Ecohydrology for sustainable urban water management

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KEYWORDS

Ecohydrology, nature-based solutions, blue-green infrastructure, WBSRC

ABBREVIATIONS

ABRC – Abiotic Biotic Regulatory Concept (Zalewski and Naiman, 1985)

BGI – Blue-Green Infrastructure

CE – Circular Economy

CW – Constructed Wetland

HSBS – Hybrid Sequential Biofiltration System

NBS – Nature-Based Solutions

SSBS – Sequential Sedimentation Biofiltration System

WBSRC – Water, Biodiversity, ecosystem Services, Resilience, Culture and education (Zalewski, 2014)

WFD – Water Framework Directive

WWTP – Wastewater Treatment Plant

ABSTRACT

Water has been always a limiting and driving factor of natural processes and civilization development. Unsustainable urbanization is exerting pressure on drinking water supplies, sewage treatment, biodiversity and ecosystems quality and functioning, as also public health. Commonly present over-engineering and predominate impermeable surfaces in urban areas generate floods, water pollution, and reduce groundwater recharge, undermining the climate adaptation process. It has been recognized that the development and maintenance of urban ecosystem services must be supported with a holistic understanding of ecological and hydrological processes. Ecohydrology, a transdisciplinary, problem-solving science, elaborated under the scope of UNESCO International Hydrological Programme is providing a new paradigm in sustainable water management. Application of ecohydrology is gaining worldwide attention, therefore the aim of the article is to discuss the latest ecohydrology solutions in the context of urban water management for harmonization of grey and blue-green infrastructure.

1 INTRODUCTION

Our civilization has recently reached a historical point when half of global population have started living in the cities and this number is projected to reach 68% in 2050 (UN, 2019). Urban areas provide jobs, accessible healthcare and socio-cultural benefits and yet due to unsustainable growth, demographical pressure, mismanagement and impact of climate change, the prosperous future of our cities remain uncertain. Existing socio-economical gaps are deepening and realization of the Sustainable Development Goals will be undermined, if business-as-usual strategy continues. Over-engineering and dominant impermeable surfaces generate floods, water pollution, and reduces groundwater recharge. Urban aquatic reservoirs, due to high catchment to surface area ratios, and long water retention times are vulnerable to external stressors such as contaminants, resulting in the low biodiversity and low aesthetic value (Jurczak et al., 2012; López-Doval et al., 2017). Increased pollutants concentration in the urban catchments, results in the acute toxicity impacting the biotic components of the ecosystem (Szklarek et al., 2015; Urbaniak et al., 2016). Obliquely it stimulates excessive eutrophication process that leads to the toxic cyanobacterial blooms, harmful for human health and undermining the recreational value of urban reservoirs and declining biodiversity (Jurczak et al, 2012). Pollution from urban areas is also one of the reasons for not meeting the goals of European Water Framework Directive (Carvalho et al., 2019). The negative impact of urban hydrology modification has been even more visible recently, due to climate change (Miller and Hutchins, 2017; Flörke et al, 2018). As a consequence of unsustainable growth, pressure on groundwater resources arises (Grönwall et al., 2010; WWDR, 2019). Further consequences can be tremendous, with a spectrum of events ranging from elevated energy uptake and CO_2 emission to the negative influence on citizens' physical health and psychical wellbeing (Rook, 2013). Hence, the urban areas development have to be correlated with human-nature interplay. In many cities globally, local administrations fail at providing safe drinking water and sanitation systems, not to mention other ecosystem services (WWDR, 2019).

