A catalogue of NBS measures for drying river networks

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Abstract

Because shifts from permanent to intermittent flow regimes represent major tipping points for rivers, with often irreversible environmental and societal consequences, the DRYvER project set out to collect, analyse, and model data from nine drying river networks (DRNs) in Europe and South America in order to craft strategies, tools, and recommendations for adaptive management of river networks. With this catalogue, we attempt to list a selection of mitigation and adaptation measures aimed at securing biodiversity, functional integrity, and ecosystem services of drying river networks in the face of climate change. It is our objective to provide examples about the range of measures that can be integrated to form Nature-Based Solutions (NBS), which can be applied to remedy and/or reverse the drying of the local freshwater ecosystems. However, the effectiveness of the measures from this catalogue will vary greatly according to the specific location of their implementation, and sometimes drying cannot be completely mitigated due to the overwhelming impacts of climate change. Finally, the intensification of the scientific research on drying rivers in recent years offers hope that many innovative measures to mitigate drying have yet to be developed.

The introductory Background section offers an overview of the status and pressures on intermittent ecosystems and explains some of the basic concepts that help us understand and sustainably manage these fragile ecosystems. Next, the NBS definition section provides a review of NBS and similar concepts, defines NBS, and explains what NBS are not. Lastly, the main body of the catalogue is a compilation of measures, with a short description, a figure, a short explanation of the measure's benefits to the water balance, and three examples of implementation for each measure. The references section will allow the reader to easily find sources of information for further reading and deeper understanding of the subject.

Keywords
Nature-based solutions, restoration, nature, dry, river, ecosystem, mitigation, adaptation, climate change

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INTRODUCTION

Background

Flow intermittency can be a part of the natural hydrology of streams and rivers globally. Approximately 69% of small and 34% of large streams below 60° latitude flow intermittently even without human-induced changes (Raymond et al., 2013). In these rivers, subsurface flows are critical for the supply of water to the downstream sections with a permanent flow (Schiller et al., 2014). The fauna and flora of these rivers have evolved in a delicate equilibrium of periodic flow, adapting their life histories and ecological traits to the specific characteristics of their home rivers (Katz et al., 2011).

Floodplain development and urbanization, forest and vegetation management, mining, river regulations, and other anthropogenic pressures are destroying and changing the characteristics of intermittent streams at alarming rates (Lindberg and Grimmond et al., 2011; Eng et al., 2015). The empty riverbeds are often used as drains for mine effluent and wastewater, corridors for vehicles and livestock, and quarries for sand and gravel. Land use change, dams, and extraction of surface and groundwater are changing runoff patterns, directly impacting instream flows (Schiller et al., 2014). These activities not only exacerbate the frequency and duration of intermittency in existing waterways but also cause the emergence of new intermittent rivers or river stretches at unprecedented rates, in which fauna and flora have no time to adapt (Arthington et al., 2014). The quality of the remaining water often declines, owing to the effects of limited flushing and evapoconcentration of salts during drying episodes (Datry et al., 2017). Consequently, the taxonomic richness of aquatic invertebrates, fish, and riparian vegetation is greatly reduced (Datry et al., 2014) and many ecological functions, such as microbially mediated nutrient cycling and dissolved organic matter dynamics change (Vázquez et al., 2015).

While causing drying and increasing intermittency on the one hand, these same pressures, most importantly land use change, also exacerbate flooding at the other end of extreme. Similar to other ecosystems (Rockström et al., 2009), we have destroyed the delicate water balance in the catchments. Therefore, we urgently need to develop harmonised solutions that will ensure redistribution of the given water quantity in time and space in order to restore the dynamic equilibrium in rivers. The NBS framework, as an umbrella concept for many approaches to addressing societal issues using nature (Cohen-Shacham et al., 2016), is currently considered the most promising solution. Professionally and locally adapted NBS are known to provide multiple benefits to nature and society (IUCN, 2020) in contrast to the traditional enginnering, grey measures.

INTRODUCTION

NBS Definition

IUCN first brought attention to the term nature-based Solutions in 2009, focusing on it in its position paper for the UNFCCC COP15, titled "No time to lose – make full use of nature-based solutions in the post-2012 climate change regime" (IUCN, 2009).

NBS have been adopted and defined by a range of leading global institutions. The International Union for Conservation of Nature (IUCN) defines NBS as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Sachman et al., 2019). The European Commission (EC) defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions" (EC, 2015).

The NBS concept is used to reframe conservation policy, climate change, and sustainability. Their multi-functionality—capability to produce several services simultaneously at the same locality—is probably the most important attribute of NBS in comparison to grey infrastructure (Somarakis et al., 2019). The concept has the power to refocus attention on sustainable development, biodiversity, and ecosystems as part of a solution to challenges posed by society like climate adaptation, food security, water crises, etc. The term NBS also commonly relates to methods for increasing resilience to climate change. As such, it has been implemented in climate mitigation and adaptation measures and improvements in urban planning aimed at elevating urban quality of life (Potschin et al., 2016).

Criterion	**Description**
Criterion 1	NBS effectively address societal challenges
Criterion 2	Design of NBS is informed by scale
Criterion 3	NBS result in a net gain to biodiversity and ecosystem integrity
Criterion 4	NBS are economically viable
Criterion 5	NBS are based on inclusive, transparent and empowering governance processes
Criterion 6	NBS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits
Criterion 7	NBS are managed adaptively, based on evidence
Criterion 8	NBS are sustainable and mainstreamed within an appropriate jurisdictional context

Table 1: A list of 8 criteria for assessing NBS measures according to the IUCN Global Standard on NBS (IUCN, 2020).

The IUCN has developed currently the only available Global Standard on NBS (IUCN, 2020), which is used to assess measures against a set of 8 criteria (Table 1). These criteria in themselves help understand what NBS are.

The standard is intended to serve planners and managers to guide them towards designing true NBS. Using the online self-assessment tool available at the IUCN web page, projects can be assessed against the 8 criteria during development (to direct design), implementation (to streamline a measure), or at any point after implementation (to learn for the future).

INTRODUCTION

How to read this catalogue

In this catalogue, we list measures that can be employed to mitigate and adapt to drying in the specific context of the drying river networks. Each measure is depicted visually and accompanied by a short textual description, providing factual information about the measure. Below, the dose-response relationships are explained in the "Benefits to water balance" section. Lastly, three referential examples of each measure allow for real-world representation of their implementation and effects.

The examples cover a range of different geographical, cultural, political, economic, etc. realms to be useful for as wide an audience as possible. They are grouped according to the function within the freshwater ecosystem. However, as already stressed, these measures on their own are not NBS. This catalogue is also not a complete list of NBS for drying rivers, nor can the solutions listed be directly transferred to any environment without detailed analysis and planning with the relevant local scientists.

While this catalogue lists a range of measures for different environments, these measures in isolation are not NBS. As evident from the NBS definition section above, numerous other aspects need to be considered for a measure to qualify as NBS. To name just one, the listed measures are small-scale actions that should be planned and implemented at scale (Table 1) to qualify as NBS. As the name implies, nature-based solutions and consequently their benefits are intrinsically related to the ecosystems in which they are implemented; they depend on and support their natural functions and processes. Moreover, their complex interaction with local ecosystems and processes also extends to the local society, their perceptions (Andreson et al., 2022), and the myriad uses of the catchment. It is therefore crucial not to understand this catalogue as a list of plug-and-play solutions but rather as a source of inspiration for a wide range of societal actors to jointly develop innovative, locally adapted measures at scale through a co-creative, science-based decision-making process, which are all important characteristics of NBS.

In addition, besides the main benefit, NBS provide multiple co-benefits for the environment and society. However, measuring all the benefits and co-benefits in practice is impossible, so individual projects monitor a subset of indicators in regard to the main benefit sought, but not the co-benefits. Therefore, the examples in this catalogue were chosen because these projects specifically monitored the adaptive and mitigation capacity of these measures for drying. However, this does not mean that the measures do not provide other benefits, including but not limited to water purification, temperature regulation, biodiversity increase, and cultural services.

NATURAL VEGETATION MANAGEMENT

Vegetation profoundly affects hydrological processes in a catchment, including rainfall redistribution, infiltration and percolation, soil moisture storage and distribution, evapotranspiration (ET), and runoff generation (Jin et al., 2020). Vegetation impacts water balance through shading and blanketing, transpiration, creation and maintenance of soil porosity, etc. Restoring, preserving, and maintaining the type and extent of naturally occurring vegetation cover has proven to be the most efficient in all climates. However, revegetation is difficult in the arid zone due to a combination of environmental factors such as low moisture and extreme temperatures, as well as financial and administrative factors (Stapleton et al., 2023). Therefore, engage with the local ecosystems' experts to understand and develop the most suitable natural vegetation management for your catchment. Finally, Stapleton et al. (2023) assessed the utility of various methods available for arid revegetation.

Open forest management

Figure 2: Prescribed forest burning (Author: Bill Gabbert/ Fotolia, source: https://www.britannica.com/science/prescribed-fire).

Examples of implementation

- Multiple examples from around the world in a Frontiers Special Issue prescribed burning in fire-prone landscapes.
- The US Forest Service (USFS) recently launched the first and largest restoration effort in US history known as the Four Forest Restoration Initiative (4FRI) in Arizona to reduce the wildfire hazard: https://www.fs.usda.gov/4fri, https://4fri.org/
- Prescribed burning has been practiced in some regions of Southern Europe to prevent wildfires since the 1970s, but its potential contribution to drought prevention has not yet been widely recognised (Fernandes et al., 2013).

Description

Targeted measures such as felling of trees, burning understory, or rotating pastures create and maintain patchy landscapes, similar to the historic distribution of small groups of trees mixed with open interspaces (Allen et al., 2002; USDA, 2013) in semi-arid regions.

Catchment response to burning depends on vegetation type (Wright, 1974), fire intensity, topography and soils, season of burning (McMurphy and Anderson, 1965), and probably most importantly, climate conditions following the burn (Simanton et al., 1990).

