Nature-based Solutions for water management

Costanza Carbonari, Giulio Hasanaj

Abstract: Within the approach "working with nature", Nature-based Solutions (NbS) for water management collect the set of actions, items and management measures aiming at reducing water-related risks, namely flooding, water scarcity and poor water quality, as well as preserving and restoring river ecosystems and creating new wet ecosystems. The more important ecosystem services provided by Nature-based Solutions for water management are definitely regulating ecosystem services such as flood mitigation, water purification and climate resilience, but also provisioning, supporting and cultural services are delivered, examples of which are, respectively, water availability, nutrient cycle support, aesthetic and recreational services. Nature-based Solutions for water management include both NbS pertaining to the riverscape, i.e. having a functional connection to the river and located in open spaces contiguous to the river, and NbS for sustainable urban drainage, which generally are not functionally connected nor contiguous to surface water bodies. Riverscape NbS include interventions for fluvial flood mitigation, riverbank erosion control and reduction of pollutant inputs into streams. NbS for sustainable urban drainage are those natural water retention and infiltration measures aiming at reducing pluvial flooding, increasing water storage and improving water quality.

Keywords: Natural water retention measures, Riverscape, Wetlands, Sustainable Urban Drainage System.

NbS for water management can at once enhance ecosystem services and ecological functioning

Nature-based Solutions (NbS) for water management are actions to protect, sustainably manage, and restore natural and modified ecosystems specifically addressing the challenge of improving water quantity and quality in an adaptive way, simultaneously benefiting people and nature (International Union for the Conservation of Nature 2016, European Commission and Tom Wild 2020). With regard to water quantity, we refer to the variability of water resources with resulting impacts on people and the anthropic and natural environment. In other words, this is the risk related both to excess water quantity resulting in floods and to water scarcity with possible droughts (United Nations 2018). Such hydrological-hydraulic variability includes both natural variability due to seasonal fluctuations in precipitation and the resulting river flows, and variability caused by anthropogenic factors such as climate change and land use change, which are responsible for exacerbating the frequency and intensity of extreme events. With regard to water quality, we refer to pollution and degradation of aquatic ecosystems losing their natural ability of purification. Water pollution is mainly due to agricultural and urban land use resulting in contaminants flows to water bodies, which thus receive nutrients, chemicals, heavy metals and even pathogens. Pollutants reach water bodies vehiculated by the water phase of runoff but also by the solid phase consisting of sediments and solid waste. It is important to emphasize that water availability -particularly scarcity- and water quality are closely linked. For example, improving water quality enables its reuse. Another example: changes in precipitation and streamflow, which reduce water quantity, directly lead to a decline

Costanza Carbonari, University of Florence, Italy, costanza.carbonari@unifi.it, 0000-0002-8681-0009
Giulio Hasanaj, University of Florence, Italy, giulio.hasanaj@unifi.it, 0000-0003-0069-3292

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in water quality (due to higher concentrations of pollutants); the resulting lower water quality levels turn out to be a form of scarcity themselves, as the water can no longer be directly used for many productive purposes (United Nations 2018).

NbS mitigating such water risks, and NbS in general, also aim at reversing environmental degradation and biodiversity loss (International Union for the Conservation of Nature 2020), hence, together with improving water management, they have to achieve a certain degree of ecological restoration, also specifically addressed and required by national and European regulation (European Commission 2022, European Parliament and Council of the European Union 2000, Ministero dell'Ambiente e della Sicurezza Energetica n.d.). Actually, biodiversity enhancement is both an NbS' goal in itself and a way to improve ecosystem functioning and services, by making ecosystems more resilient.

NbS for water management can also be labelled Natural Water Retention Measures, NWRM, these being a wide set of actions and land use types for the protection and enhancement of water retention capacity of aquifers, soil, and ecosystems with a view to improving their status. NWRM have the potential to provide multiple benefits, including the reduction of risk of floods and droughts, water quality improvement, groundwater recharge and habitat improvement (Burek et al. 2012, European Commission 2014, European Commission et al. 2015). NWRM are many and multifaceted, so various and numerous that are usually sorted per sector: hydro-morphology, urban, forest, agriculture; for a complete catalogue the reader is referred to the guide by European Commission et al. (2015).

The current contribution addresses some of the Nature-based Solutions part of the urban and hydro-morphology sectors, in particular those related to water storage and wetlands and those more directly related to surface water bodies. In the present contribution we therefore analyse

1. NbS pertaining to the riverscape, namely those NbS having a functional connection to the river and implemented in open spaces contiguous and associated to the river (Carbonari and Solari 2025); given the capillary presence of the hydrographic network on the territory, riverscape NbS can stand in urban, peri-urban and rural settings;
2. Sustainable Drainage Systems, SuDS, which are Nature-based Solutions for the regulation of the urban water cycle and are not functionally connected to rivers (Li et al. 2023).

Riverscape Nature-based Solutions

In the past -and still today in contexts where traditional urban water management planning prevails- hydraulic risk from fluvial flooding is mitigated primarily through grey infrastructure, meaning conventional structures based solely on engineering approaches. According to these approaches, flood risk is reduced, for example, by protecting urban centers with levees, diverting peak flood volumes through spillway channels to prevent critical water levels, or temporarily storing such volumes in reservoirs. These structural works can be implemented purely as grey infrastructure, but when they are part of an integrated approach that includes ecological solutions and nature-based engineering, they become components of Nature-based Solutions for flood risk mitigation and for regulating hydrological and hydraulic variability (Frantzeskaki et al. 2019). In fact, within the context of flood risk mitigation, the combined "Green + Grey infrastructure" approach is increasingly common due to its effectiveness, and NbS represent the pathway to integrating conventional engineering structures with ecological solutions. The NbS described in this section represent Natural Water Retention Measures for which it is also possible to simulate the reduction of flood peaks based on the size of the catchment and the magnitude of the flood event (Burek et al. 2012). The measures here described can, not only attenuate floods, but also store water to contrast water scarcity and increase the riverscape capacity to retain water and mitigate low flows during dry weather. Finally, riverscape NbS can significantly improve water quality through phytoremediation and vegetation filtering of runoff with its pollutant load, and through stream bed and banks' substrate reactivation with resulting enhanced microbial processes.

With regard to ecological restoration of riverscape Nature-based Solutions, biodiversity improvement for these interventions present a great potential since ecotones across aquatic and terrestrial ecosystems have a great habitat heterogeneity which is a primary support to biological diversity (Rosenzweig 1995, Chester and Robson 2013). Furthermore, rivers and channels are ecological corridors connecting different landscapes with different degrees of natural capital: for instance, the good status of ecological corridors between urban environments and more natural ecosystems represent the way urban systems can benefit from outskirt greenery.

Sustainable Drainage Systems

Grey infrastructure interventions (traditional engineering works lacking ecological solutions) aimed at retaining urban surface runoff, facilitating its infiltration into the soil, and potentially enabling water reuse, have long been practiced. These interventions seek to rebalance the altered urban hydrological cycle by increasing soil permeability and mitigating the problem of inadequate sewer networks. Examples of grey infrastructure with these objectives include drainage solutions such as permeable pavements and storage solutions like cisterns, as well as interventions to eliminate Inflow and Infiltration and to separate stormwater from wastewater. However, it has been shown that the most effective water retention in urban catchments is achieved by combining traditional storage and drainage systems with Sustainable Drainage Systems, specific NbS consisting of environmentally sustainable urban drainage solutions (Pampaloni 2022). Notably, "sponge cities" are urban plans based on the integration of grey infrastructure and SuDS for the management of stormwater flooding, effectively absorbing and reusing rainwater (Li et al. 2023).

The ecosystem services provided by SuDS go beyond mitigating the risk of pluvial flooding: the collection and reuse of rainwater help to alleviate drought and water scarcity; the vegetation in SuDS further restores the altered urban hydrological cycle by promoting infiltration and evapotranspiration; the vegetation in wetlands created through many SuDS allows for phytoremediation and microbial decomposition of organic carbon and phosphorus and nitrogen compounds. Indeed, special attention should be given to the capacity of SuDS to improve water quality by removing nutrients (carbon, phosphorus, and nitrogen) as well as solid particulates such as fine dust present in the atmosphere and on road surfaces. These pollutants, carried by rainwater, are intercepted by the wetlands of SuDS and purified and broken down by the plant and bacterial communities of the wetland ecosystem; SuDS thus serve as effective "traps" for nutrients and particulates (Tsatsou et al. 2023). An extensive network of SuDS can significantly reduce the flow of nutrients into surface water bodies, thereby alleviating eutrophication issues in inland waters -common in heavily urbanized areas. Ultimately, these nutrient traps help reduce the degradation of aquatic ecosystems in surface water bodies, since these bodies receive water from SuDS after it has undergone a genuine purification process.