With growing pressure on aquatic resources, and their key meaning in climate mitigation and adaptation, our focus should be given to the water management practices and ecosystem services which depend on water. Urban water management has been addressed with the technical concepts, e.g. Low Impact Development (LID), Best Management Practice in Stormwater (BMP) or Sustainable Urban Drainage Systems (SUDS). Another approach reflects the ecological-based understanding of urban ecosystem, e.g. ecohydrology (Zalewski et al., 1997; Zalewski, 2000; 2011), blue-green infrastructure (BGI) (Gill et al., 2007) and blue-green network (BGN) (Zalewski et al., 2012; EC, 2013) and latest Nature Based Solutions (NBS) (WWDR 2018). Nevertheless, application can be challenging and not always meet the objectives. One of the main concerns associated with application of NBS is fact that they may not meet the high expectations of society and decision makers, partly due to the boundary conditions they operate in, and their target-driven application (Krauze and Wagner, 2019). To counteract, application of NBS should be based on the profound understanding of ecohydrological processes, since most of them relay on water availability and quality (Zalewski et al., 2003; Guswa et al., 2020). Moreover, development and maintenance of urban ecosystem services must be supported with holistic understanding of hydrological processes and ecosystem interplay from molecular to catchment scale. This challenge has been addressed by ecohydrology, founded under the scope of UNESCO International Hydrological Programme (UNESCO-IHP). Ecohydrology was developed based on the three fundamental principles (Zalewski, 2002; 2011; Zalewski et al. 1997):

1. Hydrological principle - quantification of the hydrological cycle and mapping the impacts is a first step towards understanding the evolutionary shaped processes in a catchment scale.
2. Ecological principle – considering the hydrological cycle specifics, analysis of ecological structure of the catchment is necessary to create a comprehensive plan for catchment management in terms of protection, rehabilitation and management.

3. Ecological Engineering principle - based on first two steps and understanding of their interconnection, regulation of hydrological and ecological processes leads us towards low-cost and high-efficient, NBS.

Founded on those principles, ecohydrology is able to provide tools for the regulation of water dynamics and quality through the management of water-biota interplay (Zalewski 2003). Moreover it becomes possible to integrate hydrotechnical measures (grey infrastructure) with NBS (green infrastructure) (Zalewski, 2014; Jurczak et al., 2018). Since the evolutionary perspective of ecohydrology is creating a space for a new ideas and strategies, some of them have emerged in recent years. In this paper, we will discuss latest in the context of sustainable urban water resources management. First one is related to the sustainable growth achievement, which is impossible without addressing 5 key parameters. Those elements are Water, Biodiversity, ecosystem Services, Resilience, Culture and education (WBSRC) (Zalewski 2014; Zalewski et al., 2018). The second approach has emerged based on the sustainable management of freshwater resources strategy proposed by Zalewski in 1996, where a core idea is “elimination of threats and amplification of opportunities”. This strategy has been reflected in the rationale and guidelines for the Implementation of the UNESCO-IHP-V in the document entitled *Ecohydrology – A new paradigm for the sustainable use of aquatic resources* (Zalewski et al., 1997) and it was a background for the new concept linking NBS with Circular Economy (CE) under the scope of ecohydrology (Zalewski et al., 2018).

2 METHODS

Ecohydrological approach for the sustainable urban water management has been addressed worldwide through the UNESCO-IHP ecohydrology demonstration projects (http://ecohydrology-ihp.org/demosites). One of the first demo sites was located in Łódź city, Poland which is located on the watershed divided to the Vistula and Odra Rivers, covering an area of 293 km^2. Eighteen small, heavily modified rivers flow through the city. Currently, 47% of the city’s area is covered by impervious surfaces, 10% is forested and only 0.5% is covered by surface water (Ratajczyk et al., 2017). Łódź was historically a textile industry leader, with rapid development dated on XIX and XX century. As could have been expected, due to this development and highly impacting character of textile manufacturing, river valleys were transformed into the sewage system. After the collapse of industry, the slow process of city revitalization has started. Following this call, city become a polygon for the urban ecohydrology development and implementation, thus it can serve as a case study for other cities, facing similar problems with water management worldwide.

