Compendium of Nature-based and ‘grey’ solutions to address climate- and water-related problems in European cities

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Introduction

This compendium presents nature-based and 'grey' solutions to address climate- and water-related challenges in European cities. It focuses on the six challenges that are most common across European cities and which can be addressed through nature-based solutions: heat stress, river flooding, surface water (or pluvial) flooding, coastal flooding, water scarcity, and poor water quality.

The solutions were identified through a review of existing databases and collections – such as the Natural Water Retention Measures (NWRM) catalogue[1], Climate-ADAPT[2], the Danish portal for Climate Change Adaptation[3], and the (draft) RESIN Adaptations Options Library[4] – as well as various reports and scientific publications.

Tables 1 and 2 overleaf present the set of solutions identified and the corresponding climate and water hazards they can tackle. The remainder of the compendium consists of solution-specific fact sheets explaining what each solution entails, the problems – or hazards – it can address, its typical co-benefits, and a brief review of evidence regarding the solution's effectiveness and costs.

Table 3 provides an overview of the main functions and co-benefits of the 36 nature-based solutions examined, based on literature review and expert judgement.

[1] http://nwrm.eu/measures-catalogue
[2] https://climate-adapt.eea.europa.eu/
[3] http://en.klimatilpasning.dk/technologies/
[4] http://www.resin-cities.eu/resources/library/

Table 1 List of nature-based solutions and the climate hazards they can address

Nature-based solutions	Heat	Floods			Water	
		River	Surface water	Coastal	Scarcity	Quality
1. Green roofs	■		■			
2. Vertical Greening Systems	■					
3. Vertical forest	■					
4. (Peri-)Urban parks and other green spaces	■		■			
5. Green urban furniture	■					
6. Greening linear transport infrastructure	■		■			
7. Urban gardens	■		■			
8. Restoration and management of inland wetlands		■			■	■
9. Restoration and management of floodplains		■				
10. River restoration for flood control		■				
11. Restoration and reconnection of seasonal streams		■				■
12. Re-meandering		■				
13. Reconnection of oxbow lakes		■				
14. Re-naturalization of polder areas		■		■		
15. Lake restoration		■	■		■	■
16. Floodplain and riparian woodland creation		■				■
17. Managed realignment				■		
18. Restoration and management of coastal wetlands				■		
19. Sand dunes construction and strengthening				■		
20. Shore and beach nourishment				■		
21. Sustainable Drainage Systems (SuDS)			■		■	■
22. Rain water harvesting			■		■	
23. Pervious surfaces			■			■
24. Infiltration Basins			■		■	■
25. Infiltration trenches			■		■	■
26. Soakaways			■		■	■
27. Rain Gardens	■		■		■	■
28. Swales			■			■
29. Planted channels and rills			■			■
30. Detention Basins			■		■	■
31. Retention Ponds			■		■	■
32. Geocellular systems			■		■	
33. Filter strips						■
34. Blue roofs			■		■	
35. Subsurface groundwater recharge systems					■	
36. Constructed wetland						■

Table 2 List of grey solutions and the climate hazards they can address

Grey solutions	Heat	Floods			Water	
		River	Surface water	Coastal	Scarcity	Quality
1. Passive cooling of buildings	■					
2. Cool or white roofs	■					
3. Cool facades	■					
4. Cool pavements	■					
5. Cooling water fountains	■					
6. Dikes		■				
7. Floodwalls		■				
8. Longitudinal barriers (Dams)		■				
9. Temporary and demountable barriers		■		■		
10. High-water channel		■				
11. Compartmentalisation		■		■		
12. Storm surge barriers (or gates)				■		
13. Groynes, breakwaters and artificial reefs				■		
14. Higher quays				■		
15. Quay walls / sheet pile walls				■		
16. Sluices and pumping stations		■		■		
17. Dry flood-proofing		■		■		
18. Wet flood-proofing		■		■		
19. Floating and amphibious housing				■		
20. Floating or elevated roads		■	■	■		
21. Raising coastal land				■		
22. Upgrading drainage systems / increasing pipe capacity			■			
23. Flow regulators			■			
24. Smart regulation of the sewage system			■			
25. Flood control channels			■			
26. Surface water storage			■		■	
27. Underground water storage			■		■	
28. Backflow blocker			■			
29. Pump well with check valve			■			
31. Greywater recycling systems					■	
32. Desalination					■	■

Table 3 Benefits provided by nature-based solutions

- Main benefit of this solution
- Co-benefit: High provision
- Co-benefit: Medium provision
- Co-benefit: Low provision

Category	Benefit	Green roofs	Vertical greening systems	Vertical forest	Urban parks, forests,	Green urban furniture	Greening transport	Urban gardens	Inland wetlands	Floodplains	River restoration	Restoration of streams	Re-meandering	Oxbow lakes	Polder areas	Lake restoration	Riparian woodland	Managed realignment	Coastal wetlands	Sand dunes	Shore & beach	Sustainable drainage	Rainwater harvesting	Pervious surfaces	Infiltration basins	Infiltration trenches	Soakaways	Rain gardens	Swales	Planted channels & rills	Detention basins	Retention ponds	Geocellular storage	Filter strips	Blue roofs	Groundwater recharge	Constructed wetlands
Environmental	**Temperature regulation**	Main	Main	Main	Main	Main	Main	Main														Medium						Main			Medium	Medium			Medium		
	River flood mitigation									Main	Main	Main	Main	Main	Main	Main	Main																				
	Surface water flood mitigation	Main			Main		Main	Main	Main							Main						Main	Main	Main	Main	Main	Main	Main	Main	Main	Main	Main	Main	Main	Main		
	Coastal flood mitigation														Main			Main	Main	Main	Main																
	Water quality				Medium		Medium		Main	Low	High	High	High	Medium		Main	Main	Low	Low			Main	Main	Main	Main	Main	Main	Main	Main	Main	Main	Main		Main		Medium	Main
	Regulation of the water cycle	High			High		Medium	Medium	High	High	High	High	High	High	High	High	High	High	High			High		High	High	High	High	High	High	High	High	High	Medium	High		High	High
	Groundwater recharge				Medium		Low		High	High			High	High	High	High								Medium	High	Medium	Medium	High								Main	
	Soil quality & erosion prevention				Medium			Low	Medium	High	High	High	High	High	Medium	Medium	High		Low	High	High													Medium			
	Air quality	Medium	Medium	Medium	High	Low	Medium	Low			Medium											Medium															
	Noise mitigation	Medium	High	Medium	Medium		Medium																														
	Biodiversity	Medium	Medium	Medium	High	Low	Medium	High	High	High	High	High	High	High	High	High	High	High	High	Medium		Medium			Medium			Medium	Medium	Medium	Medium	Medium		Medium			High
	Pollination	Medium	Medium	Medium	High	Low	Low	High	Low								Low											Medium									
	Carbon storage	Low		High	High		Medium	Low	High	High							High	Low	High			Medium						Low			Low						High
Social/Cultural	Health and quality of life	Medium	Medium	Medium	High	Low	Medium	High	Medium		Medium					Medium	Low		Medium	Low	Low	Medium														Low	Medium
	Recreation, education & gathering	High		Low	High			High	High	Medium	High	Medium	High	Medium	Medium	High	Medium	High	High	High	Medium	Medium			Medium			High			Medium	Medium					Medium
	Regeneration of degraded areas				High		High	High			High					Medium	Medium	Low				High		Low				Medium		Low		Low					High
	Spiritual, religious &artistic values			Low	High				High		Medium	Medium	Medium			Medium	Low		Medium																		Low
	Amenity value	High	High	High	High	High	High	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium			Medium			High	Medium	Medium	Low	Low		Low	Medium		Medium
	Employment	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Medium	Medium	Medium	Medium	Low	Low	Low	Medium	Low	Low	Low	Low	Medium	Low	Low	Low	Low	Low	Low	Medium	Low	Medium
Economic	Food provision							High	Medium		Low	Low	Low				Medium	Medium	Medium																		
	Water provision								Main		Medium	High	Medium			Main						Main	Main	Medium	Main	Main	Main	Main			Main	Main	Main		Main	Main	High
	Energy savings	High	High	High	Medium		Medium															Medium													Medium		High
	Income generation				Medium			Low	Low		Low				Low			Medium	Medium			Low															Low
	Increased value of land/property	Medium	Medium	High	High		Medium	Medium	Medium		Medium					Medium	Low					Medium		Medium	Low			Medium				Low			Medium		Medium
	Increased tourism				Medium				Medium		High					High			Medium	Medium	High																

Nature-based solutions

1. Green Roofs

Description

There are two categories of green roofs: intensive and extensive. **Intensive green roofs** (also referred to as **roof gardens or terraces**) are composed of lush vegetation and based on a relatively nutrient rich and deep substrate (Greater London Authority, 2008). They can sustain large plants and even conventional lawns; therefore, intensive roofs generally require relatively high levels of maintenance, regular irrigation and applications of fertiliser, and can be of considerable weight (Greater London Authority, 2008).

Photo credits: Center for Neighborhood Technology / Flickr

Extensive green roofs are normally characterised by a shallow growing medium and self-sustaining, low maintenance planting that covers the entire roof area (Greater London Authority, 2008; NWRM, 2015). They generally provide higher biodiversity benefits than intensive green roofs, and usually receive no irrigation or fertilisation (although this may be required initially until plants become established) (Greater London Authority, 2008). Given that they have a relatively low weight (compared to intensive green roofs), extensive roofs can be retrofitted to many existing buildings (Block et al., 2012). They are sometimes referred to as **sedum roofs**. There are two main types of extensive green roofs used in the UK: 1) mat-based systems: have very shallow soils (typically 20-40mm), and are pre-grown to provide 100 per cent instant cover; 2) substrate-based systems: generally 75-150mm in depth, consisting of either a porous substrate or similar reused aggregates (Greater London Authority, 2008).

Between intensive and extensive green roofs, there is a variety of intermediate types typically referred to as **semi or simple-intensive.**

Another category is the **'blue green roof'**, which combines blue roof components (see fact sheet 34 below) and a vegetation layer. The blue, water retention component irrigates the green roof layer (Grant and Gedge, 2019).

Type of intervention: Creation of new green space

Products/services covered: green roofs; manufacturers and suppliers of green roof components; green roof installation; green roof maintenance; landscaping; construction of buildings; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Whereas dark surfaces of conventional roofs exacerbate the Urban Heat Island Effect (UHIE) by absorbing heat during the day and radiating it during the night, green roofs cool the air by shading heat-absorbing materials, increasing albedo, and through the processes of evaporation and evapotranspiration (Greater London Authority, 2008; Block et al., 2012). Green roofs also provide thermal insulation in buildings, reducing the need for air conditioning and thereby contributing to energy savings (Greater London Authority, 2008).

Green roofs control the volume of runoff entering the sewerage system by allowing water to infiltrate in the substrate and drainage layers, which is then taken up by plants (Greater London Authority, 2008). The specific cooling and runoff attenuation impacts of green roofs vary according to the characteristics of the plant, substrate and drainage layer components (Block et al., 2012). Intensive green roofs generally have the highest cooling and rainfall retention capacity, followed by extensive substrate-based ones (Greater London Authority, 2008).

Heat reduction

Studies from a wide range of climates demonstrate the building-scale cooling effects of green roofs (for reviews, see Block et al., 2012 and Greater London Authority, 2008), although the results are difficult to compare due to differences between studies in parameters measured, building types, local and micro-scale climates, type of insulation and green roof design (Block et al., 2012). This can significantly reduce dependence on air-conditioning (Block et al., 2012). For example, measurements in Singapore found that heat transfer through an intensive green roof was less than 10% of that recorded for a conventional roof (Wong et al., 2003, cited in Block et al., 2012). A modelling study in Madrid found that the surface temperature in summer of a green roof with 90 mm of growing media was 30 °C lower than that of a bare roof (Saiz et al., 2006). Summer cooling load was reduced by over 6%, while reductions in peak hour cooling load in the upper floors reached 25% (Saiz et al., 2006). Simulations in Athens found that the installation of a green roof on a two-storey office building reduced the cooling load by up to 58% (Spala et al, 2008, cited in Block et al., 2012). A study from Melbourne reported that air temperature in a room under a green roof was 1°C cooler in summer and 0.2°C warmer in winter than in a control room under a conventional roof (Chen and Williams, 2009, cited in Block et al., 2012). A study of an intensive green roof in Manchester (Speak et al., 2013) showed reductions in the monthly median overlying air temperature at 300 mm above the roof by up to 1.06°C compared to an adjacent conventional paved roof. This cooling effect was found to be strongest at night. However, the study also demonstrates the importance of adequate maintenance; the cooling effect was found to be lower (maximum average cooling of 0.78°C) on a section of the green roof which had been damaged due to drought and mismanagement (Speak et al., 2013).

The highest impacts in terms of reduced demand for cooling are achieved in buildings with high roof-to-wall area ratios and with poor insulation (Block et al., 2012).

Fewer studies have examined cooling effects at neighbourhood or city-wide scale. A systematic review by Fjendbo Møller Francis and Bergen Jensen (2017) found that 14 studies reported cooling at street level ranging between 0.03 – 1 C°, while a further three (modelling) studies reported reductions of 1.7 – 3 C° (with the highest reduction - of 3 C° - found in a study which assumed full coverage with green roofs throughout Chicago). A modelling study undertaken by the New York Heat Island Initiative showed that providing 50%

green roof cover within the metropolitan area of New York would result in an average surface temperature reduction of 0.1-0.8°C (Greater London Authority, 2008). Every degree reduction in the UHIE was estimated to correspond roughly to energy savings of 495 million kWh (Greater London Authority, 2008). The installation of extensive green roofs on 75% of buildings in Toronto (equivalent to 5,000 hectares) was estimated to reduce ambient air temperatures by 0.5 to 2 °C, depending on the season (Banting et al., 2005, cited in Block et al., 2012).

Run-off mitigation

Green roofs retain water during rainfall events, delaying run-off until after peak rainfall and returning water to the atmosphere through evapotranspiration (Oberndorfer et al., 2007). The German Guidelines for Green Roofs indicate that green roofs can retain from 40% to more than 90% of rainfall, depending on their depth and type of vegetation (Livingroofs, 2018).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of air quality
	Noise mitigation
	Biodiversity (for extensive green roofs)
	Pollination (for extensive green roofs)
	Carbon storage
Social/Cultural	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Employment enhancement
Economic	Reduced energy consumption
	Increased value of land/property

References: Greater London Authority, 2008; Enzi et al., 2017; Fjendbo Møller Francis and Bergen Jensen, 2017

Cost information

The installation and maintenance costs of extensive green roofs are generally lower than those of intensive green roofs (Greater London Authority, 2008). The latter usually require highly engineered systems which can support structural load capacities of 290-970 kg/m^2, as well as continuous maintenance (Block et al., 2012). Extensive green roofs also require little or no irrigation (hence the maintenance costs are lower than for intensive green roofs). Oberndorfer et al. (2007) report costs in the range of USD 100 to USD 300 per m^2 for extensive green roofs, and USD 200 per m^2 for the intensive (excluding maintenance costs). The Renewable Energy Hub UK estimates the costs to be around GBP 100 and GBP 150 per m^2 of extensive and intensive green roof, respectively.

Potential disadvantages / negative impacts/ trade-offs

Ascione et al. (2013) show that in cities with scarce rainfall, the cost of irrigating green roofs can outweigh the savings from reduced energy demand for air-conditioning.

Challenges / requirements for implementation

- Technically straightforward on roofs with a slope of up to 30 degrees; different techniques required for higher slopes (Tecnalia, 2017)
- Selected vegetation must be adapted to local climate conditions (Tecnalia, 2017)
- Possible restrictions concerning installation on certain building types

- Given the generally large weight of intensive green roof systems, they may require substantial reinforcement of an existing roof structure or inclusion of extra building structural support (Greater London Authority, 2008)
- Cooling properties are dependent on adequate maintenance of the vegetation (Speak et al., 2013)

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Photo source: https://www.flickr.com/photos/centerforneighborhoodtechnology/3272597172; Licence: CC BY-SA 2.0.

Other relevant sources:

Directory of green roof installers in the UK: https://www.renewableenergyhub.co.uk/green-roof-information/green-roof-designers-and-installers.html

UK Green Roof Market Report 2017: https://livingroofs.org/uk-green-roof-market-2017/

2. Vertical Greening Systems

Description

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Vertical Greening Systems (VGS) - also referred to as **green-wall technologies, vertical gardens, or bio walls** – consist of vertical structures covered in vegetation. There are three broad categories of VGS, depending on the type of vegetation and support structures used:

- **traditional green facades**: consist of woody or herbaceous climbing plants usually planted at the base of a wall;
- **'double-skin' green facades**: include engineered support structures for the climbing vegetation and an insulating layer of air between the foliage and the building wall;
- **green or living walls**: generally more complex than facades, based on a supporting structure with different attachment methods, such as panels or planters or a growing medium made from textiles (felt) in which the vegetation grows; require an irrigation system (Pérez-Urrestarazu et al., 2016; Block et al., 2012).

Type of intervention: Creation of new green space

Products/services covered: VGS, green facades, green/living walls; manufacturers and suppliers of VGS components; VGS installation; VGS maintenance; landscaping; construction of buildings; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

VGS provide cooling by intercepting solar radiation, providing thermal insulation, evapotranspiration, and modifying air movement in the building envelope (Block et al., 2012; Pérez-Urrestarazu et al., 2016). They also provide shading, reducing exterior surface temperatures and hence heat transfer into the building (Block et al., 2012). A multitude of studies report a positive effect of VGS on the thermal performance of buildings (for reviews, see Block et al., 2012, Pérez-Urrestarazu et al., 2016). For example, a simulation model predicted that a direct green façade on a building in a Mediterranean climate would reduce external wall surface temperatures by 10.79 °C (Kontoleon and Eumorfopoulou, 2010, cited in Block et al., 2012). Studies in Germany found that summer air and surface temperatures at the building wall surface were 2 to 6 °C cooler behind a direct green façade compared to a bare wall (Bartfelder and Kohler, 1987, cited in Block et al., 2012), while the green façade prevented up to 3 °C heat loss in winter (Kohler et al., 1993, cited in Block et al., 2012).

In Spain, Perez et al. (2011) showed that building wall surface temperatures in spring and summer were on average 5.5 °C cooler in areas shaded by a double skin green façade compared to sunny areas (Block et al., 2012). A comparison of double skin green façades and blinds (with equivalent transmissivity values) found the temperature of the building wall surface and intermediate air space behind the green façade to be 20% and 20-35% lower, respectively, than behind blinds (Stec et al., 2005, cited in Block et al., 2012). Simulations showed that a double skin green façade would reduce annual energy consumption for heating, ventilation and air-conditioning by about 19% compared to the use of blinds (Block et al., 2012). Similarly, modelling for the city of Toronto found that VGS reduce energy consumption for cooling by about 20% (Bass and Baskaran, 2001, cited in Pérez-Urrestarazu et al., 2016).

An experimental study in Singapore found temperatures at the wall surface behind eight different green wall systems to be 4−12 °C lower during the day and 3−6 °C cooler at night compared to a bare concrete wall (Wong et al., 2010, cited in Block et al., 2012).

As regards local ambient air temperatures, the review by Block et al. (2012) concludes that the empirical evidence is limited and VGS may be more effective at reducing internal air temperatures and summer peak cooling loads than having a significant effect on UHI.

Archer (2011, cited in Pérez-Urrestarazu et al., 2016) also concludes that the thermal benefits of living walls can be small when compared to a well-insulated building wall. At the same time, VGS deliver a range of co-benefits which are not associated with conventional walls.

Typical co-benefits

Environmental	Improvement of air quality
	Noise mitigation
	Biodiversity
	Pollination
Social/Cultural	Health and quality of life
	Enhanced amenity value
	Employment enhancement
Economic	Reduced energy consumption
	Increased value of land/property

References: Greater London Authority, 2008; Pérez-Urrestarazu et al., 2016

Cost information

According to Pérez-Urrestarazu et al. (2016), the cost of an installed green facade may vary between 100 and 300 EUR/m^2. The costs of living wall systems with a felt substrate range from 400–650 EUR/m^2 while modular systems cost between 500 and 800 EUR/m^2. The costs of active living walls reach 850–1200 EUR/m^2, but some of the associated benefits (notably those related to energy efficiency and indoor air quality) are also enhanced (Pérez-Urrestarazu et al., 2016).

The annual operation and maintenance costs are highly variable depending on factors such as the degree of complexity of the system, its height, the the type of vegetation, or the number of operations included in the maintenance service (Pérez-Urrestarazu et al., 2016). Perini and Rosasco (2013) used the following annual values: 2-5 EUR/m^2 for a simple system using climbers attached directly onto the facade (which will require minimal maintenance with low frequency) and 40-100 EUR/m^2 for more complex systems which require tasks such as pruning, plant replacement, treatments, and maintenance of the irrigation system (Pérez-Urrestarazu et al., 2016). Indeed, the cost-benefit analysis performed by Perini and Rosasco (2013) suggests that the installation and maintenance costs of living walls currently outweigh the benefits (but note that not all possible co-benefits - such as UHI mitigation or habitat creation - were quantified).

Potential disadvantages / negative impacts/ trade-offs

- Risk of spreading invasive species if non-native species are used (Block et al., 2012) – requires careful selection of the plants;
- Risk of negative impacts on runoff water quality if inputs such as fertilizers and pesticides are used (Pérez-Urrestarazu et al., 2016).

Challenges / requirements for implementation

- The building façades must be suitable from a structural point of view, to allow the installation of support elements for the vegetation (Tecnalia, 2017).
- The selection of the particular VGS (including choice of species) should take into account factors like construction and climatic restrictions (Pérez-Urrestarazu et al., 2016). The characteristics of different green wall systems and their respective benefits and disadvantages are reviewed in Manso and Castro Gomes (2015).
- Requires careful selection of species, to minimise management costs (Tecnalia, 2017). In drought-prone areas, species should be selected such that irrigation requirements are minimised. The NBS could be combined with waters torage tanks for rainfall capture or recycling of irirgation water, but this may increase the initial capital investment required (Pérez-Urrestarazu et al., 2016).
- On high buildings, VGS plants and support structures must be able to withstand high wind speeds; the design of effective VGS requires an understanding of wind behaviour around multi-storey buildings (Greater London Authority, 2008).
- Possible restrictions concerning installation on certain building types.
- Requires significant initial investment, particularly if the green facades are not integrated in bulding design from the beginning (Tecnalia, 2017).
- Potentially high management costs (to maintain species in a healthy state, replace plants when necessary, cleaning, and repairing possible unforeseen damage to the structure of the building (Tecnalia, 2017).
- Risk of social rejection of the measure (e.g. if the green wall loses it aesthetic appeal in certain seasons), hence it is critical for the general public to understand that the appearance of green facades changes with the seasons (Tecnalia, 2017).

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3. Vertical Forest

Description

Photo credits: Romero, F. / flickr.com

Designed by architect Stefano Boeri, the vertical forest is a model of sustainable building design, which incorporates various trees, shrubs, and plants into the structure of the building. Among other benefits, it mitigates the urban heat island effect (Giacomello and Valagussa, 2015). It can be considered a sub-type of green façade, but is the subject of a separate fact sheet since it has its own specific design characteristics and other properties.

A real-life example of this NBS is the 'Bosco Verticale' built in 2014 in Milan, Italy. It consists of two residential towers with 27 and 18 floors, respectively, with a system of dense vegetation along their outer envelopes (Giacomello and Valagussa, 2015). The two towers host over 90 different plant species - from ground-cover plants, to shurbs and trees - placed in concrete planters on cantilevered terraces. There are 700 trees in total, including some of which are 6 metres high. The green coverage of the two towers amounts to 10,142 m^2 (Giacomello and Valagussa, 2015). The plants are irrigated using grey water produced in the residential complex (Design & Build Network, undated). The objective of the project was to reproduce the equivalent of 1 hectare of forest vertically, with corresponding benefits for residents in terms of improved air quality, noise reduction, shading for cooling and aesthetic enhancement (Giacomello and Valagussa, 2015). Similar projects have been commissioned in Lausanne (Switzerland), Utrecht (Netherlands), and the cities of Nanjing and Liuzhou (China) (World Economic Forum, 2017).