With regard to ecological restoration, SuDS can have a relevant potential in supporting biodiversity because they represent wetlands providing significant habitats' structural heterogeneity, both abiotic and biotic. This heterogeneity is further enhanced by the fact that wetlands have ecotones across aquatic and terrestrial ecosystems (Rosenzweig 1995, Monberg et al. 2018).

Flood mitigation basins

Section A – General Description

Fig. 1 – Flood mitigation basin of the Secchia River with integrated implementation of vegetation. Basin in Rubiera, Reggio Emilia, Italy.

Description

Flood-mitigation basins are among those structural measures aiming at the mitigation of fluvial flood risk. They are reservoirs designed to temporarily store flood volumes upstream of the section of interest (the section of the watercourse where areas to be protected from river flood risk are located) and release them more slowly than they appear in the natural flood wave (Figure 1). Flood mitigation basins are differentiated in "more artificial" basins labelled flood expansion tanks and "partially natural" reservoirs: expansion tanks are areas enclosed by levees (representing the perimeter of the basins themselves), while "partially natural" reservoirs are established in areas along the watercourse that, due to their natural morphological characteristics, can store significant volumes of water. In particular, areas for the implementation of "partially natural" flood-mitigation basins are selected between the river and riverine plains and meet the principle of geomorphological and hydrodynamic consistency between the area itself and the watercourse. An example that effectively illustrates this concept is the attenuation areas created in the abandoned meanders of rivers (Burek et al. 2012, Rijke et al. 2012). The use of natural depressions to store flood volumes allows a reduced implementation of artificial levees. In general, all types of flood mitigation basins, unlike traditional, grey structures based solely on engineering approaches, can represent valuable NbS if implemented according to ecological approaches. Indeed, artificial reservoirs for flood risk prevention can be designed as multipurpose basins to fulfil the community's needs for potable water, energy, irrigation, and basins' optimal siting according to all these goals can be achieved through participatory multi-criteria decision-making (Masi et al. 2024); vegetation can be included in the basin according to an integrated design; ecological flooding can be easily supplied (Schmitt et al. 2009) as well as river ecological flows. Afforestation and the assurance of providing basins' ecological flooding and rivers' ecological flows can effectively support wetland ecosystems established by the artificial basin and the protection of the riverine ecosystem. Finally, a typical ecological design of flood-mitigation basins provides for permanent waterbodies with increased, temporary water storage during flood attenuation (Gerner et al. 2018).

Synonyms

Flood restoration; flood retention basins.

Section B – Technical details

A flood-mitigation basin is primarily a hydraulic structure that requires specific hydraulic design and planning. In the Italian framework, the design of the attenuation basin is the responsibility of the Consorzio di Bonifica (in agreement with the Region and the Municipality), as it is part of the extraordinary maintenance activities on the hydrographic network. The flood mitigation basin is generally a large-scale structure so that the reservoir can significantly reduce hydraulic risk. However, the primary criterion regarding the dimensions of the structure is the geomorphology and topography of the landscape. Two types of flood-mitigations basins exist: in-line reservoirs, in which flood water enters the basin along the watercourse and for which it is necessary a dam within the watercourse and transversal to the flow direction; and side-channel reservoirs in which flood water enters the basin through a lateral spillway on the watercourse or a lateral diversion channel. Moreover, the retention area must be equipped with several engineering works such as:

- Spillway: This is the intake structure that allows the diversion of flows arriving at the basin during flood retention. It is usually made up of a fixed structure (with a straight-lined spillway crest) which may or may not be equipped by gates.
- Bottom outlet: equipped by a gate to be open when the flow in the riverbed drops below the maximum acceptable level downstream.
- Descent ramp: For access by maintenance or repair vehicles.
- Safety overflow or emergency spillway.
- Perimeter embankments/levees: For containment (not necessary if it is possible to use exclusively the natural depression of the landscape).

In addition to the construction of works for the hydraulic functioning of the basin, the design and placement of vegetation must also be planned (in agreement with hydraulic designers to avoid loss of functionality of hydraulic structures).

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas

Flood-mitigation basins definitely increase the connectivity of natural areas being “partially natural” reservoirs as they are established in areas along the watercourse that, due to their natural morphological characteristics, can store significant volumes of water. Such zones, selected between the river and riverine plains, meet the principle of geomorphological and hydrodynamic consistency between the area itself and the watercourse. The use of natural depressions to store flood volumes allows a reduced implementation of artificial levees (thus more natural basins with respect to expansion tanks). However, also attenuation basins enclosed by artificial embankments are directly connected to the river, thus they definitely improve the connectivity of natural areas reconnecting the river to a reclaimed part of floodplain.

Increased diversity of habitats

An ecological design of flood-mitigation basins usually provides for permanent waterbodies whit increased, temporary water storage during flood attenuation, therefore such basins represent valuable Nature-based Solutions for the recovery and improvement of wetland, riparian and aquatic ecosystems in riverine environment (Burek et al. 2012, Gerner et al. 2018). Indeed, permanent water bodies with varying water level offer a variety of habitats mainly located in the transitional zone between the aquatic and terrestrial domain. Moreover, vegetation can be included in the basin according to an integrated design, and ecological flooding (i.e. planned flooding also for relatively small and frequent floods) can be easily supplied (Schmitt et al. 2009); both measures can effectively support wetland ecosystems established by the artificial basin.

Water management

Increased surface water storage and/or groundwater recharge

Flood mitigation basins definitely increase surface water storage being permanent or temporary surface water bodies whose main objective is the temporary storage of excess flood volumes, and secondarily directly stores rain water. In case of permanent water bodies (with increased temporary water storage during flood attenuation), and in case of basins releasing flood volumes to water course after long detention time, groundwater recharge is also enhanced (European Commission 2014).

Climate resilience

Improved microclimatic mitigation capacity

Flood-mitigation basins are among those structural measures aiming at the mitigation of fluvial flood risk. They are reservoirs designed to temporarily store flood volumes upstream of the section of the watercourse where areas to be protected from river flood risk are located and release them more slowly than they appear in the natural flood wave. These basins are therefore primarily built to reduce area adversely impacted by the natural disaster consisting in fluvial flooding, this natural phenomenon being often exacerbated by extreme events due to climate change. Flood mitigation basins ultimately mitigate at the local scale hazardous flood events made more severe by climate change.

Removed carbon via storage in vegetation, soil biogenic reefs

Flood mitigation basins with an integrated ecological design including vegetation implementation remove carbon through vegetation storage. Plants capture and store atmospheric carbon dioxide as well as organic carbon compounds contained both in water and soil. In particular, those flood mitigation basins designed as permanent water bodies (with increased water volume during flood events) better act as carbon sink through an effective carbon stock in sediments: organic matter from dead organisms and washed-in plant material sinks to the bottom and becomes buried in the sediment layer (Gerner et al. 2018). Organic carbon becomes trapped in the sediment, preventing the carbon from being released back into the atmosphere as a gas. Over long periods, the basins conceived as permanent water bodies can accumulate vast amounts of carbon in their sediments, acting as a long-term carbon reservoir.

Health, well-being and air quality

Improved mental health and reduced chronic stress

Flood mitigation basins enhance the recreational and aesthetic value of public spaces by providing visually appealing landscapes, offering opportunities for recreational activities, and contributing to a more pleasant landscape. They can be implemented integrating forestation along the basin shore line or in general where it is possible (i.e. avoiding interferences with hydraulic substructure of the artificial basin such as flow intake and spillover) and they can be integrated into parks and other recreational areas, adding to the overall quality of life for residents. The enhanced visual appeal of such basins stems from the presence of the water body, preferably permanent. A good implementation should include complex shorelines, featuring diverse emergent plants and presenting a naturalistic design. When integrated in public places on extensive areas, artificial basins support various recreational activities such as walking, birdwatching, picnicking, and even fishing in some cases. This provides opportunities for people to connect with nature and enjoy outdoor activities (Rijke et al. 2012, European Commission 2014).