Implementation of the ecohydrology-based idea for creation of sustainable city have started under the scope of SWITCH - *Sustainable Water management Improves Tomorrow`s Cities' Health project* (EU, 6 PF), and was later developed by LIFE project: *Ecohydrologic rehabilitation of recreational reservoirs in Upper Bzura Catchment as a model approach to rehabilitation of urban reservoirs* (LIFE08 ENV/PL/000517). Currently, with gained experience, ecohydrological concept of whole city adaptation to climate change is being implemented under the project: *Adaptation to Climate Change through sustainable water management in the city of Radom* (LIFE14CCA/PL/000101).

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3 RESULTS

3.1 Ecohydrology in sustainable urban water resources management

To understand the potential and limits of urban ecosystems, it is necessary to introduce the intermediate disturbance hypothesis, firstly introduced by Connell in 1978, when he argued that intermediate disturbances can stimulate biodiversity more effectively than low or high ones. This idea was further developed by the Zalewski and Naiman in 1985, when they proposed an abiotic-biotic regulatory concept (ABRC), based on integration of hydrological (e.g. expresses by Bernoulli law) and ecological processes (e.g. thermodynamic laws) as the determinants of energy flow and nutrient cycles in ecosystems. The results showed that when abiotic factors prevail, biodiversity structure is limited, however, when abiotic factors are stabilized, biotic ones become dominant and favours higher biodiversity. This idea was recently further developed in ecohydrology of urban area, where the patchy characteristic can be compared to a gradient of regulatory factors (abiotic vs. biotic ones). Then, city centre, usually dominated by grey infrastructure, represents a place where processes are dominated by abiotic factors (e.g. water stress, high temperature, space constrains), however, in low-urbanized areas, biotic regulation is dominating (Krauze and Wagner 2019). Traditional approach to wastewater and stormwater management in urban areas tend to favour a large-scale, centralized systems, where costs of development grows exponentially with urban sprawl. Such systems have never been sustainable due to three major reasons:

1. Provision of wastewater services is lacking in the poorest districts in global megacities. Grey infrastructure alone does not guarantee a high efficiency in pollutants removal and sanitation. As a consequence, decline of water quality can be observed.
2. Rainwater management has been neglected for last decades, by over-engineering of the urban system. In the face of climate change, expressed by drought and heavy rainfall periods intensification, rainwater becomes crucial in cities adaptation.
3. Urban landscape always represent a patchy character, with a gradient of blue-green and grey infrastructure.

Wastewater management can be approached with the concept of Decentralized Wastewater Treatment System (DEWATS) (Stefanakis et al., 2014, WWDR, 2019). By applying DEWATS, certain costs of wastewater carriage are reduced and since it is based on a hybrid systems, including Wastewater Treatment Plant (WWTP) and NBS, typically Constructed Wetlands (CW) the infrastructure and management costs are reduced too. Additionally, WWTPs do not always meet the requirements of the effluent quality, particularly in small and medium sized WWTPs (Kiedrzyńska et al., 2014). Recent studies demonstrated also a threat related to human health with antibiotic-resistant genes in relation to the WWTPs (Koniuszewska et al., 2020; Czatzkowska et al., 2020). To support the traditional WWTPs technology, application of ecohydrology-based NBS was proposed, with CWs (Stefanakis et al., 2014; Langergraber and Masi, 2017) and Hybrid Sequential Biofiltration System (HSBS) (Kiedrzyńska et al., 2017).

In terms of urban stormwater management, several strategies have been introduced and tested already (e.g. LID, BMB, BGI, NBS). As explained above, these strategies should be based on profound understanding of ecohydrological processes and hierarchy of driving factors. The functional incorporation of the ecohydrological processes into the urban water resources management was discussed by Wagner and Breil (2013). One of the living-case examples can be find in Łódź city, where ecohydrology projects have been implemented and tested (Fig. 1).