Type of intervention: Creation of new green space

Products/services covered: architectural design; construction of buildings; landscaping; maintenance of the vegetation; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

An evaluation of the energy performance of the Bosco Verticale in Milan found that the terraces and vegetation decreased annual electricity consumption by about 7.5%. Energy demand for cooling was found to decrease in summer, when the vegetation provides shading; at the same time, energy demand for heating increases in winter since the vegetation decreases the amount of collected solar radiation (Giacomello and Valagussa, 2015).

Typical co-benefits

Environmental	Improvement of air quality
	Noise mitigation
	Biodiversity
	Pollination
	Carbon storage
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Spiritual, religious, and artistic values
	Employment enhancement
Economic	Reduced energy consumption
	Increased value of land/property

References: Giacomello and Valagussa, 2015

Cost information

The construction of the Bosco Verticale complex cost EUR 65 million, which is reported to be only 5% higher than the cost of a traditional skyscraper (Design & Build Network, undated). Information on maintenance costs could not be found.

Potential disadvantages / negative impacts/ trade-offs

- Need for irrigation – hence potential trade-offs with solutions for mitigating water scarcity; at the same time, different plant species may be considered in drier climates.

Challenges / requirements for implementation

- Requires careful selection of species.
- Applicable for new developments – designed from the outset to incorporate the 'vertical forest' – but does not appear suitable for retrofitting existing buildings (since the structure has to be designed taking into account the additional load of the trees, the irrigation requirements, etc.)

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Photo source: https://www.flickr.com/photos/129231073@N06/19819235140/in/album-72157652916329083/; Licence: CC BY 2.0

4. (Peri-)urban parks, forests, green corridors and other green spaces in urban areas

Description

(Peri-)urban parks, forests and other green spaces in cities can cool temperatures by providing shade and enhancing evapotranspiration. Moreover, appropriately designed green corridors can improve urban ventilation, allowing cooler air from outside to penetrate into the more densely built areas and thereby reducing the urban heat island (UHI) effect (Climate-ADAPT, 2015). In addition, (peri-)urban parks or forests and other green spaces provide a suite of co-benefits, such as carbon sequestration (especially by trees), attenuation of surface runoff and hence reduced flood risk, air quality regulation and the provision of opportunities for recreation and contact with nature, which in turn lead to improved health. They also contribute to the maintenance of biodiversity by providing habitat and foraging resources.

Photo credits: Laura Baroni

Type of intervention: Creation of new green space

Products/services covered: landscaping; landscape architecture; tree planting; green space maintenance

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Temperature regulation:

A meta-analysis by Bowler et al. (2010) found that, on average, urban parks were almost 1°C cooler during the day than non-green areas. Armson et al. (2012) note that the small size of this difference is likely due to the fact that warm air can be easily advected into parks, while cool air from parks is advected into the surrounding streets, with the extent of such movements depending strongly on wind speeds.

Four of the studies reviewed assessed cooling effects in parks of different sizes (Barradas, 1991; Upmanis et al., 1998; Bacci et al., 2003; Chang et al., 2007; cited in Bowler et al., 2010) and showed that larger parks were either more likely to be cooler or that the cooling effect was greater (Bowler et al., 2010). In addition to size, the cooling properties of parks depend on the composition of vegetation within a park, such as the amount of tree and grass cover (Bowler et al., 2010).

Stormwater management:

Parks and forests also contribute to stormwater management since they display a lower share of impervious surfaces than other land uses (Konijnendijk et al, 2013). Trees, grass and other vegetation in urban parks can intercept, treat and infiltrate stormwater runoff, contributing to mitigating the risk of surface flooding in cities. In addition, urban parks and forests can incorporate elements such as retention ponds and pervious surfaces (discussed in separate fact sheets below) which further improve a park's overall runoff retention capacity. For example, it is estimated that the trees in the urban parks of Phoenix, Arizona (a total of about 517,000 trees) help to reduce runoff by almost 53,000 cubic metres a year (Kim and Coseo, 2018). Depending on location and topography, peri-urban forests (located at the edge of cities, at the interface with rural land) can also mitigate flood risk downstream if they capture and treat runoff that would otherwise end up in the urban areas.

An experimental study in Manchester, UK (Armson et al., 2013) measured the urban surface water runoff from 9 m^2 plots covered by grass, asphalt, and asphalt with a tree planted in the centre. The authors showed that grass absorbed almost all surface runoff, with the average runoff measuring less than 1% of the total rainfall, while runoff from tree plots was only 26% and 20% of the total rainfall in winter and summer, respectively (around 60% lower than runoff from the asphalt-only plots). The authors attribute this not only to runoff interception by the canopy area, but also interception into the tree pit. Similarly, a modelling study (Gill et al., 2007) showed that increasing the tree cover in Manchester by 10% would reduce urban run-off in residential areas by 5.7%.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of soil quality and stability, erosion prevention
	Improvement of air quality
	Noise mitigation
	Reduce peak temperature
	Biodiversity
	Pollination
	Carbon storage
	Groundwater recharge
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Spiritual, religious, and artistic values
	Employment enhancement
	Enhanced amenity value
Economic	Reduced energy consumption
	Income generation
	Increased value of land/property
	Increased tourism

References: Tecnalia (2017); NWRM (2015); Konijnendijk et al. (2013)

Cost information

Several cost-benefit assessments of public parks have been undertaken in the USA and the UK (reviewed in Vivid Economics, 2017). A study of city parks in Philadelphia, USA (Philadelphia Parks Alliance, 2008) found that for every USD 1 spent on maintenance, the parks generated an economic value of nearly USD 100 (taking into consideration a range of benefits including those for recreation and health). In Sheffield, UK, urban parks were found to generate GBP 34 in benefits for every GBP 1 spent on maintenance (Vivid Economics, 2016). Physical and mental health savings accounted for 46 and 12 % of the parks' total economic value, respectively.

In London, the benefits were estimated at GBP 27 for every GBP 1 of maintenance costs (Vivid Economics, 2017). The 'social return on investment' for Edinburgh's parks was estimated at GBP 12 for every GBP 1 spent on maintenance (City of Edinburgh Council, 2014).

Potential disadvantages / negative impacts/ trade-offs

Depending on their location and design, urban parks and green spaces may be perceived by some as providing disservices, e.g. by being an unsafe area at night time.

As a relatively high land-take measure, the establishment of urban parks can involve opportunity costs, i.e. foregone benefits associated with alternative land uses.

Challenges / requirements for implementation

It is important to select species adapted to the local environment and climatic conditions, and to avoid possible side effects such as the introduction of exotic species which can have negative impacts on local biodiversity (Climate-ADAPT, 2015).

The creation of new parks is dependent upon land availability and may conflict with stakeholders' preference for other land uses (e.g. creation of car parks, built development, roads, etc.).

Urban parks and other public green spaces require regular maintenance.

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Photo source: Author's own.

5. Green urban furniture

Description

This NBS involves the use of biomaterial in benches and other public outdoor furniture items. Such solutions can provide shading, mitigating the effect of extreme heat, and can also contribute to improving surface runoff. Depending on design, they can also deliver additional benefits such as air quality improvements. An appropriate selection of vegetation - such as perennial species to provide shade - may be a very efficient and low cost option for improving comfort in public spaces (Tecnalia, 2017).

A specific example of this NBS is the 'CityTree' – pictured above – developed by German start-up Green City Solutions. It is a vertical plant filter which uses different types of moss to bind environmental toxins from the air, such as particulate matter and nitrogen oxides (Green City Solutions, undated). A ventilation system can control air flow to maximise the air purification effects. The mosses also increase evaporation, creating a cooling effect in the surrounding area. The installation powers itself through solar panels, while a built-in irrigation system redistributes automatically the rainwater collected by the CityTree (The Crown Estate, 2018).

Other examples include the sustainable bus shelters with green roofs. Designed by the company Green4Cities, the shelters combine the photovoltaic-powered shelters 'Station by Fonatsch' with an extensive sedum planted green roof (Green4Cities, 2017). Bus shelters with green roofs have already installed in Paris (JCDecaux, 2016).

CityTree; Photo credits: Brown, M. / flickr.com

Station by Fonatsch with a green roof; Photo credits: Green4Cities / http://www.green4cities.com/?p=1900

Type of intervention: Creation of new green space

Products/services covered: CityTree; green urban furniture; landscape architecture

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

We could not find any specific studies quantifying the cooling properties of green street furniture.

In terms of air purification benefits, the CityTree is said to deliver 275 times the air cleaning capability of a single tree (The Crown Estate, 2018).

Typical co-benefits

Environmental	Improvement of air quality
	Biodiversity
	Pollination
Social	Health and quality of life
	Employment enhancement
	Enhanced amenity value

References: Tecnalia (2017)

Cost information

A CityTree costs EUR 22,000 (Scott and Priday, 2018).

Potential disadvantages / negative impacts / trade-offs

Challenges / requirements for implementation

Species should be carefully selected, taking into consideration local climate and environmental conditions.

The furniture items should be placed in optimal locations, e.g. those that provide shade should be installed in sunny areas of buildings (Tecnalia, 2017), seating items such as the "City Tree" should be placed in areas where there is demand for seating (e.g. near bus stops).

The NBS will generally require maintenance. As with any other urban furniture, vandalism and destruction of the items may occur (Tecnalia, 2017).

The solution requires an initial investment associated with the replacement of the existing furniture (Tecnalia, 2017).

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Photo sources: https://www.flickr.com/photos/londonmatt/27643001768, Licence: CC BY 2.0 and http://www.green4cities.com/?p=1900

6. Greening linear transport infrastructure

Description

This solution entails the planting of vegetation alongside high-capacity infrastructure such as highways and railways, as well as 'soft' infrastructure such as streets and tram lines. As such, it covers a range of sub-measures such as street trees, green paths, and grass-lined rail tracks. Since they involve the introduction of pervious surfaces and/or urban trees, such greening measures contribute to stormwater management. Vegetation along transport infrastructure can also help mitigate the heat island effect and reduce noise. Depending on design and location, the measures can also contribute to improving ecological connectivity by mitigating fragmentation and facilitating wildlife movement, particularly when greening is applied to high-capacity infrastructure (Tecnalia, 2017).

There is high potential to introduce nature in vacant spaces around high capacity infrastructure, transforming unused spaces into safer, attractive walking tracks or recreational areas (Tecnalia, 2017).

Photo credits: Skitterphoto / pixabay.com

Photo credits: Laura Baroni

Type of intervention: Creation of new green space

Products/services covered: landscaping; landscape architecture; tree planting; green space maintenance; construction of transport infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality
■		■			

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
	■	■	■	■			

Effectiveness

Temperature regulation:

Street trees can regulate microclimates by providing shade, through evapotranspiration, and by altering the movement of air (Block et al., 2012). They can increase the thermal comfort of pedestrians, as well as provide shading to buildings, thereby reducing energy consumption for cooling (Block et al., 2012). For example, Sanusi et al. (2016) compared similar residential streets in Melbourne, Australia, having low (<20%) and very high (up to 80%) tree canopy cover. They found that streets with high canopy cover had significantly lower air temperature, relative humidity, solar radiation, and mean radiant temperature than streets with lowpercentage canopy cover. The size of the reductions depended on the orientation of the street (with East-West streets showing the greatest air temperature reduction, of 2.1°C).

Armson et al. (2012) measured the effect of grass and trees in Manchester on surface temperatures and temperatures measured with a globe thermometer (a measurement intended to provide an indication of human comfort). They found that concrete and asphalt surfaces exposed to the sun heated up much more than grass surfaces, reaching peak temperatures on hot days about 19–23 ◦C higher than air temperature, whereas grass in full sun had peak temperatures up to 3 ◦C cooler than air temperatures. Trees also reduced peak surface temperature by up to 12 ◦C compared to concrete. However, the experiments also showed that grass surfaces did not affect globe temperatures, whereas tree shading reduced them by up to 5–7 ◦C (Armson et al., 2012).

<u>Stormwater management</u>:
Urban trees also contribute to reducing surface flood risk by reducing stormwater runoff. A recent review of evidence on the benefits of urban trees for stormwater management (Kuehler et al., 2016) concluded that "urban trees can retain a sizable volume of annual rainfall in their crowns, delay the flow of stormwater runoff, substantially increase the infiltration capacity of urban soils, and provide transpiration of sequestered runoff for additional stormwater storage." Effectiveness was found to be highest during short, low-intensity storms and lower with increased rainfall volume and intensity (Kuehler et al., 2016).

An experimental study in Manchester, UK (Armson et al., 2013) measured the urban surface water runoff from 9 m^2 plots covered by grass, asphalt, and asphalt with a tree planted in the centre. The authors showed that grass absorbed almost all surface runoff, with the average runoff measuring less than 1% of the total rainfall, while runoff from tree plots was only 26% and 20% of the total rainfall in winter and summer, respectively (around 60% lower than runoff from the asphalt-only plots). Similarly, a modelling study (Gill et al., 2007) showed that increasing the tree cover in Manchester by 10% would reduce urban run-off in residential areas by 5.7%.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of air quality
	Noise mitigation
	Biodiversity
	Pollination
	Carbon storage
	Groundwater recharge
Social	Health and quality of life
	Regeneration of degraded areas
	Enhanced amenity value
	Employment enhancement
Economic	Reduced energy consumption
	Increased value of land/property

References: NWRM (2015); Tecnalia (2017)

Cost information

A recent review of 26 studies – mainly from North America – found a median annual cost per tree (including maintenance) of USD 37 (Song et al., 2018).

No specific information could be found on the costs of grass-lined alleys and rail tracks.

Potential disadvantages / negative impacts/ trade-offs

As regards street trees, the space required will depend on the trees' crown size and root network (NWRM, 2015). The latter may be extensive and cause damage to underground infrastructure, especially leaky sewers which trees may tap for water and nutrients (NWRM, 2015). Studies on the orientation and morphology of the streets are necessary in order to determine whether the introduction of vegetation may obstruct the ventilation corridors that promote air flow and thus disperse pollutant concentration (Tecnalia, 2017).

Challenges / requirements for implementation

The selection of species requires careful consideration not only of cooling potential, but also of drought vulnerability, water availability and irrigation requirements, depending on local climatic conditions (Block et al., 2012).

Technical constraints need to be considered in order to ensure that the vegetation does not damage structures and pose a risk to traffic safety (Tecnalia, 2017).

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Photo sources: Photo 1: https://pixabay.com/en/tram-train-city-urban-1481395/; Photo 2: Author's own.

7. Urban gardens (including allotment gardens / communal courtyards)

Description

Urban gardens provide a suite of ecosystem services, from the provision of food to microclimate regulation (through plant transpiration and shading) and water regulation due to unsealed soils (Cabral et al., 2017). They can also provide space for recreation and promote social cohesion, as well as habitats for wildlife and genetic diversity (Cabral et al., 2017).

Photo credits: Malcolm, G./flickr.com

In general, such urban gardens would be set up and managed by residents, rather than professionals.

Type of intervention: Creation of new green space

Products/services covered: landscaping; landscape architecture; green space maintenance

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Similarly to other NBS, the cooling potential of urban gardens depends on the type (species) and quality of the vegetation cover.

In terms of surface water flooding mitigation, urban gardens represent pervious surfaces (provided that they are not paved gardens) and as such they can intercept intense precipitation, temporarily hold water and hence reduce peak flow, and increase infiltration into the soil thereby reducing surface flow (Cameron et al., 2012). As an example, Pauleit and Duhme (2000, cited in Cameron et al., 2012) found that lower density housing with gardens had three times less storm water run-off than higher density areas. Gardens' effectiveness in providing these ecosystem services depends on the type of soil and vegetation involved.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of soil quality and stability, erosion prevention
	Improvement of air quality
	Biodiversity
	Pollination
	Carbon storage
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Amenity value
	Employment enhancement
Economic	Food provision
	Increased value of land/property
	Income generation

References: Cabral et al. (2017); Tecnalia (2017)

Cost information

The cost of land is the most relevant aspect for this solution, and this can vary widely.

If the gardens are looked after by residents/private landowners, then there are no public maintenance costs involved in this solution.

Potential disadvantages / negative impacts/ trade-offs

Availability of land for gardening may be a limiting factor, and can compete with other land-uses.

Water needs can be high.

If chemical inputs such as pesticides and artificial fertilisers are used, this can result in negative environmental impacts.

Challenges / requirements for implementation

In drought-prone areas, using more drought-tolerant plants can reduce the water needs for irrigation (Climate-ADAPT, 2015).

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8. Restoration and management of inland wetlands

Description

Wetlands can be described as "transitional areas between terrestrial and open-water systems" (National Research Council, 1992). The Society for Ecological Restoration defines restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." Note that although floodplains can be considered a type of wetland, floodplain restoration will be treated as a separate solution.

Photo credits: Unknown/pixabay.com

Wetlands are among the world's most productive environments and particularly important for the provision of water-related ecosystem services, including water quality improvement, groundwater recharge, and flood regulation. Although wetlands can provide countless benefits, wetland areas and their quality decline as a result of, among others, spreading urbanisation and agricultural expansion. Since the beginning of the 20th century, 60% of European wetlands (both inland and coastal) were lost (Russi et al. 2013).

The restoration and management of degraded inland wetlands focus on re-establishing the hydrology conditions, plants, and soils aiming at providing predominantly water flow regulation, water supply, and nutrient and pollution uptake and retention. This can involve technical and spatially large measures, such as ditches construction or dykes removal, technical and spatially small measures, such as tree clearing, and land-use change and agricultural measures, such as adapting cultivation practices (NWRM, 2015).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; ecosystem management and maintenance; landscaping; landscape architecture

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Wetlands exhibit a natural 'sponge' effect as they store water and slowly release it (NWRM, 2015). Due to this, inland wetlands are highly effective in slowing and storing surface water run-off and thus can play an important role in flood mitigation. A meta-analysis conducted by Kadykalo and Findlay (2016), which investigated the flow regulation services of wetlands, found that, on average, wetlands provide significant flow regulation services, which decrease the frequency and magnitude of flooding. However, the level of flow regulation depends on landscape configuration, topography, soil characteristics, and management (Acreman and Holden, 2013), which makes it particularly difficult to generalize the level of effectiveness of wetlands in mitigating flood risk.

Wetlands can also provide water provision services as their water can percolate through the soil recharging groundwater resources located below them. Additionally, wetlands can act as nutrient and sediment sinks and exhibit unique water purification properties. The slow water flow permits the deposition of pollutants and in turn they can be absorbed by plants, locked up in the soil, or be transformed into nontoxic substances. However, the degree to which each wetland can provide water treatment cannot be easily estimated as it is directly affected by the type of soil and plants, the size of the wetland, the speed of water flow, etc. This explains the especially wide range of Nitrogen load reduction found in the literature. As Jenkins et al. (2010) reported, the rate at which natural forested wetlands can reduce the Nitrogen load of water ranges from <1 to >800 kg/ha/year.

Typical co-benefits

Environmental	Regulation of the water cycle
	Biodiversity
	Pollination
	Carbon storage
	Improvement of soil quality and stability, erosion prevention
Social	Health and quality of life
	Recreation and environmental education
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Food provision
	Water provision
	Income generation
	Increased value of land/property
	Increased tourism

References: NWRM (2015); Russi et al. (2013)

Cost information

The cost of restoration and management of wetlands is ecosystem and site specific. Moreover, projects of wetland restoration are often combined with other green or grey measures, and thus, separate cost data for wetland restoration is scarce (EEA, 2017). According to the EEA (2017), the costs for land acquisition and construction and rehabilitation range from around EUR 1,400 to EUR 54,000/ha. The cost of maintenance and operation of wetlands has not been examined in great detail in the literature. EEA (2017) cites an estimate of EUR 348/ha/year.

Potential disadvantages / negative impacts

Disadvantages of wetland restoration and management can involve nutrient release during non-growing season, reduction in run volume, high land take and conflicts between stakeholders that arise due to land-use change, and colonisation by invasive species (SusDrain, 2018)

Challenges / requirements for implementation

Wetland restoration projects require a baseflow, which is a sustained low flow in a river during dry weather conditions (SusDrain, 2018). Moreover, the landscape plays an important role, since in order for a wetland to be established the site cannot be steep. In addition, the initial cost from land acquisition, detailed preparatory studies, land preparation, etc., tend to be particularly high.

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9. Restoration and management of floodplains

Description

Photo credits: MidCoast Water/ flickr.com

Floodplains are low-lying areas adjacent to rivers that provide key ecosystem services, including, among others, flood protection and rainwater retention. Many floodplain ecosystems in Europe have been highly modified for agricultural development due to their fertile soil or have been separated from the river as a result of dikes and other hard engineering structures designed to control river flow (NWRM, 2015). These alterations associated with land-use change, river modification, and intensive urbanisation have led to the obstruction of the floodplains' capacity to retain run-off and river floodwater, increasing flood risk.

The objective of floodplain restoration is to reconnect floodplains with the river and increase their retention capacity and ecosystem service provision. According to Blackwell and Maltby (2006), there are two ways to restore floodplains' ability to control flooding: increase a floodplain's water storage capacity or improve the conveyance of water through the floodplain. The former would result in increased floodwater storage and thus reduction of flood risk in areas downstream of the floodplain, whereas the latter would decrease flooding risk in areas adjacent to the floodplain as well as downstream (Blackwell and Maltby, 2006). Floodplain restoration usually involves different kinds of natural flood risk-reduction measures, some of which are individually analysed in separate fact sheets: e.g. the strategic construction of dams or levees, the removal or setting-back of embankments, floodplain excavation, vegetation restoration, woodland creation, etc. Floodplain restoration can take place at a variety of scales, however, the catchment area for such a project should be at least 10 km^2 in order to provide sufficient space for river floodwater storage (NWRM, 2015).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; ecosystem management and maintenance; landscaping; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The natural function of floodplains to store river floodwater is highly effective in mitigating flood risk. However, the volume of water stored and the reduction of river peak flow are site-specific as they depend on the site's hydro-morphological factors, which are interlinked and interact in complex ways. Floodplains can be very effective in storing and decreasing runoff as well, however, storing runoff should principally take place before it reaches the floodplain in order for this space to be occupied by river floodwater (NWRM, 2015).

Examples from floodplain restoration projects are indicative of the effectiveness of floodplains in reducing flood magnitude downstream. Hooijer (1996) estimated that the retention capacity of a floodplain of 3500 ha in the Shannon valley in Ireland with an average depth of 1 m has a storage capacity of one day of the river's peak discharge, which was around 400 m^3/s. A LIFE III project in the New Forest in Hampshire, England, which aimed at restoring a floodplain and was accompanied by reconnecting old meanders and adding wood to the channel, resulted in a 21% reduction of flood peak magnitude (Addy et al. 2017).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Groundwater recharge
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
	Carbon storage
Social	Recreation, environmental education
	Enhanced amenity value
	Employment enhancement
	Regeneration of degraded areas

References: NWRM (2015); APFM (2012)

Cost information

Restoration costs depend on several factors. The market value of the land varies depending on its use, which implies that floodplain restoration projects in rural environments will usually cost less than in urban areas due to the cost of land acquisition. According to Broekx et al. (2011), this cost might range from EUR 10,000/ha for agricultural land to EUR 700,000/ha for land used for residential purposes. Costs also arise by the construction, relocation or removal of grey infrastructure. These can be as high as EUR 16,000/m for dyke heightening and EUR 19,000/ha for outlet sluices (Broekx et al., 2011). Schwarz (2006) estimated that floodplain restoration in the lower Danube after the 2006 floods, which included land acquisition costs and engineering structures, was approximately EUR 5,000/ha. However, other similar projects in the Rhine and Scheldt were estimated to cost EUR 360,573/ha and EUR 136,542/ha, respectively, which shows the variability of floodplain restoration costs. Such projects generally have relatively low maintenance costs that range from 0.5 to 1.5% of the total investment per annum (Broekx et al., 2011).

Potential disadvantages / negative impacts/ trade-offs

Floodplains can be occupied by urban settlements or used for agricultural purposes due to their fertile soil from the deposition of river sediments. Therefore, many floodplains, in order to be restored, require significant land use change. This can trigger conflicts between those that use the land for different activities and the restoration project.