River banks and terraces connectivity restoration

Section A – General Description

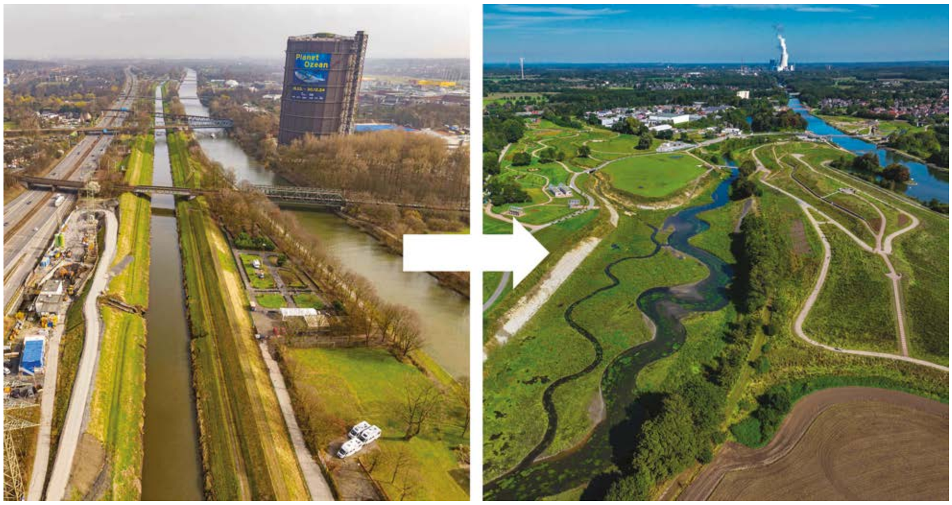

Fig. 2 – River banks and terraces connectivity restoration. Comparison between unrestored (left) and restored (right) channel's reach in the Emscher catchment in Oberhausen (left) and in Castrop-Rauxel (right), North Rhine-Westphalia, Germany. The restored reach presents restored natural sinuosity and secondary channels, larger channel sections, floodplain reconnection, presence of vegetation. Photo source: Emschergenossenchaft and Lippeverband; photo credit: Andreas Fritsche (left picture), Rupert Oberhäuser (right picture).

Description

The restoration of river banks and terraces connectivity is the recovery of the lateral connectivity between the main river channel and its banks and terraces (Figure 2), namely those landforms consisting in elongated bench-like landforms parallel and above the river channel and below the outer floodplain and representing riparian reservoirs (they mitigate flood waves by temporarily stocking flood volumes). River terraces sensu stricto are the natural landforms formed by erosion and deposition cycles and representing a former level of the floodplain, while here we intend terraces sensu lato, namely also including artificial riparian reservoirs consisting in flat-floored berms limited by levees or earthen embankments. In other words, here we address the connectivity recovery between the main active channel and river banks intended in a broad sense, namely including also the band of floodplain between the active channel and the embankments (O'Briain et al. 2024). Essential interventions in this field are the depaving and concrete removal in channelized streams (Gerner at al. 2018) allowing stream self-purification (denitrification and dephosphatation), plant colonization and habitat availability. In general, river-bank connectivity restoration aims at reshaping very channelized streams providing more natural sections and reaches, thus enabling biogeomorphological functions, among which flow patterns diversification and lateral sediment morphodynamics are of paramount importance for riparian environmental quality (del Tánago and de Jalón 2006).

Synonyms

Lateral connectivity restoration

Section B – Technical details

River banks and terraces connectivity restoration consists of morphological lateral connectivity restoration that first of all aims at reshaping very channelized streams providing wider and more natural cross-sections and reaches. Banks and terraces connectivity restoration can also include depaving and concrete removal, interventions that together with section reshaping need careful siting consideration for space requirements and infrastructure constraints. Indeed, much of the land along riverbanks and terraces has been converted for agriculture, infrastructure, and urban development. Securing land or collaborating with landowners to set back levees and reconnect floodplains can be politically and financially challenging. In particular, restoration efforts in urban areas is often more expensive due to higher land values and development density. Projects can also face public opposition if they are perceived to reduce flood protection, limit access, or conflict with development plans.

Moreover, river connectivity restoration is effective if interventions are undertaken at large spatial scales since river connectivity is affected by catchment-wide problems; in other words, issues upstream or in the wider catchment can undermine local restoration efforts. For instance, pollutants, altered water flow, and excessive sediment loads from sources like agriculture or urban runoff can re-degrade a restored area. Another typical example of connectivity restoration failure is the case of reaches widening with possible sediment replenishment in order to restore lateral sediment morphodynamics, an effect that can not persist in the long term if the watercourse faces upstream issues of disrupted natural sediment supply (i.e. dams and other barriers blockage of sediment downstream with resulting sediment starvation and possible erosion processes). Finally, river banks and terraces connectivity restoration being mainly morphological restoration involving significant changes in the channel cross-sections should be coupled with riparian vegetation recovery, in a perspective of a more complete and effective river renaturation.

Section C – Societal challenges

Biodiversity enhancement

Increased connectivity of natural areas

The restoration of river banks, terraces and possibly adjacent flood plain connectivity is the recovery of the lateral connectivity between the main river channel and the flood plain, namely the part of the alluvial plain adjacent to the river and naturally subject to flooding. This Nature-based Solution is therefore the par excellence measure allowing increased connectivity of natural areas of different domains (aquatic and terrestrial).

Increased diversity of habitats

It is of paramount importance that the river has a diversified flow patterns in a wider bed connected to riparian systems and possibly might flood some parts of the adjacent plain thus enabling an exchange of sediments and conditions for temporary wet areas and resulting hygrophilous vegetation allowing an overall increase in habitat diversity. Restored riverine ecosystems present a rich habitats' structural heterogeneity which is acknowledged to be a prerequisite for biological diversity.

Water management

Increased surface water storage and/or groundwater recharge

The restoration of river banks, terraces and possibly flood plain connectivity is the recovery of the lateral connectivity between the main river channel and the flood plain, namely some parts of the floodplain side channels, abandoned terraces and meanders are restored in water and sediment fluxes above all during floods. This produces wider streams and temporary flooded areas, therefore a gain in surface water storage, such that flood plain restoration is actually a measure for flood management (Rijke et al. 2012). Flooded areas such as reconnected river terraces return water volumes to the main channel slowly after peak flow, allowing for an improved groundwater recharge.

Improved water quality

During flood events volumes detention outside of the main active channel, as it is the case of restored riparian systems in which river terraces delay peak flow, water purification takes place through carbon, nitrogen and phosphorous accumulation in soil (Noe and Hupp 2005), provided permeable surfaces (i.e. also vertical connectivity restoration). Water purification through nutrient retention is enhanced if vegetation restoration is present, as an integral part of the project design and implementation or as a result of ecological succession. In certain cases, phytoremediation can even remove and/or retain other pollutants such as metals and plastics.

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs; Improved microclimatic mitigation capacity

River banks, terraces and possibly floodplain connectivity restoration improves soil functions and composition thanks to temporary flooding of some parts of the plain contiguous to the stream, this enabling an exchange of sediments and conditions for temporary wet areas, as well as organic carbon storage in soil (Noe and Hupp 2005). Afforestation, as an integral part of the project design and implementation or as a result of ecological succession, also contributes to carbon storage. Living plants store atmospheric CO^2 and soil organic C in their biomass. Moreover, carbon stock is also provided by the buffer vegetation on river banks, terraces and restored floodplain areas which intercept the runoff and the related transported material, thus preventing the erosion-induced transport of C to reach the water body (Gerner at al. 2018).

River depaving and daylighting

Section A – General Description

Fig. 3 – Channel depaving. Comparison between paved channel with concrete banks and restored reach of the Borbecker Mühlenbach river in Essen, North Rhine-Westphalia, Germany. Photo source: Emschergenossenchaft and Lippeverband; photo credit Klaus Baumers.