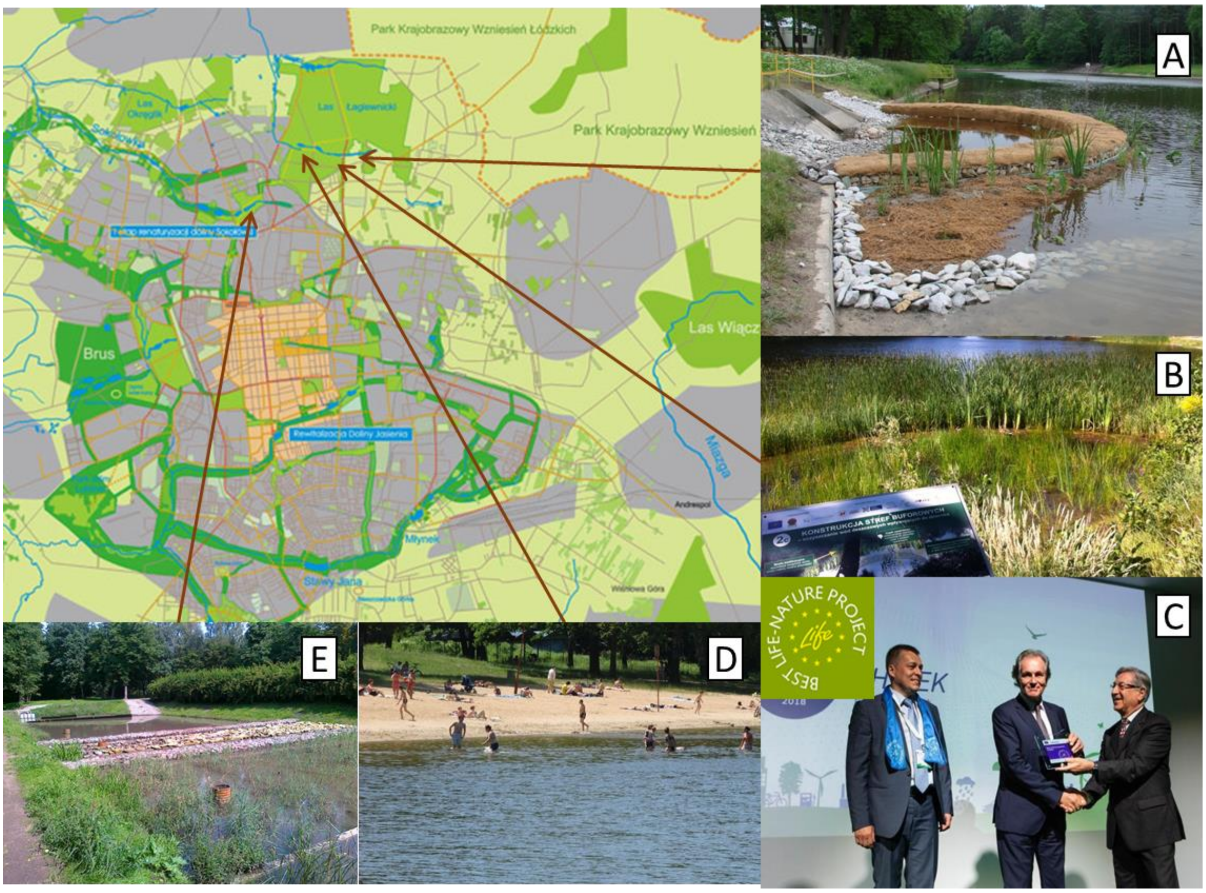

Fig. 1. The concept of Blue-Green Network (upper-left corner map) based on the ecohydrological processes, has been proposed for Łódź city as the outcome of SWITCH project. NBS have been implemented (A, E) and supported with education through stakeholder meetings, conferences and information boards (B). As one of the outcomes, water quality in recreational reservoirs have been improved, thus the ecosystem can provide valuable services for urban dwellers. Project EH-REK, which has followed the SWITCH, was awarded with Best of the Best LIFE-Environment Projects in 2018 by the European Commission (C).

