faculty of Civil Engineering in Rijeka.

Figure 5. Constructed NbS on Nazorova Street (Starum) [6]

Before the reconstruction, the pollutant load was 2309.02 kg per year, and after the reconstruction it was 270.34 kg per year. The pollution assessment was carried out using the so-called Simple Method [7].

The Simple Method is used to quickly estimate the annual pollutant load (export) from urban areas, and is based on the degree of surface impermeability.

$$L=\frac{P \cdot P_j \cdot R_v}{100} \cdot C \cdot A \cdot 10 \qquad (1)$$

L = Annual pollutant load (kg/year)
P = Average annual precipitation (mm) - for Croatia usually 800–1000 mm
Pj = Correction factor (standard value is 0.9) - takes into account rainfall that is too small to generate runoff.
C = Mean pollutant concentration (mg/l) - for example, the value of 0.26 mg/l is assumed for phosphorus in the city.
A = Area of the entire catchment (ha)
100 and 10 = Measurement unit conversion factors
Rv = Runoff coefficient

$$R_v = 0.05 + 0.009 \cdot I \qquad (2)$$

I = Percentage of impervious surfaces of a catchment

For each pollutant, estimates were then made for pre- and post-construction conditions, depending on the increase in impervious surfaces.

The Simple Method is best suited for assessing and comparing the relative changes in pollutant loads in stormwater under different land use and stormwater management scenarios and provides estimates of pollutant exports in stormwater that are probably close to the "actual" but unknown value for the development location, catchment or sub-catchment. The Simple Method provides a general planning estimate of the likely pollutant export in stormwater from an area at the development site, catchment or sub-catchment level. It ignores complex hydrological processes (such as base flow) and focuses on pollutants that are washed away from impervious surfaces during rainfall. Analysis of larger and more complex catchments requires more sophisticated modeling. A somewhat more complex method for calculating pollution loads is the Split Method [8]. To perform the calculation with this method, more input data are required than in the Simple Method. It is necessary to know the coefficients for dry and rainy seasons, and in order to obtain the values of these coefficients (input parameters), field and laboratory tests must be carried out in the dry and rainy seasons using appropriate instruments.

The Simple Method can be used to predict the increase in pollution after constructing a facility, to compare different sites or planning solutions, and as a basis for sizing a treatment system (NbS) and assessing pollution before and after the implementation of NbS.

In addition to the above methods, mathematical models such as the EPA SWMM model [9] are often used.

2.2. City bypass and Šijana basin

During the construction of the city bypass road, there was a problem with the conventional drainage system as it was impossible to accommodate the required oil and grease separator within the road profile and discharge into the nearest recipient, so it was decided to try NbS. The stormwater drainage of the city bypass was resolved by using the existing green belt between the two roadways as a bioretention area. After the end of a rainfall event and a 24-hour retention period, the excess stormwater is gradually discharged into the existing combined sewage system. This resulted in significant savings (in land acquisition, protection of existing combined drainage from sudden inflows, and landscaping of more than one hectare of area) and at a lower cost than construction of a conventional pipe drainage system.

With the construction of the "Istrian Y" highway section, large quantities of stormwater are reaching the city center itself through a conventional pipe system, and the existing city combined system was not dimensioned or built for these additional quantities. As construction was already in progress, an urgent solution had to be found without disrupting the existing drainage regime downstream. Again, NbS proved to be the only solution.

The already constructed road and the roundabout could not be reconstructed, so the curbs were cut to collect rainwater to the existing median strips, which were converted into bioretention areas, and the highway pipe system was connected to the roundabout, where three lagoons were formed within a 1.5-hectare green area. The lagoons receive stormwater from the highway, and after 24 hours, the stormwater is discharged into the city's combined sewage system. Although the soil becomes saturated during rainy periods and discharge into the underground is not possible, controlled discharge into the existing combined sewage system allows the stormwater to be additionally purified in the treatment plant.

