Nature-based Solutions for water risks resilience

Costanza Carbonari, Luca Solari

Abstract: Urban environments face increasing threats from a range of physical water risks, including flooding, water scarcity, and poor water quality, all exacerbated by climate change, rapid urbanization, and ecological degradation. Traditional water management has historically prioritized hydraulic risk, especially flooding, due to its immediate and visible impacts on lives, infrastructures, and economies. However, this narrow focus overlooks equally critical but less apparent threats such as drought and pollution, which pose long-term risks to human and ecological health. The concept of water security offers a broader framework, encompassing the availability, quality, and sustainability of water for people, ecosystems, and economies while addressing all water-related hazards. In this context, Nature-based Solutions (NbS) present a holistic and resilient approach, integrating ecological processes with engineered systems to manage water risks more sustainably. A shift from solely grey infrastructure to hybrid "blue-green" systems demonstrates how certain infrastructures, like multipurpose retention basins, can evolve into NbS, while others, such as centralized treatment facilities, may remain conventional. This blended paradigm enhances resilience by aligning risk reduction with environmental restoration. Emphasizing NbS within urban water management represents a necessary evolution toward comprehensive, adaptive, and sustainable responses to the growing complexity of global water challenges.

Keywords: Water-related risks, Risks mitigation, Integrating ecological approach in risk management.

1. Key concepts and different approaches in water management

Surface water bodies and ground water have been a key resource for human development since ancient times, but the relationship between man and this natural capital has changed over time passing from a use of resources without degrading the environmental integrity to an overexploitation together with depletion and ecological decline of natural capital because of anthropic stressors and anthropogenic climate change. The drive of progress and rapid population growth leading to unprecedented exploitation and ecological degradation of water resources applies to almost all types of water bodies, but it is particularly systematic and severe in rivers (Dudgeon et al. 2006, Dudgeon 2019, Harrison et al. 2018). Major anthropic pressures are present in urban and densely built as well as agricultural river basins where soil sealing, dams construction, dense infrastructure network and polluting land use practices have altered the river environment at the hydrological, morphological and ecological level, increasing flood risk and worsening physico-chemical water quality.

The traditional water management poorly addresses water scarcity and water quality issues and almost disregards the ecological status of riverine environments, being mainly focused on the mitigation of flood risk. Moreover, in this framework traditional hard engineering works and techniques have been widely adopted: grey detention basins for temporary storage of flood water; in-channel modifications to increase channel capacity and speed up water flow, such as channelization, dredging, diversion spillways; bank reinforcement such as levees to increase streams water-holding capacity.

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More recently, a comprehensive approach relying on multiple water risks reduction joined by the definition of targets to halt ecological degradation and biodiversity loss has been spreading. Indeed, at the European level the Water Framework Directive (European Parliament and Council of the European Union 2000) is an overarching regulatory tool with the goal of protecting and improving freshwater and wetland ecosystems (achievement of good ecological status), supporting a sustainable water use based on long-term protection of resources, mitigating floods and droughts effects. Also the Floods Directive (European Parliament and Council of the European Union 2007) couples flood mitigation and environmental goals by recommending Natural Water Retention Measures, NWRM, (Burek et al. 2012 European Commission 2014, European Commission et al. 2015). Both the Water Framework Directive and the Floods Directive enforce a river basin district approach in order to better address catchment-scale environmental issues and make the cooperation of neighbouring authorities more effective in facing transboundary river management. The set-up and goals of these directives definitely meet the efforts of the Nature Restoration Law (European Commission 2022) in recovering river connectivity and ecological functioning. Overall, this new green approach to water management can be implemented by adopting Nature-based Solutions, NbS, which both aim at mitigating water risks and halting, and possibly reversing, environmental degradation and biodiversity loss (International Union for the Conservation of Nature 2016 2020).

In the present contribution we illustrate water risks, their causes and their impacts (section 2); in particular, we analyse flood risk and the reasons why traditional water management mainly focuses on it overlooking other risks water-related (subsection 2.1); in the following we argue on the importance of moving beyond hydraulic risk in the perspective of adopting a water security approach (subsection 2.2). We then illustrate how NbS can represent an effective integration of conventional engineering works with ecological solutions (section 3), and within this framework we focus on some emblematic examples (subsection 3.1). We finally draw up conclusions and perspective remarks (section 4).