Description

River depaving and daylighting are the two main measures to adopt in extremely artificial streams, the objective of such measures being the recovery of vertical and lateral connectivity. Depaving is the concrete bed removal in channelized streams (Gerner et al. 2018), it addresses not only strictly the streambed, but also embankments, since usually paved streams present also impermeable, fixed banks at least in their lowermost part (Figure 3). The impermeable shell removal not only allows vertical and lateral connectivity restoration, but also aims at reshaping very channelized streams providing more natural sections and reaches, thus enabling biogeomorphological functions. River daylighting and restoration of culverted rivers consists in removing streams from buried conditions and bring them to the surface in order to improve their ecological status (Wantzen et al. 2022). It is worth noting that culverted streams almost always present also impermeable bed pavement, so that restoration interventions of buried streams should include both daylighting and depaving. Deculverting allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Ecologically designed deculverting projects must include the improvement of aquatic and marginal habitats by recreating floodplains and replanting banks (Wild et al. 2011). A particularly important effect of deculverting is the improvement of longitudinal mobility and habitat availability of aquatic fauna (Baho et al. 2021). Further ecosystem services provided by river daylighting are flood mitigation and community revitalization (Wantzen et al. 2022, Wild et al. 2011).

Synonyms

Stream deculverting; Stream reopening; Impervious streambed removal.

Section B – Technical details

Paved and culverted streams are located in urban areas with an extremely high degree of human-made structures and infrastructures, therefore any potential depaving and daylighting project needs siting considerations accounting for space requirements and infrastructures intersections. Actually, extremely dense urban areas may be highly constrained by existing buildings, roadways and buried utilities lines for a sufficient space to build out a restored channel. In case of depaving interventions only, which presents less constraints with respect to deculverting, buried infrastructures like energy pipelines, sewage systems and water supply systems are quite common. In deculverting projects even major difficulties are encountered since, in addition to hidden utility lines underneath the stream bed, also structures and infrastructures covering the channel are present. Although, built infrastructures can always be moved, the associated costs can be prohibitive, especially in urban areas with very high land values. For this reason, daylighting projects are often integrated into broader economic revitalization effort that can capitalize on the new environmental benefits provided by the restored stream. Moreover, successful projects require ample width to allow for a natural flow path and gentle, stable slopes, which will almost always require a significantly wider area than the area occupied by a buried stream.

In addition to siting consideration, maintenance considerations must be accounted for, being usually burdensome. Indeed, depaving and deculverting interventions require significant monitoring and maintenance in the first few years to ensure that the channel and bank are stable and the vegetation is established. However, after the setting-up and the consolidation of stable conditions of bed, banks and vegetation an open stream will require far less ongoing maintenance than a culvert or other grey infrastructure.

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas; Increased diversity of habitats

River daylighting and restoration of culverted rivers consists in removing streams from buried conditions and bringing them to the surface in order to improve their ecological status; in case of depaving the ecological improvement consists in restored vertical connectivity. This allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Ecologically designed deculverting and depaving interventions must include the improvement of aquatic and marginal habitats by recreating floodplains and replanting banks (Wild et al. 2011). A particularly important effect of deculverting and depaving is the improvement of longitudinal mobility and habitat availability of aquatic fauna (Baho et al. 2021).

Increased local diversity (species and/or taxonomic groups)

River depaving and above all daylighting are the river restoration measures that best increase local diversity in terms of both species richness and functional diversity. Indeed, this biodiversity enhancement is rapid and certain more than in other river restoration interventions, since the starting point of culverted and paved streams is the most ecologically degraded with respect to the great majority of streams in other unrestored conditions, being actually culverted and paved streams almost ecologically dead. By allowing sunlight to reach the stream, the growth of plants and algae that form the base of the food web is enabled. This new food source, along with the improved physical habitat from creating an open channel, leads to the colonization of more species, including invertebrates and vertebrates.

Water management

Increased surface water storage and/or groundwater recharge

Removing streams from buried conditions and bringing them to the surface definitely increases the surface collecting rain water: the impermeable cover is removed and the restored water body directly receives rain water and run off. Deculverting allows the recovery of i) light and consequent processes based on primary production, ii) lateral connectivity to riparian zone and consequent ecological processes, iii) biologically active surfaces and consequent stream self-purification (Wantzen et al. 2022). Stream depaving restores vertical connectivity between the stream, surface sediment layer and subsurface: the sealed, impervious stream bed is replaced by permeable, filtrating material, therefore a vertical water flow between the stream and groundwater is recovered. Since culverted streams almost always present also impermeable bed pavement, restoration interventions of buried streams should include both daylighting and depaving, thus an improvement river-groundwater exchange.

Improved water quality

The hydro-morphological and biological processes provided by deculverting and depaving drastically improve water quality because the daylighted, desealed, restored and revegetated stream guarantees the ecosystem service of nutrient regulation; this condition has to be compared to the ecologically dead zone with no stream self-purification represented by the buried and/or sealed configuration.

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

River depaving restores the vertical connectivity of the stream, both improving soil functions thanks to impermeable surface removal and to re-establishment of vegetation (Gerner et al. 2018). Permeable substrate on river bed allows a better aeration and infiltration as well as organic carbon storage. Living plants store atmospheric CO_2 and soil organic C in their biomass. River daylighting allows the recovery of light and consequent processes based on primary production: daylighting allows photosynthetic carbon fixation (Wantzen et al. 2022).

Riparian vegetation restoration

Section A – General Description

Fig. 4 – Riparian vegetation restoration. Comparison between unrestored and restored reach of the Marsh Creek in Oakley, California. The restored reach presents a gradient of different hydrophilic macrophytes from the in-channel zones to the terrestrial ones. Photo courtesy Restoration Design Group, Inc., Berkeley, California.

Description

Riparian forestry restoration (Figure 4) is a key measure for water security and quality as well as for climate adaptation (O'Briain et al. 2024). Riparian vegetation indeed enables several biogeomorphological functions such as shading the river channel and thus lowering water temperature, providing the detritus food chain for aquatic community, increasing spatial heterogeneity and thus habitat availability and biodiversity (Naiman and Decamps 1997, Pringle 2003), retaining excess nutrients dissolved in water (Gerner at al. 2018), protecting the water body by acting as a trapping buffer zone with respect to pollutants coming from the flood-plain. Riparian vegetation restoration is a key measure in river renaturation because it significantly improves river-bank connectivity from an ecological perspective (Pringle 2003). Indeed, riparian zones are valuable ecotones with a rich gradient of vegetation species having a variety of different characteristics, behaviours and ecological roles as we move from aquatic/in channel settings to terrestrial ones.

Synonyms

Riparian vegetation recovery; Tree and shrubs belts/strips along rivers.

Section B – Technical details

Riparian vegetation restoration can be safely implemented without increasing the hydraulic risk, and indeed new planning and ordinary maintenance of the hydrographic network can and must present a vegetation maintenance approach taking into account both hydraulic requirements and the ecological aspects of riparian and aquatic ecosystems. Riparian vegetation restoration can be implemented in river reaches with unchanged channel geometry, namely with "constant cross-section" or "quasi-constant cross-section"; in this case interventions concern only vegetation management changes and innovations. However, in a perspective of a more complete and effective river renaturation, riparian vegetation recovery can be coupled with morphological restoration involving significant changes in the channel cross-sections and possibly the adjacent floodplain.

The removal of in-channel and riparian vegetation is carried out because vegetation can have negative effects from a hydraulic perspective. Vegetation increases hydraulic roughness, which leads to reduced flow velocity, higher water levels, and an increased risk of flooding during high-flow events. Furthermore, the reduction in flow velocity promotes sediment deposition, which results in a reduced effective channel cross-section and, consequently, a further increase in flood risk. In addition to the primary issue of increased roughness, tree and shrub vegetation is also removed because, if carried by the current during flood events, it can increase the risk of blockages in narrow sections. Finally, vegetation removal is also carried out to ensure adequate visibility and access for monitoring and maintaining hydraulic structures.

However, in-channel vegetation in natural watercourses, and even in artificial channels, plays a fundamental role in shaping the chemical, physical, and biological conditions of habitats for numerous bacterial and animal species. It also helps maintain the ecological corridor function of the watercourse, ultimately contributing to biodiversity conservation. Moreover, vegetation plays an important role in bank stabilization and supports both phytoremediation and the self-purification capacity of the watercourse, particularly by mitigating pollution from nutrients such as nitrogen, phosphorus, and organic carbon. In addition to all these regulatory ecosystem services, the presence of vegetation along a watercourse enhances its aesthetic quality and potential recreational value.