Challenges / requirements for implementation

Floodplain restoration firstly requires a spatial analysis throughout the river basin to identify flood spots using highly technical methodologies and tools. Furthermore, the initial cost from land acquisition, detailed preparatory studies, land preparation, etc., tend to be particularly high (EEA, 2017). In addition, floodplain restoration projects take place usually out of the jurisdictional boundaries of a city, their spatial extent is at least 10 km^2, and there are multiple stakeholders involved, such as municipalities, river basin authorities, citizens, farmers, etc. Due to all these factors, the implementation of such projects requires a high degree of interinstitutional coordination, which can be essential for their success.

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10. River restoration for flood control

Description

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Rivers, riparian zones and floodplains have been significantly altered from their natural state by human activities, leading to increasing risk of flooding. There are a number of measures available that can restore the natural state and function of rivers. Restoring the natural state of the river can benefit the water cycle, increase biodiversity, control erosion, and reduce the risk of flooding. The NBSs that focus on the restoration of rivers with a view to control floods are presented here. These are not a set of solutions meant to be used altogether, but rather an inventory of different measures from which one or several can be selected to best address the needs of each site.

Re-naturalization of riverbed (or streambed)

Riverbed (or streambed) refers to the floor of the river and its riverbanks. In the past, riverbeds were modified by artificially reconstructing their floor and banks by adding concrete or big stones, aiming at preventing floods, supporting agricultural practices, and enabling navigation (NWRM, 2015a). However, this has led to the alteration of river flows, reducing water travel time and making water flows uniform along the river. Their re-naturalization involves the removal of some inert and concrete structures and replacing them with vegetation structures. Such interventions could positively impact erosion processes, restore biodiversity, and mitigate flood risk (NWRM, 2015a).

Re-naturalization of riverbed material

The riverbed material consists of the sediment that was eroded upstream, transferred by the flow, and deposited on the river floor. Human-induced modifications of river basins and their vegetation cover can disturb sediment supply, transport, and deposition patterns (Liébault et al., 2005). Such problems typically cause coarse sediment deficit (or fine sediment excess), which can detrimentally affect biodiversity and can cause river incision and inundation downstream (Liébault et al., 2005). The re-naturalization of the riverbed material involves the recovery of the nature-like structure and composition of the riverbed material and especially the balance between fine and coarse sediment (NWRM, 2015b). This can be achieved either by reactivating erosion on banks that can provide the desirable type of sediments or by controlling erosion on banks providing the undesirable type of sediments (NWRM, 2015b).

Riverbank protection removal

Riverbank protections are inert (e.g. stone, concrete) or living (e.g. vegetation) structural measures aiming to provide bank fixation in order to manage bank instability and erosion. However, they also constitute an obstacle for the lateral connection of the river. The removal of some parts of the riverbank fixation, especially the inert ones, can enhance the lateral connection of the river, re-introduce diversity of flows along the river as well as diversity of habitats, and cap floods in the mainstream (NWRM, 2015c).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; landscape planning; environmental engineering; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this measure varies depending on the chosen combination of the abovementioned solutions. Riverbed re-naturalization and riverbank protection removal involve vegetation planting that in principle makes the riverbed rougher, effectively slowing down the river flow, which reduces flooding risk. Similarly, re-naturalizing the riverbed material increases the water storage capacity of the river and its floodplains, thereby contributing to flood risk reduction. Restoring and reconnecting seasonal streams increases water storage capacity from both run-off and river water, and consequently flood risk is reduced. No quantitative estimates of the effectiveness of these measures could be found.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of soil quality and stability, erosion prevention
	Improvement of air quality
	Biodiversity
Social/cultural	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Income generation
	Food provision
	Water provision (from the *restoration and reconnection of seasonal streams*)
	Increased value of land/property
	Increased tourism

References: Gallacher, 2017

Cost information

Relevant costs to be considered for this measure include land acquisition, planning studies, and capital costs. All are context specific and a general extrapolation of costs is not possible.

Potential disadvantages / negative impacts/ trade-offs

Such measures do not appear to have significant trade-offs, however, since riverbank protection enables safer navigation, their removal might potentially affect their navigability. Re-naturalization of rivers might also increase the presence of pests, particularly mosquitos, which would pose an extra cost for pest control.

Challenges / requirements for implementation

River restoration measures require technical knowledge; in particular, the restoration and reconnection of seasonal streams and riverbank protection removal are considered tasks that require high technical expertise. Moreover, river restoration should pay particular attention to citizens' safety (Tecnalia, 2017). In addition, the implementation of such projects requires a high degree of interinstitutional coordination.

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Photo source: https://commons.wikimedia.org/wiki/File:Boneyard_Creek_Second_Street_Basin_Champaign_Illinois_looking_to_east.jpg; Licence: CC BY-SA 4.0.

11. Restoration and reconnection of seasonal streams

Description

Photo credits: Unknown/Wikipedia.org

Seasonal streams are rivers for which water flow ceases at some point in space and/or time. Such streams provide flood control and a high level of groundwater recharge and infiltration, but their abundance, distribution, and flow regimes are altered by water abstraction, climate change, and inter-basin transfers (NWRM, 2015). The protection of their ecological value requires rigorous management that can restore and reconnect them with the river. Their management should focus on restoring lateral connectivity, diversifying their flows, and ensuring better water retention during floods (NWRM, 2015).

The restoration and reconnection of seasonal streams with the river aims at restoring lateral connectivity, and diversifying flows, which favours the overall functioning of the river. Through that, there is high potential for this solution to mitigate river floods and increase groundwater recharge (NWRM, 2015). However, since seasonal streams exhibit a high diversity of hydrological functions, restoration measures should be implemented with caution, recognising that some measures might not fit the site-specific conditions of each watershed, thus this solution requires thorough study of the local hydrological variables before its implementation.

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; landscape planning; landscape architecture; environmental engineering

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Seasonal streams increase the length of the river that they are connected with, which increases the amount of run-off and river water they can store. Moreover, due to the additional storage, seasonal streams can also slow down run-off and river water (NWRM, 2015). Their effectiveness depends on the length of the river system and the location of the seasonal streams. The effectiveness of this solution in recharging groundwater reservoirs is largely dependent on the level of precipitation, since it affects the run-off flow and the flood intensity, but, when precipitation is high, groundwater recharge can be significant (NWRM, 2015).

Typical co-benefits

Examples of co-benefits can be seen in the table below.

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
Social/cultural	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Food provision
	Water provision

Source: NWRM (2015)

Cost information

The cost of the restoration and reconnection of seasonal streams is highly site-specific. It would involve costs for land acquisition, hydrological and other studies, and capital costs. All these costs depend on the desired length of the secondary streams, the existing development of the site (e.g. urban, agricultural land, wilderness, etc.), and the geological and topographic conditions of the area.

Potential disadvantages / negative impacts/ trade-offs

This solution involves land acquisition, which might be previously developed either as an urban or an agricultural area. By restoring seasonal streams, buildings, infrastructure, and agricultural land in these areas might be partially or fully removed. Apart from the forgone income, this might trigger conflicts among different stakeholders. In addition, the heavy engineering constructions that are usually required could generate large disturbances in the river ecology, which will be stabilized only after a few years (Burek et al., 2012).

Challenges / requirements for implementation

To effectively design and implement this measure requires the involvement and consultation of local stakeholders and water managers (NWRM, 2015).

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Photo source: https://commons.wikimedia.org/wiki/File:Bell_Creek_at_Caspers_Park.JPG; Licence: CC BY-SA 4.0.

12. Re-meandering

Description

Photo credits: Golubovic, M./commons.wikimedia.org

A river's meander is one of a series of U-shaped formations taken by the river. In the process of river straightening, a common practice to enable better navigation with bigger vessels, control floods, and free up land for agricultural purposes, meanders were cut off (NWRM, 2015). However, this often resulted in higher flow velocity, greater erosion, and lower biodiversity (Stella Consulting, 2012). Higher flow velocity in combination with cut-off access to floodplains, which was usually the result of river straightening, could increase the risk of flooding as excessive water could not discharge into the landscape, flooding in greater severity the downstream areas.

Re-meandering refers to restoring the "curving" course of the river by creating new meanders and reconnecting old cut-off ones. Cut-off meanders might have completely disappeared or exist as oxbow lakes, which are U-shaped lakes formed when meanders are separated by the central stem of a river (Stella Consulting, 2012). In the first case, re-meandering should be based on old maps to reveal the former course of the river and meanders should be newly created, whereas, in the case of oxbow lakes, the barriers between the two water bodies (i.e. the oxbow lake and river) have to be breached (NWRM, 2015). The re-meandering of a river reduces the risk of river flooding by two hydro-morphological changes. Firstly, the water flow becomes slower and secondly, by increasing the length of the river, the volume of water that it is able to carry increases (Burek et al., 2012).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; environmental engineering

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Re-meandering can achieve a win-win situation in which the low flows of a river can increase locally by up to 15% and its flood peaks can decrease by up to 15% (Burek et al., 2012).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
	Improvement of soil quality and stability, erosion prevention
	Reduce peak temperature
	Biodiversity
	Carbon storage
Social/cultural	Recreation, environmental education, enhanced space for social gathering
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Food provision
	Water provision

Reference: NWRM, 2015

Cost information

The cost of a re-meandering project includes land acquisition, construction, and operation costs. Putting all these costs together from different projects all over Europe, EEA (2017) estimated that the average annual costs for re-meandering is about EUR 93,000/ha/yr.

Potential disadvantages / negative impacts/ trade-offs

As is the case with other restoration measures, the land in which a re-meandering project takes place might be already occupied and a productive activity (e.g. agriculture) might already take place. This means that the land-use has to change, which could be a potential reason for conflict among the various stakeholders. Moreover, the heavy engineering constructions that are usually required could generate large disturbances in the river ecology, which will be stabilized only after a few years (Burek et al., 2012).

Challenges / requirements for implementation

Re-meandering requires thorough and long-term planning and should be based on accurate climate change data in order to account for climate impacts on precipitation and water flows (Stella Consulting, 2012). Moreover, the natural conditions of the river before its straightening, on which the re-meandering planning should be based, are often unknown. In addition, re-meandering will usually require a high degree of interinstitutional cooperation and heavy engineering constructions.

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13. Reconnection of oxbow lakes

Description

Photo credits: Koester, L. / flickr.com

Oxbow lakes are ancient meanders disconnected from rivers, which create a small U-shaped lake. They develop when rivers are straightened and the meanders are cut off in this process. This happened intensively in Western Europe during the last century, but also in other parts, leaving oxbow lakes and similar features in many European countries. Oxbow lakes can also form naturally depending on the dynamic of the river.

When the land between the river and the oxbow lake is removed, the water bodies can reconnect, restoring the "curving" course of the river, which ultimately constitutes a special case of re-meandering. In this way, the length of the river and thus the retention capacity during floods can be increased. Furthermore, the oxbow lake can temporarily store run-off water from surrounding areas in the event of heavy precipitation, hinder or delay run-off into the river and thus contribute to reducing flood levels. By slowing down the river flow, they reduce erosion in the river bed and support sediment deposition, which can have further positive impacts on flood protection. Combined with grey measures that regulate the outflow, like sluices, the storage capacity and run-off can be controlled even more (NWRM, 2015).

The re-connection of oxbow lakes can decrease flooding risk downstream as well as in areas adjacent to the floodplain. While oxbow lakes can store water and protect adjacent areas from pluvial flooding also at a smaller scale, in order to reduce river flood risks the measure needs to correspond to a drainage area of at least 10 km^2 (NWRM, 2015).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; environmental engineering

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Re-connected oxbow lakes and similar features are highly effective for slowing down and storing run-off water from rivers and heavy precipitation and thus mitigating flood risk. The overall effect depends however on the position of the lake, the terrain, the morphological structure, size and length, the river, soil, storage capacity, etc. The effect of reconnecting a single oxbow lake is not high in relation to river floods, but is the cumulative effect of several structures plus other measures. The combination with grey measures such as dams and sluices can increase the effectiveness for flood management as more water can be stored temporarily and released at appropriate times (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Groundwater recharge
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
Social	Recreation, environmental education
	Enhanced amenity value
	Employment enhancement

References: NWRM (2015)

Cost information

The costs of re-connecting oxbow lakes depend on the local circumstances, such as the size, amount and type of land that needs to be removed to create the connection. Based on case studies, NWRM (2015) indicates the following cost ranges for different cost categories:

Land acquisition :	0 – 60,000 EUR
Investigations and studies:	0 – 100,000 EUR
Capital costs:	100,000 – 2,000,000 EUR
Maintenance costs:	10,000 – 1,000,000 EUR

Potential disadvantages / negative impacts/ trade-offs

The removal of land, necessary construction work for remodelling and potential supplementary grey measures like dams, sluices etc. can damage valuable natural or cultural values if they have been established in this area since the lake was disconnected from the river. In some cases, buildings and infrastructure needs to be removed and established in different places; resistance of owners and users (such as farmers and foresters) can be expected. However, the area is usually relatively small.

The lake ecosystem and dynamics will change as a result of implementing this measure. Over time, the oxbow lake has developed as a standing water body and biodiversity has adjusted to it, possibly including valuable habitats and/or endangered species. Reshaping it into a flowing water body and constructions at the edges will change the habitat and its biodiversity. Sedimentation processes will change the morphology and further change habitats. These changes can impact on the water quality, as well as usability for fishing (if the area was previously used for fishing). The changes can be both negative and positive (if the ecological state of the lake was poor).

Challenges / requirements for implementation

The measure needs to be considered as part of a wider flood risk management; a single measure is often too small to have a significant impact on the river flood risk. This requires the collaboration between different stakeholders and at regional level.

Further challenges for the implementation of the measure depend highly on the site specifics and structure of the measure. For example, owners and users of the land that needs to be re-opened or users of the lake itself need to be informed, action coordinated and compensation provided where necessary. The morphology and soil conditions can pose challenges for the construction of channels and of supplementing grey measures.

If the river bed is significantly deepened due to river bed erosion, the connection is not possible at normal water levels. It would require constructing a weir or water from side tributaries for raising the water level. If the measure involves the cutting of a dyke or embankment, it is important to ensure appropriate consideration of flood management requirements, including potential flood protection for surrounding areas (NWRM, 2015).

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14. Re-naturalisation of polder areas

Description

A polder is a low-lying tract of land, which has been enclosed by embankments (dikes) that form an artificial hydrological entity (NWRM, 2015). It has no connection with the outside except through manually operated devices (weirs). They are built in areas adjacent to water bodies such as rivers, deltas, coasts. Since the 12th century, polders have been built in the Netherlands to gain agricultural land. With a complex system of pumps, windmills and adapted farm management practices, farmers keep the water out by pumping it to the sea or river and manage occasional flooding (NWRM, 2015). Polder areas are seen across Europe along the rivers Elbe, Oder, Po, Danube and others.

Photo credits: MabelAmber / Pixabay.com

Polders are most relevant in the lower reaches of larger rivers and coastal areas. In contrast to retention areas, the inundation on polders can be controlled. The re-naturalisation of polder areas – which involves changing agricultural use from intensive to extensive forms, removing buildings and infrastructure, and lowering the dikes towards the river – allows for temporarily flooding the polder and providing additional space for the river in case it is needed to reduce the risk of flooding in other areas. It is typically effective at a catchment area of 100-1000 km^2 (NWRM, 2015). Apart from storing flood water, polders can also recharge groundwater

Type of intervention: Intervention in an existing ecosystem; ecosystem management and maintenance.

Products/services covered: Ecological restoration; landscaping; landscape architecture

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Polder areas can be highly effective in mitigating flood risk as they – depending on their size – can store a very large amount of water from large catchment areas (NWRM, 2015).

They can cap the flood peak effectively, which will remain relatively at the same level along the river downwards. Strobl et al. (2006) found in simulations along the Danube river that the caption of the flood peak by polders can be even more effective than by uncontrolled retention areas. The effect depends however on the way the polders are built and managed under floods (Huang et al., 2009; Nijssen et al., 2009).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
Social	Recreation
	Enhanced amenity value
	Employment enhancement
Economic	Income generation

References: NWRM (2015)

Cost information

As an example, the development of the Kruikeke Bazel Rupelmonde (KBR) Controlled Flood Area in Belgium as a key component of the Belgian Sigma Plan for the Scheldt Estuary cost around EUR 100 million for 600 hectares of re-naturalised polders from three formerly separated polder areas (Climate-ADAPT, 2014).

Potential disadvantages / negative impacts/ trade-offs

The re-naturalisation of polder areas requires the change of land use. For agriculture this means a restriction of certain practices, replacing intensive use with extensive management practices, and potentially lower income. The flooding of the area requires extra effort in moving stock to other ground, temporarily not useable areas with production failures and possibly some reconstruction needs after a flood event. Polder areas are a relatively costly flood protection measure.

If not planned well to different types of flood events and improperly operated, polders might fill too fast and too much and unintended backflow might occur or overtopping of dykes can appear and create higher flood damages (Nijssen et al., 2009).

Challenges / requirements for implementation

Establishing polder areas requires space. As a combination of nature-based and technical solutions, they require also continuous maintenance and wise operation under flood events.

The effect depends however on the way the polders are built and managed under floods. Timing is important when opening the polder to cap the peak discharge (Huang et al., 2009). The complexity of different possible flood conditions has a substantial impact on the flood mitigation potential of the polder area. When planning the polder area, it is important to consider a variety of flood scenarios and not only a worst case scenario, in order to improve effectiveness and avoid adverse effects. Carefully designing, placing and managing weirs and the combination with other measures are necessary (Nijssen et al., 2009).

In addition, the measure should be considered in combination with other measures as part of a wider flood risk management system. When planning, a variety of flood events should be simulated to find the appropriate construction and operation of the polder to achieve high effectiveness.

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Photo source: https://pixabay.com/en/tree-meadow-rural-country-farmland-3008519/

15. Lake restoration

Description

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As natural and sometimes artificial water reservoirs, lakes can both store water and recharge underground reservoirs. They also provide other services, such as fish provision, water supply, recreation, and habitat for species. Some lakes have been altered in the past – they have been drained, silted up or have had their water quality impaired. Lake restoration enhances their function and structure.

Restored and well-functioning lakes can store additional flood water from rivers flowing through them and from small tributaries of the catchment area. They can, thus, slow run-off and delay the discharge. They also recharge groundwater resources and serve as a water reservoir, which is particularly important for coping with droughts and water scarcity situations (see measure *Restoring the natural infiltration to groundwater*). Lakes are abundant in almost all parts of Europe and this measure can be used in many regions. Catchment areas start form 1 km^2 (NWRM, 2015).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; ecosystem management and maintenance; landscaping; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Lakes can drain large catchment areas. Depending on the size and structure of the lake, it can store large volumes of flood water and slow down run-off and river water. For very high storage volumes, additional hydraulic infrastructures need to be used (NWRM, 2015). Lake restoration can have a high relevance for erosion and sedimentation processes, which could be positive and negative. Sediment can deposit easier in the lake due to a slowed down river runoff. This reduces the sediment delivery on the river. On the other hand, if there is too much sedimentation in the lake and coarse sediment reduced, this can accelerate erosion in the river (NWRM, 2015). According to NWRM (2015), the recharge of groundwater aquifers is relatively low. Natural and artificial lakes are important and widely used as reservoirs to provide water for drinking and other uses.

In combating water scarcity, lakes are used as part of a water retention area. For example, in Tamera, Portugal they have been proven to be very effective in contributing to stopping erosion and desertification. The water retention system has created a regenerative basis for autonomous water supply of the farm land, the regeneration of topsoil, forest, pasture and food production, and greater diversity of wild species (Climate-ADAPT, 2015)

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Groundwater recharge
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Spiritual, religious, and artistic values
	Regeneration of degraded areas
	Employment enhancement
Economic	Increased value of land/property
	Increased tourism

References: [NWRM, 2015]

Cost information

Costs for lake restoration vary widely depending on the local and regional circumstances, such as the current situation of the lake, the morphology of the area, the use of the shores of the lake.

NWRM (2015) mentions capital costs of 4000 EUR /ha based on the example of habitat restoration at Crocall Leakes Nature Reserve. Other costs, e.g. for land acquisition, investigation and studies, remodeling of existing infrastructure etc. need to be considered. Maintenance costs are considered to be low (NWRM, 2015).

In the case of the Tamera water retention landscape, the benefits outweigh the high construction costs with a positive balance of roughly EUR 260,000 EUR (Climate-ADAPT, 2015)

Potential disadvantages / negative impacts/ trade-offs

While the benefits of lake restoration are generally seen as high, the measure can also involve adverse effects when the water regime and thus habitats change, in particular, when hydraulic infrastructure is involved and allows for much higher storage capacities. If sedimentation in the lake is too high and coarse sediment reduced, it can accelerate erosion in the river (NWRM, 2015).

It can be necessary to change the use of the lake and its shores, including the removal of buildings and infrastructure, agricultural or forest use. Acceptance of residents, tourists, farmers, foresters or fishermen can be low.

For the creation of new lakes or when hydraulic infrastructure elements are involved, construction costs can be high.

Challenges / requirements for implementation

Land purchase and potential land use changes can require compensation. The design of the measure needs to consider the potential disadvantages to avoid or minimise these. The effective restoration and maintenance of lakes may include local planning authorities, environmental regulators, private landowners and land managers, farmers and other bodies with responsibilities for water management (e.g. irrigation bodies, drainage boards, etc.) requiring an effective governance and participation approach.

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Photo source: https://pixabay.com/de/wasser-natur-gr%C3%BCn-fluss-landschaft-3519938/

16. Floodplain and riparian woodland creation

Description

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Riparian woodlands (or riparian forests) are found at the interfaces between terrestrial and aquatic ecosystems, including floodplains and their adjacent terraces (Naiman et al., 1998). The creation or preservation of a floodplain and riparian woodland can provide significant benefits related to water quality and flood control. It can act as a sink for potential sources of diffuse pollution and could play a role in the rehabilitation of degraded and/or contaminated land, as well as slow down run-off and reduce downstream flooding (Nisbet et al., 2011). Despite these advances in the understanding of the linkages between forests and water resources, the role of woodlands in water resource management has not yet been fully utilised (Stella Consulting, 2012).

According to Nisbet et al. (2011), there are three main mechanisms through which woodlands can contribute to alleviating flooding. Firstly, trees use a greater amount of water than shorter types of vegetation, mainly due to the interception of rainwater by their rougher canopies. Secondly, woodland soils can hold back and delay rainwater that flows to streams and rivers, due to their more open structures that result in higher infiltration rates. Thirdly, the greatest potential of floodplain and riparian woodlands to delay the progression of flood flows derives from the hydraulic roughness created by the trees, shrubs, and deadwood in the river or streams and on the floodplains.

Type of intervention: Intervention in an existing ecosystem & Creation of new green space

Products/services covered: Landscape planning; landscape architecture; tree planting; ecosystem management and maintenance.

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to Nisbet et al. (2011), the infiltration rate of a woodland shelterbelt can be 60 times higher compared to grazed pasture, and planting shelterbelts across the lower parts of grasslands could reduce peak flows by 13 to 48%. Moreover, Nisbet & Thomas (2006) modelled the effect of planting native floodplain woodland along a 2.2km grassland, comprising less than 2% of the total river catchment, and according to their analysis the water velocity can decrease by 50% and the water retention can increase by 71% as a result of the increased terrain roughness. Riparian buffer woodland, meaning linear strips parallel to the river flow, can have similar effects, in a smaller scale, due to the large woody debris dams within the streams, out-of-bank flows, and increased flood storage in addition to the increased roughness in the riparian zone (Nisbet et al. 2011).

One of the major factors affecting the effectiveness of riparian woodlands on sediments, nutrients, pathogens, pesticides, and toxins is their width. According to a literature review on riparian buffers, forested buffers with an average width of 38 to 50m can reduce nitrate concentrations by between 78 and 99% (Mayer et al., 2005).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
	Pollination
	Carbon storage
Social/cultural	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Food provision
	Increased value of land/property

References: Soman et al. (2007)

Cost information

Kohler and Heinrichs (2011) assumed a relatively low cost for creating riparian forests, between EUR 1,000 and 10,000. They do not refer to a specific land size, however, they do state that the final cost will be dependent on scale. Stella Consulting (2012), based on a case study, assumes that the average cost of creating a riparian forest in Europe would be around EUR 7,500/ha for five years and additionally assumes annual operation and maintenance cost of around EUR 500/ha.