2. What are water risks and why they are exacerbated in urban settings

"Water risk" refers to the possibility of an entity, such as a community, a business, an ecosystem, experiencing a water-related challenge, this being for instance drought, water scarcity, water stress, flooding, infrastructure failure. The risk consists in the impact of an event, and, following the terminology by the United Nations (United Nations Office for Disaster Risk Reduction 2017), this impact is given by the combination of hazard, exposure and vulnerability: hazard is a process, phenomenon or human activity that may cause loss of life or health impacts, property damage, social and economic disruption or environmental degradation; exposure is the situation of people, housing, infrastructure, businesses and other tangible human assets located in hazard-prone areas; and vulnerability is the conditions determined by physical, social, economic and environmental factors that increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (United Nations Office for Disaster Risk Reduction 2017).

Water risks are many and are grouped in two main categories: physical water risks and regulatory water risks. The second class consists in changes in public policy or ineffective regulations that can impact water accessibility, availability, quality and management; regulatory water risks also include transboundary water management conflicts; in the present contribution we just provide the definition of regulatory water risks, but the in-depth discussion of this subject is outside of our scope. We rather aim at analysing physical water risks.

Physical water risks relate both to water quantity and quality and are strongly interconnected with one another (United Nations 2018): excess water quantity may lead to flooding, that depending on the source is generally distinguished in pluvial, fluvial and coastal flooding; insufficient water quantity to meet demand consists in water scarcity risk; poor quality is the risk of unfit water for use or habitats due to pollution (Figure 1). It is worth stressing that the concept of risk is defined and quantitatively assessed if all the three elements of hazard, exposure and vulnerability are present, clearly identified and quantified (this condition is graphically represented in Figure 1 through the intersection of the hazard, exposure and vulnerability elements). For instance, in case of a flood event (presence of hazard) if there is no human assets located in the flooded area (absence of exposure), there is no overall flood risk. Another illustrative example is the case of a drought taking place in a certain populated area (presence of both hazard and exposure), but if a successful water management strategy provides water supply and solutions in general that completely remove people's susceptibility to drought (absence of vulnerability), there is no overall water scarcity risk. It is therefore clear that water risks are exacerbated in urban areas because in cities the exposure is maximum, being densely populated and built, and in general characterized by the highest values of economic assets. Moreover, urbanization and dense population represent a factor that worsen the hazardousness of phenomena (both natural and anthropogenic) that may cause water risks: prevalence of impervious surfaces increases runoff and flooding, dense population raises water demand, industrial and domestic waste raise pollution. Finally, climate change has intensified extreme weather events, while in general, and in cities in particular, infrastructures for risk reduction and water management are designed for conditions prior to climate change, thus face difficulties in reducing impacts of unprecedented events with magnitude not previously experienced (Kreibich et al. 2022). Collectively, these factors increase the likelihood of both water scarcity and pollution-related health issues and ecological decline, as well as the risk of flooding and infrastructure damage.

2.1. Why traditional water management mainly focuses on the mitigation of hydraulic risk

Hydraulic risk refers to the potential for harm from excess quantity of water in various forms, including floods, landslides, and the consequences of malfunctioning water systems and infrastructures. Floods and flooding represent a primary aspect of hydraulic risk, where intense rainfall or sea-level rise causes rivers and channels to overflow, leading to inundation of land and structures. Hydraulic risk is the dominant focus in water risks because it directly relates to the destructive forces of water, leading to significant immediate and catastrophic damage, including widespread flooding, landslides, and the failure of critical infrastructure like dams, bridges and other hydraulic structures. Unlike other water-related risks, hydraulic risk emphasizes the physical impact and danger posed by excessive or uncontrolled water, which can cause high numbers of casualties and widespread socioeconomic disruption, as seen in major flood events. Indeed, hydraulic risk, and in particular flood risk, is treated as predominant with respect to other water risks mainly because resulting impacts are especially evident and clearly identifiable above all when subject exposed to flood hazard are people and human assets in densely populated areas. In other words, what makes flood risk the most considered among water risks is the high socioeconomic impact with widespread and direct threat to life and property and the catastrophic potential (e.g. dam and levee

Fig. 1 – Physical water risks (central box), their causes (left box) and their impacts (right box). Risk assessment is given by the combination of hazard, exposure and vulnerability; risk assessment allows for the quantification of impacts.

failure leading to sudden, uncontrolled release of large amounts of water, creating immediate and devastating consequences) that configure it as a disaster risk. Finally, flood risk assessment is generally "easier" with respect to the assessment of other water risks, in particular those related to poor water quality, since frequency and magnitude of floods can be unambiguously determined as well as exposure and vulnerability (Grey and Sadoff 2007).