Traditional vegetation management, adopted by the majority Italian river authorities among others, is featured by a complete mowing of both banks and the channel bed leading to a complete (or, at best, substantial) loss of the ecological and self-purification functions of the channel. It also causes resuspension of accumulated sediments, destabilization of the banks, and increased water temperature, resulting in decreased dissolved oxygen levels. This has led some river authorities and managers to develop and adopt a type of vegetation maintenance that better preserves the ecological and environmental functionality of canals. In practice, this approach is known as "gentle maintenance" (ANBI VENETO 2020, Consorzio di Bonifica Acque Risorgive n.d.), which involves less frequent cutting and different methods and timing compared to traditional management, with the aim of: i) always ensuring the hydraulic functionality of the channel; ii) maintaining good ecological functionality; iii) preserving ecosystem regulatory services.

This type of vegetation maintenance can be applied in channel sections where the design flood discharge, even for high return periods, is safely contained with an adequate hydraulic freeboard. In contrast, in sections where such flood discharges are not fully contained or only just pass through without a minimum safety freeboard, complete vegetation removal is required. In other words, depending on the actual flood conveyance capacity, it is appropriate to apply either traditional or gentle vegetation maintenance in a site-specific and case-specific manner, based on flood flow behaviour, determined through hydraulic simulations, of the relevant watercourse sections.

Section C – Societal challenges

Biodiversity enhancement

Increased connectivity of natural areas; Increased diversity of habitats

Riparian forestry restoration is a key measure for increasing connectivity of natural areas as well as habitats availability and diversity. Riparian zones represents ecotones between the terrestrial and aquatic domains, in other words transitional areas between different ecosystems (Naiman and Decamps 1997). Riparian vegetation recovery increases spatial heterogeneity and thus habitat availability and biodiversity, and also dead vegetation has an important ecological role providing both different ecological niches and the detritus food chain for aquatic community.

Increased local diversity (species and/or taxonomic groups)

Riparian forestry restoration should be designed envisaging the use of a great variety of plants, which is actually supported by the varying water levels and flows and different degrees of hydrophilic conditions. The increase of local biodiversity in terms of both species richness and functional diversity is provided both by the use of new plants starting from the implementation of the recovery intervention and by the ecologically succession that takes place in restored riparian zones (Carbonari and Solari 2025).

Water management

Increased surface water storage and/or groundwater recharge

Riparian vegetation restoration improves water quality due to plants' role in nutrient regulation and water course shading. Indeed, plants absorb excess nitrogen and phosphorous compounds and reduce total organic carbon dissolved in water. Plants shade on the water course enables lower water temperature and resultant higher dissolved oxygen. Plants also enhance water infiltration and evapotranspiration, therefore overall contribute in water cycle regulation (Gerner et al. 2018, O'Briain et al. 2024).

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

Riparian forestry restoration envisages extensive setting of a variety of plants which store in their biomass atmospheric carbon dioxide and carbon component of soil organic matter. Furthermore carbon stock is also provided by the buffer vegetation on the river bank which intercept the runoff and the related transported material, thus preventing the erosion-induced transport of C to reach the water body (Gerner et al. 2018, Naiman and Decamps 1997). Moreover, a vegetated permeable surface favours carbon stock in the soil itself, which acts as a sink in the carbon cycle.

Health, well-being and air quality

Improved air quality

Riparian forestry restoration plays a fundamental role in improving air quality both through carbon sequestration and absorbing and degrading airborne pollutants. In addition to CO_2 sequestration, plants can remove further carbon compounds called volatile carbon compounds (VOCs). Other gaseous pollutants (different from carbon compounds) removed by vegetation are sulphur dioxide and nitrogen oxides, and also particulate matter. It's crucial to remember that riparian zones are vital ecotones characterized by a natural resilience since riparian plants are adapted to geomorphic and hydrologic perturbations and tolerate great seasonal and annual variability of environmental conditions (Naiman and Decamps 1997). Therefore riparian vegetation is more resilient to climate change effects with respect to vegetation in adjacent upland habitats; thus ultimately also ecosystems services, including air quality enhancement, provided by riparian vegetation are robust.

Constructed wetlands

Section A – General Description

Fig. 5 – Phytoremediation in a Constructed Wetland (CW). CW for the treatment of grey water through gravel bed filtering and phytoremediation using *Cyperus papyrus*; Florianopolis, Brazil. Photo credit: Heike Hoffmann.

Description

Constructed Wetlands (CWs) are engineered systems that mimic the functions of natural wetlands to treat various types of contaminated water. They enhance water quality through a combination of physical, chemical, and biological processes, ultimately purifying used water before it is either discharged into natural surface water bodies or used to recharge aquifers (Hsu et al. 2011). CWs are effective for treating municipal and agricultural wastewater and are commonly employed as a cost-effective alternative to conventional tertiary treatment systems. They are also used for managing Combined Sewer Overflows (Rizzo et al. 2020) and domestic Grey Waters, as reported in Figure 5 (Boano et al. 2020). Constructed Wetlands can reduce organic matter, nutrients, suspended solids, and landfill leachate from polluted waters. Based on the flow path, CWs are categorized into surface-flow and subsurface-flow systems, both of which utilize plants for phytoremediation (Rizzo et al. 2020). In subsurface-flow CWs, the wastewater flows through a porous medium, which plays a key role in physically filtering contaminants and supporting the growth and interaction of bacteria and plant roots, thereby enhancing pollutant removal.

Synonyms

Engineered reedbeds; Treatment wetlands; Wetlands for tertiary treatment of effluent.

Section B – Technical Details

Constructed Wetlands are valuable and multipurpose Nature-based Solutions whose field of application however needs to be carefully delimited. Actually, CWs presents several limitations and in many cases can not replace conventional waste water treatment plants (WWTPs), as well as other NbS can not completely perform the function of large engineering facilities designed to respond to particular societal challenges, as it is the case of systems of SuDS in "sponge cities" that can not reduce flood risk as much as large flood mitigation basins (Li et al. 2023). In such contexts, the combined "Green + Grey infrastructure" approach turns out to be particularly effective, more than NbS alone. In particular, Constructed Wetlands cannot substitute large wastewater treatment plants because of their performance limitations, lack of standardized design, and sensitivity to varying conditions. Two main limitations are intrinsic of CWs compared to WWTPs such that CWs can not match WWTPs performances: i) CWs do not offer the consistent, high-level treatment of WWTPs in case of constant, high amount of pollutant load per day (i.e very large equivalent inhabitants) because CWs are less effective than WWTPs in primary and secondary treatment; ii) on equal pollutant load, CWs require direct land area larger than a traditional plant, thus presenting an overall lower "land use efficiency" (at least for large scales and large equivalent inhabitants).

Constructed Wetlands are therefore suitable as a cost-effective alternative to tertiary treatment, namely they can be used as a "polishing" step after primary and secondary treatment in conventional plants in order to remove residual contaminants; they are also implemented in case of used water without high pollutant load as it is for grey water (Boano et al. 2020), as well as in case of water quality improvement for non-potable uses such as irrigation. CWs are also suitable for storm water management and Combined Sewer Overflows' treatment (Rizzo et al. 2020), in this case providing large areas in order to buffer rapid discharge events releasing large volumes and considerable pollutants loads (i.e. much lower water quality comparable to mechanically treated domestic waste water). Overall, Constructed Wetlands implementation is recommended in small, decentralized systems, being cost-effective and sustainable solutions for small communities and scattered applications where traditional plants are not feasible.

Section C – Societal Challenges

Biodiversity enhancement

Increased connectivity of natural areas

Constructed wetlands with emergent vegetation support a variety of plants, which in turn provides diverse habitats for other organisms. Indeed, wet ecosystems, with the typical transitional zone between aquatic and terrestrial domains, present a rich habitat heterogeneity, which in turn provides a variety of niches for different species and ultimately enhances biodiversity. Constructed Wetlands create diverse habitats through their shallow depths, generally large surface areas, and complex, irregular shorelines, supporting a wide range of plants, invertebrates, and animals. Furthermore, the water purification capabilities of wetlands can lead to healthier ecosystems with a better regulation of nutrient cycles (Boano et al. 2020; Hsu et al. 2011).