Potential disadvantages / negative impacts/ trade-offs

Apart from the many (co-)benefits that the floodplain and riparian woodlands have to offer, they can also come with trade-offs on the water environment. Although woodlands next to waterbodies can help in reducing extreme water temperature and thus protect freshwater life by the shadow they cast over them, too much shading can significantly reduce the temperature of the water and reduce fish growth (Forest Research, undated). Moreover, some tree species can use a lot of water, reducing stream water levels and water supply during summer (Forest Research, undated). According to Stella Consulting (2012), riparian woodlands can overgrow the water body by the woody debris falling in the streams that can divert river water by blocking passages and retain water. In addition, trunks, branches and leaves can obstruct the drainage of flood events acting as natural dams, which can also increase backwater and aggravate flood events. Lastly, trunks and branches can cause some infrastructure damage when dragged by high flows downstream (Stella Consulting, 2012).

Challenges / requirements for implementation

In the design of floodplain and riparian woodlands, there are many individual considerations to be taken into account, as it determines the water use by the trees and the roughness of the terrain and to a lesser extent the rainwater retention capacity (Nesbit and Thomas, 2006). According to Nesbit and Thomas (2006), the species, structural diversity, and forest cover and open space balance are decisions of great importance during the design of such measures, since they can limit the effectiveness of trees to control flood flows. In addition, the authors maintain that riparian buffers would have a significantly lower effect on flood attenuation than floodplain woodlands, mainly as a result of the limited width of the woodland. They also warn that the management of the site can determine the effectiveness of this solution on flood risk. Felling, for example, can have dramatic effects on flood-related impacts, as it minimises the tree water use and increases run-off, and timber harvesting and extraction can have an even greater effect on flooding (Nesbit and Thomas, 2006). Therefore, management measures should be carefully adjusted to accommodate all the uses of such ecosystems, including flood attenuation and water purification.

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Photo source: https://pixabay.com/en/germany-landscape-scenic-mountains-1933558/.

17. Managed realignment

Description

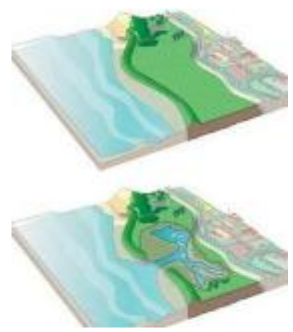

Photo credit: Climatetechwiki.org

Traditional sea defence provides a fixed protection of people and their assets against coastal flooding and erosion. However, fixing the position of the coastline obstructs the natural coastal processes, which in turn can have significant detrimental effects on these dynamic and adaptive ecosystems (Turner et al., 2007). Managed (or controlled) re-alignment refers to moving the line of hard flood defences further inland and/or on rising ground, in order to recreate intertidal habitats between the new and the old defence line (Climate-ADAPT, 2015).

Managed realignment can involve deliberately breaching the engineered defences or completely removing any hard sea defence infrastructure, such as dikes, and relocating the defences further inland (Climate-ADAPT, 2015; Turner et al., 2007). Moreover, if the realignment is undertaken to higher grounds, hard defences might not be needed at all (Xianli et al., 2010). In many cases, realignment aims to create saltmarshes, which are usually developed mean high and mean low water springs, in areas where silts and mud are predominant (Xianli et al., 2010). By allowing the coastline to recede and the intertidal zone to expand, the created or restored resulting habitat can provide natural protection from flooding and erosion, as well as a number of other ecosystem services and constitute significant reservoirs of biodiversity (Turner et al., 2007). Moreover, the presence of this natural protection can reduce the cost of installing and maintaining hard defence structures further inland, if any, since they can be of reduced height and strength (Xianli et al., 2010).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Environmental engineering; ecosystem restoration; construction of flood control infrastructure; landscaping; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Intertidal habitats are highly effective at attenuating wave energy, meaning that waves are smaller in height and not as powerful as when they reach the shore, which results in lower coastal flood risk and erosion (Xianli et al., 2010). As studies on saltmarshes have shown, their attenuation capacity can reach up to 97% of incoming wave energy (Xianli et al., 2010). However, the level of wave energy attenuation, and consequently the degree of coastal flood protection, is directly affected by the width of the intertidal habitats, their flora, ground elevation, and other geomorphological factors, which implies that the effectiveness of this solution is site-specific.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Biodiversity
	Carbon storage
Social/cultural	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Enhanced amenity value
	Employment enhancement
Economic	Food provision
	Income generation

Reference: Xianli et al., 2010

Cost information

According to AMPmer (2015), who reviewed the costs of 45 of the 64 managed realignment projects completed in the UK, the overall cost of such projects in Britain is on average GBP 40,000/ha (in 2014 prices). The lowest costs reported in their review was just under GBP 800/ha, while the highest was almost GBP 123,000/ha. The main cost of this solution in Europe is usually the cost of land acquisition. However, total costs can vary depending on site-specific factors, such as compensation to land owners, engineering effort for the demolition of the existing defences and development of new ones, size of the new defences, labour costs, and monitoring requirements (Xianli et al., 2010).

Potential disadvantages / negative impacts/ trade-offs

One of the main disadvantages of this solution is that land has to be yielded to the sea, which makes such schemes suffer from a lack of public acceptance, since the public might perceive as a threat the fact that the sea will come closer to their properties or might be reluctant to lose valuable land in case the coast is used for other purposes (Xianli et al., 2010). Moreover, this land allocation to nature can involve a trade-off with food production, as such projects often take place on agricultural land (Xianli et al., 2010). In addition, in case old infrastructure is abandoned, the nearby areas might become isolated, leading to increased poverty (Xianli et al., 2010).

Challenges / requirements for implementation

There are several objective requirements in order for such projects to be undertaken. A key prerequisite is the availability of low-lying coastal land behind the existing defence structure in order for the intertidal habitat to be created after the realignment (Xianli et al., 2010). The implementation of managed realignment needs to be well-planned through monitoring and modelling studies that examine the effects of such projects on the site in order to avoid unwanted consequences (Xianli et al., 2010). Furthermore, due to the lack of public acceptance often noticed in such projects, societal awareness about the benefits of realignment needs to be raised, while active participation in the planning and decision making process of those affected needs to be promoted (Xianli et al., 2010).

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18. Restoration and management of coastal wetlands

Description

The many definitions used in the literature to describe wetlands include saltwater marshes, mangroves, estuaries, lagoons and coral reefs. Although wetlands of all kinds have common characteristics, the management and restoration of inland and coastal wetlands are described separately in this report given the different set of measures employed to restore and manage them, as well as the different climate and water-related hazards that the two types of wetlands tackle.

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Coastal wetlands have a unique buffer capacity as they increase the roughness of the surface over which waves and tides travel resulting in reducing wave and tidal energy, lowering their erosive power and consequently coastal erosion. Moreover, this attribute of wetlands reduces the risk of coastal flooding by diminishing the height of storm surges (UNEP, 2015). In addition, coastal wetlands can reduce the impact of sea-level rise as the constant supply and accumulation of sediment to the coast leads to maintaining their elevation relative to sea level (Nicholls & Wong, 2007). Similarly to inland wetlands, coastal wetlands are hotspots of biodiversity, since, besides the diversity of plant and animal species they can host, they often constitute breeding and nursery grounds for fish, shellfish, birds, and mammals (UNEP, 2015).

The restoration of coastal wetlands involves the addition of sediment to raise land above the water level in order for wetland plants to colonise the area or the rewetting of drained wetlands by restricting groundwater extraction and blocking drains (Climate-ADAPT, 2015). Another measure can be the removal or relocation of coastal defences further inland and converting reclaimed land between the sea and the flood defence to wetlands (Climate-ADAPT, 2015).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; ecosystem management and maintenance; landscaping; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality
			■		

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
					■		

Effectiveness

The capacity of wetlands to protect the coasts against waves and tides and the inland areas against storm surges and flooding is dependent on the large- and small-scale characteristics of these ecosystems. Seagrass has an especially high capacity to dissipate wave energy, protecting the seashore from erosion, whereas mangroves and salt marshes are particularly effective in protecting the coast from surges (Duarte et al., 2013). Furthermore, these two different types of wetland vegetation often occur in juxtaposition, with seagrass growing mostly in subtidal areas and marshes and mangroves in the intertidal zone, combining their effectiveness in protecting from waves and surges (Duarte et al., 2013). It has been estimated that every kilometre of marshes can reduce storm surge levels by 5 to 10 cm and every kilometre of mangrove forests width can reduce storm surge levels by 40 to 50 cm (Temmerman et al., 2013; Wamsley et al. 2010; Zhang et al. 2012).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Improvement of soil quality and stability, erosion prevention
	Biodiversity
	Carbon storage
Social	Health and quality of life
	Recreation and environmental education
	Enhanced amenity value
	Spiritual, religious, and artistic values
	Employment enhancement
Economic	Food provision
	Income generation
	Increased tourism

References: Russi et al. 2013

Cost information

The restoration of coastal wetlands is usually more expensive than that of inland wetlands (Russi et al., 2013). Since the term 'coastal wetlands' refers to a rather diverse range of habitats, the cost estimation of restoration projects of such ecosystems is highly variable, as different types of wetlands require different types of restorative measures. Factors that affect the cost of wetland restoration include the type of wetland to be restored, the degree of degradation, the intended degree of restoration, land acquisition costs, labour costs, remoteness of wetland, cost of vegetation nursery and transplantation, and monitoring costs (Linham & Nicholls, 2010)

Potential disadvantages / negative impacts

Wetland restoration in coastal areas has to take place on land that has been set aside for this purpose, however, coastal areas usually exhibit high value of land, hence wetland restoration projects might often conflict with other types of coastal development.

Challenges / requirements for implementation

When restoring a coastal wetland, the hydrology of the local environment has to be considered as a whole, since coastal management and restoration often depend on inland freshwater sources (UNEP, 2015). Additionally, the interactions of the wetland that is being restored with another wetland and/or with the surrounding marine and terrestrial habitats as well as with human activities and sectors should be thoroughly studied and taken into account in its management (UNEP, 2015).

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Photo source: https://commons.wikimedia.org/wiki/File:Coastal_wetlands_(5187274473).jpg; Licence: CC BY 2.0.

19. Sand dunes construction and strengthening

Description

Photo credits: Martins, M./ pixabay.com

Dunes occur naturally along most less-developed sandy coastlines and protect the coast from erosion and inland areas from flooding. They form a natural barrier to wind and waves; they absorb part of their force. However, wind and waves can erode this natural barrier, and sea level rise is expected to exacerbate the problem.

Dunes can be protected, strengthened and rehabilitated where damaged in order to maintain their shoreline protection function. This includes grass planting, dune thatching by covering dunes' face with branches and plant debris, and dune fencing, which requires the construction of fences along the seaward face. All these measures help to catch and accumulate sand. These measures are complementary and usually combined or used in conjunction with grey measures (Climate-ADAPT, 2015). In addition, new dunes can be built. They are artificial but mimic nature.

Type of intervention: Intervention in an existing ecosystem

Products/services covered: Ecological restoration; ecosystem management and maintenance; construction of flood control infrastructure; landscaping; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality
			■		

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
					■		

Effectiveness

If they are well managed, dunes can offer a high degree of protection against flooding and erosion. However if erosion is very severe, other or additional measures are necessary. Dune construction or rehabilitation can be combined with beach nourishment and building hard physical structures (grey measures) to improve coastal resilience and land near the coastline (Climate-ADAPT, 2015).

Compared to hard physical structures of coastal protection, dunes are more aesthetic, beneficial for both tourism and nature. Dune construction and reinforcement can even improve beach resilience and act as sand reservoirs, thus improving effectiveness of beach nourishment.

Typical co-benefits

Environment	Improvement of soil quality and stability, erosion prevention
	Biodiversity
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Employment enhancement
Economic	Increase tourism

References: Climate-ADAPT (2015)

Cost information

Dune thatching, fencing and grass planting are low cost solutions to reduce dune erosion, however, maintenance such as regular grass planting or fencing is required. Beach construction costs are of similar range to beach nourishment costs. Additional costs may be incurred for planting or fencing (Climate-ADAPT, 2015; Linham and Nicholls, undated).

Climate-ADAPT (2015) cites the following cost estimates from Scottish Natural Heritage in 2000:

- Dune grass planting: EUR 250-2,500 per 100m length for each visit; the lower cost estimates are for small schemes largely carried out by volunteers; the higher costs for large schemes undertaken by contracted operators. Costs for transplanting depend on labour costs, sources of transplants, extent of works, the need for ongoing management and the cost of ancillary works.

- Dune thatching: EUR 250-2,500 per 100m length excluding costs of transplanting and annual maintenance. Costs for thatching depends on labour, material sources, extent of works, the need for ongoing management and the cost of ancillary works.

- Fencing: EUR 500-2,500 per 100m frontage length, excluding costs of transplanting and on-going repairs. Fencing costs vary according to labour, type of material used, quality, length and spacing of posts, frequency of spurs, number of public access points, need for management and the cost of ancillary works.

Potential disadvantages / negative impacts/ trade-offs

The artificial rehabilitation or construction of dunes can repress natural dynamics and functions. Planting grass and hindering landward dune migration and sand drift diminishes habitats on and behind dunes for species that require pioneer conditions. Thatching can also bring unwanted plants growing in the more nutrient rich ground and depress the originally planted grass (Climate-ADAPT, 2015).

Dune construction can conflict with other land uses. Some forms can impact the aesthetic quality of the area by hindering views or showing fencing and thatching material. Restricting the use of the area and limiting the access to the beach or sand blown to residential or commercial areas can be an inconvenience (Climate-ADAPT, 2015; Linham and Nicholls, undated).

The measures have a limited lifetime and require frequent maintenance in terms of replacing plants, adding fertiliser, replacing branches blown away, repairing after vandalism, etc. (Climate-ADAPT, 2015). Dunes are dynamic and not completely controllable (Linham and Nicholls, undated).

Challenges / requirements for implementation

The construction of dune systems can require large land availability. Where coastal erosion is very high, supplementary green and grey measures are necessary to avoid erosion.

Dune construction and strengthening need to be planned carefully to avoid or minimise conflicts with other users, e.g. by providing walk ways and confined paths, and negative side-effects on nature. The latter should ideally consider space for some natural dynamic and eventually include the hinterland.

The short life-time of the measure requires a maintenance plan (Climate-ADAPT, 2015) and the inherent dynamic a flexible management approach. As dunes are dynamic, their state needs to be monitored regularly and management needs to be adjusted.

Awareness campaigns might be necessary in relation to the use restrictions of the dune area and to avoid breaching of the rules and vandalism.

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Photo source: https://pixabay.com/en/cape-cod-provincetown-dune-grass-2232972/;

20. Shore and beach nourishment

Description

Beach nourishment is the artificial replenishment of sand on eroded shores in order to compensate for natural erosion. Sandy beaches dissipate wave energy and protect against storm surge impacts. Beach nourishment is a common practice in the Netherlands, Germany, Spain, France, Italy, the UK and Denmark (Climate-ADAPT, 2015; Linham and Nicholls, undated).

Photo credits: eroyka / Pixabay.com

The method can involve spreading sand over the beach where erosion occurs, stockpiling sand on the backshore that is exposed to waves only under extreme events to strengthen the dunes, or nourishing the shoreface close to the water, where the reduction of wave energy can lead to enhanced accumulation at the beach (Climate-ADAPT, 2015; Linham and Nicholls, undated). Sand can also be deposited under water close to the beach and will be gradually moved onshore under the normal movement of waves. Sand is excavated from accumulating areas close to the shore and transported to beach by trucks, dredged from the seafloor and pumped through pipelines directly to the beach, or suction-dredged from source, transported and dumped by ship or pumped ashore (Climate-ADAPT, 2015; Linham and Nicholls, undated). Beach nourishment can happen at different scales: at medium scale to, e.g., eroded parts of the beach or channel walls or at large scale, as in the so-called 'Sand Motor' project in the Netherlands. It provides sediment re-distributed by waves and currents to beaches and dunes over distances of several kilometres (Climate-ADAPT, 2015; Linham and Nicholls, undated).

Type of intervention: Intervention in an existing ecosystem

Products/services covered: shore/beach nourishment; environmental engineering

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

As a flexible and fast measure, beach nourishment is relatively easy to establish and adaptable to changing conditions. Additional nourishment can be simply added. It is even reversible. Beach nourishment can work effectively as a standalone measure or complement grey measures such as seawalls and green measures like dune reinforcement. Thereby, beach nourishment can provide additional benefits for coastal tourism, recreation activities and coastal habitats preservation (Climate-ADAPT, 2015; Linham and Nicholls, undated).

Typical co-benefits

Environment	Improvement of soil quality and stability, erosion prevention
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Employment enhancement
Economic	Increase tourism

References: Climate-ADAPT (2015).

Cost information

Due to its flexibility and reversibility, beach nourishment is relatively cheap to plan for, as long-term design criteria are usually not taken into account. However, as the application needs to be repeated continuously, the frequency of replenishment times and the volume per nourishment will affect the long-term costs. The costs depend on the length and means of transportation, availability of sand, and local conditions (Climate-ADAPT, 2015). They range per m^3 of sand between EUR 4-6 (DIVA model for Europe); EUR 2-6 in the Netherlands and EUR 3.5-35 in UK sources (Climate-ADAPT, 2015). Scottish Natural Heritage (2000, cited in Climate-ADAPT, 2015) provides a cost of EUR 6,300-251,700 per 100m frontage, not including control structures, ongoing management and minor works. The Sand Motor in the Netherlands moves 20 million m^3 sand. The estimated unit cost was 2.5 EUR/m^3 compared to up to 6 EUR/m^3 for traditional nourishment (Climate-ADAPT, 2015).

Potential disadvantages / negative impacts/ trade-offs

Beach nourishment does not end erosion, it is an ongoing process. Once the stock of sand is depleted by coastal erosion or storm surges, it needs to be repeated. This involves ongoing maintenance costs and energy.

A sufficient and matching source of sand is necessary. The wrong material not only has negative visual impacts, but can even jeopardise the success of the measure. For example, in Hel Peninsula (Poland), the grain size of dredged sand from a nearby bay was much smaller than the grain size of sand taken in the open sea. It was more easily dispersed and the erosion continued even though a large amount of sediment was spread over the beach (Climate-ADAPT, 2015).

Beach nourishment impacts natural dynamics. Offshore dredging should be used carefully and should not occur in the submerged beach close to the coast to avoid impacting beach dynamics. The method can have negative impacts on the ecosystems of the foreshore by covering habitats, loss of sandbar habitats, or the disruption of bird and other animal nesting. Some species, such as sand-dwelling invertebrates, are sensitive to a change of sediment types (Climate-ADAPT, 2015).

There can be negative impacts on biodiversity living on landside area or the seabed where the sand is excavated.

Challenges / requirements for implementation

As an ongoing measure and due to its impacts on natural dynamics, beach nourishment needs to be done carefully based on an understanding of, and concern for the potential adverse consequences for the environment. It should be integrated within a wider and flexible approach that includes, e.g., managed realignment, setback definition, re-planning and zoning of coastal areas, particularly for large-scale beach nourishment (Climate-ADAPT, 2015; Linham and Nicholls, undated).

The dynamic character of beach nourishment and beach erosion, which is not completely controllable, requires a continuous monitoring of the state of the beach and flexible application of the method according to the needs.

The flexibility of the measure is also an asset in reducing negative side effects. For example, the Sand Motor in the Netherlands seeks to address negative impacts by a low frequency of replenishment and therefore the number of disturbances of the ecosystem. Using the natural forces of wind and waves for the transport and distribution of material, as the Sand Motor does, can cut energy consumption from other sources (Climate-ADAPT, 2015).

Beach nourishment requires highly specialised equipment and knowledge from specialised contractors.

The public may not be aware of how beach nourishing and in particular underwater nourishment works. They might interpret the repeated nourishment as a failure of the measure. Information and awareness raising can help to provide knowledge and create understanding.

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Photo source: https://pixabay.com/de/baggerarbeiten-sanierung-strand-2955269/

21. Sustainable Drainage Systems (SuDS)

Description

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Sustainable drainage systems (SuDS) are a set of measures that use natural features and processes to slow down and reduce the volume of surface water runoff in order to manage downstream flood risk and reduce the risk of runoff-caused pollution (Woods Ballard et al., 2015). Therefore, SuDS generally contribute simultaneously to tackling surface flooding and water quality issues, and can also enhance water availability by capturing and storing rain water. They can be implemented either as a new development or by retrofitting existing structures (Davis and Naumann, 2017). In addition to delivering high quality drainage, SuDS also provide a range of co-benefits (depending on the design and site), such as improving groundwater supplies, enhancing the aesthetic and amenity value of urban developments, reducing noise, and providing opportunities for recreation and education (Woods Ballard et al., 2015). Due to their multifunctionality, SuDS make efficient use of space and are usually less costly than underground conventional drainage systems.

SuDS are an interconnected system of different components (often referred to as the 'SuDS management train') which work together to manage, treat and make best use of surface water, from the site where it falls as rain to the point where it is discharged into the receiving environment (Woods Ballard et al., 2015). A SuDS scheme can involve different combinations of components, depending on the site and specific objectives. SuDS components can be classified into five categories, depending on their functions; it should be noted that the functions are not independent, and one component may provide two or more functions (Woods Ballard et al., 2015; susDrain, 2018):

- **Source control**: features that capture rainwater and facilitate its use within the building or local environment, such as **rainwater harvesting, green roofs** and **pervious surfaces;**
- **Infiltration systems**: components that facilitate water infiltration into the ground and often include temporary storage of runoff before it is slowly released into the soil. These are **infiltration basins, infiltration trenches, soakaways, rain gardens.**
- **Conveyance systems**: components that convey flows to downstream storage systems, and in some cases also provide runoff flow and volume control and treatment; these include **swales, channels and rills.**
- **Storage systems:** components that control the flows and, in some cases, volumes of runoff discharged from the site, by storing water and releasing it slowly. These systems may also provide further treatment of the runoff to prevent pollution. They include **detention basins, retention ponds, geocellular drainage systems, wetlands**.
- **Treatment (or filtration) systems,** such as **filter strips**: components that remove or facilitate the degradation of runoff contaminants.

These components are the subject of individual fact sheets since their specific characteristics in terms of effectiveness, co-benefits and prerequisites vary. We also discuss SuDS as a whole in this fact sheet since the components are normally implemented as a system rather than independently.

Type of intervention: Creation of new green space

Products/services covered: SuDS; stormwater management; landscaping; landscape architecture; manufacturing of SuDS components; SuDS maintenance; construction of buildings; construction of transport infrastructure; water management; construction of drainage and sewage systems

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

SuDS schemes can attenuate runoff flow before it enters a watercourse, provide areas for water storage, and allow water to infiltrate into the ground, be evaporated from surface water and/or transpired from vegetation (susDrain, 2018b). Depending on the design, conveyance and storage techniques used, SuDS can reduce the frequency and/or severity of surface flooding if the scale and size of the measures can cope with larger rainfall events (susDrain, 2018b).

With regard to water quality, some SuDS components can reduce sediment and contaminants from runoff by allowing them to settle or through biological breakdown of pollutants (susDrain, 2018c). This can improve the quality of downstream water bodies into which the runoff is discharged. Moreover, where SuDS reduce the volume of runoff entering combined sewers, this can reduce combined sewer overflow discharges, which in turn improves the quality of the receiving water body (susDrain, 2018c). Information the effectiveness of specific components is provided in the respective fact sheets.

The Excel-based Benefits of SuDS Tool (B£ST) developed by CIRIA allows each benefit of SuDS schemes to be quantified and monetised.[5]

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
	Temperature regulation
	Improvement of air quality
	Biodiversity
	Carbon storage
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Regeneration of degraded areas
	Employment enhancement
Economic	Reduced energy consumption
	Income generation
	Increased value of land/property

[5] https://www.susdrain.org/resources/best.html

References: Woods and Ballard et al., 2015; Davis and Naumann, 2017.