Benefits to water balance

The vegetation of arid and semi-arid regions generally consists of a mosaic or pattern composed of patches with high biomass cover (e.g., trees) interspersed within a low-cover component such as bushes and grasslands (Saco et al., 2006; Ludwig et al., 2004). Vegetation affects soil properties through soil-vegetation interaction (soil organic matter content, porosity, and bulk density) that results in a higher infiltration rate and greater soil water retention capacity (Wang et al., 2013; Sarah, 2002; Ludwig et al., 2004). Therefore, open forest management is a method of restoring the natural pattern of vegetation cover typical for semi-arid and arid regions that results in a higher infiltration rate and greater soil water retention capacity (see also Revegetation).

Natural revegetation
(also land abandonment or rewilding)

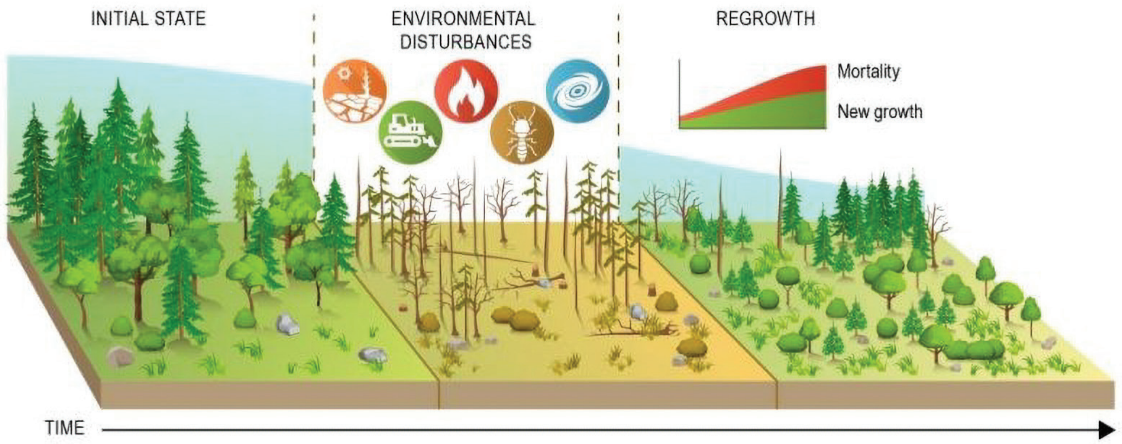

Figure 3: A schematic representation of a natural revegetation process (Source: Pacific Northwest National Laboratory).

Description

Revegetation includes natural or supported regrowth of natural vegetation—a mix of herbacious plants, shrubs, and/or trees that were historically present in the catchment. Parameters such as altitude, slope, radiation, temperature, precipitation, and many others determine natural vegetation cover and should therefore be considered when planning re-vegetation actions (Gao et al., 2017).

Benefits to water balance

The enhanced infiltration rates under vegetated patches are due to improved soil aggregation and macroporosity related to biological activity (e.g., termites, ants, and earthworms are very active in semi-arid areas) and vegetation roots (Ludwig et al., 2005). The amount of water received and infiltrated into the vegetation patches, which includes runon from bare areas, can be up to 200% the actual precipitation (Valentin et al., 1999; Wilcox et al., 2003; Dunkerley, 2002). The runoff-runon mechanism triggers a positive feedback that increases soil moisture in vegetated patches, thus reinforcing the pattern (Puigdefabregas et al., 1999; Valentin et al., 1999; Wilcox et al., 2003). The redistribution of water from bare patches (source areas) to vegetation patches (sink areas) is a fundamental process within drylands that may be disrupted if the vegetation patch structure is disturbed (Saco et al., 2006; Ludwig et al., 2004). Finally, Yosef et al. (2018) found that large-scale semi-arid afforestation can change local climatic conditions by enhancing precipitation and carbon sequestration potential and thus mitigating climate change.

Examples of implementation

- Landscape interventions in the arid and semi-arid regions around the world show that establishment of tree plantations instead of natural vegetation leads to the deterioration of soil ecosystems and exacerbates water shortages (Chazdon, 2008) in China (Jia et al., 2017; Rodríguez et al., 2016; Shao et al., 2018; Liu et al., 2020; Cao et al., 2011; Cao et al., 2018), Patagonia (Milkovic et al., 2019), Nebraska (Adane et al., 2018), and Ecuador (Balthazar et al., 2015). These and many other cases clearly show the danger of ignorance to climate, pedological, hydrological, ecological, and landscape factors when implementing NBS. Great care should be taken not to confuse NBS with plantations, exotic or economically efficient species planting, or similar.
- Li and Shao (2006) found that soil physical properties improved with a succession of natural vegetation from pioneer grassland to climax forest on degraded farmland in semi-arid Loess Plateau in China. Changes such as reduced soil bulk density increased soil aggregate stability, and saturated hydraulic conductivity were detected.
- The research conducted in the Western Mediterranean Mountains (Romero-Díaz et al., 2017) showed that vegetation recovery after abandonment was very successful under different parent materials and climate conditions except on marls under semiarid conditions. The vegetation recovery determined the increase in SOM, which in turn resulted in a general improvement of soil properties with an increase in the infiltration rates and soil moisture levels and a reduction in the soil losses.

Restoration and conservation of riparian vegetation

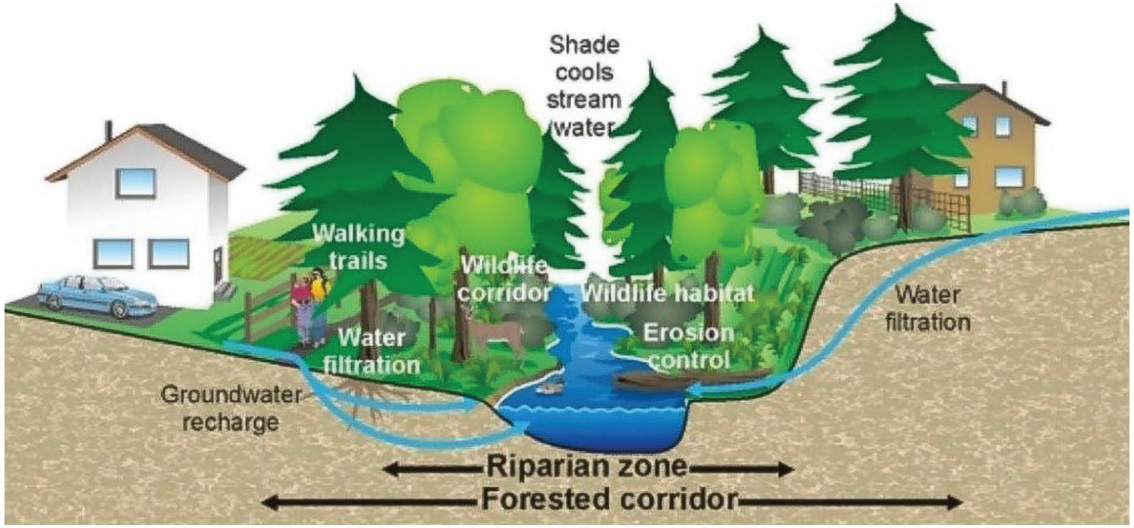

Figure 4: A schematic representation of riparian vegetation functions (Source: Karin'ga, 2018).

Examples of implementation

- A revision by Li et al. (2021) suggests that planted forests and shrubs are acceptable only when precipitation is greater than 480 mm, while grassland may be the best restoration type if precipitation is less than 480 mm.
- Salinas and Guirado (2002) found that successful restoration of riparian vegetation in semiarid zones in Spain is relatively easy but slow.
- Opperman and Merenlender (2004) monitored passive restoration through fencing in the Meditteranean climate of California. Dense vegetation established within a decade with benefits to channel morphology and water temperature, greatly restoring fish habitat.

Description

A riparian zone includes vegetation along river margins and banks, characterised by hydrophilic plants. Semiarid riparian vegetation is the only type of arboreal/shrubby vegetation in these areas and differs markedly in phenology from the other communities, thus giving the landscape distinctive features (Salinas and Guirado, 2002).

It functions as a buffer and an exchange zone between aquatic and terrestrial ecosystems, with an influx of seasonal water deposits making water availability high, making it especially important but also vulnerable. Cole et al. (2020) and Riis et al. (2020) present a good review of the many aspects of riparian vegetation.

Specialised revegetation approaches and techniques are required for arid and semi-arid regions (Greet et al., 2020; Webb and Erskine, 2003), from deep planting, dormant pole planting, or live stake planting (Dreesen and Fenchel, 2010), to exotic species control and eradication (McCown, 1998). However, these techniques will only be effective if natural flow dynamics are restored simultaneously (Stromberg, 2001).

Benefits to water balance

The highest ecological impacts in river restoration are achieved for actions focusing on enhancing the riparian vegetation (Palmer et al., 2014). Riparian buffers simultaneously provide natural flood control for the arid landscape (McCown, 1998) by reducing bank erosion, slowing the flow of water from the land into receiving water bodies, increasing soil porosity and infiltration, providing temporary water storage (Rood et al., 2014; Dixon et al., 2015; O'Hare et al., 2016; Perez et al., 2017), trap pollutants (Knight et al., 2010; Erktan et al., 2013; Lin et al., 2011), sequester carbon ((Borin et al., 2010; Udawatta and Jose, 2012; Christen and Dalgaard, 2013) and contribute to the regulation of the river's microclimate (Riis et al., 2020; Broadmeadow et al., 2011; Thomas et al., 2016), thus buffering climate extremes (Boutin et al., 2003; Maisonneuve and Rioux, 2001; Paine and Ribic, 2002).