Increased diversity of habitats

The design and implementation of constructed wetlands include the planting of numerous and various plants with specific roles of phytodepuration, therefore the plants themselves represent an increase of local diversity in terms of species and taxonomic groups. Furthermore, the new habitats provided by constructed wetlands supply food and shelter for numerous invertebrates, which in turn support higher trophic levels like amphibians, birds, fishes, and mammals, leading to a greater abundance of species than might be found in the surrounding landscape.

Water management

Increased surface water storage and/or groundwater recharge

A constructed wetland consists of a properly designed basin that contains water, a substrate of water-saturated sediments, plants and microbial communities. This shallow water basin intercepts rainfall and surface runoff, and, because of the large surface area of the water and its shallow depth, the system interacts strongly with the atmosphere through rainfall: the basin receives the rainfall directly on the water surface, and the runoff of a larger surface drained by the basin (both pervious and impervious cover). This shallow water basin therefore stores relevant water quantities (Hsu et al. 2011).

Improved water quality

Constructed wetlands are basins characterized by slow flows and shallow water depths which provide prolonged contact times between the water and the surfaces within the wetland (i.e. water-saturated sediments with biofilm, plants roots with biofilm) enabling gas/water interchanges and microorganisms activity of transforming a wide variety of substances including pollutants. Phytoremediation by plant also contributes to water quality improvement (Hsu et al. 2011). Plants purify water through denitrification, dephosphation and the removal of organic carbon compounds including various human-made pollutants such as industrial chemicals and pharmaceuticals, which make domestic waste- and grey-water rich in total organic carbon (Boano et al. 2020).

Climate resilience

Removed carbon via storage in vegetation, soil biogenic reefs

Constructed wetlands plays a role in carbon sequestration, which is the process of capturing and storing atmospheric carbon dioxide (CO_2) because the design of constructed wetlands includes the use of emergent aquatic plants. Plants absorb CO_2 during photosynthesis and convert it into biomass (photosynthetic carbon fixation). In addition to CO_2 sequestration, plants used in constructed wetlands can remove further carbon compounds contained in polluted waters for the treatment of which constructed wetlands are designed (Boano et al. 2020). Indeed, domestic waste- and grey-water have high values of total organic carbon (TOC) which includes various human-made pollutants such as industrial chemicals and pharmaceuticals. Furthermore, also the substrate of gravel and sand that form the bottom layer of constructed wetlands effectively store carbon organic matter from dead organisms and washed-in plant material sinks to the bottom and becomes buried in the sediment.

Health, well-being and air quality

Improved air quality

Constructed wetlands include numerous and various plants mainly used for water purification, however they also ensure phytoremediation processes improving air quality both through carbon sequestration and absorbing and degrading airborne pollutants. In addition to CO_2 sequestration, plants used in constructed wetlands can remove further carbon compounds called volatile carbon compounds (VOCs). Other gaseous pollutants (different from carbon compounds) removed by vegetation are sulphur dioxide and nitrogen oxides. Plants absorb gaseous pollutants, which are then metabolized or broken downs in less harmful substances (phytodegradation) and in some cases can be released back into the atmosphere in less harmful form (phytovolatilization). In addition to gaseous pollutants reduction, plants also remove particulate matter.

Bioswales

Section A – General Description

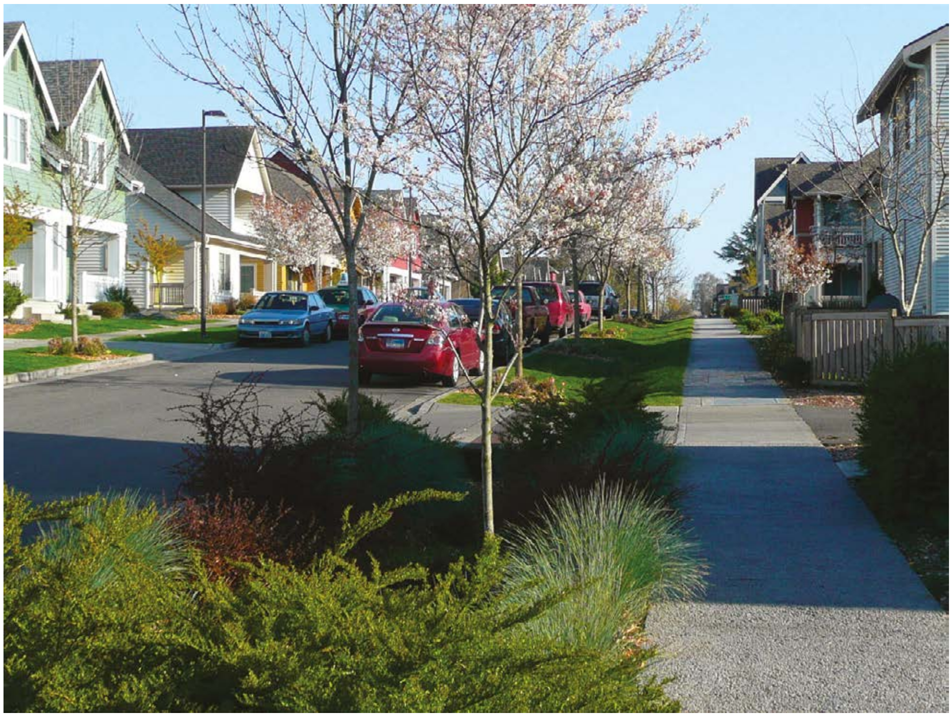

Fig. 6 – Bioswales for treating stormwater runoff from street in Seattle (Source: Architectsea 2011).

Description

Bioswales (also referred to as swales) are open, vegetated, broad and shallow channels specifically engineered to convey, treat, and, in many cases, attenuate surface runoff generated during rainfall events (World Bank 2021). As key components of Sustainable Drainage Systems (SuDS), bioswales integrate hydraulic conveyance, water quality treatment and ecological functions, thereby contributing to sustainable stormwater management in urban environments.

Characterised by gentle longitudinal gradients and continuous vegetated surfaces, bioswales reduce surface runoff velocities and mitigate flood risk during intense precipitation (Blanc et al. 2012; Atkins 2010; Woods-Ballard et al. 2015). They may operate as alternatives to conventional underground drainage systems, offering additional benefits through pollutant removal and the moderation of urban hydrological responses (Blanc et al. 2012).

Recognised as NbS, bioswales constitute shallow, vegetated depressions designed to intercept, infiltrate, divert and treat stormwater, thereby enhancing both hydrological and ecological performance within urban landscapes (Eisenberg and Polcher 2019). Their geometry promotes flow retardation, erosion reduction and temporary water storage, helping to regulate peak discharges (Woods-Ballard et al. 2015; World Bank 2021).

Water quality improvements are achieved through sedimentation, filtration and biological assimilation. As stormwater passes through vegetation and substrate layers, sediments, nutrients and particulate pollutants are progressively retained or degraded, resulting in measurable improvements in downstream water quality (World Bank 2021; Kazemi et al. 2011). The vegetative cover - typically composed of herbaceous species

- facilitates sediment trapping, evapotranspiration and infiltration, and contributes to soil ecological function and urban microclimate regulation (World Bank 2021).

Bioswales may be differentiated according to function within SuDS (World Bank 2021):

- standard conveyance bioswale, primarily designed to transport runoff to subsequent treatment facilities.
- enhanced dry bioswale, incorporating a prepared filter media and a subsurface underdrain to improve treatment and prevent waterlogging.
- wet bioswale, engineered to maintain permanently moist or marshy conditions at the base, supporting extended treatment processes for stormwater.

Synonyms

Swales; Green swales; Grassed swales; Vegetated filter strips; Stripswale.

Section B – Technical Details

Implementation conditions

Effective implementation requires a detailed assessment of environmental, topographical and design conditions to ensure hydraulic, treatment and urban landscape performance (NWRM s.d.; Woods-Ballard et al. 2015). Bioswales are most suitable for sites with sufficient space to accommodate shallow, wide channels; their spatial requirements exceed those of conventional piped drainage systems, making installation challenging in high-density urban areas (Woods-Ballard et al. 2015; Eisenberg et al. 2022).