Cost information

The costs of SuDS components and overall SuDS schemes depend on several site-specific factors, including soil type, groundwater vulnerability to pollution, design criteria, access issues and space requirements, location, whether the SuDS is installed in new development or as a retrofit (Royal Haskoning, 2012). Therefore, generalised information on costs should be interpreted with caution. Defra (2011, cited in Royal Haskoning, 2012) concluded based on case study examples that the construction costs of SuDS may be up to 30% lower than traditional drainage systems, however for challenging sites the costs can be 5% higher. Similarly, Royal Haskoning (2012) conclude from case study evidence that SuDS are generally less expensive to install and maintain than a traditional drainage system, however, there are exceptions. Maintenance costs also vary according to site and components used. The fact sheets below on specific components provide estimates of the cost ranges. Components that require significant land take (e.g. detention and infiltration basins, ponds) also have land cost implications (Royal Haskoning, 2012); these are discussed in the fact sheets on the respective components. However, in many cases SuDS can be based on multifunctional use of space (such as a permeable parking area).

The UK Sustainable Drainage website includes a SuDS construction and maintenance costs calculator: http://geoservergisweb2.hrwallingford.co.uk/uksd/costintro.aspx

Potential disadvantages / negative impacts/ trade-offs

Challenges / requirements for implementation

The effectiveness of SuDS in tackling flood risk and water quality issues increases if their implementation is widespread throughout the urban infrastructure (Tecnalia, 2017).

Implementation usually requires coordination between different departments of the local public authority, such as environment, urban planning, public space (Tecnalia, 2017).

References

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Photo source: https://www.flickr.com/photos/philadelphiawater/9087958202; Licence: CC BY 2.0.

22. Rainwater harvesting

Description

Rainwater harvesting is the collection and storage of rainwater for later use. Traditionally, it is collected from roofs, but can be retained also from all other impermeable surfaces, such as industrial buildings or parking houses (NWRM, 2015). It is stored in individual water butts, in underground cisterns or large storage tanks. The main purpose is to save tap water and cope with water scarcity during dry spells. At the same time, if appropriately designed rainwater harvesting systems can be a source-control element in Sustainable Drainage Systems (SuDS) to reduce run-off volume and mitigate the impacts of stormwater from heavy percipitation events (Woods Ballard et al., 2015).

Photo credits: Mommaerts, R./flickr.com

The harvested water can be stored, then used for a range of non-potable purposes, such as watering green space and gardens or, if treated, as grey water for households or industries (Woods Ballard et al., 2015). In some regions, particularly in rural areas, like Fuerteventura, rainwater harvesting was the traditional source of water.

Rainwater harvesting can be implemented in almost all locations with roofs and other hard surfaces appropriate for collection; hence, it can be very applicable in dense urban settings. The contributing area to a rainwater harvesting system is usually less than 0.1 km^2 (NWRM, 2015).

According to the CIRIA SuDS Manual (Woods Ballard et al., 2015), rainwater harvesting systems fall in three categories, depending on their objectives:

- for water storage (supply) only: systems designed to supply water to the building that it serves, with storage capacity sized to capture and retain an appropriate volume of runoff to meet the building's projected water demand. Although such systems will generally capture a proportion of the runoff from large events, they cannot be relied upon to manage extreme events.

- for water storage (supply) and surface water management, passive systems: systems with tanks designed to accommodate the volume of storage required for water supply, as well as that required to manage a specific depth of rainfall during a large event. The water level in the tank is not actively managed.

- for water storage (supply) and surface water management, active systems: systems in which the tank water level is actively managed to ensure that sufficient tank volume is available to cope with extreme rainfall. This involves either forecasting a large event and pumping the stored water away, or pumping out the stored water down to a set level when thresholds are exceeded (Woods Ballard et al., 2015).

In terms of design, rainwater harvesting systems can be gravity-based (rainwater is collected by gravity and stored at elevation such that it can also be supplied by gravity), pumped systems (storing water underground or at ground level and then pumping it out for supply purposes), and composite systems (Woods Ballard et al., 2015).

Rainwater harvesting systems could arguably be considered grey or technical interventions insofar as they involve man-made collection systems. Nevertheless, as a SuDS component, they are treated as NBS in this report.

Type of intervention: Intervention in an existing ecosystem

Products/services covered: stormwater management; sustainable urban drainage systems; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The traditional water butts are a rather small scale solution and provide supplementary water for garden irrigation. According to Woods Ballard et al. (2015), there is no robust evidence on the effectiveness of water butts to control run-off from large scale rainfall events. Cisterns of larger dimensions and storage tanks can have a bigger impact in terms of water storage and, if specifically designed for this purpose, can attenuate run-off (NWRM, 2015).

According to susDrain (2018), rainwater harvesting systems can have 'high performance' (depending on design) in terms of both peak flow reduction and volume reduction.

Typical co-benefits

Social	Employment enhancement

Reference:

Cost information

Costs for rainwater harvesting can differ largely, depending on the size, situation and intended use. NWRM (2015) provides the following cost ranges for smaller solutions based on UK sources:

Investigations & Studies:	EUR 0 -10,000
Capital Costs:	EUR 5-60 per m^2 roof area services
Maintenance Costs:	EUR 0.25-1.00 per m^2 roof area services

Campling et al. (2008) found in case studies that rainwater harvesting for private households in Belgium costs 1.8 to 4 EUR/m^3 of rainwater used and in Malta 5-11 EUR/m^3 due to the use of much larger cisterns.

The UK Sustainable Drainage website includes a SuDS construction and maintenance costs calculator: http://geoservergisweb2.hrwallingford.co.uk/uksd/costintro.aspx

Potential disadvantages / negative impacts / trade-offs

Rainwater depends on the seasons and weather conditions. Control over this water supply is limited and users need to cope with the uncertainty of sufficient water at all times (NWRM, 2015; Campling et al., 2008).

The use of rainwater in households might meet resistance of users afraid of hygienic reasons or water availability. Indeed, inappropriate management and maintenance practices of the harvesting and treatment systems can result in low water quality (Campling et al., 2008).

For use in households as non-potable water and depending on the site, the investment costs might be higher than those of using other water supply. A double water distribution system is needed. Families with low income cannot afford the investment costs and house owners, which rent out apartments, might refrain from the investment as they do no benefit from the lower water costs (Campling et al., 2008).

Challenges / requirements for implementation

Harvesting and using rainwater in cities at a larger scale will require substantial investment in infrastructure to collect, connect, store and treat the water and finally feed in to the water supply system. If used for other purposes than watering green areas, the water needs to be treated. A double water distribution system has to be installed (Campling et al., 2008). The CIRIA SuDS Manual notes that contaminants potentially present in the run-off should be carefully considered to ensure suitability for harvesting; for instance, runoff from roofs made up of materials containing copper or zinc, or treated with fungicides or herbicides, may not be suitable, depending on the envisaged use of the harvested water (Woods Ballard et al., 2015).

The availability of space for large tanks in dense urban settings can be a challenge. Large scale solutions require the close collaboration of different actors, like such as building and land owners, users, architects and building companies, city administration, water utility companies, etc. (NWRM, 2015).

The limited control over the water availability requires having an alternative water supply in place if needed. However, the high investment costs associated with rainwater harvesting can deter consumers from choosing this option when an affordable and running central water supply is available. Incentives are needed to encourage the wider application, such as the storm water fees in Berlin (Campling et al, 2008).

Detailed guidance on the design, construction, operation and maintenance of rainwater harvesting systems can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

NWRM (2015). Rain water harvesting. Available at: http://nwrm.eu/measure/rainwater-harvesting [Accessed 06 August 2018]

Campling, P., De Nocker, L., Schiettecatte, W., Iacovides, A.I., Dworak, T., Kampa, E., Álvarez Arenas, M., Cuevas Pozo, C., Le Mat, O., Mattheiß, V., Kervarec, F. (2008). Assessment of alternative water supply options. Available at: http://ec.europa.eu/environment/water/quantity/pdf/Summary%20Report_extended%20version.pdf [Accessed 06 August 2018]

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Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/rmommaerts/3619535165; Licence: CC BY-SA 2.0.

23. Pervious surfaces

Description


Photo credits: Unknown/ Wikipedia.org

Pervious surfaces (or pavements) allow rainwater to infiltrate through the surface and into underlying layers (susDrain, 2018). Some types of pervious surfaces allow infiltration to underlying groundwater, thereby contributing to increased groundwater levels and/or flows, while others do not interact with groundwater, but regulate the rate of runoff by storing rainfall and releasing it at a controlled rate (NWRM, 2015).

Porous surfaces infiltrate water across the entire surface (e.g. reinforced grass or gravel, or porous concrete and cobblestones), while **permeable surfacing** is composed of material that is itself impervious to water but contains a pattern of voids through the surface which allow infiltration (NWRM, 2015; susDrain, 2018).

Type of intervention: Creation of new green space

Products/services covered: pervious/permeable pavements; SuDS; landscaping; landscape architecture; stormwater management; construction of transport infrastructure; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), pervious surfaces have 'good' performance in terms of peak flow reduction, volume reduction, and water quality treatment. A review of the effectiveness of permeable paving for runoff reduction (Blanc et al., 2012, cited in NWRM, 2015) found that values for runoff reduction varied between 10%-100%, while reported peak flow reductions varied between 12-90%. Effectiveness can decrease significantly over time in the absence of sediment management (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
Social	Regeneration of degraded areas
	Employment enhancement
Economic	Water provision *(if designed to allow infiltration to underlying soils or groundwater)*
	Increased value of land/property

References: Tecnalia, 2017; NWRM, 2015.

Cost information

NWRM (2015) reports capital costs of EUR 40 - 90 per m^2 of permeable paving area and maintenance costs of EUR 1 – 5 per m^2. The capital cost of permeable paving is generally 10-15% higher than that of standard paving, however, without taking into account the additional rainwater management benefits (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

Pervious surfaces cannot be used where large sediment loads may be washed or carried onto the surface (susDrain, 2018).

Challenges / requirements for implementation

Pervious surfaces cannot be used where large sediment loads may be washed or carried onto the surface (susDrai8n, 2018). Pervious surfaces should be regulalrly cleaned of silt and other sediments to maintain infiltration capacity (Wood Ballard et al., 2015), otherwise there is a risk of long-term clogging and weed growth if the surfaces are poorly maintained (susDrai8n, 2018).

They are particularly suitable for surface car parks, pedestrian streets, spaces between buildings, squares and playgrounds, and should not be located on underground amenities, such as underground car parks (Tecnalia, 2017). In the UK, perviosu surfaces are commonly used on highways with low traffic volumes, low axle loads and speeds of less than 30 mph (susDrai8n, 2018).

Infiltration is generally not recommended in areas where the soil or geology has low permeability, groundwater levels are high, or the underlying substrate is contaminated (NWRM, 2015).

Detailed guidance on the design, construction, operation and maintenance of pervious surfaces can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

Blanc, J.; Arthur, S.; & and Wright, G. (2012). Natural flood management (NFM) knowledge system: Part 1-Sustainable urban drainage systems (SUDS) and flood management in urban areas.

NWRM (2015). Permeable surfaces [online] Available at: http://nwrm.eu/measure/permeable-surfaces [Accessed 07 May 2018].

susDrain (2018). Component: Pervious surfaces. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/source-control/pervious-surfaces/pervious-surfaces-overview.html [Accessed 7 August 2018].

Tecnalia (2017). Nature-based solutions for local climate adaptation in the Basque Country. Bilbao: Ihobe, Environmental Management Agency.

Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://en.m.wikipedia.org/wiki/File:Rasenpflasterstein_1.jpg.

24. Infiltration basins

Description

Infiltration basins are shallow vegetated depressions designed to store runoff on the surface and infiltrate it gradually into the ground (susDrain, 2018). They are normally dry except in periods of heavy precipitation (susDrain, 2018). Infiltration basins also treat runoff through processes of physical filtration to remove solids, adsorption onto the material in the surrounding soil, or biochemical reactions involving micro-organisms growing on the fill or in the soil (susDrain, 2018). They can provide additional amenity benefits (NWRM, 2015).

Photo credit: Lance Cpl. Jason Jimenez

Type of intervention: Creation of new green space

Products/services covered: SuDS; landscaping; landscape architecture; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The performance of infiltration systems is dependent on soils' infiltration capacity and the depth to groundwater (Woods Ballard et al., 2015). Overall, according to susDrain (2018), infiltration basins have 'average' performance in terms of peak flow reduction and 'good' performance with respect to volume reduction.

Infiltration basins are typically used to treat runoff from a small number of properties in residential areas and are effective at storing runoff from drainage areas of less than 0.2 km^2 (NWRM, 2015). According to Barber et al. (2003, cited in NWRM, 2015), infiltration basins can reduce peak runoff by up 65-87% (from "small storms"), 50-60% ("medium storms") and 40% ("large storms"). If designed correctly with an appropriate outfall, infiltration basins can also slow runoff for events that exceed the storage capacity of the basin (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
	Biodiversity
Social	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value
	Increased value of land/property
	Employment enhancement

References: NWRM, 2015.

Cost information

NWRM (2015) reports capital costs in the range of EUR 15-90 per m^3 of detention volume. Costs are generally lower where greater use is made of natural or existing topographic features (NWRM, 2015). Annual maintenance costs range from EUR 0.15 to EUR 5.5 / m^2 basin area, depending on the design and maintenance activities required (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

There is a risk of polluted runoff entering groundwater, hence pre-treatment may be required in certain areas before allowing runoff to infiltrate in the basin, for example through swales or detention basins to reduce sediment loading and retain heavy metals and oils (NWRM, 2015).

Challenges / requirements for implementation

Infiltration basins require a large, flat area and can fail to function appropriately in case of improper siting, poor design and lack of maintenance (susDrain, 2018).

Detailed guidance on the design, construction, operation and maintenance of infiltration systems can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

Barber, M. E.; King, S. G.; Yonge, D. R. & Hathhorn, W. E. (2003). Ecology Ditch: A best management practice for storm water runoff mitigation. *Journal of Hydraulic Engineering*, 8(3), 111-122.

NWRM (2015). Infiltration basins [online] Available at: http://nwrm.eu/measure/infiltration-basins [Accessed 07 May 2018]

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Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA

Photo source: https://www.cherrypoint.marines.mil/Photos/igphoto/2001272049/.

25. Infiltration trenches

Description

Photo credits: Unknown/ Flickr.com

Infiltration trenches are shallow excavations filled with rubble or stone which allow water to infiltrate into the surrounding soils from the bottom and sides of the trench (NWRM, 2015). They thereby enhance soil's natural capacity to store and drain water. In addition to reducing runoff rates and volumes, infiltration trenches also remove pollutants and sediments through physical filtration, adsorption onto the material in the trench, or biochemical reactions in the fill or soil (NWRM, 2015). They are, however, not intended to function as sediment traps, and thus need to be designed with a pre-treatment system where sediment load is high (NWRM, 2015). Infiltration trenches are easy to incorporate into a site and ideal for use around playing fields, recreational areas or public open space (susDrain, 2018). They also increase soil moisture content and help to recharge groundwater (susDrain, 2018).

Type of intervention: Creation of new green space

Products/services covered: SuDS; landscaping; landscape architecture; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), infiltration trenches can significantly reduce both runoff rates ('medium' performance) and volumes ('high' performance), as well as the pollutant load discharged to a receiving body ('high' performance). Infiltration trenches are generally designed to infiltrate all water from the contributing drainage area up to a 1 in 30 year event (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
Social	Employment enhancement

References: NWRM, 2015

Cost information

NWRM (2015) reports construction costs of EUR 70-90 / m^3 stored volume, depending on the depth, geometry and underlying soil/geology conditions. Maintenance costs are in the range of EUR 0.25-4.00 / m^2 surface area (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

There is a risk of introducing pollutants to groundwater, but the risk is low as long as infiltration trenches are not used to drain pollution hotspots (NWRM, 2015).

Challenges / requirements for implementation

Infiltration trenches are generally restricted to relatively flat sites (NWRM, 2015). They are not suitable for sites with fine particle soils (clay/silts) in the upstream catchment; there is a high clogging potential without effective pre-treatment (susDrain, 2018).

Detailed guidance on the design, construction, operation and maintenance of infiltration systems can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

NWRM (2015). Infiltration Trenches. Available at: http://nwrm.eu/measure/infiltration-trenches [Accessed 07 May 2018]

susDrain (2018). Component: Infiltration trenches. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/infiltration/infiltration_trench.html [Accessed 07 May 2018]

Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/75012107@N05/14660267252; Licence: CC BY-SA 2.0.

26. Soakaways

Description

Soakaways are buried square or circular chambers filled with either rubble or lined with brickwork or polyethylene rings that store surface run-off and allow it to soak into the ground (NWRM, 2015). They can be linked together to drain large areas including highways (susDrain, 2018). They provide stormwater attenuation, treatment, and groundwater recharge. Soakaways require minimal land take, are easy to construct and operate, and can be retrofitted (susDrain, 2018). They are most suitable for the infiltration of runoff from small areas such as residential building roofs (Woods Ballard et al., 2015). Soakaways are easy to integrate into a site, but offer very little amenity or biodiversity value as they are underground and water should not appear on the surface (susDrain, 2015).

Photo credits: Andras Kis/ nwrm.eu

Type of intervention: Creation of new green space

Products/services covered: soakaways; SuDS; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), soakaways have 'good' performance in terms of peak flow reduction, volume reduction and water quality treatment. Soakaways are generally designed to capture and infiltrate runoff up to the 1 in 30 year event (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
Social	Employment enhancement

References: NWRM, 2015

Cost information

NWRM (2015) reports construction costs of EUR 90-140 / m^3 stored volume. Maintenance costs are in the range of EUR 0.25-1.25 / m^2 surface area, depending on design, size and location (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

Challenges / requirements for implementation

According to susDrain (2018), soakways are not suitable for poor draining soils, for locations where infiltration water may put structural foundations at risk, or where infiltrating water may adversely affect existing drainage patterns. They are also not suitable for draining polluted runoff. The risk of groundwater pollutions needs to be considered in certain areas (NWRM, 2015).

Runoff with significant concentrations of sediment should not be discharged directly to a soakaway, as the sediment deposition over time may reduce the performance capacity of the soakaway (NWRM, 2015). Pre-treatment (such as an oil and sediment collector) should be applied to reduce the sediment loading (NWRM, 2015).

Detailed guidance on the design, construction, operation and maintenance of infiltration systems can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

NWRM (2015). Soakaways. Available at: http://nwrm.eu/measure/soakaways [Accessed 07 May 2018]

susDrain (2018). Component: Soakaways. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/infiltration/soakaways.html [Accessed 07 May 2018]

Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: http://nwrm.eu/measure/soakaways

27. Rain gardens

Description

Rain gardens are small-scale vegetated depressions in the ground that can infiltrate roof drainage and other 'clean' surface water (which is low in contaminants) (susDrain, 2018). The term is often used interchangeably with '**bioretention area**' (although the latter could also be applied to other SuDS components such as filter strips or swales) (NWRM, 2015). Rain gardens are typically applied at a property level, close to buildings (susDrain, 2018). They are easy to retrofit, require minimal land take, can be planned as landscaping features, and are easy to maintain (susDrain, 2018).

Photo credits: Alisha Goldstein, EPA / flickr.com

Rain gardens typically include a range of components, such as: grass filter strips to reduce incoming runoff flow velocities and to filter particulates; ponding areas for temporary storage of surface water (which promote additional settling of particulates); organic/mulch areas for filtration; planting soil (for filtration and as a planting medium); woody and herbaceous plants to intercept rainfall and promote evaporation and vegetative uptake of pollutants; sand beds to provide good drainage and a final treatment to runoff through infiltration (NWRM, 2015).

Type of intervention: Creation of new green space

Products/services covered: landscaping; landscape architecture; SuDS; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), rain gardens are effective at reducing the rate of run-off (are assessed as having 'good' performance in terms of peak flow reduction), and can also reduce run-off volume to some extent ('medium' performance, mainly due to their relatively small scale). With respect to water quality, they can also effectively adsorb hydrocarbons and heavy metals through vegetative uptake and the inclusion of clay components in planting soils (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Groundwater recharge
	Biodiversity
	Pollination
	Carbon storage
Social	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Enhanced amenity value
	Employment enhancement
Economic	Increased value of land/property

References: NWRM, 2015.

Cost information

No specific cost information could be found. Construction costs will vary depending on the site preparation required and the type of planting selected (NWRM, 2015). As regards maintenance costs, NWRM (2015) notes that a simple rain garden constructed at property level will require comparable maintenance to standard gardening and hence few additional costs for the homeowner. Rain gardens at the street level require maintenance by municipal authorities, but these can be incorporated into regular street cleaning and drainage maintenance activities (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

Risks of pollution to groundwater have to be considered on a site-specific basis (NWRM, 2015).

Challenges / requirements for implementation

Rain gardens are not suitable for areas with steep slopes (susDrain, 2018). They are susceptible to clogging if the surrounding landscape is not managed (susDrain, 2018).

Detailed guidance on the design, construction, operation and maintenance of bioretention systems – including rain gardens – can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

NWRM (2015). Rain Gardens [online] Available at: http://nwrm.eu/measure/rain-gardens [Accessed 07 May 2018].

susDrain (2018). Component: Rain gardens. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/infiltration/rain-gardens.html [Accessed 07 August 2018].

Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/usepagov/15455930908

28. Swales

Description

Photo credits: Hamby, C./ Flickr.com

Swales are shallow, broad and vegetated channels which store and/or convey runoff between different stages of a SuDS treatment train (susDrain, 2018; Woods Ballard et al., 2015). They can also remove pollutants via filtration. Swales can also be designed to promote infiltration where soil and groundwater conditions allow (susDrain, 2018). Swales are often used to drain road, paths or car parks or to convey runoff on the surface – replacing conventional pipework (Woods Ballard et al., 2015). Check dams or berms can be installed along the flow path, to promote the settling and filtration of runoff and further decrease flow velocity (susDrain, 2018; Woods Ballard et al., 2015).

There are three main types of swales (NWRM, 2015):

- Standard conveyance swale: are used to convey runoff from the drainage catchment to another stage of a SuDS train; may be lined or un-lined.
- Enhanced dry swale: includes an underdrain filter bed of soil in order to accommodate extra water treatment and ability to convey water above that of a standard swale. The main channel remains dry except for larger rainfall events. Lining can be incorporated in the underdrain if infiltration to the ground is not appropriate.
- Wet swale: applicable when prolonged treatment is required; uses liners or is sited in an area with high water table in order to hold water for longer periods.

Type of intervention: Creation of new green space

Products/services covered: Sustainable Drainage Systems (SuDS); stormwater management; landscaping; landscape architecture; water management; construction of drainage and sewage systems

Problems addressed (climate threats)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality
		■			■

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
	■						

Effectiveness

According to susDrain (2018), swales have 'Medium' performance in terms of both peak flow reduction and volume reduction. A review of the hydrological effectiveness of swales found it to be highly dependent on good design and catchment/local landscaping characteristics (Blanc et al., 2012, cited in NWRM, 2015). The literature reviewed by Blanc et al. (2012) showed that swales generally achieved reductions in mean runoff of more than 50%, although there were significant variations (NWRM, 2015). SNIFFER (2004) reported peak flow reductions of 52% and 65% in two swales in Scotland (cited in NWRM, 2015).

As regards water quality, swales are effective at removing suspended pollutants through filtration and sedimentation (susDrain, 2018). The ability to treat run-off is further enhanced in the case of wet swales (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Biodiversity
Social	Enhanced amenity value
	Employment enhancement

References: Woods Ballard et al., 2012; susDrain, 2018; Davis and Naumann, 2017.

Cost information

NWRM (2015) reports capital costs of EUR 15 - 80 per m^2 of swale area, depending on design (type of vegetation, dimensions, connections to upstream and downstream drainage). The highest costs are attributed to 'enhanced' swales with an underdrain filter bed. Maintenance costs also vary with design and range from EUR 0.50 to 4 per m^2.

Potential disadvantages / negative impacts/ trade-offs

- Generally involve higher land uptake than conventional drainage solutions (NWRM, 2015);
- Limits opportunities to use trees for landscaping (susDrain, 2018);
- Risks of blockages in connecting pipe work (susDrain, 2018).