3.2. Ecohydrology for the integration of Circular Economy and Nature Based Solutions

With growing carbon dioxide (CO_2) emission by 1% annually over the last decade (Jackson et al., 2019) and the same rate of water demand growth globally (WWDR, 2018) our civilization is continuing a collapse course. However, growing ecological consciousness and intergovernmental agencies efforts paved a way towards more optimistic future. As listed in the introduction, there are certain strategies in urban water resources management, that can be considered as sustainable. Yet, all of them have to meet the expectations of local societies, therefore, applied methods should address more goals than climate adaptation alone. Among ecosystem services, one can mention space regeneration, improved human well-being, economization of resource use, and stimulation of the CE and green growth (Krauze and Wanger 2019). Cost-efficiency of the NBS is becoming more discussed recently, particularly in the face of SARS-CoV-2 pandemic, when strategies as green economy or green recovery become compulsory (Barbier, 2020). These ideas are not novel, since the necessity of green economy to create jobs was already discussed and implemented (Pollin et al. 2008) with lesser or higher success, for instance after the great recession in 2008-2009 (Barbier, 2020). Yet, it has been recently adopted by the European Commission and is becoming structurally and politically supported, thus is getting more funds and opportunities (EU Green Deal, 2019). CE action plan proposed for Europe, under the scope of European Green Deal (EU, 2020) is forecasting a systemic and deep transition. Keeping the resource consumption within planetary boundaries, e.i. reducing the ecological footprint, is a first step of risk reduction, a part of successful aquatic resources management (Zalewski 1996, 2006; Zalewski et al., 1997). With this idea, a concept of NBS and CE utilization has emerged and was elucidated during an International Symposium on *Ecohydrology for the Circular economy and Nature-based solutions towards mitigation/adaptation to Climate change* organized in Łódź city in 2017 (Zalewski et al., 2018).

The integration potential between NBS and CE has been recently recognized, among others, in linking sanitation to energy and food security (Langergraber and Masi, 2017), greywater reuse for irrigation (Rozos et al., 2013) or green roofs used at providing purified rainwater for the non-consumers usage in the buildings (Naked et al., 2019). Identification of the potential areas of this connection is necessary for further implementation of both strategies in urban areas. One of the most recognizable NBS for water quality and quantity management are definitely CWs (Mitsch, 1992; Vymazal, 2007). Both natural and artificial wetlands play an important role in water self-purification, utilizing microbiological processes, plant metabolism and geochemical processes. One of their components, vegetation, can support maintaining urban river valley biodiversity, accumulate pollutants and provide an alternative source of energy (bioenergy) and help to reduce CO_2 emissions from fossil fuels. The obtained product of anaerobic digestion or direct combustion of biomass can later be used as fertilizer to achieve complete circularity. This kind of green economy generates new employment opportunities, thus the use of ecohydrology results not only in a good quality environment but also can help to boost the economic status and level of sustainable development in local communities (Zalewski, 2006; Banaszuk et al., 2020).