Secondly, also droughts are disasters that can be assessed through the "hazard times exposure times vulnerability" procedure almost as easily as flood risk, and also frequency and intensity of droughts can be determined through time series, even though there is the same difficulty found for floods dealing with unprecedented extreme events due to climate change (Kreibich et al. 2022). Conversely, the assessment of ecological risk due to poor water quality is scarcely integrated in water management and ecological disasters are overlooked. This insufficient consideration is probably driven by several reasons among which greater difficulty in identifying frequency and intensity of hazardous processes, and indirect impacts on people. The underestimation of ecological risks in water management is further analysed in the following section within the wider framework of water security.

2.1. Moving beyond hydraulic risk towards water security

An integrated water management needs a more comprehensive evaluation of water risks beyond hydraulic risk, and in particular ecological risk requires more consideration. A first reason contributing to an insufficient integration of ecological risks in water management is that ecological degradation has apparently less direct effects on people, even if it severely impacts people through decline and disruption of ecosystem services. Moreover, the exposure assessment traditionally focuses almost exclusively on people and human assets directly exposed to hazard, and usually ecosystems are not sufficiently included in the exposure evaluation. In addition, also hazard assessment is generally complex, and frequency and magnitude of hazardous processes are not always possible to determine, for instance in case of continuous water quality decline due to diffuse and continuous pollution, and in case of resulting continuous impoverishment of local diversity in terms of taxa richness and functionality. Overall, therefore, the traditional risk assessment by means of the "hazard times exposure times vulnerability" evaluation suits well for floods and droughts, but may not suit other water risks for which is reductive or may be more difficult to apply (Grey and Sadoff 2007, Hall and Borgomeo 2013).

A second issue that contributes to an underestimation of ecological risk is that it seemingly appears less catastrophic with respect to other disasters such as intense floods and droughts. However, also ecological disasters exist, and among them the current mass extinction of species caused exclusively by human activities is particularly severe. Indeed, it represents an unprecedented loss with extinction rates currently over one thousand times the natural "background" rate, and even accelerating (Pievani 2014). Pievani (2014), among others, argues that mass extinction happening in the Anthropocene is not just an environmental problem for nature; it is an existential threat to humanity because it dismantles the natural systems that make human life possible. Actually, it is a major threat to humans because it destroys the ecosystem services we depend on, such as clean air and water, pollination for crops, and soil fertility. The loss of biodiversity makes ecosystems less efficient and stable, leading to more extreme weather, a decline in food and water security (e.g. from pollinator loss, from soil and water impoverishment of purifying microorganism communities), and increased risk of zoonotic diseases, ultimately undermining human survival and well-being.

An integrated water resources management needs therefore the widespread adoption of the water security concept, which is a complex and broader framework encompassing acceptable quantity and quality of water for health, livelihoods, ecosystems and production, and acceptable levels of water-related risks to people, environments and economies (Grey and Sadoff 2007). In particular, with respect to traditional water risks management the water security approach adopts a wider formalization of risks definition (Hall and Borgomeo 2013) also better considering the ecological status of aquatic ecosystems, for instance valuing attributes such as the frequency of violating water quality standards and the counts of aquatic species (Hall and Borgomeo 2013). Conceptions of water security integrate the protection of natural water resources with societal efforts to meet human needs, recognize trade-offs and synergies across interconnected systems, and support transitions from negative to positive tipping points (Scheffran 2025). Water security implies a holistic approach, namely a comprehensive strategy addressing the interconnectedness of different water-related hazards and vulnerabilities, as well as ecosystem services. This approach can be successfully implemented in practice through Nature-based Solution, an analysis of which is provided in the following section.

3. Grey + Blue-green infrastructures, a new paradigm for water risks resilience

Nature-based Solutions for water management are described as actions within the blue-green infrastructure - organized networks of natural and modified green areas and water bodies across a variety of landscapes - (Krauze and Wagner 2019) or even synonym of blue-green infrastructures (Santiago Fink 2016); this discrepancy notwithstanding, there is general consensus in the scientific community that blue-green infrastructures should be formally classified as "critical infrastructure" and overseen by the same national and international laws and operational regulations (Wagner 2022). Wagner (2022) argues that most authorities consider "critical infrastructures" a top priority. By contrast, national and local governments are frustratingly slow to adopt blue-green infrastructure, even though it may largely contribute to climate adaptation by buffering hydrometeorological extremes such as floods, droughts and heat waves.