Challenges / requirements for implementation

Key limitations/prerequisites heighted by Woods Ballard et al. (2015):

- Difficult to incorporate into dense urban developments where space is limited;
- Should not be located in areas with high risks of excess fertiliser or pesticide application which could cause pollution of runoff;
- Unlined swales should not be used on brownfield sites unless the risk of leaching is managed to acceptable levels;
- Unlined swales should not be used to treat runoff from areas with high pollutant loadings if there is a high of groundwater pollution through infiltration;
- Not suitable for areas where shading would limit vegetation growth;
- Must meet standards concerning public safety;
- Should normally use native species;
- Require regular maintenance to continue operating to design performance standards.

NWRM (2015) adds that swales should be located in areas where they can have a shallow gradient over their entire length, and where runoff from impermeable catchments can flow into the swale.

Detailed guidance on the design, construction, operation and maintenance of swales can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

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Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/chrishamby/17102513879/in/photostream/; Licence: CC BY-SA 2.0.

29. Planted channels and rills

Description

Channels and rills are shallow channels that collect surface water run-off. They can be incorporated at the start of a SuDS train. They can slow down run-off water, capture silt and oil, and convey the runoff to downstream SuDS features (NWRM, 2015; susDrain, 2018). They can also serve as connectors between SuDS components. Channels and rills can include planting to enhance amenity and biodiversity value. As such, they can be considered a nature-based solution. Channels and rills require minimal land take since they are narrow features, and they can be incorporated in all new developments or retrofitted to existing developments (NWRM, 2015).

Photo credit: Peter Skynner

Type of intervention: Creation of new green space

Products/services covered: SuDS; landscaping; landscape architecture; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), the performance of this component with respect to both peak flow reduction and volume reduction is 'medium'. Effectiveness in terms of water quality treatment is medium to high, depending on design (susDrain, 2018).

Typical co-benefits

Environmental	Regulation of the water cycle
	Biodiversity
Social	Enhanced amenity value
	Regeneration of degraded areas
	Employment enhancement

References: NWRM (2015)

Cost information

NWRM (2015) notes that it is not appropriate to assign costs to this measure in isolation since they are incorporated in wider SuDS schemes.

Potential disadvantages / negative impacts/ trade-offs

Challenges / requirements for implementation
• Should only be used to collect runoff from a small area (NWRM, 2015)

References

NWRM (2015). Channels and rills. Available at: http://nwrm.eu/measure/channels-and-rills [Accessed 07 May 2018]

susDrain (2018). Component: Channels & rills. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/swales-and-conveyance-channels/channels-and-rills.html [Accessed 07 May 2018].

Photo source: https://www.geograph.org.uk/reuse.php?id=3936441.

30. Detention basins

Description

Photo credits: Volkening, A. / Flickr.com

Detention basins are vegetated depressions intended to store and slow down the flow of runoff water (NWRM, 2015). The sediments and other pollutants contained in the stored water can be filtrated, absorbed by the surrounding soil, or biochemically degraded, while the stored water may be slowly drained to a nearby water course using an outlet control structure to control the flow rate. Detention basins generally do not allow infiltration (NWRM, 2015). Detention basins are normally dry except during and immediately after a storm, and can function as a recreational or other amenity facility (Woods Ballard et al., 2015). Detention basins are normally placed towards the end of the SuDS management train, so are used if extended treatment of the runoff is required, or for wildlife or landscape reasons (susDrain, 2018).

Type of intervention: Creation of new green space

Products/services covered: SuDS; landscaping; landscape architecture; stormwater management; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), the performance of detention basins is 'good' with respect to peak flow reduction, 'poor' in terms of volume reduction, and 'medium' in terms of water quality treatment. The capacity to store runoff depends on the basin's design, which can be sized to accommodate any size of rainfall event (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Reduced peak temperature
	Biodiversity
	Carbon storage
Social	Enhanced amenity value
	Recreation, environmental education, enhanced space for social gathering
	Employment enhancement

References: NWRM, 2015.

Cost information

Land acquisition costs (as well as the opportunity cost of not using that land for development) can be high, since detention basis are high land-take measures. This cost will, however, depend on the land values at the site in question (NWRM, 2015).

Construction costs in the UK typically range between EUR 20 and EUR 40 per m^3 of storage volume provided, but other sources suggest the costs can reach EUR 90 – 110 per m3 detention volume (NWRM, 2015). According to NWRM (2015), annual maintenance costs range between EUR 0.5 and EUR 5 per m^2 of basin area.

Potential disadvantages / negative impacts/ trade-offs

Challenges / requirements for implementation

Detention basins require relatively high land take, however, they are suited to dual purpose use (e.g. sports fields) (NWRM, 2015).

Detention basins should not be sited in areas where water storage may cause slope instability or foundation problems, e.g. in areas prone to landslides or at the top of slopes (NWRM, 2015).

Unlined detention basins should not be used on sites with a risk of contamination to groundwater (NWRM, 2015).

Detailed guidance on the design, construction, operation and maintenance of detention basins can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

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Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/87297882@N03/8027724588/in/photostream/; Licence: CC BY 2.0.

31. Retention ponds

Description


Photo credits: Daniel X. O'Neil / flickr.com

Retention ponds are ponds or pools designed with additional storage capacity to provided runoff attenuation during rainfall events (NWRM, 2015). They consist of a permanent pond area with landscaped banks and surroundings (NWRM, 2015). Retention ponds can be created by using an existing natural depression, by excavating a new depression, or constructing embankments (NWRM). Retention ponds can also provide water quality treatment, as rainwater runoff is detained and treated in the pool via sedimentation and/or biological uptake that reduces nutrient concentrations (susDrain, 2018). In addition, retention ponds can have high ecological, aesthetic and amenity benefits, and may add value to local properties (susDrain, 2018).

Type of intervention: Creation of new green space

Products/services covered: SuDS; stormwater management; landscaping; landscape architecture; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), retention ponds are effective a reducing peak flow and improving water quality ('good' performance), but do not offer volume reductions. They attenuate storm water flow by allowing runoff to be retained and released at a controlled rate once the risk of flooding has passed (NWRM, 2015). Retention ponds are typically designed to attenuate runoff for events up to at least the 1 in 30 year storm for the drainage area (sometimes greater), with the excess storm volume drained within 24 to 72 hours (NWRM, 2015).

Typical co-benefits

Environmental	Regulation of the water cycle
	Biodiversity
	Reduced peak temperature
Social	Enhanced amenity value
	Regeneration of degraded areas
	Recreation, environmental education, enhanced space for social gathering
	Employment enhancement
Economic	Increased value of land/property

References: NWRM (2015).

Cost information

Land acquisition costs (as well as the opportunity cost of not using that land for development) can be high, since retention ponds are high land-take measures. This cost will, however, depend on the land values at the site in question (NWRM, 2015). According to NWRM (2015), capital costs range between EUR 10 and EUR 60 /m^3 storage volume, and may increase if pond lining, or construction on steeper slopes or less stable land is required. Annual maintenance costs are in the range of EUR 1 – EUR 5 per square metre of retention pond area (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

In warmer climates, standing water can provide a suitable ecosystem for mosquitoes, which may promote transmittance of some diseases (NWRM, 2015).

Challenges / requirements for implementation

Retention ponds must be appropriately sized according to the catchment area and critical storm depth (NWRM, 2015).

Lining may be required in sites where soil contamination may influence the water quality within the pond (NWRM, 2015).

Detailed guidance on the design, construction, operation and maintenance of ponds can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

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susDrain (2018). Component: Retention ponds. Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/retention_and_detention/retention_ponds.html [Accessed 07 May 2018]

Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: https://www.flickr.com/photos/juggernautco/10651053243/in/album-72157637268693884/; Licence: CC BY 2.0

32. Geocellular storage systems

Description

Photo credits: susDrain/ www.sustdrain.org

Geocellular storage systems are a type of SuDS component for temporarily storing water below ground before controlled release or re-use (Woods Ballard et al., 2015). They are modular plastic units with a high porosity, assembled to form a storage structure (Woods Ballard et al., 2015).

The modular or honeycomb structure allows geocellular systems to be tailored to suit the specific requirements of any site (susDrain, 2018). They are light and easily installed without the need for heavy machinery, which leads to time and cost savings during construction compared to alternatives such as concrete tanks or pipework (Woods Ballard et al., 2015).

Different types of geocellular units exist, each having different structural characteristics and load carrying capacities (Woods Ballard et al., 2015). They can be installed beneath trafficked or non-trafficked areas, as well as beneath public open spaces, such as play areas (susDrain, 2018).

The technique can be considered 'grey' since it involves man-made structures. However, for the purposes of this analysis we treat them as NBS alongside other SuDS components, since they are not 'competing' with grey solutions but contributing to a broader SuDS train.

Type of intervention: N/A

Products/services covered: sustainable drainage systems; stormwater management; manufacture of geocellular units; installation of geocellular systems; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Geocellular systems have high void ratios (up to 96%) providing high storage volume capacity (susDrain, 2018). According to susDrain (2018), they have 'good' performance in terms of both peak flow reduction and volume reduction (when they allow for infiltration).

Typical co-benefits

Environmental	Regulation of the water cycle
Social	Employment enhancement

Cost information

No cost information found

Potential disadvantages / negative impacts/ trade-offs

Geocellular systems can be difficult to maintain and their performance is difficult to measure (susDrain, 2018).

Challenges / requirements for implementation

Detailed guidance on the design, construction, operation and maintenance of geocellular systems can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

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Woods Ballard, S.; Wilson, S; Udale-Clarke, H.; Illman, S.; Scott, T.; Ashley, R.; & Kellagher, R. (2015). The SuDS Manual. London: CIRIA.

Photo source: susDrain (2018). Geocellular systems [online] Available at: https://www.susdrain.org/delivering-suds/using-suds/suds-components/retention_and_detention/geocellular-storage-systems.html [Accessed 27 August 2018]

33. Filter strips

Description

Filter strips are gently sloping, vegetated strips of land that promote sedimentation and filtration by allowing runoff from an impermeable area to flow across and, where appropriate, infiltrate (susDrain, 2018; Woods Ballard et al., 2015).

Photo credits: Unknown/ flickr.com

The runoff is designed to flow slowly as a sheet across the filter strip such that treatment processes can take place effectively (Woods Ballard et al., 2015). They are often used as either a pre-treatment component before swales, bioretention systems and trenches in order to extend the life of these components by capturing sediments, or as a treatment component (where the surface is sufficiently long) (Woods Ballard et al., 2015).

Filter strips are often placed between a hard-surfaced area and a receiving stream, surface water collection, treatment or disposal system (susDrain, 2018).

They are generally easy to construct, have low construction costs, can be easily integrated into landscaping and can be designed to provide aesthetic benefits (susDrain, 2018).

Type of intervention: Creation of new green space

Products/services covered: sustainable drainage systems; stormwater management; landscaping; landscape architecture; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

*The primary function of filter strips is pollutant removal (water quality), but they are often used in combination with other SuDS components for runoff management, hence they are also relevant to surface water flooding.

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

According to susDrain (2018), filter strips only attenuate runoff flow slightly, but can be used to reduce the drained impermeable area. In terms of water quality, they are effective at removing polluting solids through filtration and sedimentation (susDrain, 2018).

Typical co-benefits

Environmental	Regulation of the water cycle
	Biodiversity
	Improvement of soil quality and stability, erosion prevention
Social	Enhanced amenity value
	Employment enhancement

References: NWRM (2015)

Cost information

Costs vary widely depending on the design of the filter strip, the density and variety of vegetation, and whether substrate materials such as gravel are used to increase effectiveness of the filter strip (NWRM, 2015). Sources reviewed by NWRM (2015) indicate that capital costs range from EUR 3 to EUR 30 per m^2 filter strip area. Maintenance costs are in the range of EUR 0.50 – EUR 6.50 per m^2 filter strip area, depending on design and location (NWRM, 2015).

In terms of land acquisition costs, it is usually more expensive to retrofit filter strips to already developed areas than to construct them in an undeveloped area (NWRM, 2015).

Potential disadvantages / negative impacts/ trade-offs

According to susDrain (2018), filter strips are not suitable for steep sites, for draining hotspot runoff or for locations where there is a risk of groundwater contamination, unless infiltration is prevented. They also do not provide significant attenuation or reduction of extreme event flows (susDrain, 2018).

Filter strips are moderately high land-take measures in the urban environment, therefore there may be opportunity costs associated with implementation (NWRM, 2015).

Challenges / requirements for implementation

Appropriate design (including slope, width and vegetation type) is important for achieving high effectiveness in terms of pollutant treatment (NWRM, 2015). Filter strips also require regular inspection and maintenance to ensure effective operation (NWRM, 2015).

Detailed guidance on the design, construction, operation and maintenance of filter strips can be found in the CIRIA SuDS Manual (Woods Ballard et al., 2015).

References

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Photo source: https://www.flickr.com/photos/34071056@N03/3173919823/in/album-72157612200711101/; Licence: CC BY-ND 2.0.

34. Blue roofs

Description

Photo credits: The Urban Greening Company

Blue roofs detain and slowly release stormwater runoff by using various types of flow control devices or structures (Foster et al., 2011; Sustainable Technologies Evaluation Program, undated). They can consist of different technologies, including gutter storage systems, cisterns, valves, pipe systems and trays that function in an active or passive way to collect and discharge rainwater (Foster et al., 2011; Eagle, 2017).

Active roofs - also referred to as 'automated roof runoff management systems' - function according to a pre-designed mechanism, sometimes involving programmable, hydraulically controlled valves to control the retention and release of water (Eagle, 2017). They range from highly sophisticated techniques to more limited mechanisms. The more sophisticated variety can involve the use of communications or data tools such as 'forecast integration', which employs sensors and Internet-based data feeds to estimate rainfall quantities (Eagle, 2017). Passive blue roofs simply collect and hold rainwater, and may also function as temporary holding tanks which later release water via evaporation (Eagle, 2017). They typically require little to no upkeep, whereas active blue roofs require regular maintenance (Eagle, 2017).

The water captured by blue roofs can be used for non-potable uses on-site or for irrigation, direct groundwater recharge (e.g. through the use of downspout disconnections and infiltration systems), or discharged directly into sewer systems at a reduced flow rate or after peak flow from heavy rainfall (Foster et al., 2011). It can also be sprayed directly onto the roof to increase the cooling effect caused by evaporation (Foster et al., 2011).

Blue roofs can be installed on flat roofs of buildings that are structurally capable of holding the additional load of system components and collected stormwater (Sustainable Technologies Evaluation Program, undated). Several factors are taken into consideration when determining the suitability of a blue roof and potential design options for a given building; for example, the building's structural capacity, roof type and slope, the local climate and local regulatory requirements (Sustainable Technologies Evaluation Program, undated).

Type of intervention:

Products/services covered: blue roofs; sustainable drainage systems; stormwater management; construction of buildings; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

In general, the volume of water that a blue roof system can retain depends on several factors, in particular roof size, quantity and depth of trays or containers being deployed, and the overall configuration of the blue roof (Eagle, 2017).

As an example, monitoring of a pilot project in New York showed that installation of a blue roof system with trays resulted in a 45% reduction in roof runoff during rainfall events (Roy et al., 2014).

Typical co-benefits

Environmental	Temperature regulation
Social	Enhanced amenity value
	Employment enhancement
Economic	Reduced energy consumption
	Increased value of land/property
	Water provision

References: Eagle (2017)

Cost information

Blue roof costs depend, among others, on the specific type (active vs. passive roof) and equipment used, but they are generally considered a relatively inexpensive solution to stormwater management (Eagle, 2017; Foster et al., 2011). According to Foster et al. (2011) – based on United States estimates – installing a blue roof adds less than $1 - 4 per square foot in additional cost compared to the design of a new flat roof.

Potential disadvantages / negative impacts/ trade-offs

If the blue roof is not adequately designed and constructed, there is a risk of leakage, which can eventually lead to ponding, water damage, infiltration, or even structural failures over the long term (Eagle, 2017). To avoid this, building standards in some jurisdictions require blue-roof basins to have a secondary membrane, which can catch any leaks penetrating the primary membrane and prevent the leak from gathering on the roof (Eagle, 2017).

Challenges / requirements for implementation

The technology requires appropriate planning and design, taking into consideration the existing structure and load capacity. Where blue roofs are installed on existing rooftops, the existing roof structure will need to be thoroughly checked to ensure it can carry the new water and equipment loads (Eagle, 2017). The system must be able to carry the weight at peak load (Eagle, 2017). The local climate also needs to be considered; for example, in some cases, the choice of materials will need to take into account the building's orientation to the sun (Eagle, 2017).

The design of blue roofs should also address water-borne bacteria, insects, and plants that are susceptible to grow in standing water (Eagle, 2017). Before being used (even for non-potable uses), the water retained in blue-roof structures must be routinely checked (Eagle, 2017).

Given the relative novelty of blue-roof technologies, there may be some resistance from owners to install blue roofs. Buildings owned by multiple people may face greater obstacles to investing in a blue roof due to the need for consensus among owners (Eagle, 2017).

References

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Foster, J.; Lowe, A.; Winkelman, S. (2011). The value of green infrastructure for urban climate adaptation. The Center for Clean Air Policy.

Roy, S.; Quigley, M.; and Raymond, C. (2014). From Green to Blue: Making Roof Systems Sustainable in Urban Environments. *Roofing*. Available at: http://www.roofingmagazine.com/green-blue-making-roof-systems-sustainable-urban-environments/ (accessed 8 February 2019).

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Photo source: The Urban Greening Company, http://tugc.co.uk/products/blue-roofs/

35. Subsurface groundwater recharge systems

Description

Groundwater is one of the most important sources of freshwater. Soils with a high amount of impervious surfaces, particularly in urban areas, have lost some or all of their infiltration capacity, which limits the amount of precipitation that recharges groundwater. High water abstraction for agricultural, industrial or household use has put further stress on groundwater resources.

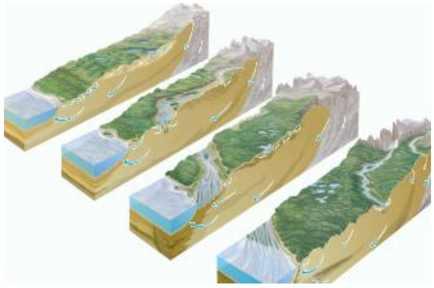

Photo credits: Winter et al., 1998

Groundwater infiltration occurs naturally on permeable soil, wetlands and other water bodies with permeable beds, or can be artificially introduced. According to NWRM (2015), techniques to restore or enhance natural infiltration capacity can be classified into three categories:

- **surface structures to facilitate/augment recharge**, such as soakaways and infiltration basins (discussed in separate NBS fact sheets above);
- **subsurface indirect recharge systems**, whereby infiltration capacity is enhanced through wells drilled within the unsaturated zone, in order to introduce water from other sources to the aquifer; and
- **subsurface direct recharge systems**, which use wells reaching the saturated zone to achieve infiltration and recharge of the groundwater aquifer.

This fact sheet deals only with the second and third category, whereas surface structures promoting groundwater recharge are treated in separate fact sheets (see wetland restoration and some of the SuDS components). Given that they make sure of artificial structured (notably wells), it is debatable whether such systems are NBS. For the purposes of this report, we consider that groundwater recharge systems meet the European Commission's definition of NBS - "*actions which are inspired by, supported by or copied from nature*" (European Commission, 2015).

Applied in coastal areas, such recharge systems can maintain groundwater level and avoid the intrusion of saltwater (Campling et al., 2008; UNEP 1999).

Groundwater recharge measures are on the rise in Europe, mainly driven by the demand of water to meet agricultural, industrial, environmental, and municipal needs. In southern Europe, the demand is mainly driven by agricultural and municipal uses; in northern Europe, it serves mostly households in densely populated areas, like Berlin or the Netherlands (Campling et al., 2008). Groundwater recharge can be widely used almost anywhere in Europe by means of centralised or decentralised approaches (Campling et al., 2008), at almost every scale (NWRM, 2015) where aquifers exist (UNEP, 1999).

Type of intervention: intervention in an existing ecosystem

Products/services covered: environmental engineering; water management

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of artificially introduced recharge depends upon site conditions, as well as the specific construction, number and capacity of structures and their management. In general, such techniques serve well in a local or regional context to supply groundwater, which is a finite resource, and therefore help to cope with temporary or ongoing water scarcity impacts (Campling et al., 2008).

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
Social	Health and quality of life
	Employment enhancement

References: NWRM (2015); Campling et al. (2008)

Cost information

Costs vary according to the specific technique applied and local circumstances. Case studies in Campling et al. (2008) suggest the cost of producing water from groundwater recharge systems is lower than the cost of water transferred from outside the region (in Flanders in 2008, 0.5EUR/m³ compared to 0.77EUR/m³).

Potential disadvantages / negative impacts/ trade-offs?

If polluted water is used, it poses a risk for the quality of the groundwater (NWRM, 2015). Pathogens or traces of toxic chemicals originating from public consumption and introduced to groundwater can result in human health risks. Once a groundwater basin has been contaminated, it is very difficult to restore it (Campling et al., 2008).

In comparison to natural infiltration, investment and maintenance costs are higher, as is energy consumption.

Shafts and wells have little storage capacities and require a continuous source of water. The use of water from rivers or lakes can threaten those ecosystems.

Users might refuse to consume water that is associated with greywater reuse (Campling et al., 2015).

Challenges / requirements for implementation

The systems are complex and require careful planning and tailoring of the technology, taking into consideration geological, hydrological, and climate conditions, as well as land use and water abstraction.

Depending on the planned measure and local circumstances, permits are needed and regulations need to be considered.

Infiltrated water, depending on its source, may require pre-treatment to avoid groundwater pollution. This can be costly and strict quality controls are necessary (Campling et al., 2008). The technical structures, such aswells, require continuous maintenance.

References

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Photo source: Winter, T. C.; Harvey, J. W.; Franke, O. L.; Alley, W. M. (1998). Ground water and surface water: a single resource U.S. Geological Survey Circular Vol. 1139

36. Constructed wetlands

Description

Constructed wetlands (sometimes referred to as 'artificial wetlands') are engineered systems that replicate the functions of natural wetlands to filter pollutants from water; they are "treatment systems that use natural processes involving wetland vegetation, soils, and their associated microbial assemblages to improve water quality" (EPA, 2004). Constructed wetlands can prevent pollutants in stormwater runoff from reaching downstream environments such as lakes and streams, and can also mitigate the risk of surface flooding by retaining water and releasing it slowly, similarly to natural wetlands.

Photo credits: NC Wetlands / flickr.com

Constructed wetlands are increasingly used as a solution to treating Combined Sewer Overflow (CSO), i.e. the excess flow of combined sewage and rainwater that cannot be treated by the receiving waste-water treatment facility during heavy rain events (Liquete et al., 2016).

Various designs of constructed wetlands exist, and are usually classified according to the flow pattern of the effluent:

- **free water surface constructed wetlands**: usually of depths between 0.1 and 2 m, with a plant community that can be composed of algae, and submersed, floating or emergent wetland plants (Land et al., 2016).
- **horizontal subsurface flow constructed wetlands**: typically designed with a permeable filter material ("soil") planted with emergent wetland plants. Water is fed in at an inlet and flows horizontally in and beneath the plants' rhizosphere, to an outlet where it is collected before leaving through a water level control structure (Land et al, 2016; Vymazal, 2011). They are commonly called 'reed beds' in the UK (Vymazal, 2011).
- **vertical flow constructed wetlands**: constructed similarly to the horizontal type, but water is applied on the surface of the filtering material, and percolates through the rhizosphere (Land et al., 2016).

Subsurface constructed wetlands have been commonly used in Europe, while free water surface systems predominate in North America and Australia (Vymazal, 2011). More recently, different constructed wetland types have been combined in order to increase treatment efficiency (Vymazal, 2011).

Free water surface constructed wetlands are usually used for tertiary treatment of municipal wastewater, as well as stormwater runoff and mine drainage waters, while horizontal subsurface flow constructed wetlands are commonly employed for secondary treatment of municipal wastewater (although other applications have also been reported) (Vymazal, 2011).

In addition to their water purification and flood protection functions, constructed wetlands often provide a suite of other environmental and socio-economic benefits, such as enhancing biodiversity (De Martis et al., 2016), recreational and educational opportunities, and carbon sequestration (Liquete et al., 2016; Moore and Hunt, 2012).