Deep planting techniques

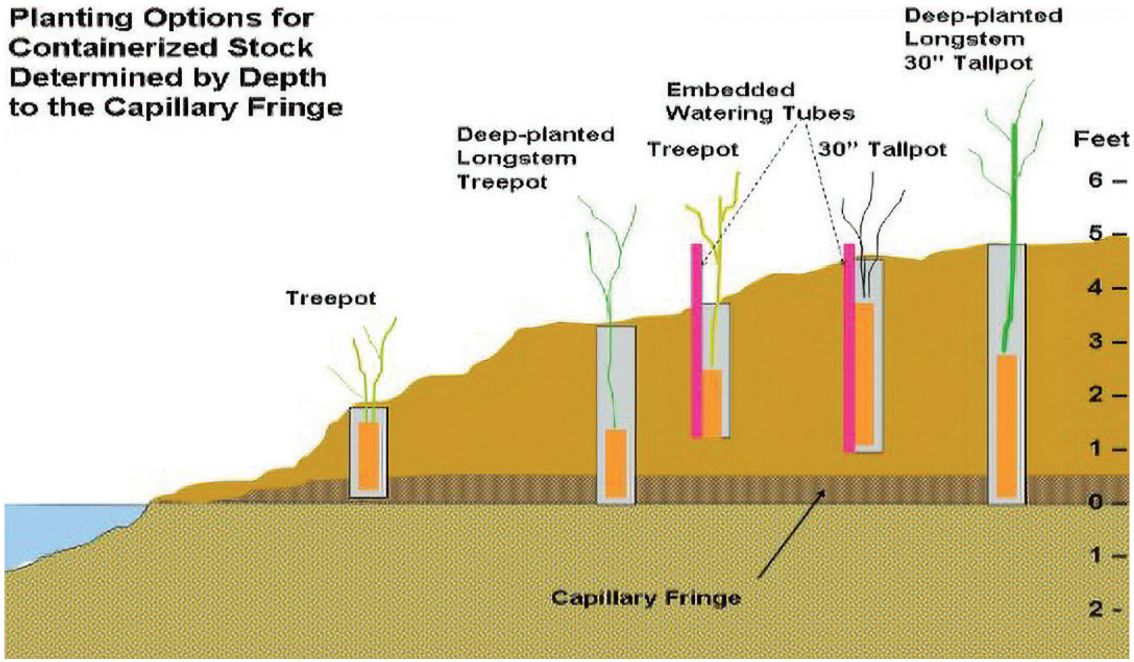

Figure 5: Planting options for containerised stock determined by depth to the capillary fringe (Source: Guidelines for Planting Longstem Transplants for Riparian Restoration in the Southwest, USDA).

Description

Deep planting techniques, which require minimal or no post-planting irrigation in arid and semiarid regions, include the planting of dormant pole cuttings, dormant whip cuttings, tallpots with long root systems, as well as long-stem nursery stock whose root crowns are deeply buried (Dreesen and Fenchel, 2010). Note that this approach violates several basic horticultural tenets that consider deep burial of the root crown and transplants that have large shoot-to-root ratios as detrimental practices (Dreesen and Fenchel, 2010).

Benefits to water balance

These techniques aim for the immediate exploitation of capillary fringe moisture by the existing root system of nursery stock or the adventitious root system of a cutting. The depth of the planting hole must be sufficient for the stump end of the pole to be in groundwater throughout the growing season even if the water table drops (Anderson, 1996; Mahoney and Rood, 1998; González-Sargas et al., 2018). The deep-planting of long-stem stock can preclude or drastically reduce the need to apply irrigation water to establish riparian shrubs and trees (Dreesen and Fenchel, 2010).

Examples of implementation

- Chirino et al. (2008) conclude that deep containers produce seedlings of Quercus suber L. with a longer tap root that can quickly reach the deeper soil horizons by means of higher growth in the number and biomass of new roots. The higher root water transport capacity of these root systems contributes to a better water status under drought stress conditions.
- Hall et al. (2015) indicate that in Oregon, USA, deep-planting cottonwood (Populus trichocarpa) and willow (Salix spp.) pole cuttings in augered holes that penetrated the water tables up to 1.9 m below the surface significantly increased the probability of survival by a factor of 7. In combination with 0.9-m vented plastic tree shelters, the probability of survival resulted in over 50% higher survival after three years compared to unprotected and 1.-m circular fence caged plants that were also deep-planted with access to water.
- On the San Rafael River in Utah (USA), Laub et al. (2019) found that elevation above the water surface and soil properties were the primary limiting factors for successful riparian restoration. Survival probability decreased with elevation above the river channel bottom and was greater in auger-dug than hand-dug holes. Survival probability was lower in soils with the highest salinity levels and was lower in sandy soils than soils with silt and clay. However, a full recovery of desired riparian habitat throughout the floodplain will require natural flows.

Buffer strips and hedges

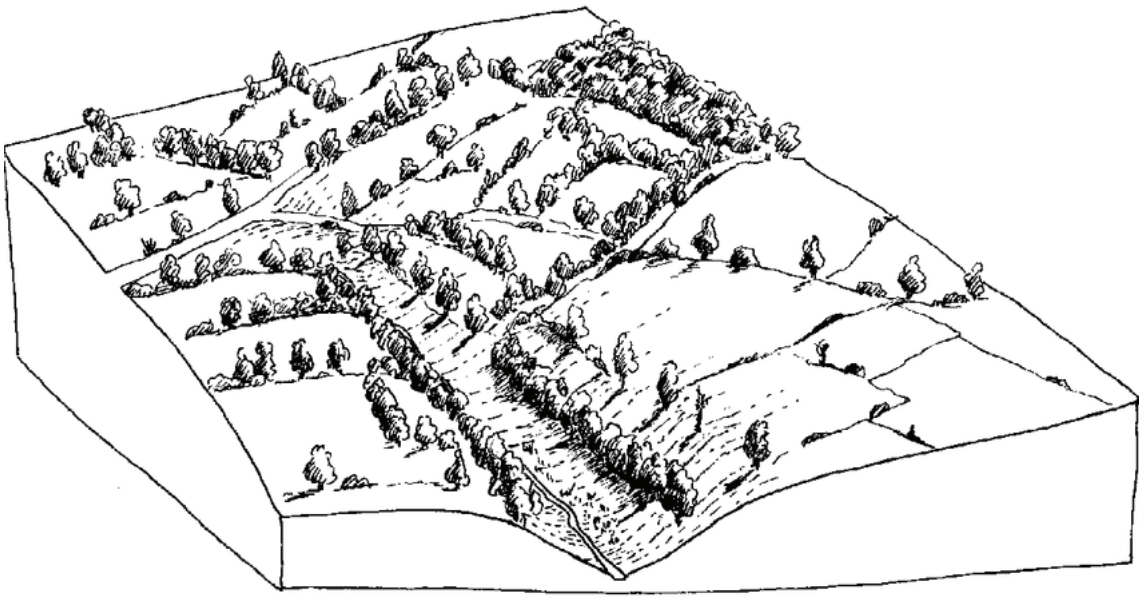

Figure 6: A schematic representation of buffer strips and hedges in a catchment (Source: Baudry et al., 2010).

Description
Buffer strips and hedges are vegetated margins of fields, arable land, and/or transport infrastructure made up of grass, shrubs and/or trees (NWRM illustrated, 2013). Since the vegetative cover is permanent, it offers effective water infiltration, prevention of surface flow, and water retention. These buffers mitigate nutrient leaching in groundwater and reduce surface water runoff velocity. Along streams, vegetated buffer zones decrease phosphorus loading and enhance water quality by mitigating sediment and nutrient erosion from nearby watersheds (Vought et al., 1995).

Benefits to water balance
Vegetation along naturally meandering streams serves as effective flood control by reducing stream flow. While natural inputs of woody debris may lead to localised flooding, downstream flooding can be minimised (Vought et al., 1995). Furthermore, large permanent vegetation strips enhance water infiltration and herbicide adsorption (Piscoya et al., 2018), attributed to increased water ponding above the hedges (Liu et al., 2018).

Examples of implementation
- In a study from Burkina Faso in a north-sudanian climate, surface water runoff was effectively controlled by combining stone rows and grass strips. This approach enhanced surface water storage and infiltration while also reducing runoff velocity (Zougmore et al., 2004).
- In mountainous olive production systems in the Mediterranean basin with 30% slope in Spain, Zuzazo et al. (2009) found that using native vegetation and barley strips reduced runoff by 94%-95%. Plant strips slow down runoff and encourage infiltration, providing water to the roots of olive trees.
- In India, vegetative hedges from native Veitver grass were established to decrease runoff and conserve water in agriculture (Lal, 2008).

CONSERVATION AGRICULTURE

Agriculture is the largest water consumer in the world, accounting for 70% of total use (Qin et al., 2019). Global warming and irregular rainfall patterns are responsible for the shortage of water resources, which limit agricultural production in arid and semi-arid regions (Qin, 2015; Li et al., 2017). Conservation agriculture is a group of approaches for improving agricultural productivity while maintaining water availability, soil structure, function, and biodiversity. The primary goal of soil moisture conservation is to reduce the quantity of water lost from plants via transpiration and from the soil through evaporation or combined evapotranspiration (FAO, 2003).

Keyline design

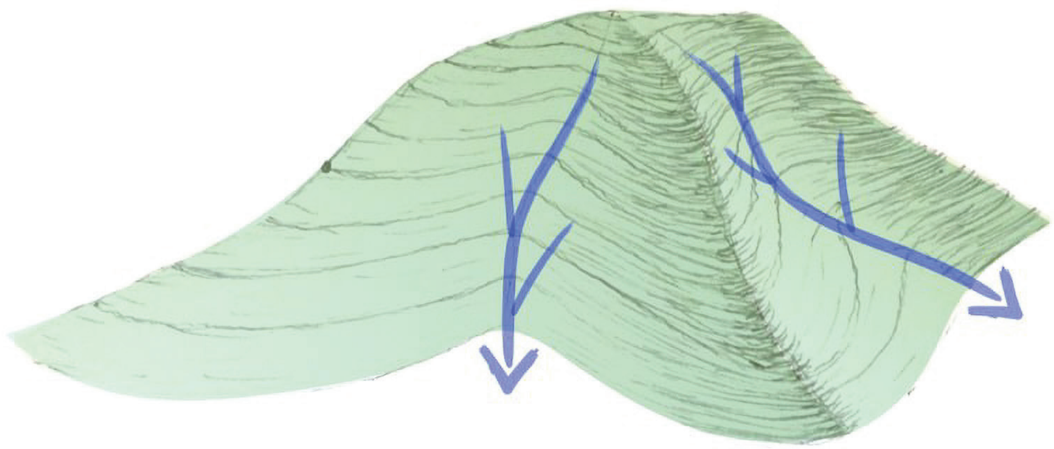

Figure 7: Schematic representation of the landscape application of the keyline/soil bund principle (Source: https://www.elegantexperiments.net).