They are commonly employed to manage runoff from roads, parking areas and other impervious surfaces, and are frequently located along road margins or integrated into parking facilities (NWRM s.d.; Woods-Ballard et al. 2015). Bioswales typically function as an early-stage SuDS component, receiving inflows from adjacent catchments.

Slope conditions strongly influence hydraulic performance. Recommended longitudinal slopes range from 0.3% to 1%, ensuring low flow velocities, reduced erosion risk and effective infiltration (NWRM s.d.; Woods-Ballard et al. 2015). Where natural slopes exceed 2%, check dams may be installed to create a stepped profile, enhancing retention time and infiltration capacity (Woods-Ballard et al. 2015). Conversely, extremely flat sites may experience poor drainage and require careful grading to avoid prolonged water stagnation (NWRM s.d.).

Design features

For optimal hydraulic efficiency and operational safety, bioswales should adhere to established geometric criteria (Woods-Ballard et al. 2007). Cross-sections are typically trapezoidal or parabolic, with side slopes between 1:3 and 1:4 and a maximum depth of approximately 60 cm to maintain safe and controlled flow conditions. Longitudinal slopes must remain shallow to promote flow attenuation, and the channel base is generally designed with a width of 0.5–2 m.

These configurations ensure low flow velocities, increased wetted perimeter, enhanced infiltration processes and improved safety for users and the surrounding environment (Woods-Ballard et al. 2007).

Soil permeability, groundwater level and the risk of groundwater contamination must be carefully evaluated. Bioswale type selection depends on soil infiltration capacity, with infiltration generally considered feasible when the soil exhibits a hydraulic conductivity ≥ 10^{-6} m/s. Where infiltration is not possible or appropriate, an impermeable geomembrane may be installed to prevent undesirable percolation (Woods-Ballard et al. 2015).

If infiltration is intended, groundwater should lie at least one metre below the base of the bioswale or associated infiltration device (NWRM s.d.). Sites with shallow groundwater may support wet bioswales, though infiltration should be limited or avoided (Woods-Ballard et al. 2015). In contaminated sites, infiltration must be preceded by environmental risk assessment to prevent pollutant mobilisation towards groundwater (Woods-Ballard et al. 2015; NWRM s.d.).

Soil compaction must be strictly avoided, as it significantly reduces infiltration capacity (Eisenberg et al. 2022). Excavation should be carried out from the sides to avoid loading the channel base. Bioswales should not receive runoff until vegetation is fully established and nearby construction activities are completed, preventing sediment pollution and functional degradation (Woods-Ballard et al. 2015).

Maintenance

Long-term performance depends largely on vegetation quality and regular maintenance. Dense herbaceous vegetation is essential to retard flow, facilitate sediment capture and enhance pollutant removal (Woods-Ballard et al. 2015). Bioswales should be located in areas receiving adequate sunlight to promote vigorous plant growth.

Species selection must consider local climatic conditions, soil characteristics, light availability and rainfall regimes. Vegetation should tolerate periodic inundation and be robust enough to remain functional during extreme weather events (Woods-Ballard et al. 2015; NWRM s.d.).

Maintenance programmes must ensure access for inspection, sediment removal, channel cleaning and periodic mowing. Regular maintenance is essential to preserve hydraulic, treatment and aesthetic performance (Woods-Ballard et al. 2015; Eisenberg et al. 2022).

Section C – Societal Challenges

Biodiversity enhancement

Bioswales provide multifunctional green spaces capable of substantially enhancing biodiversity, depending on vegetation type and spatial distribution (NWRM s.d.). When trees or hedgerows are present, bioswales form high-quality habitats and ecological linkages supporting wildlife movement in urban areas (Warner 2022). Native vegetation ensures resilient cover and suitable habitat for local fauna (Woods-Ballard et al. 2015). Integrated within wider green networks, bioswales contribute to ecological corridors that sustain terrestrial biodiversity (NWRM s.d.). Wildflower mixes and diverse planting schemes further support insects, invertebrates and birds (Woods-Ballard et al. 2015).

Climate Resilience and Water management

Through evapotranspiration, bioswales lower ambient temperatures, mitigating urban heat island effects and contributing to climate change adaptation. Vegetation also sequesters carbon in biomass and soil (Bowler et al. 2010). Bioswales effectively reduce runoff rates, particularly from impervious urban surfaces, and can decrease flood risk during short, intense rainfall events (Zölch et al. 2017). When combined with other Nature-based Solutions, they contribute to reducing peak river flows in small catchments (NWRM s.d.).

Health, well-being and air quality

By improving access to green and blue public spaces, bioswales support public health and well-being. They remove pollutants such as hydrocarbons, nitrogen compounds and heavy metals (NWRM s.d.), while infiltration stabilises soils and reduces subsidence risk (World Bank 2021). Their integration into streetscapes enhances the quality of public spaces and can foster recreation and informal social interactions (Kim and Song 2019). Public participation in design and maintenance can strengthen community cohesion, while combined traffic-calming measures contribute to safer and more liveable urban environments (World Bank 2021).

Vegetated permeable surfaces

Section A – General Description

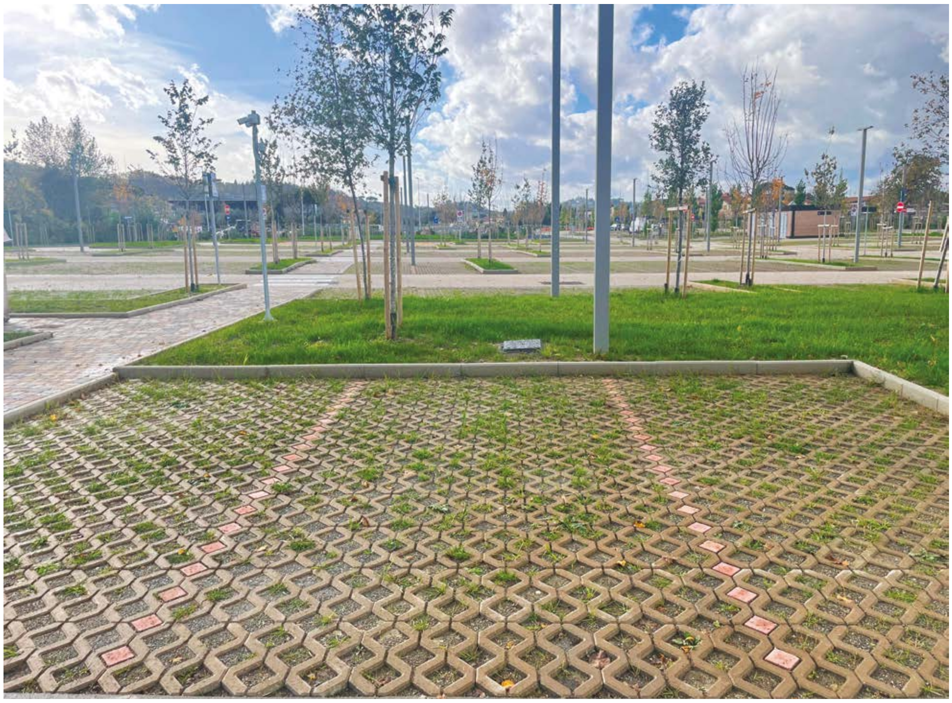

Fig. 7 – Example of vegetated permeable pavements in a parking lot in Florence, Italy (Source: Hasanaj 2025).

Description

Vegetated permeable pavements represent a specific type of filtering surface belonging to the broader group of pervious pavements, designed for the sustainable management of stormwater and the enhancement of urban resilience (World Bank 2021). These solutions are designed to allow rainwater infiltration through the surface and its subsequent percolation into the underlying soil, thereby contributing to the reduction of surface runoff and the improvement of water quality (Musco et al. 2018).

The structure of vegetated permeable pavements generally consists of prefabricated modular elements, such as concrete grass grids or reinforced plastic gratings, which contain voids that facilitate water infiltration and support vegetation growth (Woods-Ballard et al. 2015).

The vegetative component, integrated within the surface layer, enhances infiltration, absorption, and evaporative cooling capacity, while improving the ecological quality and microclimatic conditions of urban environments (Musco et al. 2018; Bono et al. 2020).

Vegetated permeable pavements are mainly applied in low-traffic areas, such as car parks, residential driveways, cycle paths, and pedestrian zones. To ensure long-term performance, design considerations must include adequate sunlight exposure and vegetation resistance to mechanical stress, since insufficient light, repetitive wheel loading, and heat radiation can impair grass growth and solution functionality (Woods-Ballard et al. 2015).