Type of intervention: Creation of new green space

Products/services covered: environmental engineering; water management; constructed wetland; landscape architecture

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

A meta-analysis by Land et al. (2016) concluded that constructed wetlands significantly reduce the transport of nitrogen and phosphorus in treated wastewater and urban and agricultural runoff, thereby contributing to counteract eutrophication. Generally, surface constructed wetlands are very effective at removing organic material, suspended solids, and ammonia, while nitrogen removal varies depending on several factors (Vymazal, 2011). They also provide sustainable removal of phosphorus, but at relatively slow rates (Vymazal, 2011). Horizontal flow subsurface wetlands are very effective at removing organics, suspended solids, microbial pollution, and heavy metals, while phosphorus removal is low unless special media are used (Vymazal, 2011). Vertical flow wetlands effectively remove organics and suspended solids (Vymazal, 2011).

A case study of a hybrid system of constructed wetlands to treat Combined Sewer Overflow in Gorla Maggiore, Italy (Liquete et al., 2016) showed the high water purification effectiveness of such systems; the system achieved average removal efficiencies of 72–96%.

Recently, studies have shown that constructed wetlands can also be effective in removing special compounds such as linear alkylbenzene sulphonates (often used in laundry and cleaning products, and hence a common constituent of municipal and industrial wastewaters) and pharmaceutical and personal care products (Vymazal, 2011).

In terms of flood prevention, the Gorla Maggiore system considerably reduced peak flow and flooding downstream (by 86%, and 82.9%, respectively) (Masi et al., 2016). However, there is less evidence available on this function of constructed wetlands.

Typical co-benefits

Environmental	Regulation of the water cycle
	Surface water flooding prevention (in special cases)
	Biodiversity
	Carbon storage
Social	Health and quality of life
	Recreation, environmental education, enhanced space for social gathering
	Regeneration of degraded areas
	Spiritual, religious, and artistic values
	Enhanced amenity value
	Employment enhancement
Economic	Reduced energy consumption
	Water provision
	Increased value of land/property
	Income generation

References: Liquete et al. (2016); Moore and Hunt (2012)

Cost information

According to Dublin City Council (2006), constructed wetlands require minimal maintenance; which "can be as little as 1/20 of that of a conventional wastewater treatment plant maintenance." Constructed wetlands also have low operation costs since they are often only dependent upon gravity flow (Dublin City Council, 2006). According to the same source, construction costs are about 10-20% of the costs of constructing a conventional wastewater treatment plant (Dublin City Council, 2006).

The cost-benefit ratio of the solution appears even more favourable when benefits other than water purification are taken into account. For example, an analysis of a constructed wetland that treats the third largest lake in Florida, US, shows that it provides ecosystem services worth USD 1.79 million annually (using a benefit transfer approach), while the annual operation and maintenance costs of the wetland were on average USD 455,000 (Dunne et al., 2015).

Potential disadvantages / negative impacts/ trade-offs

Depending on design, constructed wetland may require relatively high land-take (compared to the grey alternatives). This can be an important constraint for local authorities since land prices can be high; however, leasing land and contracting land services may reduce the cost (Dublin City Council, 2006).

Challenges / requirements for implementation

A collection of design guidelines from various countries can be found on the website of the Constructed Wetland Association, UK: https://www.constructedwetland.co.uk/resources/design_guides

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Grey solutions

1. Passive cooling of buildings

Description

This solution involves building design techniques that focus on preventing heat gains, modulating heat gains, and/or controlling heat dissipation, in order to improve indoor thermal comfort and air quality, while reducing energy consumption (Santamouris and Kolokotsa, 2013; Geetha and Velraj, 2012).

The most common techniques include:
- **Shading systems**, designed to control solar radiation (Oropeza-Perez and Østergaard, 2018);
- The use of **construction materials with certain properties for controlling heat gains**; e.g. Phase Change Materials (PCM) which consist of microcapsules that store latent heat and later release it (Oropeza-Perez and Østergaard, 2018);
- **Natural ventilation systems**, such as night ventilation that uses the cool night air to cool down heat absorbed by the building during daytime (Santamouris and Kolokotsa, 2013) or other types of controlled ventilation (Oropeza-Perez and Østergaard, 2018);
- **Ground cooling**, or using the ground as a heat sink; this is achieved through direct contact between part of the building envelope and the ground, or by injecting air circulated underground into the building through earth-to-air heat exchangers (underground air tunnels) (Geetha and Velraj, 2012; Santamouris and Kolokotsa, 2013);
- **Eco-evaporation cooling**, which uses a water source (such as a pond or fountain) near the building fabric combined with an airflow to decrease indoor temperatures (Oropeza-Perez and Østergaard, 2018);
- **Radiative cooling** techniques such as the use of moveable insulation systems on the roof, which allow exposure during the night but cover the roof during the day (Geetha and Velraj, 2012);
- **Intelligent façades** composed of devices attached to the building envelope or openings which change their position or shape in response to different temperatures, humidity or wind (Oropeza-Perez and Østergaard, 2018).

While green roofs and walls and cool roofs and walls are in some classifications considered to fall under this category, they are not covered by this fact sheet.

Products/services covered: Architectural design; passive cooling techniques; construction of buildings

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The degree of effectiveness of the various passive cooling techniques depends on the type of technique used, location, building-specific parameters and prevailing local climatic conditions. Results of several empirical studies are presented in Geetha and Velraj (2012) and Oropeza-Perez and Østergaard (2018). The general conclusion emerging from these literature reviews is that passive cooling techniques can be very effective at reducing indoor air temperatures during hot periods.

Typical co-benefits

Economic	Reduced energy consumption

References: Santamouris and Kolokotsa, 2013

Cost information

None identified

Potential disadvantages / negative impacts / trade-offs

None identified

Challenges / requirements for implementation

None identified

References

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2. Cool or white roofs

Description

Cool or white roofs are made of materials selected for their high solar reflectance (albedo) and high thermal emittance (Greater London Authority, 2008). Since they absorb less solar energy during the day, they emit little heat at night (Greater London Authority, 2008). The high albedo of the roofs can also improve their durability, since the materials are not subject to excessive contraction and expansion due to high differences in temperature or to damaging ultraviolet rays (Greater London Authority, 2008). Reflectivity can, however, decline with age or with the accumulation of pollution, hence proper maintenance is required to maintain effectiveness (Greater London Authority, 2008).

Photo credits: Unknown/Flickr.com

Products/services covered: Cool roofs; white roofs; construction of buildings

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

There is evidence that conventional roofs can be 31-55°C hotter than the air, while cool roofs generally remain within 6-11°C of the background temperature (Foster et al., 2011). This cooling effect can reduce ambient temperature and mitigate the UHI effect (Foster et al., 2011). Studies have shown that cool roofs can reduce the daily heat gain by 11-60%, depending on the roof's thermal resistance and the local climatic conditions (Hernández-Pérez et al., 2014). In terms of ambient temperatures, cool roofs can reduce peak summer indoor temperatures by up to 2°C (Santamouris, 2014). Lower temperatures at roof level also decrease the sensible heat flux to the atmosphere, thereby helping to mitigate the UHI effect, although few studies have examined this impact (Santamouris, 2014).

Vinyl roofs are the most reflective common material used, reflecting 80% of the sun's rays (whereas a conventional black roof reflects only 6%) and avoiding 70% of the heat absorption occurring on black roofs (Foster et al., 2011). Some coatings can achieve even higher levels of reflectivity (Foster et al., 2011).

These temperature effects translate into reduced energy demand for cooling. For example, Synnefa et al. (2007, cited in Hernández-Pérez et al., 2014) showed – in a study of residential buildings in 27 cities – that increased roof reflectance reduces cooling loads by 18-93% and peak cooling demand by 11-27%, with the highest reductions achieved in roofs with low or no insulation.

Besides comparisons of cool and conventional roofs, several studies have examined the relative thermal performance of cool roofs and green roofs. The general conclusion emerging from this literature is that both cool (highly reflective) roofs and green roofs can be effective in reducing the roof's outer surface temperature, thus contributing to UHI mitigation, although the specific results (in terms of relative effectiveness of the two roof types) depend on the model parameters, especially the building, roof and climatic characteristics (for reviews, see, e.g. Costanzo et al., 2015 and Santamouris, 2014). For example, Savio et al. (2016) found equal temperature reductions (of 0.4 k) for both reflective and green roof systems of the same area. Takebayashi and Moriyama (2007) found that reflective roofs had a higher UHI mitigation potential during the day, while green roofs make a more important contribution at nighttime (Santamouris, 2014). Scherba et al. (2011) found reflective roofs to be slightly more effective at mitigating UHI than green roofs, while the opposite results were reported by Simmons et al. (2008). The review by Santamouris (2014) concludes that reflective roofs with an albedo of 0.7 or higher have a higher heat island mitigation potential than green roofs during the peak period, although very well irrigated green roofs with high Leaf Area Index can perform equally well or better.

Typical co-benefits

Economic	Reduced energy consumption

References: Foster et al. (2011)

Cost information

According to Foster et al. (2011), the cost of white roofs is comparable to that of conventional roofs.

Potential disadvantages / negative impacts/ trade-offs

Reflective materials can be a disadvantage in winter as they reflect heat, which can increase energy demand for heating. However, empirical studies conclude that this increase is generally lower than the cooling energy savings achieved in warm seasons, resulting in net energy savings for buildings in warm and temperate climatic conditions (Hernández-Pérez et al., 2014).

Challenges / requirements for implementation

None identified

References

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Photo source: https://www.flickr.com/photos/walmartcorporate/5258813444; License CC BY 2.0.

3. Cool façades

Description

This solution involves the use of highly reflective materials on the walls of buildings to increase albedo and thus reduce heat absorption. It can be used in combination with a cool or green roof and other passive cooling techniques.

White or light-coloured materials have been used on façades for many centuries in regions such as the Mediterranean, and new types of materials with high reflectance (e.g. cool coloured materials, mineral-based coatings) have been investigated in recent years (Zinzi, 2016).

Photo credits: Unknown/Flickr.com

Products/services covered: cool facades; construction of buildings

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Cool white materials can stay 10 - 25°C cooler on the surface than standard materials, while cool coloured materials (which have a higher reflectance than common materials in the infrared spectrum) can reduce surface temperatures by 5-13°C compared to conventional materials of the same colour (Hernández-Pérez et al., 2014).

Experiments on 'test cells'[6] found that cool materials were able to reduce indoor air temperatures by 2 to 14°C, depending on the size and the thermal mass of the cells (the lower the size and the thermal mass, the higher the temperature reductions achieved) (Hernández-Pérez et al., 2014, and references therein). Cool coloured materials were shown to reduce indoor air temperatures by 1-2°C (Hernández-Pérez et al., 2014, and references therein). Simulation studies also found significant reductions in indoor air temperatures due to cool materials, of up to 10°C (Hernández-Pérez et al., 2014).

A dynamic simulations study of the Mediterranean region (Zinzi, 2016) found that cool façades significantly reduced exterior surface temperatures, the number of hours above 27°C indoors, and energy demand for cooling.

[6] This approach involves constructing units without doors and windows and varying the types of materials used in the building envelope, then measuring temperatures to determine the impact of the reflective coatings colour (Hernández-Pérez et al., 2014).

In terms of relative effectiveness compared to NBS, Lassandro and Di Turi (2017) examined the thermal performance of different façade retrofitting solutions. The results show that green walls represent the best solution with respect to all the performance indicators considered (operative indoor temperatures, wall heat gain, sensible cooling, and exterior surface temperature), while cool walls with 85% albedo have the second highest effectiveness.

Typical co-benefits

Economic	Reduced energy consumption

References: Hernández-Pérez et al. (2014)

Cost information

No cost information could be found.

Potential disadvantages / negative impacts/ trade-offs

Reflective materials can be a disadvantage in winter as they reflect heat, which can increase energy demand for heating. However, empirical studies conclude that this increase is generally lower than the cooling energy savings achieved in warm seasons, resulting in net energy savings for buildings in warm and temperate climatic conditions (Hernández-Pérez et al., 2014).

Challenges / requirements for implementation

None identified

References

Hernández-Pérez, I.; Álvarez, G.; Xamán, J.; Zavala-Guillén, I.; Arce, J.; Simá, E. (2014). Thermal performance of reflective materials applied to exterior building components - A review. *Energy and Buildings* 80, pp.81-105.

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Photo source: https://www.flickr.com/photos/gtzecosan/26973899592/ Licence: CC BY 2.0.

4. Cool pavements

Description

Photo credits: Los Angeles Bureau of Street Services

Similarly to dark roofs and façades, dark pavements absorb 80-90% of sunlight and exacerbate the Urban Heat Island (UHI) effect by warming the local air (Heat Island Group, undated). A potential solution to mitigate heat stress is the application of reflective pavements which stay cooler in the sun compared to traditional materials. Cool pavement technologies are well-developed and many commercial products are available on the market (Santamouris, 2013). Cool pavements can be made from traditional paving materials, such as new cement concrete which has a solar reflectance of 30–50% (Heat Island Group, undated). Other techniques include the use of highly reflective white coatings and infrared reflective coloured pigments on the pavements' surface (Santamouris, 2013) or the use of a clear binder that reveals a highly reflective (light-coloured) aggregate (Heat Island Group, undated).

Products/services covered: cool pavements; construction of buildings; construction of transport infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Numerous studies have examined the correlation between pavement materials and their surface temperature, using experimental and computational simulation techniques (for a review, see Santamouris, 2013 and Qin, 2015). The use of reflective paints on the surface of concrete pavements was found to reduce daily surface temperature during hot summer days by up to 10 kelvins, compared to a non-coated concrete pavement of the same colour (Santamouris, 2013). On asphalt pavements, the use of reflective paints achieved reductions of up to 24 k (depending on the specific technique used) compared to conventional asphalt (Santamouris, 2013).

A few studies examined the impact of cool pavements on the ambient temperature, on the basis of assumptions regarding the increase in a city's albedo due to cool pavements (Santamouris, 2013). The reductions in average ambient temperatures are between 0.15-0.8 k (Santamouris, 2013). For example, a study of Californian cities found that raising the albedo of all paved surfaces by 0.2 would reduce summertime outdoor air temperatures by 0.1 to 0.5 °C, depending on the city's geography and climate (Heat Island Group, undated). Smaller-scale simulations of specific areas within a city showed that replacing conventional pavements with cool ones could decrease the average peak ambient temperature by up to 2 k (Santamouris, 2013). However, Yaghoobian and Kleissl (2012, cited in Qin, 2015) found that although the difference between light and darker surfaces in terms of surface temperature was 15.8 k, the difference in the street canyon air temperature was only 0.4 k.

Typical co-benefits

No significant co-benefits identified. The reduction in ambient temperatures is generally considered insufficient to have a significant impact on energy demand for cooling. For example, in Californian cities with a lot of air conditioning, the energy savings due to lowered air temperature were estimated to be less than 1 kWh a year per m^2 of cool pavement installed (Heat Island Group, undated).

Cost information

The cost of reflective pavements is considered to be comparable to that of conventional pavements (Qin, 2015).

Potential disadvantages / negative impacts/ trade-offs

A recent life-cycle assessment study based on Californian cities concluded that the manufacturing of cool pavement materials typically requires more energy and carbon to manufacture than conventional pavement materials, which outweighs the savings attributable to the reductions in air temperature (Levinson et al, 2017).

Challenges / requirements for implementation

No specific challenges identified.

References

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Photo source: Los Angeles Bureau of Street Services, https://www.sciencemag.org/news/2017/09/los-angeles-paints-streets-white-stay-cool

5. Cooling water fountains (outdoor water spraying)

Description

Open water can decrease the air temperature by evaporation, absorption of heat and transport of heat and flowing water has even greater effect (ClimateADAPT, 2016).

Photo credits: Unknown/ pixabay.com

Products/services covered: water fountains

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Fountains can decrease the temperature of the surrounding air by up to 3°C, and this cooling effect can be felt up to 35 metres away from the fountain (ClimateADAPT, 2016).

A water spray from a fountain can have a significant cooling effect because of the large contact surface of the water and air, which stimulates evaporation. The wetting of streets for cooling is also an established practice in Mediterranean cities, and increasingly common in summer throughout Europe. When 1L/m2 of water is applied, air temperatures can decrease by 2-4°C (ClimateADAPT, 2016).

Typical co-benefits

Social/cultural	Recreation
	Enhanced amenity value

References: ClimateADAPT (2016)

Cost information

-

Potential disadvantages / negative impacts/ trade-offs?

There is a trade-off between implementation and water consumption.

Challenges / requirements for implementation

Not suitable in situations of water scarcity. If it is not integrated in a broader water management plan, this measure could result in an increase in water consumption, which could be unsustainable during droughts and heat waves (ClimateADAPT, 2016).

Fountains require regular monitoring and maintenance of the water quality, filters and spray nozzles (ClimateADAPT, 2016).

References

Climate-ADAPT (2015). Water uses to cope with heat waves in cities. Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/water-uses-to-cope-with-heat-waves-in-cities [Accessed 07 May 2018]

Photo source: https://pixabay.com/en/water-fontaine-fountain-1442561/

6. Dikes

Description

Photo credits: Unknown/ commons.wikimedia.org

Dikes (also known as levees or flood defence embankments) are earth structures on coasts or riverbanks aimed at protecting coastal and riverine areas against coastal and fluvial floods (CIRIA, 2013). They are generally long linear structures, usually part of greater flood defence systems that might include floodwalls, gates, pumping stations, and other natural and engineered features most of which are discussed in separate fact sheets. Dikes can be natural, formed by the accumulation of sediments, or artificial, often composed of a hard core of masonry covered by other impermeable material, such as rocks and gravel (EEA, 2017).

Dikes have primarily three hydraulic functions (CIRIA, 2013):

- Retain: reduce risk of flooding by temporarily retaining water out of the leveed area to a defined water level;
- Channel: channel floodwater downstream or to a non-leveed area;
- Control release: provide a controlled release of floodwater in a specific area, minimising flooding downstream.

The larger the area between the river or sea and the dike, the more effective this infrastructure is expected to be, as its absorption capacity is increased and the flood water will not exercise damaging pressure on the structure (EEA, 2017). Moreover, dikes can be placed further away from the water bodies permitting the flooding of floodplains and wetlands, making this solution 'greener' since habitats that depend on flooding are not significantly disturbed (EEA, 2017).

Products/services covered: Dike design, construction, maintenance; environmental engineering; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)*

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

There are three factors that affect the efficacy of a dike, according to the EEA (2017): the distance of the dike from the river or coast, its height, and the pressure that the dike can withstand from water overflows. Dikes are typically constructed to protect areas from specific flood intensities, and a well-designed and well-maintained dike can be very efficient in minimising flood damages in the leveed area for flooding incidents under or equal to the estimated level of intensity.

Typical co-benefits

Social/cultural	Recreation

Reference: EEA (2017)

Cost information

Building a dike does not require a large amount of land to be acquired, and thus the cost of land acquisition generally accounts for 0 to 11% of total project cost, with construction costs representing 75 to 95% of the total (EEA, 2017). EEA (2017) compiled information regarding the total cost for river dike building, which ranges from EUR 0.7 million/km to EUR 4 million/km (the latter estimate refers to retreating and rebuilding a dike). Climate Adapt (2015) presents estimates from the Netherlands where building river dikes ranges between EUR 3 million/km and EUR 5 million/km, depending on their height, and the cost of building estuarine and coastal dikes is EUR 5 million and EUR 7.5 million/km, respectively. One interesting result from Climate Adapt (2015) is that constructing dikes within dunes, using sand, which preserves the existing character of the shore, can significantly increase the cost, reaching more than EUR 45 million/km.

The cost of dike reinforcement may be even higher. EEA (2017) indicates that the cost of reinforcement of dikes in the Elbe river was estimated to be between EUR 4 million and 6 million/km. Jonkman et al. (2013) present cost estimates for coastal dike raising in the Netherlands, differentiating between rural and urban areas. According to these estimates, the unit cost of raising dikes in urban areas ranges between EUR 15.5 million and EUR 22.4 million/km per metre raising and EUR 4.5 million and EUR 12.4 million/km per metre raising in rural areas. Finally, dikes require constant maintenance, which costs between EUR 400 and EUR 100,000/km per year (EEA, 2017; Jonkman, 2013).

Potential disadvantages / negative impacts/ trade-offs?

The construction of dikes, as all hard coastal defences, can have detrimental effects on coastal systems, since it fixes the position of the coastline, limiting the dynamic nature of the ecosystem by obstructing natural coastal processes, such as sediment input, beach/dune interactions, and responses to sea level-rises (Xianli et al., 2010). Furthermore, dikes are massive constructions that require significant areas of land, which can prevent the use of this area for other development (Xianli et al., 2010). Finally, dikes make access to rivers and coasts more difficult, harming the aesthetic and recreational value of these ecosystems (EEA, 2017).

Challenges / requirements for implementation

References

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Photo source: https://commons.wikimedia.org/wiki/File:Kiel_Dike_-_200811_-_Maack.jpg; Licence: CC-BY-SA-4.0.

7. Floodwalls

Description

Photo credits: Jakec/ commons.wikimedia.org

Floodwalls are fixed vertical barriers built next to waterbodies (mainly rivers) in which the water may fluctuate either seasonally or due to extreme weather events aiming to temporarily contain the water that spills out of the waterbody's banks and protect nearby property from inundation (CIRIA, 2013). This solution is preferred in locations where the space is scarce and thus other measures, such as dikes, cannot be installed. However, it reaches its maximum efficiency when used in combination with other hard defences and tools, working as a system (CIRIA, 2013).

Floodwalls consist of a barrier above ground, a foundation that supports the barrier, a cut-off barrier below the foundation that blocks seepage and uplift, and joints that connect the floodwall panels (Ogunyoye, 2011). They can be made from concrete, mortared stone, or brick and can be founded on rock, soil, or piles (CIRIA, 2013). Floodwalls that are cast-in-place concrete structures can have either a gravity or cantilever design, meaning that the former relies on the mass of the structure to provide stability while the latter are thinner and need to be reinforced (CIRIA, 2013).

Products/services covered: Floodwall design and construction; environmental engineering; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of a floodwall depends on its height and the pressure it can withstand from the hydraulic loading. Floodwalls are designed for a specified return period of a flooding event, which determines both the height and strength of the structure (CIRIA, 2013).

Typical co-benefits

No co-benefits identified

Cost information

Floodwalls are typically more expensive than dikes, however, they are used for shorter distances, which lowers the total price (EEA, 2017). Based on three German river flood protection projects, EEA (2017) estimated that the average cost of 1 km of floodwalls in rivers was between EUR 3 and EUR 5 million.

Moreover, a well-designed, well-constructed floodwall requires minimal maintenance, which implies that the maintenance costs are low (CIRIA, 2013).

Potential disadvantages / negative impacts/ trade-offs?

Floodwalls, as many hard flood defences, prevent riverine (and coastal) ecosystem processes that depend on periodic inundation, such as sedimentation. A main disadvantage of floodwalls is that they diminish the aesthetic appeal of the area as well as its recreational value, since they obstruct access to the river or coast. In addition, floodwalls upstream can potentially worsen the flood incident downstream, since they can increase the volume and the speed of water, which can put greater stress on dikes and floodwalls downstream (Zurich Insurance Company, undated)

Challenges / requirements for implementation

There are no significant requirements for the implementation of this measure. The most important one is that the underlying soil should meet specific requirements in order to be able to support the wall foundation and resist seepage of water underneath it (Rickard, 2009).

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Photo source: https://commons.wikimedia.org/wiki/File:Floodwall_in_Sunbury,_Pennsylvania.JPG; Licence: CC-BY-SA-4.0

8. Longitudinal barriers on rivers (or dams)

Description

Longitudinal barriers (or dams) are built across a river with the intention of blocking its flow and controlling the amount of water released downstream. In case of large discharges of water, a dam can be very effective in preventing flooding downstream, since by blocking the river passage, it can collect the water that would otherwise overflow the river downstream and release it in a controlled manner. Apart from flood control, longitudinal barriers can act as water reservoirs, which can supply water for irrigation, household and industrial consumption, and energy generation (EEA, 2017).