Figure 6. City bypass under construction and after planting (Starum) [10]

Figure 7. City bypass after planting (Starum) [10]

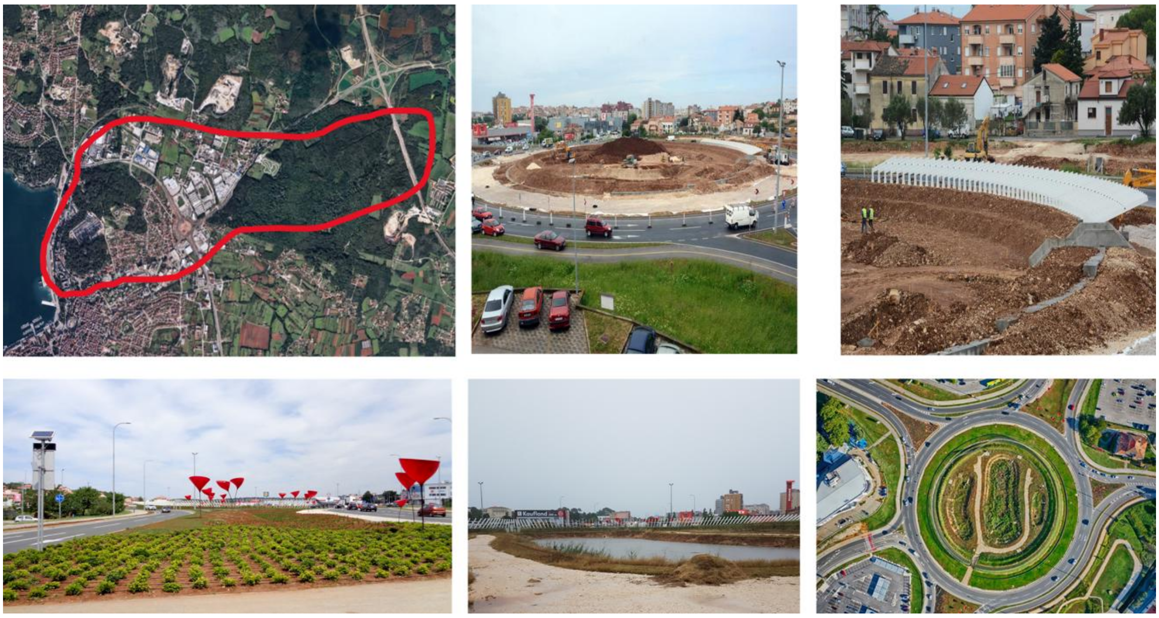

Figure 8. Constructed NbS of the Šijana basin, approximately 200 ha (Starum) [4]

These examples involved reconstruction of the existing network and introduction of NbS in the existing city sewage system, but it is also very important to take into account the introduction of NbS and blue-green infrastructure in the planning process.

3. BLUE-GREEN INFRASTRUCTURE OF THE MUNICIPALITY OF VELIKA

The Municipality of Velika is located in the Požega-Slavonia County, and the settlement of Velika has great potential for establishing a permanent green infrastructure network. Great potential for green infrastructure lies in connecting existing green areas, while the construction of front gardens, green roofs and green facades in building construction should be emphasized as significant possibilities for the development of green infrastructure.

In order for green infrastructure to be fully efficient, other steps need to be taken in urban areas to promote a healthy environment and people. These include: reducing noise, improving the (public) transport system, establishing a network of bicycle paths, and reducing and relocating polluting traffic away from residential and work areas, producing healthy food without pesticides, generating clean energy from renewable energy sources, recycling and reusing materials, products, buildings and spaces, using healthy materials, and environmentally friendly disposal of all hazardous materials. Also, the application of green infrastructure in the urban rehabilitation of unplanned and illegal construction, as well as degraded and neglected urban areas and public spaces, has great potential for improving the quality of these spaces and the environment, while also enhancing the quality of life of the entire population. An integrated approach to urban rehabilitation, among other things, with the application of green infrastructure elements, also includes comprehensive energy renovation, while respecting the principles of circular management of space and buildings.

The green urban renewal strategy is a strategic basis of importance for the Velika settlement, and is related to the achievement of green infrastructure development goals, integration of nature-based solutions, improvement of circular management of space and buildings, achievement of energy efficiency goals, adaptation to climate change, and strengthening of resilience to risks.

Within the framework of the concept of temporary use, abandoned and unused spaces and buildings can be activated by using green infrastructure elements such as, for example, public open spaces (public parks, urban gardens, children's playgrounds) and sports and recreation areas (adrenaline parks, theme parks, etc.).

The reason for developing the green urban renewal strategy lies in the context of current European and global practices, the transition to a carbon-neutral society with the preservation of natural resources, but also sustainable development, making the city more pleasant and healthier to live in, on the completely new economic foundations of the circular economy.

The strategy was developed in such a way that natural and anthropogenic effects on an area are equally valuable, and that the preservation of the natural environment is not an obstacle to development but an encouragement for sustainable development, and as such, the natural and already built environment is the basis for further sustainable development with the introduction of a circular economy as a way of life for current and future generations.