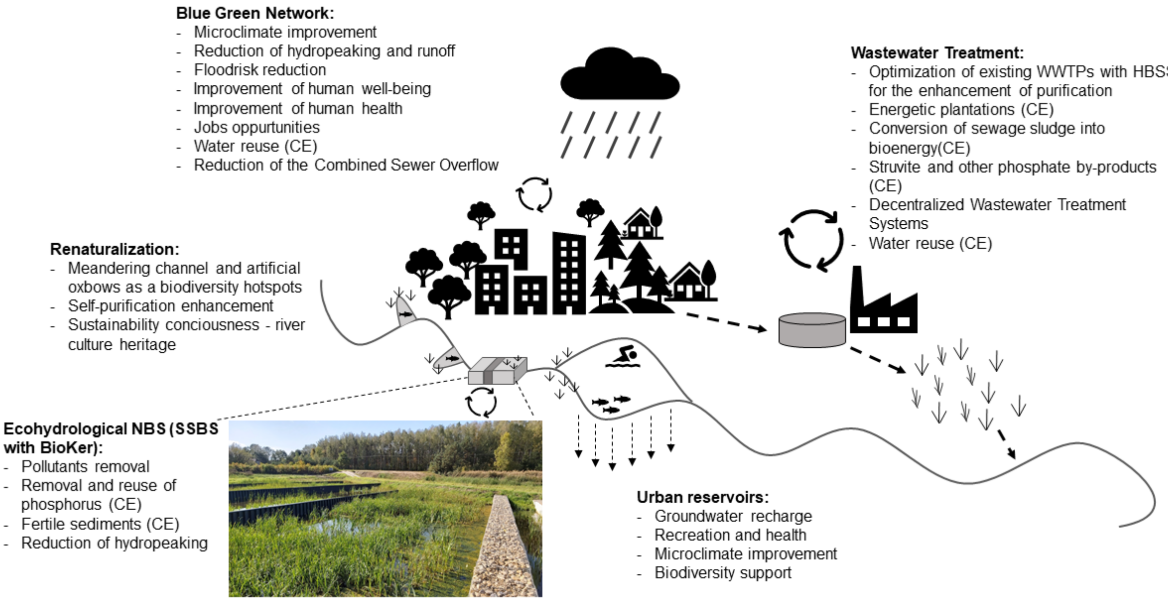

Fig. 2. Application of the Ecohydrology, NBS and CE for water resources management in the urban landscape. Several hotspots can be defined, as permeability of surfaces and ability to absorb water in sealed urban areas, restoration of river valleys, increase of self-purification, more efficient wastewater (including sludge) management adjusted to the economical status of the city (based on Wagner and Zalewski, 2009).

As one of the ecohydrological NBS, hybrid system (blue-green and grey infrastructure) has been implemented in Łódź. System consists of an underground separators combined with Sequential Sedimentation Biofiltration System (SSBS) for pollution removal. It can remove 86.0% of total suspended solids, 71.5% of total nitrogen and 66.7% of total phosphorous. In addition, the system was able to reduce the hydraulic stress and mitigated discharges for precipitation amounts less than 9 mm due to only limited capacity (Jurczak et al., 2018) and it provides cheaper solution than traditional (Jurczak et al., 2019). The removal of pollutants in CWs can undergo several pathways. For instance, denitrification, when fully completed in urban SSBS, can remove nitrates (NO_3) as they are transformed to the gaseous form (Nájera et al., 2020). However, labile form of phosphorus (P), represented by phosphates (PO_4), can contribute to the eutrophication of urban reservoirs, thus limiting their services (Jurczak et al., 2012). Technologies applied in CWs aim to adsorb the P on the substrate (Izydorczyk et al., 2013; Łożyńska et al., 2020) or transform into non-labile pool. On the same time, phosphate-containing rocks are non-renewable source and their availability is depleting (Van Vuuren et al., 2010) To sustainably remove and reuse P from aquatic resources, a new material was developed (Zalewski and Jarosiewicz, 2017). The BioKer is composed of a light expanded clay aggregates coated with biopolymer with fixed components. When entering the water it serves as adsorbent, ready for the contaminants reduction. Due to the applied biopolymer properties, after thermal processing, material can be uncoated, thus separation and reuse of the pollutant is possible. Idea was awarded a gold medal of the *International Exhibition of Inventions Concours Lepine* in Paris in 2018. Application of BioKer to the NBS is creating the next step towards better efficiency of ecohydrological solutions and is closing the gap between NBS and CE.

3.3. WBSRC concept for urban blue-green infrastructure development

In urban areas ecohydrological processes are often degraded to such extent that ecosystems conservation and restoration are doomed to failure. To approach these irreversible changes understanding of the abiotic-biotic processes should be incorporated and ecosystem carrying capacity increased. One of recent ecohydrology theories is postulating to consider this capacity through the five dimensions of WBSRC (Zalewski, 2015; Zalewski et al. 2018). These requires harmonization of the society needs with enhanced ecosystem potential and transdisciplinary approach.