In urban settings where water risks are exacerbated and ecological degradation is particularly severe, blue-green infrastructure represents the backbone of ecosystem restoration interventions and Nature-based Solutions (Frantzeskaki et al 2019, Krauze and Wagner 2019, Wagner and Breil 2013). However, the implementation of NbS alone to reverse severely altered hydrological cycle and extreme ecological decline typical of urban areas is unrealistic. For instance, a channelized stream enclosed by a concrete shell with very low water quality because directly receiving contaminated waters from domestic waste and urban runoff can not sufficiently improve through restoration interventions and riverscape NbS such as depaving, connectivity and riparian vegetation restoration (Carbonari and Solari 2025). A traditional treatment of waste waters is also needed. In this case, as in many others such as piped drainage systems interspersed with bio-swales and SuDS ponds, residential developments with sunken rain gardens, buildings with green and blue roofs, the "blue-green + grey infrastructure" turns out to be the most effective, and due to its efficacy for water risks resilience it is becoming increasingly common (Li et al. 2023); within this framework, NbS represent the pathway to integrating conventional engineering structures with ecological solutions.

3.1. Some water management infrastructures can effectively integrate or be transformed into NbS and some other can not

The acknowledgement of the effectiveness of integrating blue-green infrastructures with grey ones for water risks management (Li et al. 2023) is the first step, then very careful consideration is needed in order to determine if an integrated design of new works or the design of retrofitting projects can achieve water management infrastructures that affectively include NbS. Actually, both the following issues are quite diffused: a certain resistance among local authorities and "traditional practitioners" in including more green, ecological and multipurpose solutions in conventional water management projects even if such innovation is feasible; on the other hand, above all subjects which are not in charge of practical applications tend to emphasize the use of NbS, in some cases overextending the range of applicability of such solutions with no sufficient attention to technical limitations. In the present section, we provide two emblematic examples: the first case illustrate multipurpose basins, which represent an example of infrastructure that actually can be implemented as NbS rather than traditional, grey solutions; the second example addresses constructed wetlands illustrating the limitations and ultimately the inapplicability in certain circumstances of the NbS for the treatment of waste water.

As an effective example of integrated green + grey solution we select the case of multipurpose basins: often artificial reservoirs are planned with the primary aim of fluvial flood mitigation but also designed in order to meet the community's needs for potable water, irrigation, energy as well as the ecosystems' requirement of improving ecological conditions. A first important ecological choice consists in preferring flood-mitigation basins as permanent waterbodies with increased, temporary water storage during flood attenuation, instead of dry detention basins flooded only during major floods. This choice provides a twofold ecological advantage: a valuable permanent wetland and the possibility of discharging water volumes from the reservoir to the river during lean periods. Moreover, vegetation can be included in the basin according to an integrated design; ecological flooding (i.e. flooding during events with minor return periods) can be easily supplied. It is obvious that an ecological implementation like ecological flooding requires the double of engineering works equipping the reservoir, for instance the spillway and the bottom outlet, but no technical impossibility prevents this choice. Overall, multipurpose basins can be designed and implemented (and retrofitted in case of grey structure conversion) as NbS since they answer several societal challenges, they can be designed according to ecological principles, but they also include indispensable engineering works such as mechanical devices and hydraulic structures.

The second example we select is that of Constructed Wetlands (CWs), a common Nature-based Solution for sustainable urban drainage consisting in engineered systems that mimic the function of natural wetlands to treat various type of contaminated waters through physical and biological processes. In all types of Constructed Wetlands, plants providing phytoremediation are always present and largely provide pollutants reduction before discharging water into natural water bodies or before aquifer recharge. Two main limitations are inherent to Constructed Wetlands compared to wastewater treatment plants (WWTPs), preventing CWs from achieving equivalent performance levels: i) CWs cannot provide the same consistent, high-quality treatment as WWTPs when subjected to a constant, high pollutant load (i.e. very large population equivalents), as they are less efficient in primary and secondary treatment; ii) for an equivalent pollutant load, CWs require a significantly larger land area than conventional plants, resulting in a lower overall "land use efficiency".

We finally want to point out that considerations similar to those illustrated for the two examples of this section must be carried out for each traditional engineering work for water management as well as for each SuDS and riverscape NbS; in any case when designing site-specific projects further insights about the above considerations are necessary taking into account local constraints.

4. Concluding remarks

NbS can represent a powerful tool to address water security challenges (such as water availability, flood risk, water quality aspects) also considering climate change which is typically increasing extreme events in both floods and droughts worldwide. NbS can, in some cases such as reservoirs and storage areas, be implemented in traditional engineering work for water management thus potentially providing relevant societal benefits.

While NbS can improve water risks resilience in urban settings, their functions in case of both extreme water events (floods and droughts), due to the lack of field evidence, can be uncertain; therefore, some caution needs to be paid in their design to avoid trade-offs or bad practices (Penning et al. 2025). Additionally, monitoring the effects of NbS on proper environmental indicators (related to both water quantity and quality) at various temporal scales is crucial to derive quantitative evaluations of their benefits and impacts.

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