Description

Keyline design is a group of similar measures from across the world that aim to consciously slow, sink, spread, and store rainwater by relieving compaction, opening up pore space in compacted soil, and distributing excess water towards drier parts of the landscape. On mild hillslopes, regular vegetation bends form naturally perpendicular to the overland sheet flow (Saco et al., 2006). This can also be achieved by artificially establishing relief lines that fall slightly off contour, thus maximizing the flow to drier ridges and allowing water infiltration across the broadest possible area (P. A. Yeomans, 1954; Ouesar, 2021; Jabali et al., 2017). In this respect, keyline design strategies can be both a flood and drought mitigation strategy. Examples include, but are not limited to, plow lines/keylines, contour farming, terraces, trenches, soil bunds, stone bunds, grass strips, micro basins, semi-circle terraces, tied ridges, etc. In Africa and Asia, furrows combined with windbreaks have improved water use efficiency (Jitan and Mudabber, 2011).

Benefits to water balance

Contour farming reduces runoff and enhances water infiltration into vadose and aquifer zones, resulting in raising shallow groundwater levels in surrounding wells and contributing to streamflow during the extended dry seasons (Meaza et al., 2022; Keyline Water Management). These measures, if implemented correctly, can also reduce soil loss and increase crop yield in the farmlands considerably (Gebremeskel et al., 2018).

Examples of implementation

- Keyline design was first developed in the late 1940's by Australian mining geologist and engineer P. A. Yeomans (Hill, 2003). Recent examples of application include the Keyline Water Management project in Canada and a reference page on keyline design application in Australia.
- Soil bunds in Ethiopia (Guadie et al., 2020; Chimdesa, 2016; Meaza et al., 2022).
- A review of a variety of different keyline design measures introduced in Tunisia over many centuries is available in Ouessar et al. (2021). Lamachère and Nasri et al. (2004) and Nasri et al. (2004) found that the contour ridges in central Tunisia called tabia reduced surface runoff to essentially zero.

Intercropping

Figure 8: Typical intercropping patterns based on maize, including (c) maize-pea intercropping; (d) maize-soybean intercropping; (e) maize-peanut intercropping; and (f) maize-rape intercropping, respectively (Source: Yin et al., 2020).

Examples of implementation

- Mao et al. (2012) confirmed reduced water consumption of maize (Zea mays L.)-pea (Pisum sativum L.) strip intercropping in the arid region of Wuwei, Gansu Province, Northwestern China, only for a specific spatial arrangement.
- In South Africa, Chimonyo et al. (2019) associated an increase in WUE for sorghum biomass (WUEb) and yield (WUEg) with reduced WU across different water regimes, including rainfed.
- In the semi-arid state of Pernambuco, Brazil, Souza et al. (2023) found that intercropping the cactus and millet considerably increased the WUE of the production system.

Description

Intercropping is a farming practice where two or more crop species with contrasting growth habits are planted on the same field. It can increase the utilization efficiency of resources such as light, heat, water (Fan et al., 2012) and nutrients (Hauggaard-Nielsen and Jensen, 2005; Chu et al., 2004) in order to enhance yield (Fan et al., 2012; Willey, 1990; Brooker et al., 2015; Hu et al., 2017; Yin et al., 2020). As with all NBS, water consumption of intercropping systems varies greatly due to environmental conditions, crop types (Morris and Garrity, 1993), and spatial arrangement (Yin et al., 2020), so detailed knowledge of the crops and growth conditions is required to ensure an efficient intercropping system.

Benefits to water balance

The advantage of efficient water utilization in intercropping results from the physiological and ecological characteristics of intercrops (Yin et al., 2020) and spatiotemporal differences in water demand/complementarity between intercrops (Dong et al., 2018; Morris and Garrity, 1993; Bai et al., 2016; Fan et al., 2013). Soil evaporation is lower due to increased shading/increased canopy closure (Cooper et al., 1987; Wallace, 2000; Mushagalusa et al., 2008) and consequent lower soil surface temperatures (Cooper et al., 1987). Therefore, selection of intercropped species and their spatial arrangement is the key for success (Mao et al., 2012; Raza et al., 2022; Souza et al., 2023).

Mulching

Figure 9: Examples of mulching practices: A. Leaves (Source: http://www.ecosecretz.com/2017/12/all-about-mulching.html), B. Crop residue (Source: http://www.agritech.tnau.ac.in/agriculture/agri_majorareas_dryland_agromeasures_mulching.html), C. Straw mulch (https://eorganic.org/node/4871) and D. Straw mulch (Sherry Galey / Getty Images).

Examples of implementation

- El–Metwally et al. (2021) found that soil mulching, particularly when using peanut straw, was the effective practice for maintaining soil moisture as well as suppressing weed growth and increasing the marketable yield under a specific trickle irrigation regime in the arid region of Egypt.
- In the semi-arid area of the Central Dry Zone of Myanmar, Michelon et al. (2020) confirmed that an accurate drip irrigation system combined with mulching technology increases yield and improves the WUE of lettuce production.
- In the semi-arid eastern Rwanda, Hitimana et al. (2021) established that the soil moisture content increased up to 1.3 times when mulched with rice straw, 1.25 times for bean straw, and 1.24 times for cut grass in the top soil of the depth between 0-10 cm, but no change was detected in the deeper layer (10-30 cm).

Description

Mulching is a farming practice of covering bare soils with an organic or synthetic mulch to insulate soil and protect organisms, thus saving water and rising production, especially in dryland farming (Chakraborty et al., 2008; Kader et al., 2017; Kasirajan and Ngouajio, 2012; Souza et al., 2023; Abd El-Mageed et al., 2016). Kader et al. (2019) offer a good review of the benefits of mulching. Locally available organic mulch such as crop residue, leaves, fruit shells, and straw decays over time and adds nutrients to the soil (Larentzaki et al., 2008; Ranjan et al., 2017), while plastic mulch is discouraged due to the negative impacts of micro- and nano-plastics on human and environmental health (Steinmetz et al., 2016, Gonzalez-Dugo et al., 2014; Dai et al., 2022).

Benefits to water balance

By physical insulation of soil from water droplets hitting the soil surface, compaction is reduced, thus increasing its water holding capacity while also reducing the need for tillage (Kumar et al., 2021; Kader et al., 2019; Andoh-Mensah et al., 2023). Soilwater loss is reduced due to reduced soil temperatures and evaporation (Tarara, 2000; Liu et al., 2015; Kader et al., 2017). Mulch creates a buffer that helps with water absorption by plants and rainfall infiltration (Kader et al., 2019). All these contribute to a considerable increase in water use efficiency.

Agroforestry

Figure 10: Tanzania. Photo: Elin Larsson (Agroforestry Network, 2022).

Examples of implementation

- Bai et al. (2016) found that in the semi-arid area of the Khorchin region in Liaoning, China, mixing crops and trees did not increase water extraction from the top 100 or 200 cm soil profile compared to sole trees. Apricot yields were not significantly affected in the agroforestry, while crop rows near tree rows had lower yields than monoculture stands. They conclude that apricot-based agroforestry improves the productivity and water use efficiency of rain-fed agriculture.
- A review from Krishnamurthy et al. (2019) presents a number of different agroforestry systems in Latin American countries and includes a range of benefits as perceived by farmers as well as measured by scientists.
- Droppelmann et al. (2000) found complementarity in water use between pruned trees and annual intercrops in the Turkana district of Northern Kenya. The water use efficiency of the agroforestry system was not affected by the pruning of the trees but by their planting density and the presence of an intercrop.

Description

Agroforestry is the planting of multiple native species of woody perennials, vegetables, and/or other crops on the same land management unit, predominantly in arid and semi-arid regions around the world. Detailed knowledge of local growth conditions and species' characteristics is required to select a successful and efficient combination. Specifics such as leafing phenology (Broadhead et al., 2003; Muthuri et al., 2005), rooting architecture (Ong et al., 2007; Bargués et al., 2017; Bayala and Prieto, 2020), nutrient requirements (Ong et al., 2007), pests, competitive interactions, and similar are important on the species side, while water cycle, solar irradiance, soil composition, wind, and the like are to be taken into account on the growth conditions side (Muthuri et al., 2007; Bayala and Prieto, 2020; Feng et al., 2022).

Benefits to water balance

Rather than conserving water, agroforestry systems increase water and nutrient use efficiency (Feng et al., 2010; Bai et al., 2016; Broadhead et al., 2003; Muthuri et al., 2007; Bayala and Prieto, 2020). Soil evaporation is reduced due to shading by the canopy and increased root density (Wallace et al., 1999; Ghanbari et al., 2010). Additional water resources are exploited by deep rooting tree species, as these capture water that percolates to soil horizons below the crop rooting zone after heavy rainfall (Ong et al., 2007) and redistribute it back to the surface in dry periods (Bayala and Prieto, 2020). Finally, temporal complementarity ensures water usage throughout the year, as trees are deciduous during part of the cropping season or continue to extract water during the dry season (Black and Ong, 2000; Broadhead et al., 2003; Ong et al., 2007; Xue et al., 2021).

Natural stock management

Figure 11: Semi-arid grass in three different states: A –healthy and dense vegetation; B – degraded due to overgrazing; C – close-up view of picture B (Source: https://www.frontiersin.org/articles/10.3389/fenvs.2022.846045/full).

Description

Natural stock management includes measures that reduce grazing pressure on native vegetation. This can be achieved either by reducing the number of animals on a given unit of grazing area (reduced stocking density) or completely excluding grazing animals from an area for a set amount of time (exclusion or rotation). The aim of this management approach is to replicate natural ecosystems where the livestock population aligns with the specific ecosystem's capacity and cycles. This approach helps preserve resources such as water, soil, wildlife, and plants (Encinias and Smallidge, 2023; Bailey and Brown, 2011; Asner et al., 2004).