Table 1. Application of ecohydrology in the urban catchment considered in the frames of WBSRC concept.

	WBSRC guideline for water resources management in the cities
W – Water	• Increasing of the city retentiveness (also referred as a sponge city concept) through water harvesting and retention • Recreation of the hydrological cycle through the ecohydrological processes • Protection of water quality and enhancement of resilience with NBS • Water recycling and reuse should be promoted and implemented on larger scale. • Infiltration of water as a strategy of groundwater replenishment
B – Biodiversity	• Aquatic and water-related ecosystems should be consider as a biodiversity refugia • Building the BGN as a system of ecological corridors and nature-protected areas • Protection of the aquatic ecosystems with NBS • Habitats re-creation, with a gradient of conditions that favours higher biodiversity • Increasing the gene pool through NBS and BGI • Wise and ecosystem-based vegetation management for biodiversity stimulation
S – ecosystem Services	• Blue-green ecosystems stimulate human immune system, reduce the stress and increase well-being (Rook, 2013) and reduce asthma and allergies in the children (Kupryś-Lipińska et al., 2009) • Microclimate regulation • Local reservoirs serves as a recreational places, making a low-cost alternative for holidays for the poorest urban dwellers • Increasing the air humidity. High humidity reduces the amount of particulates in air, one of a major causes of lungs damage in urban areas • Additional purification of the WWTPs effluent is supporting the water resources quality. CWs can serve as independent wastewater treatment

	facilities, however, they require more space, but on the same time they are using less energy, and provides other ecosystem services • Aesthetic value increase in urban area
R – Resilience	• By stabilizing the water pulses and providing enough space, urban communities (at the level of plants, fungi and bacteria) can gain more resilience to anthropogenic and climatic stress. • Management of BGI creates additional workplaces within the city, and on the same time generating positive feedbacks. • Circular Economy, enables to provide more green economy and reduce the ecological footprint of urban society. • Application of ecohydrology in the city means also the reduction of greenhouse gasses emission, through reduced air conditioning and temperature reduction in water reservoirs.
C – Cultural heritage and education	• Since the historical development of the cities is always related to the existence of water resources, protection, rehabilitation or management of aquatic ecosystems are a part of cultural heritage. • Building everlasting, resilient and durable environment is possible only when local societies are involved. • Since the application of ecohydrological solutions in urban areas are limited by local conditions, human-dominated, their existence and proper functioning depends mostly on the local society dedication. • Education of young generations is essential for a future maintenance of ecosystems.

Conclusions

With global water crisis the application of ecohydrology approach in urban areas, through strategies such as Blue-Green Infrastructure, Nature-Based Solutions and Circular Economy, can effectively mitigate the impact of climate change and simultaneously improve a variety of ecosystem services. Discussed above, recent ecohydrological strategies (e.i. WBSRC and CE+NBS) present a sustainable and evolutionary approach to the management of urban water-dependent ecosystems, taking into consideration both, social well-being and ecological potential. Recently adopted Fitness Check for the Water Framework Directive (https://cor.europa.eu/en/our-work/Pages/OpinionTimeline.aspx?opId=CDR-541-2020), have revealed the potential of ecohydrology, through the application of NBS, to achieve WFD objectives and protecting biodiversity. Ecohydrology is also rapidly developing worldwide with the endorsement of UNESCO-IHP where it has been established as one of six priority themes (2012-2021) with a focal area on urban ecohydrology. With recent developments in environmental sensing, data, and modelling the potential to drive further improvements in ecohydrological solutions is evident (Guswa et al., 2020). Latest concepts are further developed and optimized with new technologies (e.g. BioKer) that accelerate the integration of CE and NBS. With available technical and scientific resources, the implementation of new urban water management strategies in the framework of ecohydrology has acquired the necessary momentum. The next step is to create a framework of blended financial support and decision-makers interest towards the development of the sustainable cities of the future.

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