Blue-green infrastructure strengthens the urban ecosystem through natural processes in the human environment. Similarly, the circulation of water in nature is part of the natural hydrological process where water remains in the basin. In the case of gray infrastructure (roads, sewerage), the principle used in the conventional design is "as soon as possible" to take the pollution out of the settlement as soon as possible, especially through combined sewage systems, while in the case of blue-green infrastructure, the principle is to leave the water as long as possible in the catchment where it originated, using the principle "slow the flow", and return the water to the natural hydrological cycle, reuse it and as such it becomes part of the circular economy. This applies to both sanitary and storm water, as well as water used in municipal wastewater treatment plants.

In recent years, consideration of green infrastructure has shifted from ecology to economics. Resources such as rural areas, coastlines, wetlands, parks, street trees and their ecosystems are considered critical to sustainable economic growth and social goals, rather than just as a means of supporting the environment. There are many benefits of green infrastructure, and there are many ways in which it can support the success of other economic sectors, while offering improved environments, jobs, sustainable businesses, social benefits, economic security and cost savings. These savings include reduced healthcare needs, better employee productivity and better adaptation to climate change, and the economic value of the environment, not direct monetization.

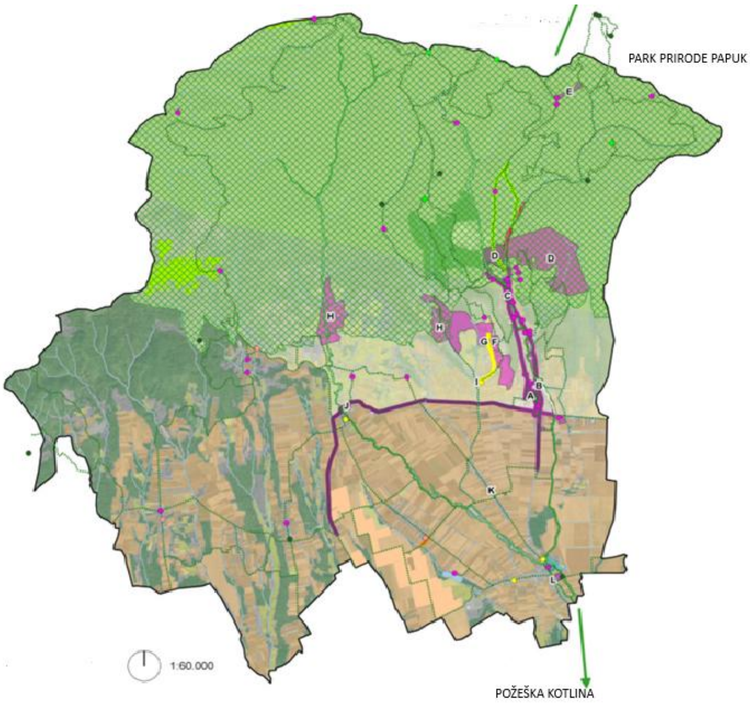

Figure 9. Blue-green infrastructure of the Municipality of Velika (Starum) [11]

3.1. Revitalization of the Veličanka stream

The Veličanka stream flows through the settlement, and untreated wastewater flows into the watercourse itself. Revitalization of the stream will give a new impetus to the development of the settlement, tourism and coexistence of people and nature in the same area. The very name Velika, derived from the toponym Veličanka, is indicative of the ancient connection between water and people in this area, and will represent a new beginning for the development of the Velika settlement.

In the revitalization of the Veličanka stream, it is planned to introduce NbS as a measure to implement this revitalization [4].

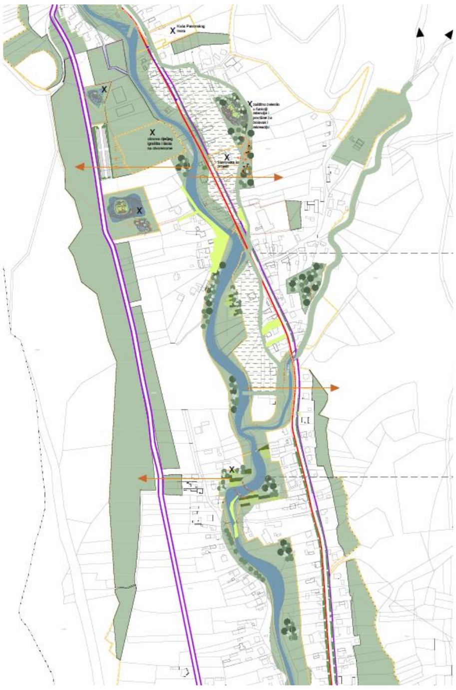

Figure 10. Revitalization of the Veličanka stream (Loodus Punkt, Starum) [12]