Benefits to water balance

Long-term grazing management impacts the ecosystem stability (Greene et al., 1994). Low stocking rates reduce the amount of soil compaction and improve vegetation cover (Teague and Kreuter, 2020). This leads to faster infiltration during precipitation events and higher water retention capacities (McDonald et al., 2019). Only grasslands in good condition effectively respond to rainfall fluctuations within their ecosystem limits (Snyman, 1999). The infiltration rate of simulated rainfall at 30 mm h-1 between bare and natural soil in Australia increased from 4-6 mm h-1 to >20 mm h-1 in natural soil (McDonald, 2019).

Examples of implementation

- Different models for water use efficiency in South Africa's semi-arid Savanna ecosystem show that lower animal density reduces uncertainty in response to climate scenarios, with less variation in water use efficiency compared to higher densities. Proposed solutions include diversifying herbivores, increasing plant diversity, and reducing grazer stocking rates (Irob et al., 2024).
- Degraded steppes can be rehabilitated by planting native grasses to stimulate natural regeneration. Additionally, adopting rotational grazing systems, which involve short periods of free grazing alternated with grazing exclusion, along with effective grazing management practices, can help prevent overgrazing and soil trampling (Chenchouni and Neffar, 2022).
- The Loess Hills Grassbank in Loess Hills State Forest, Iowa, United States, is grazed by a third of the normal stocking rate for grazing, to open up a stand of grass, encourage more diversity in plants and structure, and ultimately leave a lot of grass in the pasture after grazing (Leopold Center, 2009).

RESTORING CONNECTIVITY

River or freshwater connectivity is essential for healthy ecosystems, supporting biodiversity, and delivering various ecosystem services. River connectivity extends in four dimensions, as presented by Ward (1989): 1st longitudinally (upstream and downstream in the river channel, including to estuarine and ocean systems), 2nd laterally (between the main channel, floodplain, and riparian areas), 3rd vertically (in relation to groundwater, river, and atmosphere), and 4th temporally (seasonal variations in natural flow; Ward, 1989; Thieme et al., 2023). Alterations to these dimensions affect river processes and ecological integrity, leading to fragmentation, biodiversity loss, and changes in energy flow and vegetation (Ward, 1989; Thieme et al., 2023). As pointed out by Lytle and Poff (2004), river connectivity represents the template upon which freshwater species have evolved. Restoring connectivity means rehabilitating floodplains, recharging groundwater, and supporting diverse habitats, flood protection, carbon storage, and providing new areas for recreation (Garcia de Leaniz et al., 2023).

Removal of barriers

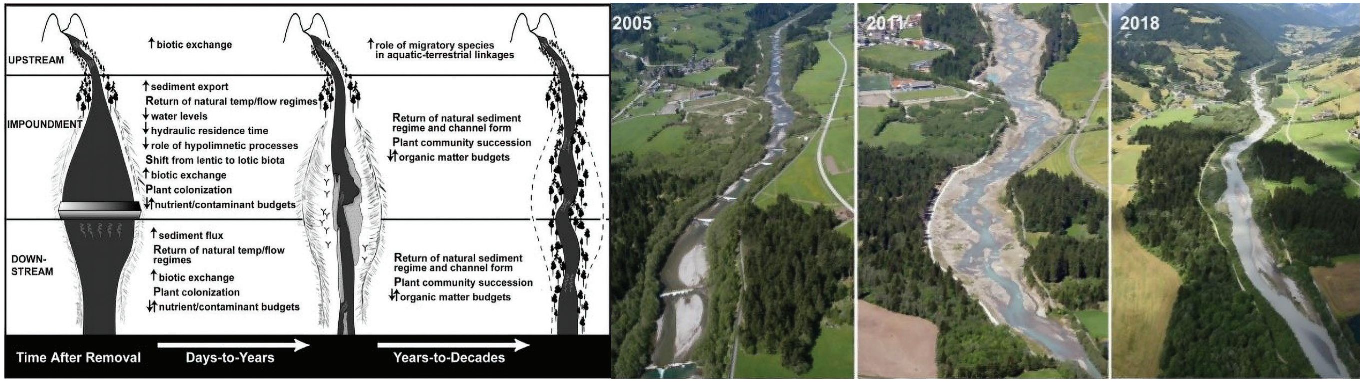

Figure 12: The changes in channel morphology after dam removal (Source: Hart et al., 2002 & Scorpio et al., 2020).

Descriptions

Barrier removal is a form of river restoration that eliminates artificial obstacles disrupting water flow, sediment transport, organism movement (Poff et al., 1997; van de Bund et al., 2024; Dam Removal Europe, 2024), water temperatures (Poff and Hart, 2002), and natural hydrological regimes (Beatty et al., 2013). It restores longitudinal processes and connectivity, enhancing riverbed dynamics, discharge patterns, and biodiversity (Beatty et al., 2013; Poff and Hart, 2002; Graf, 2002) by enhancing nutrient transport and increasing food sources for aquatic organisms (Lei et al., 2023). Many barriers in the 21st century are non-functional and expensive to maintain, with removal being 10 to 30 times cheaper (Grabowski et al., 2018; Costa and Vieira, 2023). Particularly, aging dams pose serious safety risks (Yang et al., 2011).

Benefits to water balance

Restoring natural flow improves the management of excess runoff, reduces the extremes of high and low water levels, and contributes to a more stable hydrological regime (Bednarek, 2001; Beatty et al., 2013). In arid and semi-arid landscapes, barrier removal greatly reduces evaporation losses from reservoirs (Shiklomanov, 1998) and enhances the resilience and health of freshwater ecosystems (Beatty et al., 2013).

Examples of implementation

- Since dam removal has only recently appeared as a management option, monitoring is commonly not implemented or focuses on benefits to the biodiversity; examples of measured benefits to water balance are not yet available. However, existing data indicates that rivers recover fast and the negative impacts of dams are reversed. This means that huge evaporation losses from reservoirs are mitigated immediately, which is especially important for arid and semi-arid regions.
- The removal of the 14-meter-wide and 1.1-meter-high Vaqueiros Weir on the Alviela River in Portugal, led by GEOTA and local stakeholders, restored a 100-meter section of the river. This effort stabilised banks, rehabilitated riparian vegetation, and re-established 3.3 km of connectivity, improving water turbidity and reducing the number of invasive species in the river (DRE, 2024, accessed June 29, 2024; Brotherton, 2024, accessed June 29, 2024).
- In April 2018, the Duero River Basin Authority began demolishing the 22-meter-high Yecla de Yeltes Dam, reconnecting 27 km of the Huebra River. As the dam was inside the Natura 2000 network, its removal positively contributed to the habitat restoration, benefiting otters, European pond turtles, trout, the endangered endemic species Sarda, as well as oak trees and the local community (Schiermeier, 2018).
- The removal of 4 large dams on the Klamath River in Oregon, US, could be the most studied dam removal in recent years (USGS, 2022). While a number of ecological, geological, and other aspects are monitored, this case is especially valuable in terms of its socio-economic aspects, presented in the study by Gosnell and Kelly (2010).

Restoring natural flow dynamics

Figure 13: After years of no flow due to extensive hydropower and irrigation upstream, water returns to the Colorado delta as part of a flow restoration project (Source: Raise the River).

Description

Rivers exhibit seasonal and interannual flow variations due to factors such as river size, climate, geology, topography, and vegetative cover (Poff et al., 1997; Rood et al., 2005). Natural flow dynamics can be restored through dam removal or changes in dam operations (Hughes and Rood, 2003; Stromberg, 2001; Glenn et al., 2017). Water storage in aquifers, recycling municipal water into stream channels, using stream channels for water delivery, and increasing water-use efficiency can help reduce extraction demands (Stromberg, 2001). Appropriate flow regulation should allow for flow variation reflecting the natural hydrograph (Poff et al., 1997; Richter and Richter, 2000; Hughes and Rood, 2003) and interannual dynamics (Rood et al., 2005). Five critical flow regime components—magnitude, frequency, duration, timing, and rate of change—regulate ecological processes in river ecosystems (Poff and Ward, 1989; Richter et al., 1996; Poff et al., 1997).

Benefits to water balance

Flow variability through time is linked to higher biological diversity (Costelloe et al., 2003). Natural flood dynamics are essential for the perpetuation of floodplain forests (Hughes and Rood, 2003; Colloff & Baldwin, 2010; Cunningham et al., 2011), refilling groundwater supply (Xu et al., 2007; Hao and Li, 2014; Zhu et al., 2016; Stromberg, 2001), fish reproduction (Scoppettone et al., 2000; Enders et al., 2009), sediment deposition, and fire-proofing riparian ecosystems by flushing deadwood down the river (Stromberg, 2001; Ralston and Sarr, 2017). Other organisms, including bats, insects, and other invertebrates, as well as understory plants, also benefit directly and indirectly from changing flow regimes and woodland restoration (Holloway and Barclay, 2000; Ellis et al., 2001; Holl and Crone, 2004). In arid regions, opportunities for altering flow operations are particularly important during high-flow years because it is these years that are naturally responsible for pulses of woody plant recruitment (Rood et al., 2005; Poff et al., 1997).

Examples of implementation

- The Ecological Water Conveyance Project (EWCP) in Western China (Xu et al., 2007; Hao & Li, 2014; Zhu et al., 2016) resulted in a considerable increase in groundwater level in the floodplain with related benefits to vegetation and biodiversity.
- The Colorado River Basin Authority (US) allocated 195 hm3 of water for environmental flows into the CR delta over a five-year period (2013–2017). Monitoring showed an increase in water table (Ramírez-Hernández et al., 2017) and vegetation cover (Nagler et al., 2018).
- Konrad et al. (2011) offer an extensive overview of past flow management projects from North America, Africa, and Australia.

Floodplain restoration

Figure 14: Left: Previously dry floodplain with "The Middle Training Wall" –a tall linear structure constructed by dredge miners to redirect the river's flow. Right: The perennial channel now running through the floodplain that will, hopefully, be frequently inundated (Source: CBEC, Inc. Eco Engineering).