Synonyms

Vegetated permeable pavements; vegetated grid paves

Section B – Technical Details

Implementation conditions

The implementation of vegetated permeable pavements depends on the application context, environmental constraints, and site conditions, with reference to traffic intensity and soil characteristics. These systems are particularly effective in contexts characterised by moderate structural loads and are designed as alternatives to traditional impermeable surfaces, without requiring additional space for their installation. They can be integrated both into new urban developments and into projects involving the regeneration or replacement of existing pavements (Bono et al. 2020).

For proper design, it is essential to analyse the geological and hydrological characteristics of the native soil, with particular attention to permeability (Bono et al. 2020). Specifically, in clayey soils, a sub-surface drainage system (underdrain) is required to allow runoff to the stormwater network. In sandy soils, by contrast, the infiltration capacity is generally sufficient (Iwaszuk et al. 2019).

Vegetated permeable pavements are also suitable for flat terrain, provided that the surface layer is appropriately configured to ensure efficient capture and conveyance of stormwater (Bono et al. 2020; Woods-Ballard et al. 2015). Recommended installation conditions include a slope of less than 5%, and the absence of sensitive elements such as wells within 30 m, foundations within 3 m, or groundwater tables less than 1,2 m below the laying surface. Installation is also discouraged in the proximity of potentially contaminating sources such as fuel stations (Iwaszuk et al. 2019).

In areas subject to groundwater contamination risk or slope instability, it is possible to waterproof the pavement base layer to enable the retention and controlled treatment of stormwater before discharge to designated drainage points (Bono et al. 2020).

In car parks with high daytime usage, vegetation growth may be limited by reduced sunlight and heat radiated from parked vehicles. In such cases, it is advisable to replace the vegetated infill with gravel or inert aggregates to ensure surface stability and permeability (Bono et al. 2020; Musco et al. 2018).

Design features

The design of vegetated permeable pavements must combine hydraulic functionality, structural capacity, and ecological value. From a construction perspective, the solution is composed of the following functional layers: i) surface layer, consisting of modular elements made of concrete, reinforced plastic, or natural materials, designed with voids or cavities that facilitate water infiltration and allow vegetation to establish within the pavement structure; ii) base layer of gravel, which serves a dual function: providing structural support and acting as a temporary reservoir for infiltrated rainwater (its thickness varies according to the expected loads and the site's hydraulic requirements); iii) sub-base or natural soil, which promotes percolation and infiltration of water into the subsoil (in low-permeability soils, drainage pipes may be installed to channel water towards the stormwater network and prevent stagnation); iv) an optional geotextile filter layer may be placed between the gravel base and the underlying soil, serving to prevent the migration of fine particles and reduce the risk of clogging, thereby ensuring the long-term efficiency of the system (Woods-Ballard et al. 2015).

In grass-grid or resin-reinforced systems, the surface layer provides limited structural contribution; therefore, the thickness of the sub-base must be determined according to road pavement design criteria, based on the expected loads (Woods-Ballard et al. 2015; Bono et al. 2020).

The design must include an estimation of the volume of stormwater that the pavement will need to absorb. Considering the gradual reduction in permeability over time due to pore clogging, it is recommended to apply a long-term permeability reduction factor (Bono et al. 2020).

Permeable pavements can also drain water from adjacent impermeable surfaces, such as roofs or other paved areas; however, to avoid premature clogging, it is advisable to maintain a maximum ratio of 2:1 between drained impermeable surface and permeable surface. To ensure the hydraulic safety of the system, integration with an overflow or emergency drainage system is also recommended (Bono et al. 2020).

Maintenance

Regular and preventive maintenance is essential to ensure the durability, hydraulic functionality, and ecological performance of vegetated permeable pavements.

The surfaces should undergo periodic inspections to ensure they are free from sediments, debris, and waste, and to verify that the system allows effective drainage between successive rainfall events (Bono et al. 2020; Woods-Ballard et al. 2015).

Periodic vacuuming and brushing operations must be scheduled to remove fine sediments and restore infiltration capacity. Such maintenance is generally recommended every three to four years (Bono et al. 2020).

Surface clogging may occur due to the accumulation of sediments carried by runoff or vehicle loads, leading to a gradual reduction in infiltration capacity (Bono et al. 2020). It is therefore crucial to implement preventive measures and sediment source control strategies to preserve the system's hydraulic performance over time.

Planned and continuous maintenance helps extend the service life of the pavement and ensures its effectiveness as a green urban solution, contributing to the hydraulic and climatic resilience of the urban environment.

Section C – Societal Challenges

Biodiversity enhancement

Vegetated pervious pavements offer an ecologically valuable alternative to conventional impermeable urban infrastructure. As Bonthoux et al. (2019) demonstrate in their study of street-level biodiversity in Blois, France, street margins and pavement cracks, when allowed to support spontaneous vegetation, become unexpected hotspots of plant diversity. Over 300 plant species, including many natives, were recorded across just 48 kilometres of urban streets, representing approximately 20% of the region's flora. These findings underline the ecological potential of pervious pavements that allow for plant colonisation, particularly in low-maintenance or peripheral urban zones. By shifting urban management practices - such as reducing herbicide use and incorporating design elements that support spontaneous greening - vegetated pavements can actively promote biodiversity, enhance ecological connectivity, and encourage a more resilient and environmentally integrated cityscape.

Climate Resilience and Water management

The adoption of vegetated permeable pavements, integrated into broader green infrastructure strategies, represents an effective solution for mitigating urban flood risk. By enhancing the absorption of stormwater and limiting surface runoff, these solutions strengthen urban resilience and reduce the impacts of extreme events on communities. A study conducted in Humboldt Park, Chicago, demonstrated that the combined use of bioswales and permeable pavements led to a 61% reduction in total stormwater runoff, decreasing pressure on sewer networks and lowering the number of people exposed to flood-related damage (Zachary Bean et al. 2007).

Permeable pavements allow rainfall to infiltrate into the soil, helping to moderate peak flows through temporary storage within the underlying layers and subsequent controlled release. This capacity, confirmed by full-scale urban experiments, makes such surfaces a technically reliable component of sustainable urban drainage systems, with additional positive effects on groundwater recharge (Marchioni and Becciu 2015; Bono et al. 2020; Woods-Ballard et al. 2015).

Beyond hydraulic management, high-permeability pavements offer further environmental benefits. Vegetated surfaces and filtering layers improve the quality of stormwater runoff by trapping suspended solids and heavy metals, while the use of permeable materials and grassed grids contributes to lowering surface temperatures, enhancing urban cooling, and mitigating the urban heat island effect (Musco et al. 2018).

Health, well-being and air quality

Vegetated permeable pavements can play an important role in enhancing public health and overall well-being within urban environments. By increasing the presence of green and blue elements in cities, these systems help create more pleasant, restorative, and thermally comfortable spaces. The combination of permeable materials and vegetation not only supports natural rainwater infiltration - reducing runoff and contributing to groundwater recharge (Fletcher et al. 2015) - but also improves local microclimatic conditions, helping to lower surface temperatures and mitigate heat stress, a factor closely linked to human health.

Incorporating vegetated permeable pavements into urban design enriches biodiversity and strengthens ecological quality, providing residents with greater exposure to natural elements known to reduce stress, enhance psychological well-being, and encourage outdoor physical activity. By expanding interconnected networks of green and blue spaces, these pavements ultimately contribute to healthier, more resilient, and more livable urban environments (Gill et al. 2007).

Vegetated permeable pavements have been shown to enhance pro-environmental behaviour among urban residents by increasing awareness and engagement with sustainable water management practices. These pavements not only provide tangible environmental benefits, such as reducing stormwater runoff and improving urban greenery, but also serve as visible demonstrations of eco-friendly infrastructure, thereby fostering a stronger environmental ethic in local communities (Sanicola, 2018).

Furthermore, when integrated within green infrastructure networks and accompanied by educational initiatives, permeable pavements can encourage citizens to adopt more sustainable habits, including water conservation and support for urban biodiversity (Zhou et al. 2018). Such interventions contribute to building a culture of environmental stewardship essential for urban sustainability and resilience.

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