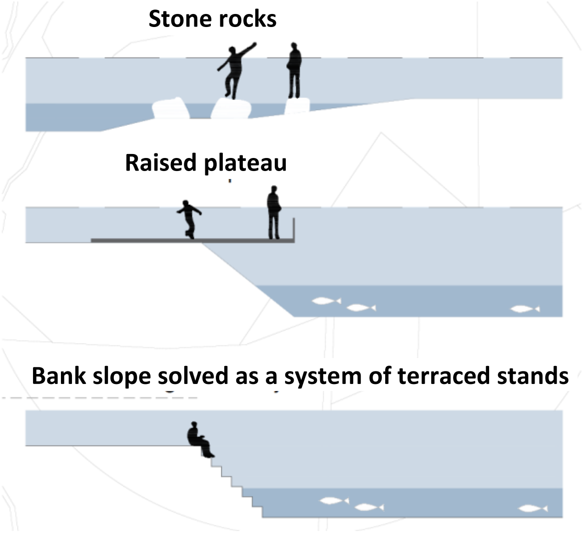

Figure 11. Revitalization of the Veličanka stream (Loodus Punkt, Starum) [12]

3.2. MAR (Managed Aquifer Recharge) systems as part of NbS on the example of the town of Vodnjan

The Vodnjan area is characterized by a typical karst environment with pronounced seasonality of water resources, where periods of heavy precipitation alternate with long dry periods. Such a hydrological regime results in significant losses of precipitation water through rapid runoff and infiltration without the possibility of its efficient storage for later use. At the same time, increased pressures of climate change, including rising temperatures and diminishing amounts of water available during the vegetation season, further emphasize the need for sustainable water resource management.

In this context, the concept of Managed Aquifer Recharge (MAR) represents one of the key solutions for increasing water availability and stabilizing the hydrological system. MAR systems enable the controlled introduction of water into the underground, thereby recharging aquifers, reducing seasonal fluctuations in groundwater levels, and ensuring long-term resilience to drought conditions.

Unlike natural infiltration, which is often rapid and uncontrolled in karst systems, the MAR approach involves technically managed processes that combine retention, filtration and gradual release of water into the soil. This has a dual effect: increasing the quantity of available groundwater, but at the same time improving its quality through natural purification processes in the soil and unsaturated zone.

The Vodnjan area is particularly suitable for the application of the MAR system due to the combination of geological, climatic and spatial conditions. Permeable carbonate layers enable infiltration, while the available retention surfaces and infiltration structures open up the possibility of implementing different system typologies, including infiltration basins, rain gardens, dry retentions and underground infiltration structures. At the same time, the integration of the MAR system with the nature-based solutions approach provides additional benefits, such as improving the microclimate, increasing biodiversity, and reducing the overall carbon footprint of the water management system.

3.2.1. Applied NbS as part of MAR

As part of the Interreg project Blue - Recharge [5], the construction of lagoons with extended retention, underground infiltration retentions and rain gardens is planned for urban catchments.

Retention of surface water on agricultural land is planned by the revitalization of puddles, renovation of dry stone walls and construction of contour embankments, with the application of forest reclamation.