Description

Floodplain restoration involves reinstating floods through lowering, relocation, or removal of dykes coupled with the restoration of natural flow dynamics (Serra-Llobet et al., 2022), as well as legacy sediment removal, afforestation, plantation of native vegetation, and the adjustment of agricultural practices (NWRM report, 2013). The aim is to restore lateral connectivity, and with it, a functional water cycle in the floodplains with documented benefits to biodiversity (Jenkins and Boulton, 2007; Serra-Llobet et al., 2022) and other ecosystem services (Tockner and Stanford, 2002; Hohensinner et al., 2014; Dawson et al., 2017; Díaz-Redondo et al., 2021).

Benefits to water balance

After restoration, natural functions of floodplains are reinstated. A recovered floodplain naturally slows down the river flow, increases groundwater recharge through increased infiltration (i.e., up to 25% reduction in flood peak (Ahilan et al., 2018)) and soil water retention (NWRM report, 2013), reduces erosion (McMillan and Noe, 2017), and improves riparian as well as terrestrial habitats, including riparian vegetation recovery (González et al., 2017). Water quality is improved due to the increased sediment trapping, coupled with the retention of nutrients and pollutants (McMillan and Noe, 2017).

Examples of implementation

- In 2008, the New South Wales and Australian governments restored a 2436 ha area of the Macquarie Marshes in the Murray-Darling Basin. Results show that different biodiversity baselines need to be taken into account when planning for restoration (Dawson et al., 2017).
- The Hallwood Side Channel and Floodplain Restoration Project (Yuba River, California, USA) aims to restore the seasonally inundated floodplains (157 acres) with riparian and aquatic habitats on a former mining site (Southall et al., 2022).
- The project on the Orbigo River in Spain reconnected the floodplain to the main stream, revitalised the flowing water, levelled longitudinal barriers, stabilised the natural banks, eliminated the riverbank protection, and restored the riparian buffer zone to improve the lateral and longitudinal connectivity and natural dynamics of the river (Rodríguez Muñoz et al., 2013).

Re-meandering

Figure 15: Left: Picture Canyon in May 22, 2010. Right: Picture Canyon in May 15, 2011. A result of the Rio de Flag Meander Restoration Project (Source: Friends of the Rio de Flag, Meander restoration, accessed June 17, 2024, photo by Tom Bean).

Description

Re-meandering is one of the practices for restoration of the original river course (Lancaster and Brass, 2002; Sand-Jensen et al., 2006; Feld et al., 2011; Eekhout et al., 2015). The re-meandering process should follow old meanders when possible – planning needs to be in line with local historical maps (Feld et al., 2011), as the modification on rivers historically without meanders showed potential for the increased risk of flooding (NWRM report, 2013). Meandering sections can be re-established through excavations to accelerate the recovery of the stream or naturally through manipulating the streambank vegetation and utilizing the power of running water (Zeedyk, 2009).

Benefits to water balance

Re-meandering has the potential to increase channel heterogeneity, water storage capacity of the river (enhanced water retention time also increases denitrification (Jeppesen et al., 2011), hydraulic habitat diversity and suitability, and to reduce flood flow velocity (Gilvear et al., 2013; NWRM report, 2013). When planned appropriately, it can also lead to riparian vegetation recovery and thus through land cover modification to altering soil water retention capacity (NWRM report, 2013). It also aids the lowland stream and wetland restoration, and increases the invertebrate diversity (Bullock et al., 2011; Pedersen et al., 2014; Giergiczny et al., 2022). Re-meandering in arid climates, such as in Australia, improves the instream habitat while minimizing the increase in flood risk (Rutherfurd et al., 2000).

Examples of implementation

- Megdal et al. (2006) list projects restoring rivers in Arizona, USA. The Yuma East Wetland Project included structural changes in channelization and open water elements, coupled with the removal of non-native vegetation. This reduced evaporative losses of water, resulting in consumptive water savings of 1073135.43 m3 per year.
- Tributary streams of the Clauge were prone to intermittence, resulting in the drying of the main river. The historical hydrological conditions were restored on 32 tributaries (2007-2019). Monitoring after the re-meandering showed that water remained in the soil for an additional 15-20 days in springtime, and the number of EPT macroinvertebrate taxa (Ephemeroptera, Plecotera, Tricoptera) doubled between 2006 and 2018 (Magand et al., 2020).
- Since the 1870s, 66 meanders have been cut off on the Latrobe River, Australia, reducing the stream by 25%. Six of the original meanders were restored by the Lake Wellington Rivers Authority, leading to the pilot cut development in the historical channels within the next 2 years. The effect of re-meandering on the bank erosion was not formally monitored or evaluated (Rutherfurd et al., 2000).

Restoration of channel morphology

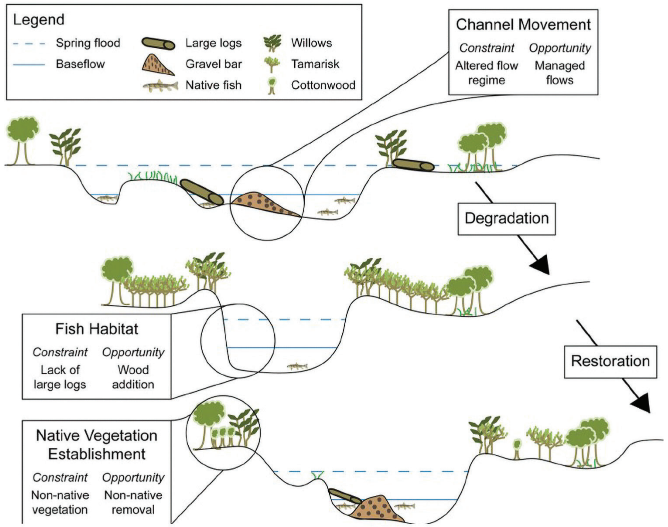

Figure 16: Cross-sectional diagram showing historical changes on the San Rafael River and the expected long-term outcome of restoration (Laub et al., 2015).

Description

Restoration of channel morphology aims to restore the natural riverine processes and functions (Lepori et al., 2005). It includes the removal of artificial bank and riverbed stabilization measures (see also barrier removal), natural stabilization of riverbanks, reconnection of seasonal riverbeds, reestablishment of the pool-riffle sequence and connectivity, plant colonization, etc. (Miller and Craig Kochel, 2010).

Benefits to water balance

Channel restoration measures improve water quality, vertical connectivity (Kurth et al., 2015), recharge groundwater (Zhu et al., 2016), and provide recreational opportunities for locals (Fischer, 2023). The establishment of native vegetation in the river influences further channel diversity by creating a diverse stream with narrow channels, bank undercuts, and pools, thereby enhancing aquatic biodiversity (Palmer et al., 2005; Kauffman et al., 1997). The key to restoration in intermittent streams in arid areas is also the restoration of temporal variability in discharge pulses, which impacts ecosystem structure and function and contributes to the diversity of habitats and higher water table (Sonam et al., 2022; Hill and Platts, 1998).

Examples of implementation

- The restoration of the Tarim River, flowing through the Taklimakan Desert in China, resulted in significant ecological improvements. Opening of reservoirs led to an increase of forests, grasslands, and scrublands, and increased the riparian corridor by factor 1.5 in 12 years after restoration. In 15 years, water depth decreased from a mean of 12.6 m to 5.5-6.2 m (Glenn et al., 2017). Zhu et al. (2016) found that at the Tarim River Basin, the groundwater level rose from a depth of 9.87 m to 3.16 m after the third water delivery.
- Hill and Platts (1998) present a multiyear passive or natural restoration of channel morphology in the Owens River Gorge, California. A stable hydrological regime during the vegetative growing period was established to support riparian growth and reproductive potential. Due to higher water tables, riparian vegetation is now growing and stabilizing landforms at successively higher elevations. Additionally, a stable brown trout population was established after stocking, confirming the establishment of quality habitats.
- In the Heihe River basin in China, unified water regulation enabled the natural restoration of the ecosystem, slowing desertification and reversing the declining trends of groundwater levels, with the occurrence of oases after five years of implementation (Jiang and Liu, 2010).

URBAN REGREEN

Urban Regreen is an NBS with multiple benefits, with landscape connectivity, nature conservation, recognizing the needs of local residents, and optimizing the land use as the highlighted characteristics. It promotes installation or restoration of green areas in urban settings (Benedict et al., 2006**;** Meneguetti and Lemes de Oliveira, 2021**), including concepts such as urban green infrastructure (UGI) or low-impact development (LID) (**Golden and Hoghooghi, 2018**). These measures mitigate water quality problems, flooding, and the urban heat island effect, while offering other benefits, for example, improved air quality (**Benedict et al., 2006**;** Bartesaghi-Koc et al., 2020**;** Meerow et al., 2021**;** Meneguetti and Lemes de Oliveira, 2021**;** Semeraro et al., 2021**). These areas should be planned and designed according to specific local conditions and through a participatory approach to ensure that green spaces are ecologically functional (**Laurenz et al., 2021**;** Semeraro et al., 2021**), and socially equitable (**Park, 2023**), shifting the focus from quantity to quality of urban green areas (**van den Berg et al., 2015**).**

Green roof rainwater harvesting

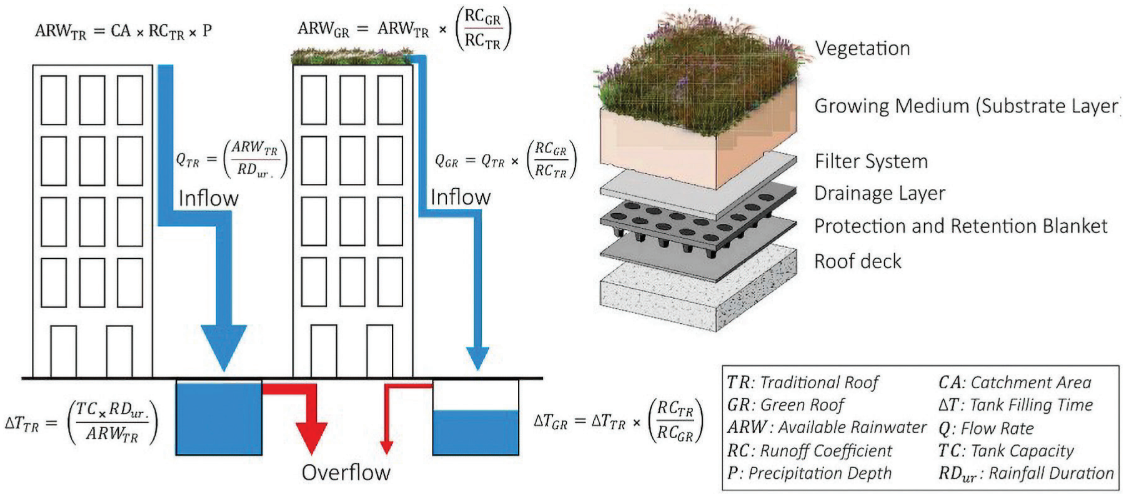

Figure 17: The diagram compares stormwater management between a traditional roof (TR) and a combined rainwater harvesting system (RWH) with a multi-layer extensive green roof (GR) (Almeida et al., 2021).