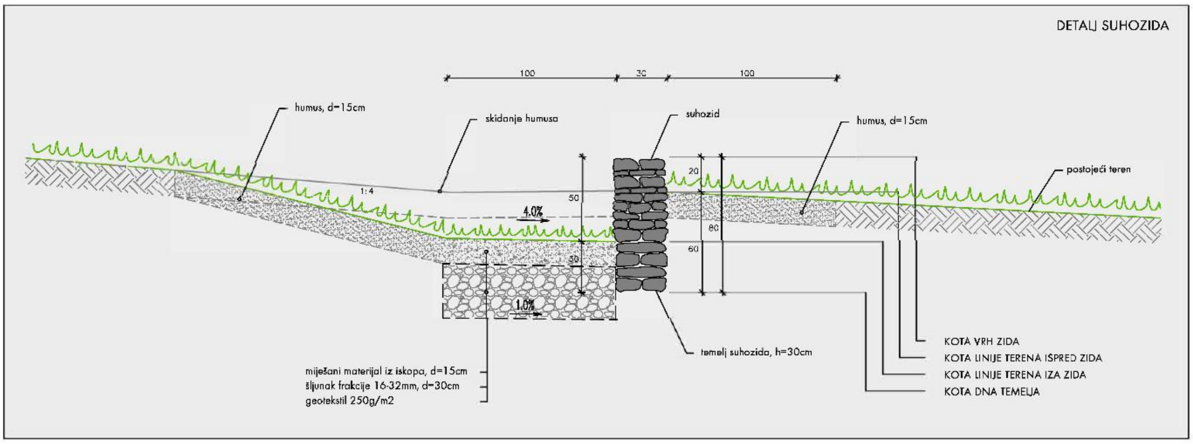

Figure 12. Dry stone wall renovation for the purpose of retaining surface rainwater (Starum) [13]

Figure 13. Freedom Square. NbS functioning as MAR (Starum) [13]

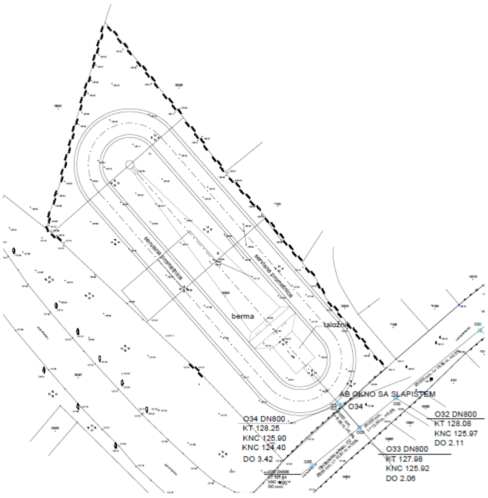

Figure 14. Extended retention lagoon functioning as MAR (Starum) [13]

The Vodnjan area forms part of a karst hydrogeological system, characterized by high permeability, fractured and cavernous structure, and exceptionally heterogeneous infiltration behavior. Under such conditions, natural infiltration of rainwater is often rapid and uncontrolled, with water passing through the soil without significant retention and purification. Managed groundwater recharge (MAR) in karst requires an adapted approach compared to non-karst areas. The key objective is not merely infiltration, but the controlled slowing of water flow, the extension of retention time, and the improvement of water quality before entering the aquifer. Therefore, the MAR systems in Vodnjan are regarded not as individual structures, but as a hybrid system of surface and underground elements that includes retention, filtration and infiltration in multiple phases.

The typology of the system depends on:

- geological structure (shallow/deep karst)
- depth of groundwater
- availability of space
- quality of incoming water
- purpose (irrigation, aquifer protection, landscape)

In this context, the optimal approach for Vodnjan involves a combination of several types of MAR systems, which together form a functional network and also achieve stormwater purification through a "treatment train" approach where several systems in series have the function of gradual treatment before discharge into the underground.

Figure 15. San Antonio Park functioning as MAR (Starum) [13]

4. CONCLUSION

Climate change, rapid urban development and increasing pressures on water resources require a fundamental transformation of the approach to urban water management. Conventional, centralized drainage systems have shown limitations regarding capacity, resilience, and long-term sustainability—

thereby opening up space for the application of nature-based solutions (NbS) as a key tool for modern urban development.

Practical examples, particularly from the City of Pula, clearly demonstrate that NbS can efficiently reduce hydraulic loads on the system, improve water quality, and significantly reduce the pollution load. In addition, their application enables the integration of technical, environmental, and landscape functions into a single system that contributes to the resilience of urban environments.

Blue-green infrastructure represents an evolution of the water management concept, from the approach of "draining water as quickly as possible" to the principle of "retaining, slowing down, and reusing water in the space where it is generated." In this way, water becomes a resource rather than a problem, thereby further strengthening the connection between urban systems and the natural hydrological cycle.

The integration of NbS into strategic planning, as demonstrated by the cases of the Municipality of Velika and the MAR system in Vodnjan, confirms that these solutions have a broader significance than drainage alone—they include water resource management, climate change adaptation, biodiversity enhancement, and the development of a circular economy.

In conclusion, nature-based solutions and blue-green infrastructure are not just an alternative approach, but a necessary direction for the development of urban systems. Their successful implementation requires an interdisciplinary approach, integration into spatial planning and a paradigm shift in which natural processes become the basis for technical solutions. In this context, NbS represents a key tool for building more resilient, sustainable and high-quality urban spaces for future generations.

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