Description

Green roofs delay runoff, aid infiltration, and promote evapotranspiration. They also increase local biodiversity by planting native vegetation and providing habitats for insects and birds (Oberndorfer et al., 2007; Stovin et al., 2012; Almeida et al., 2021). Rainwater harvesting (RWH) captures, stores, and treats rainwater from roofs to prevent runoff and provide flood protection, enhancing sustainability by supplying water for cleaning, irrigation, and other uses (Nolde, 2007; Stephan and Stephan, 2017; Wanjiru and Xia, 2017). Combining green roofs with RWH improves system efficiency (Chao-Hsien, 2014; Ghaffarian Hoseini et al., 2016; Almeida et al., 2021), as well as providing alternative sources of water for housholds, gardens, car washing, etc. (Tamaddun et al., 2018).

Benefits to water balance

Green roof rainwater harvesting can harness the natural hydrological cycle in urban areas, decrease the risk of flooding (Marlow et al., 2013; Stephan and Stephan, 2017; Almeida et al., (2021), and mitigate the heat island effect (Oberndorfer et al., 2007; Bates et al., 2015; US EPA, 2016). Rainwater harvesting offers a free water source for non-potable uses, alleviating pressure on aquifers and surface watercourses, reducing water stress and pollution, and decreasing sewer loads (Marlow et al., 2013; Wanjiru and Xia, 2017), allowing for larger storage volumes during high-intensity summer rainfall events (Angrill et al., 2012; de Sá Silva et al., 2022).

Examples of implementation

- The two-year study of green roof beds in Adelaide, Australia (Razzaghmanesh and Beecham, 2014) investigated their hydrological performance and demonstrated the average retention of 74% and 88.6% from extensive and intensive roofs, respectively. With an average runoff delay of 3 hours and 17 hours in extensive and intensive roofs, green roofs can ameliorate seasonal flooding in urban drainage systems.
- In Genoa, a Mediterranean town, a green roof was monitored for thirteen months, during which nineteen rainfall events occurred. Four did not produce any subsurface outflow, five with a peak flow lower than 0.1 L/s, and three with a peak flow greater than 1 L/s. Green roof system appeared as an excellent storm water control, preventing flooding phenomena in urban areas and in waste water treatment plants (Fioretti et al., 2010).
- In Portugal, Almeida et al. (2021) combined rainwater harvesting systems with an extensive green roof on a university building. The study showed a marked decrease in available water volume due to the additional retention and storage capacity of the green roof.

Urban parks

Figure 18: The Phil Hardberger Park Conservancy is a 330-acre urban park in San Antonio (Texas, USA), incorporating bioswales, wetland restoration techniques, and a connectivity-supporting bridge between the two sides of the park. The park includes a 946 L3 water catchment system (Image by Phil Hardberger Park Conservancy, accessed July 17, 2024).

Description

Urban parks are one of the common measures to reduce climate change effects in cities (Kabisch et al., 2016; Gunawardena et al., 2017; Mabon et al., 2019), improving air and water quality, reducing erosion (Mexia et al., 2018), and mitigating the urban heat island effect through evapotranspiration. Water bodies in parks are a major heat sink, while nocturnal cooling is more pronounced in open parks with dry soils–a feature of parks in (semi-) arid zones (Spronken-Smith and Oke, 1998; Kim and Coseo, 2018; Brown et al., 2015; Santamouris, 2015; Chen et al., 2016; Bartesaghi-Koc, Osmond, and Peters, 2020; Semeraro et al., 2021). Guizani et al. (2024) highlight the knowledge gap in understanding the links between land cover changes, the effects of urban heat islands, and the water cycle in rapidly growing urban areas.

Benefits to water balance

Trees within urban park systems significantly reduce surface runoff through precipitation interception, while their root systems increase water storage in the soil (Leung et al., 2015; Kim and Coseo, 2018). Parks also provide urban heat island effect mitigation, which indirectly affects the urban water cycle (Qui et al., 2013). In an experimentally designed study, tree-shaded areas produced a greater cooling effect (0,5°C), with a reduced total water use of over 50% compared to the unshaded lawn (0.3°C) (Shashua-Bar et al., 2009).

Examples of implementation

- A comprehensive review of green infrastructure in arid and semi-arid urban environments by Meerow et al. (2021) confirms multiple benefits of urban parks (trees) but also highlights the gaps in data due to a lack of monitoring campaigns.
- Kim and Park (2016) studied urban green areas in four largest metropolitan statistical areas in semi-arid Texas, USA, highlighting that increasing the amount of trees, shrubs, and grass enhances the storm water infiltration and the water storage of an area during flooding.
- The study in two urban reserves in Victoria (Australia) showed the significance of the soil type for the water status of urban (native) vegetation. Clay soils help plants buffer the decline in groundwater during dry periods (Marchionni et al., 2020).

Permeable pavements

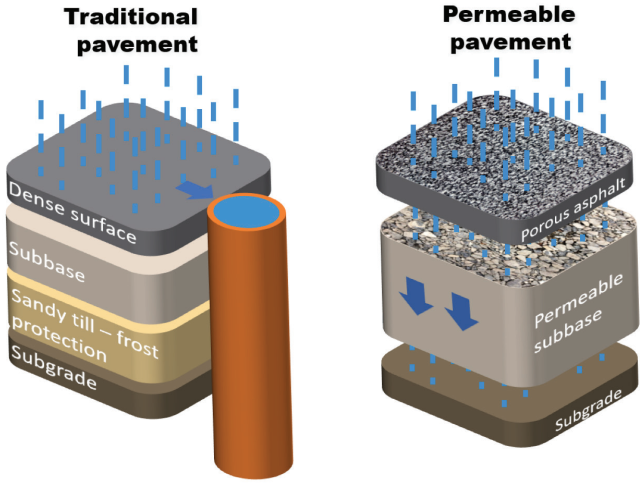

Figure 19: Principle sketch of a permeable pavement (Muttuvelu et al., 2022).

Description

Permeable pavements (also called water retention pavements; Santamouris, 2015) are a type of pavement integrated into the urban environment (Admute et al., 2017; Fini et al., 2017; Singh et al., 2024), made of impermeable modular elements (for example, interlocking concrete pavers) with additional voids allowing for water infiltration and soil-atmosphere gas exchange (Fini et al., 2017). Water holding fillers in sublayers retain (storm)water, and the latent heat from its evaporation is used to decrease the surface temperature of the pavement, mitigating the urban heat island effect (Santamouris, 2015; Singh et al., 2024).

Benefits to water balance

Santamorius (2015) highlights the general lack of monitoring of permeable pavement projects and so the lack of performance information. The measure has the potential for groundwater recharge (Tota-Maharaj et al., 2024), reduction of water and soil pollution, and preservation of soil's water filtration functions (Fini et al., 2017). If used to harvest stormwater for non-potable purposes in buildings, they could lower the water supply requirements and reduce the environmental impacts of traditional drainage systems (Antunes et al., 2020; Tota-Maharaj et al., 2024). Design depends heavily on rainfall and soil conditions in a particular area (Fini et al., 2017; Iqbal et al., 2022) to optimise water infiltration and retention processes (rooted soil preserves higher suction than bare soil during rainfall) (Leung et al., 2015).

Examples of implementation

- The 5-year 'Grow Green Project' in Valencia involves the sub-project in the Benicalap neighborhood (GrowGreen (Bruno Sauer et al., 2022)). The combination of permeable pavements and other NBS measures (infiltration basins, and filter ditches) delayed the impact of water flow by up to 5 hours and reduced the amount of water reaching the water collectors by 66% to 100% (Hipolito et al., 2022).
- Joshi and Dave (2022) studied permeable pavements as a form of rain harvesting in Ahmedabad, India, where the average annual rainfall is 2.54 × 10–5 mm/s, while the infiltration rate of the designed pavement was 1.54 mm/s, proving to be an efficient solution, especially during the monsoon. 40–45% of water from the permeable pavement was recollected into a percolation well, recharging the groundwater.
- Alam et al. (2019) observed a significant percentage of (storm water) peak flow attenuation of approximately 31–100% when permeable pavements were constructed in the semi-arid Lower Rio Grande Valley of South Texas, United States. The testing of interlocking block pavement with gravel showed that it was capable of handling storms as large as 50-year frequency over a 24-hour time period.

Infiltration basins

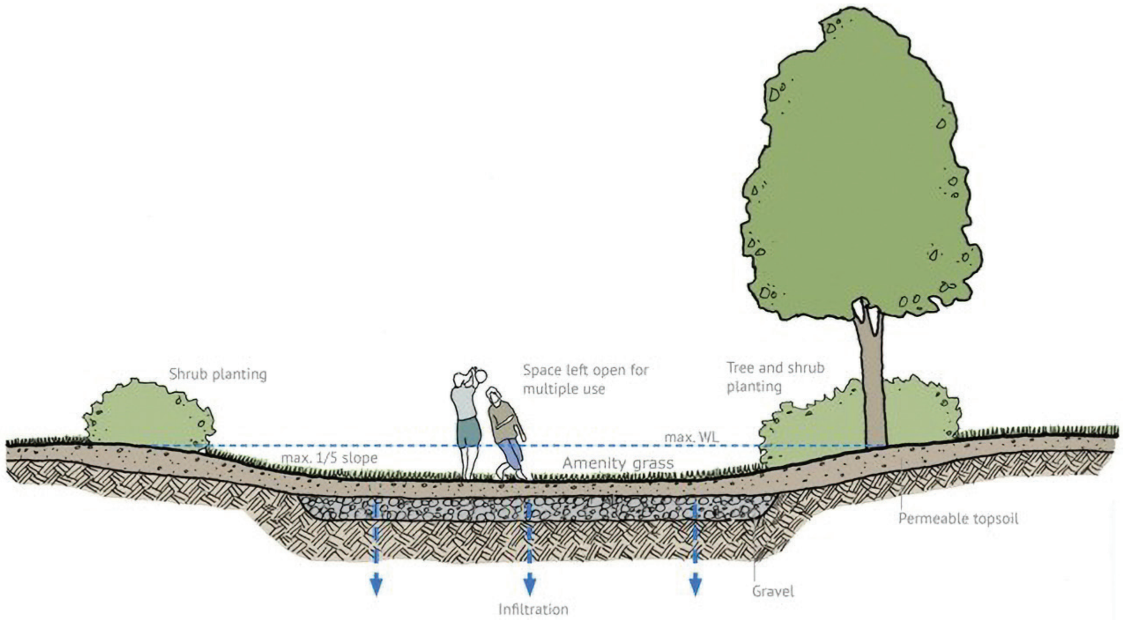

Figure 20: An example of infiltration basin design, promoting infiltration of the surface water runoff into the ground, with plants adjusted to periods of ponding and drought (Source: susdrain.org, accessed July 15, 2024, Susdrain).

Description

Usually, infiltration basins consist of a large (up to 50 acres) soil basin with a directed inflow and a permeable base, where stormwater infiltrates within 72 hours of inundation (Linsenmayer and Van Sluijs, 2018). Infiltration basins are increasingly used to control urban stormwater runoff (Mikkelsen et al., 1996), while floodplain restoration serves the same purpose in rural areas (Buijse et al., 2002; Serra-Llobet et al., 2022). Projects need to predict the impacts of basins on subsurface flows and understand how the infiltration process affects groundwater (Göbel et al., 2004; Locatelli et al., 2017; Ferreira et al., 2020).

Benefits to water balance

Infiltration basins imitate the natural infiltration of rainwater, allowing for the chemical and microbial processes in the humic root zone of the soil, and thus protect the groundwater from contamination (Mikkelsen et al., 1996; Ghofrani et al., 2019). Stormwater infiltration can increase groundwater levels throughout a catchment (Locatelli et al., 2017; Urbaniak et al., 2024). The runoff volume and peak are decreased (Meerow et al., 2021), returning the urban hydrological cycle to a more natural state (Mikkelsen et al., 1996). If planned in alignment with NBS standards, the basins can support climate regulation, increase the water storage capacity of the soil, reduce the sediment load, and remove metals, such as zinc, lead, manganese, and cobalt (Meerow et al., 2021).

Examples of implementation

- A hydrological model developed by Tanyanyiwa et al. (2023) shows a significant increase (at least 118%) in infiltrated water when a detention basin is retrofitted into an infiltration basin in Cape Town, South Africa. Furthermore, future scenarios—where the CFA groundwater table is reduced—suggest a further increase of 244% compared to the pre-retrofit scenario.
- Chauka is an infiltration pond—a traditional rainwater harvesting technique—which was developed to supply pastoral lands with water during the dry season in Rajasthan, India. The system consists of bunds that collect rainfall runoff and allow its infiltration into the soil. A case study found that an additional 5% of the rainfall depth was recharged into the groundwater due to the use of Chaukas (Yadav et al., 2022; Rawat et al., 2023).
- In the City of Francistown, Botswana, with an arid to semi-arid climate, Alemaw et al. (2020) propose a combination of bioretention areas, infiltration basins, and green roofs to receive runoff and direct rainfall, store excess inflow, and generate surface outflow into the drainage system or adjacent land areas.

Urban gardens

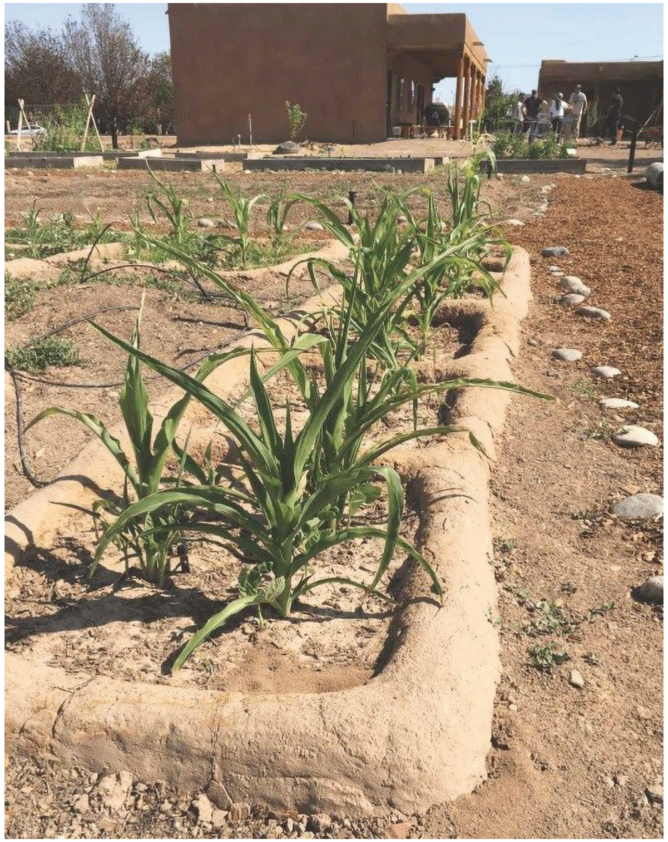

Figure 21: Resilience Garden at the Indian Pueblo Cultural Center–a waffle garden has hand-formed wall-like structures around plants to catch rainfall and keep soil damp during dry periods (Photo courtesy of IPCC, accessed July 16, 2024).

Description

As the name implies, plants and vegetables grown in urban areas, either on patches of land or in pots, outdoor or indoor, are called urban gardens. Their design needs to be cost- and resource-efficient, e.g., using rainwater or treated sewage water instead of drinking water or artificial irrigation, and utilizing smart irrigation controls like drip irrigation that slowly and accurately applies water to plants, with a potential irrigation efficiency of up to 90% (Nolasco, 2011) to avoid unnecessary water loss (Ignatieva et al., 2020).

Benefits to water balance

Urban gardens enhance (storm) water regulation, contribute to food security, mitigate the urban heatwaves, and shape the urban microclimate (Lehmann, 2021). Organically fertilised soil in sustainable gardens results in an increase in the soil's permeability, allowing substantial water to infiltrate, recharging the groundwater in the garden (Nolasco, 2011). Urban gardens and lawns can reduce water runoff (Pauleit and Duhme, 2000), increase water infiltration, and increase groundwater recharge (Ignatieva and Hedblom, 2018; Cameron et al., 2012). Native, drought-resistant plant species, adapted to local climate (e.g., succulents), should be used to minimise the water footprint (Van Jaarsveld, 2013; Lizárraga-Mendiola et al., 2017; Ignatieva et al., 2020; Madrid, 2023; Thompson, 2019; Wilson and Feucht, 2007).

Examples of implementation

- In Redlands, California, Zuni Waffle Garden—a traditional Native American design—was constructed on the base of the dense clay soil from the area, which is tightly packed and retains water for extended periods, allowing food crops to be grown even in the arid climate. Drought-tolerant natives were planted as a priority (Ryan, 2015).
- Perth City Council (Australia) transformed the strips of council land between the street and the footpath into native low maintenance "verge gardens" using a water-wise approach. Low-growing native plants were planted instead of high-water demanding grass, using the principles of xeriscaping, to reduce/eliminate the need for irrigation and reduce the city's water use (Ignatieva et al., 2020).
- In the Las Vegas Valley, The Southern Nevada Water Authority converted unsustainable turf landscapes to low-water-use areas (through xeriscaping), which resulted in significant water savings of 2273,6 l/m2 annually, with homes reaching a 30% decrease in their yearly total household water use (Sovocool et al., 2006).

Bioswales

Figure 22: A schematic representation of the structure (left; Tait, 2014), and a photograph of a bioswale (right; Coe & Van Loo Consultants, Inc., 2018).

Description

A bioswale is a linear, sloped infiltration trench with dense, self-sustaining native vegetation (Lizárraga-Mendiola et al., 2017). Bioswales incorporate native terrestrial vegetation, which filters pollutants from stormwater before entering the storm sewers (Jacklin et al., 2021; University of Florida, 2008). Bioswales can also improve the aesthetics of the living environment and represent an additional habitat for wildlife, which can lead to a biodiversity increase (Kulkarni, 2012).

Benefits to water balance

Vegetation evapotranspiration increases the water storage capacity of a bioswale prior to a rain event by reducing the water content within a swale (Nasrollahpour, 2021). A layer of highly permeable soils underneath the vegetation layer infiltrates and attenuates excess stormwater from impervious surfaces (Irvine and Kim, 2018; Dinic Brankovic et al., 2019; University of Florida, 2008). A bioswale also increases groundwater recharge (University of Florida, 2008).

Examples of implementation

- Bioswales have been installed in Denver, Colorado (US) as a combination of Low Impact Development (LID) and Green Infrastructure (GI) in order to allow the stormwater to soak into the ground slowly, which increases its filtering time, and recharge underground aquifers. Bioswales were also used as attractive vegetated areas (US EPA, 2016).
- The NE Siskiyou Green Street (Oregon, US) stormwater retrofit for sustainable water management showed that the curb extensions featuring bioswale systems can reduce the runoff intensity of a 25-year storm event by 85 percent. Bioswales were made of packed earth and river rock. Native Juncus patens was used to slow down water flow and capture pollutants, and some non-native plants were used for decorative purposes (ASLA, 2007; Syranidou et al., 2016).
- Jacklin et al. (2021) conducted a simulation of typical urban bioswales using various indigenous South African plant species, accustomed to different environmental conditions, and demonstrated the removal of significant quantities of dissolved metals and nutrients.

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