Photo credit: unknown/pixabay.com

The size of dams and hence their water storage capacity varies significantly. Around 5,000 dams in the world are higher than 30m, 15,000 are between 15m and 30m, and thousands are between 5m and 15m (Lempérière, 2017). According to the International Commission on Large Dams, 'large dams' are considered those that are 15m or higher and those that are between 5 and 15m and can store over 3 hm^3 of water (ICOLD, undated).

Products/services covered: environmental engineering; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Dams are constructed to have a specified level of water capacity. Until this threshold is surpassed, longitudinal barriers are very effective in protecting downstream areas from flooding, although a certain upstream area needs to be permanently flooded (EEA, 2017).

Typical co-benefits

Economic	Water provision
	Electricity production

Cost information

Dams are very expensive constructions. EEA (2017) collected cost information on several European projects, estimating the cost of longitudinal barrier per metre, which ranges from EUR 0.55 million to EUR 2.73 million/m. Given that many dams are of massive size, their construction can be very costly. Moreover, maintenance costs are considered to be very high, mainly due to the fact that dams are constantly under water pressure (EEA, 2017).

Potential disadvantages / negative impacts/ trade-offs

Damming rivers can have significant negative environmental, social, and economic impacts that can occur upstream, downstream, and in the reservoir. The dam wall itself blocks the flow of water, obstructing fish and other organism migration and the flow of sediment and nutrients downstream (Beck et al., 2012). This can harm biodiversity by reducing fish populations and by limiting the fertility of riverine ecosystems and can induce coastal erosion (Beck et al., 2012; EEA, 2008). Moreover, the altered river flow downstream as well as the altered water temperature and dissolved oxygen caused by river damming both in the reservoir and outflows can negatively affect aquatic organisms that depend on a certain water level, velocity, or temperature (Beck et al., 2012). Social impacts include the resettlement of communities and loss of land due to reservoir inundation, while economic impacts emerge due to the loss of fish and other riverine resources, which are important to sustain rural livelihoods (Beck et al., 2012). Finally, the cultural, recreational, and aesthetic values of natural rivers can be severely impacted by dams (Beck et al., 2012).

Challenges / requirements for implementation

No significant challenges in building dams were identified.

References

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Photo source: https://pixabay.com/en/reservoir-dam-water-building-1030292/

9. Temporary and demountable flood barriers

Description

The number of available options of temporary and demountable flood protection products have increased over the past decades (Ogunyoye et al., 2011). Temporary flood protection systems involve the installation of flood protection products during a flood event and their subsequent complete removal when the floodwater levels have receded (Ogunyoye et al., 2011). Demountable flood protection systems involve either the operation of fully pre-installed flood protection products during a flood event or the part-installation of these products into pre-installed guides within a pre-constructed foundation (Ogunyoye et al., 2011). Both can be utilized either in the absence of permanent flood defence or as complementary measures when floodwater passes over, under, around or through a defence system. Each of the temporary and demountable flood barriers has its own form, function, structure, and operation. Ogunyoye et al. (2011) have gathered a comprehensive list of the main temporary and demountable flood barriers used extensively in coastal and river flood incidents, and the following summary of these solutions is largely based on this source, unless stated otherwise.

Temporary flood barriers

Rigid frame barriers

Rigid frame barriers consist of impermeable membranes that cover metal frames with rigid panel elements, spanning between the frames. They are modular and are connected together to form a long continuous barrier, while the water weight provides their stability. Due to their very solid structure, these barriers are most useful when the use of a barrier is required over relatively long periods of time (Haaland & Walderhaug, 2016). The advantages of this type of barriers are that they can easily adapt to various kinds of terrain, their height can often be increased while in use, and can be repaired while in use. Their disadvantages include high seepage at low water levels, high pressure on soil, high storage volume and heavy transportation, and the membranes may be susceptible to wind.

Photo source: Ogunyoye et al., 2011

Flexible frame barriers

Flexible frame barriers are made of metal frames and a flexible impermeable membrane spanning between them. The membrane has to face upstream to form a long skirt and the weight of water acting on the membrane stabilizes the structure and seals with the ground surface. Their advantages include high adaptability to various kinds of terrains and possibility for repair while in use. Their disadvantages that must be considered are the high seepage at low water levels, the high pressure on soil, the high storage volume and heavy transportation, the membranes' susceptibility to wind, and their susceptibility to puncture damage.

Photo source: Ogunyoye et al., 2011

Rigid freestanding barrier

Rigid freestanding barriers include a number of different products in terms of their design, however, their function and operation are similar. These barriers consist of rigid self-supporting units (single elements), prefabricated materials or hinged panels with internal support, connected together to form a long continuous barrier. Their support relies on the weight of the floodwater, which presses down the front leading edge that seals the ground surface. Due to the way that the single elements are connected together, the barrier as a whole can form arcs or corners. The advantages of these barriers consist of their quick and easy installation, low mobilization and demobilization requirements, and use without requiring heavy machinery. Their disadvantages include the significant seepage that can occur in uneven terrains due to their rigidity, their heavy transportation and high storage volume, and the high bearing pressure onto the soil.


Photo source: Ogunyoye et al., 2011

Flexible freestanding barrier

Flexible freestanding barriers consist of self-supporting freestanding sections which are covered by flexible impermeable barrier material (usually membranes). The impermeable barrier has to face upstream to form a long skirt and the weight of water acting on the membrane stabilizes the structure and seals with the ground surface. Their advantages are their easy and quick installation, which does not require the use of heavy machinery, the small storage space requirement and easy transport, their low mobilisation and demobilisation, and the low bearing pressure onto the surface. Their disadvantages include the high seepage at low floodwater levels, the high susceptibility of the impermeable material to the wind, and their susceptibility to puncture.


Photo source: Ogunyoye et al., 2011

(Filled) Impermeable containers

These containers are cellular barriers made of impermeable material, such as polyethylene, polyester, and plastic, filled with aggregates or water, and are connected together to form gravity dams stabilised by the weight of the filling material. Their advantages are that the height of some types of these barriers can increase while in use, do not rely on the filling material for water tightness, can be filled with any available material, and minor repairs can usually be made while in use. Their disadvantages concern the significant seepage that can occur in uneven terrains due to their rigidity, the high bearing pressure on soil, their high storage volume, and the high mobilisation and demobilisation.


Photo source: Haaland & Walderhaug, 2016

(Filled) Permeable containers

The permeable containers are cellular barriers made of permeable material, such as geo-synthetic fabric or geo-textile, filled with aggregates, and are connected together to form gravity dams. Sandbags, a very common form of temporary flood product is included in this category. These barriers are stabilised by the weight of the filling material, but can also be reinforced and held in place by wire meshes, pins, and frames. Their water tightness is ensured by the properties and density of the filling material. The advantages of these


Photo source: Ogunyoye et al., 2011

barriers are that they are flexible and adapt to uneven terrains, can be filled with readily used material, are easily installed and require small storage place, and their height can usually be increased by stockpiling. The disadvantages include the limited amount of times they can be reused, the disposal of the contaminated filling material after use, the significant width of land that is required for their installation when they are stacked, and the high bearing pressure on bedding pressure.

Air filled tubes

These products are pre-fabricated geo-membrane or reinforced PVC tubes filled with air and they are more suitable for long lengths rather than filling small gaps. Due to their light weight, air tubes are anchored down with pins or by an extended pre-weighted skirt to ensure stability and sealing with the surface. Their advantages are their low bearing pressure on the surface, their small storage place requirement, their easy installation, and their high versatility (they can be used for many other emergencies). The disadvantages of these products are their susceptibility to puncture, the rapid failure of the whole flood defence system in case of puncture, and the requirement for relatively flat surfaces.

Photo source: Ogunyoye et al., 2011

Water filled tubes

These barriers can be made from the same material as the air filled tubes, which instead are filled with water. Due to the weight of the water, they usually do not require to be anchored as the water provides stability. They can also be stackable to increase the height of the defence, but that needs to be performed with caution since they do not adhere to each other in the same way that they do to the ground. Their advantages include their quick and easy installation, their small storage place requirement, and the fact that they can be repaired while in use. The disadvantages include the high width-to-height ratio, since for two metres of height a width of seven metres is required, the susceptibility to puncture, the rapid failure of the whole flood defence system in case of puncture, the requirement for relatively flat surfaces, and the risk of water freezing in the tube.

Photo source: Ogunyoye et al., 2011

Demountable flood barriers

Sectional barriers

Sectional barriers are made of multiple sections of rigid material, such as steel or fiberglass, which are jointly connected or interlocked to form a continuous barrier. The barriers are fully preinstalled, normally hidden in an underground compartment or housing, and once deployed during an emergency, they stay attached to an adjacent structure or permanent protection. Sectional barriers can be either automatic or manual. The automatic barriers are activated by the onset of flooding, while manual ones require the removal of a top cover or the unlocking and lifting of the barrier. Their advantages are the easy and quick operation, which does not require any installation or construction, and their stability and high resistance to impact. Their disadvantages include the fixed height of the defence that cannot be increased, the possibility of failure of

Photo source: Ogunyoye et al., 2011

the mechanical installation, and the jamming of the cover or structure by debris, which will prohibit their deployment.

Part pre-installed frame barriers

These barriers consist of rigid panels that are placed horizontally between stanchions supported on permanent foundations. To ensure water tightness, the panels and stanchions are lined with seals, which are normally of high quality. The stanchions can be either permanently installed or capable of being attached to permanent foundations. Their advantages are the very durable construction and their stability and high resistance to impact, the very low seepage that can occur, and the ability to increase the height by adding more panels. Their disadvantages are the large storage area required, the difficult transportation due to their weight, and the long installation and mobilisation period.

Photo source: Ogunyoye et al., 2011

Demountable flexible free-standing barriers

The demountable flexible free-standing barriers are similar to the flexible free-standing barriers with the difference that their fixation and stabilisation do not rely on long skirts, but their leading edge is connected to a permanent foundation. Their advantages include the availability of long unit lengths, the small storage and easy transport, and the convenience in their installation. Their disadvantage is that the existing systems come in fixed size.

Photo source: Ogunyoye et al., 2011

Demountable rigid free-standing barriers

These barriers are similar to the rigid free-standing barriers with the difference that their fixation and stabilization is provided by pre-installed connections and does not rely on the weight of the floodwater. Their advantages are that they are easy and quick to install, while their disadvantages are that they require large storage place and their height is fixed.

Photo source: Ogunyoye et al., 2011

Floodgates

Flood gates consist of a single or pair of rigid sections that swing, roll, or raise into position to close a gap within a flood defence. They are usually pre-installed and require closure in case of a flood event, which can be done automatically, semi-automatically, or manually. Their advantages is that no installation or construction is required, they are easily operated, and they are stable and highly resistant to impact. Their disadvantage include their fixed height, the possibility of mechanical failure, which can prevent their deployment, and the possibility of debris jamming the cover or structure.

Photo source: Ogunyoye et al., 2011

Products/services covered: Individual flood defence products; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Both temporary and demountable barriers are highly effective in limiting the impact of river and coastal flooding. Most of them are designed with a predetermined level of protection that is fixed or can be increased while in use according to the floodwater level. Moreover, since they are removed after use, their environmental impact is negligible. However, their length is quite limited and thus can protect a targeted public space or building but might not be able to sufficiently protect larger areas, such as a village or city.

Typical co-benefits

Not applicable

Cost information

Keating et al. (2015) present a list of indicative costs of a number of temporary and demountable barriers found in the UK, which are presented in the table below.

Rigid frame barriers	GBP 200-520/m*
Flexible frame barriers	-
Rigid freestanding barrier	GBP 145-470/m
Flexible freestanding barrier	GBP 188-350/m
(Filled) Impermeable containers	GBP 150-1,000/m
(Filled) Permeable containers	GBP 40-110/m
Air filled tubes	GBP 318/m*
Water filled tubes	GBP 290/m
Sectional barriers	Automatic: GBP 2,100/m* Manual: GBP 600-1,900/m*
Part pre-installed frame barriers	GBP 400-800/m*
Demountable flexible free-standing barriers	GBP 600/m
Demountable rigid free-standing barriers	GBP 470-10,000/m
Floodgates (5 x 1m)	Automatic: GBP 17,000* Manual: GBP 5,500*
Floodgates (12 x 1m)	Automatic: GBP 50,000* Manual: GBP 21,000*

Note: * Training costs included

Potential disadvantages / negative impacts/ trade-offs?

Not applicable

Challenges / requirements for implementation

Each of the temporary and demountable barrier has its own form, function, structure, and operation. Therefore the main challenge for the most efficient use of these products is to choose the right solution for each place that they aim to protect.

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10. High-water channel

Description

When the water-level in a river increases above a certain height, and the risk of flooding is consequently high, a channel for high water can help in reducing water levels upstream. The high-water channel is essentially a branch of a river with the inlet being upstream and the outlet downstream, acting as a bypass to drain extremely high water levels of a river via a different route, such that the water will be able to flow more rapidly to the sea.

Photo credit: Dutch Water Sector (2017)

The high-water channel was a solution developed in the IJssel river, near the villages Veessen and Wapenveld in the Netherlands, which was part of a bigger programme called 'Room for the River'. This solution aimed to protect against flooding by mainly redesigning and fortifying the river dikes and the areas out and inside of the dike area, to give more space to the river (Landezine International, undated). Instead of digging the ground, the channel is constructed by building two dikes, which form a flood channel (Ruimte voor de river, undated). In the Veessen-Wapenveld flood channel, the width between the two dikes varies between 500 and 1,500 meters and the area within the dikes has maintained its agricultural function as most of the time the channel will not be filled with water (Ruimte voor de river, undated). The inlet of the channel consists of a large-scale valve mechanism, while the outlet has a fixed barrier with a sluice and two pumping stations, and only in conditions of extreme water levels, the inlet will open to drain excess water from the river (Landezine International, undated).

Products/services covered: pumping stations; environmental engineering; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The Veessen-Wapenveld channel is constructed to be able to drain up to 45% of the total discharge capacity of the IJssel river in case of extreme high water (Ruimte voor de river, undated). When the channel is full, it will be able to provide a 71 centimetre water level reduction of the IJssel river (Ruimte voor de river, undated).

Typical co-benefits

Social/cultural	Recreation, environmental education, enhanced space for social gathering
	Enhanced amenity value

Reference: Ruimte voor de river (undated)

Cost information

The cost of building the Veessen-Wapenveld bypass channel alone was estimated at around EUR 190 million (Nijland, 2014). However, the total cost of this solution is higher if the cost of spatial planning and design and compensation and reimbursement costs are included.

Potential disadvantages / negative impacts/ trade-offs?

To build this 8-kilometre-long channel at Veessen-Wapenveld, several farmers had to move and houses were demolished (Dutch Water Sector, 2017). This shows that such a solution would potentially require land acquisition, which might be of high value. For this reason, and as was the case in the Veessen-Wapenveld project, such schemes might face significant resistance by the local residents and farmers (Dutch Water Sector, 2017).

Challenges / requirements for implementation

The high-water channel is designed to be flooded only during extreme river-water levels, which in the case of the IJsee river, is considered a once-in-a-lifetime incident. This means that for the remaining period this channel will be dry. Therefore, this area, in order to be useful and practical during these periods, has to be utilised for alternative purposes.

References

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Photo source: Dutch Water Sector (2017). Room for the River programme nears completion with new by-pass on IJssel river, the Netherlands [online] Available at: https://www.dutchwatersector.com/news-events/news/23707-room-for-the-river-programme-nears-completion-with-new-by-pass-on-ijssel-river-the-netherlands.html

11. Compartmentalisation

Description

Compartmentalisation is the act of splitting up large polder areas into smaller portions or compartments in order to reduce the flooding area, and thus the economic damages and the number of people exposed, resulting from the failure of an embankment (Asselman and van Vilet, 2012). This solution implies dividing large dike areas into smaller ones by building embarkments with the same, smaller, or various levels of height as the primary defence (Klijn et al., 2010). The size of embarkments is determined by their intended use, which could be to merely slow down floodwater or guide it to less flood-prone areas, in which case they can have lower height than the primary defence (Klijn et al., 2010).

According to Klijn et al. (2010), who reviewed the existing literature on controlling flooding processes and patterns, compartmentalisation can be used against both fluvial and coastal floods and its benefits include the reduction of flooded surface area, the slower growth of breaches on embarkments, the slower flood development that allows counter-measures to be taken, the easier and faster evacuation, and the need to evacuate fewer people, as well as the reduction of flood duration.

Products/services covered: landscape planning; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
	■		■							

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
	■						■

Effectiveness

Compartmentalisation aims at reducing the consequences of flood events. The Dutch case shows that compartmentalisation is an effective method in slowing down the flooding process and limiting the flood extent (Klijn et al., 2010). However, its effectiveness depends on the social benefits that can be produced by its implementation compared with the economic costs of the construction of dikes or the use of other measures, such as dike reinforcement (Asselman and van Vilet, 2012); thus, the cost-effectiveness of this measure is still site specific.

Typical co-benefits

No co-benefits identified

Cost information

The cost of compartmentalisation is estimated at between EUR 2 million/km for the elevation of existing dikes on undeveloped land with little to no structure and EUR 15 million/km for the significant elevation of existing dikes or the construction of dikes on developed land (Asselman and van Vilet, 2012).

Potential disadvantages / negative impacts/ trade-offs?

The disadvantages of this measure include the increased risk of life loss due to the faster water-level rise, the loss of space devoted to embankment construction, the high cost of implementation and maintenance, and the destruction of natural and cultural landscape values (Klijn et al., 2010).

Challenges / requirements for implementation

The construction of dikes that might be necessary for the compartmentalisation of an area requires substantial amount of land, which, in case of developed areas, might not be readily available or be very expensive to acquire.

References

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12. Storm surge barriers (or gates)

Description

Photo credits: ClimateChangeAdaptation (2014)

Storm surge gates are fixed installations located in the sea mouth of a river or waterway that close off entirely these inlets if storm surge events occur and remain open during normal water levels (ClimateChangeAdaptation, 2014). The role of such barriers is twofold. Firstly, to prevent coastal flooding and secondly, to shorten the length or height of the defence structures behind them (Xianli et al., 2010). Therefore, storm surge gates are usually linked with other flood protection measures, such as dikes and floodwalls. Since they are normally used to protect infrastructure that is excessively affected by storm surges and coastal flooding, their number is quite limited in Europe (Climate-ADAPT, 2015). Moreover, the installation of surge gates requires the simultaneous implementation of storm surge monitoring and forecasting systems, which would allow their timely close-off (Xianli et al., 2010).

Products/services covered: Storm surge gates; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The existing gate barriers are effective against storm surges and those that already exist have protected many times the land behind them from coastal flooding (Climate-ADAPT, 2015). Besides flood protection, in some cases, storm surge gates can close to regulate the sea-water penetration into freshwater, and thus they also provide ecosystem services (Climate-ADAPT, 2015).

Typical co-benefits

Environmental	Saltwater intrusion prevention

Source: Climate-ADAPT (2015)

Cost information

The Thames Barrier, which is a storm surge barrier built in the Thames river in 1982, with hydraulic head at more than 7 metres, cost about EUR 1.5 billion (in 2007 prices) and its operation costs are about EUR 9.5 million (in 2013 prices) (Hillen et al., 2010; Climate-ADAPT, 2015). The Maeslankering storm surge barrier (photo) in the Netherlands, with hydraulic head height at 5 metres, cost EUR 656 million (Hillen et al., 2010).

Potential disadvantages / negative impacts/ trade-offs?

One of the main disadvantages of this solution is the high capital and maintenance costs; when the investments for flood warning systems are taken into account, the costs of this solution rise even higher (Xianli et al., 2010). Furthermore, in case the gates remain closed for long periods or if the level of the river is already high, they can cause landward flooding (Xianli et al., 2010). Finally, such barriers have the capacity to alter the chemical, physical, and biological properties of the estuary systems in which they are installed, such as the salinity, temperature, and nutrients, affecting local biodiversity (Xianli et al., 2010).

Challenges / requirements for implementation

This measure requires extensive engineering studies in order to be designed and installed, as it is likely to be technologically challenging. Moreover, a system of flood warning should also be installed, which might entail significant institutional capacity (Xianli et al., 2010). In addition, such measures can only be installed in narrow river mouths or inlets (Xianli et al., 2010).

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13. Groynes, breakwaters and artificial reefs

Description

A **groyne** is a rectangular structure built perpendicularly to the shoreline of the coast, located over the beach and into the shoreface, with the aim of trapping sediments and reducing longshore drift (Climate-ADAPT, 2015). **Breakwaters** are rectangular structures that comprise stone layers armoured with large stones or concrete units and built typically parallel to the shore, either at the shoreline or offshore (Climate-ADAPT, 2015). **Artificial reefs** are rubble mound breakwaters of mostly single-sized stones located offshore that similarly to breakwaters reduce wave energy (Climate-ADAPT, 2015). All three measures are used to protect the coastal profile from erosion, which is one of the factors that exacerbates the effects of coastal flooding.

Groyne
Photo credits: Unknown/Flickr.com

Breakwater. Photo credits: Harrys, B./ commons.wikimedia.org

Products/services covered: Groynes, breakwaters, and artificial reefs; construction of flood control infrastructure; civil engineering

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
			■							

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
					■		

Effectiveness

Groynes' effectiveness depends on their extension into the sea (Mangor et al., 2017). In general they are efficient in protecting certain parts of the shore from erosion and maintaining upper beach stability, however, this usually comes with several adverse effects (Climate-ADAPT, 2015). Breakwaters can effectively protect the shore from erosion and shelter vessels from waves and currents (Climate-ADAPT, 2015).

Typical co-benefits

Environmental	Biodiversity (artificial reefs)
	Recreation

Source: Climate-ADAPT (2015)

Cost information

According to Climate-ADAPT (2015), in the Netherlands, the cost of constructing and installing groynes ranges from EUR 3,000 to 15,000 per running meter, breakwaters cost from EUR 10,000 to 50,000 per running meter, and artificial reefs cost between EUR 15,000 and 35,000 per meter of structure.

Potential disadvantages / negative impacts/ trade-offs

All three measures and other similar artificial structures tend to modify longshore drift affecting the transportation and sedimentation pattern of underflow areas and thus cause downdrift erosion (Climate-ADAPT, 2015). In addition, mud, seaweed, and debris from ships can be captured by breakwaters, which can make the beach unpleasant and unsafe (Climate-ADAPT, 2015). Moreover, the currents in the end of the breakwaters and reefs might become stronger and dangerous for swimmers (Climate-ADAPT, 2015). Navigation and water sports can also be adversely affected by artificial reefs if they do not function as intended (Climate-ADAPT, 2015).

Challenges / requirements for implementation

Considering the downdrift erosion in adjacent beaches and the other significant adverse effects that these structures can have on coasts, their use should only be examined as part of a broader adaptive management policy, taking into consideration the site-specific characteristics and the potential effects on the whole coast (Climate-ADAPT, 2015). Combining groynes and breakwaters with artificial nourishments and/or dune development could mitigate their negative effects on the coast (Climate-ADAPT, 2015).

References

Climate-ADAPT (2015). Groynes, breakwaters and artificial reefs. Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/groynes-breakwaters-and-artificial-reefs [Accessed 07 May 2018]

ClimateChangeAdaptation (2014). Stone garden (artificial reefs) [online] Available at: http://en.klimatilpasning.dk/technologies/sea-level-rise/stone-gardens-artificial-reefs.aspx [Accessed 07 May 2018]

Mangor, K., Drønen, N. K., Kaergaard, K.H. and Kristensen, N.E. (2017). Shoreline management guidelines. DHI

Photo source: Groyne: https://pixabay.com/en/groyne-meeresbuhne-stone-embankment-3307296/, Breakwater: https://commons.wikimedia.org/wiki/File:Bovisand_Pier_and_Plymouth_Breakwater_-_geograph.org.uk_-_914061.jpg Licence: CC BY-SA 2.0.

14. Higher quays

Description

Quays are the platforms alongside the sea, used to load and unload ships. Making existing quays higher can reduce the risk of coastal flooding from rising sea levels (ClimateChangeAdaptation, 2014). However, this solution does not only involve the addition of concrete on top of existing quays since the forces acting on the sheet pile from the additional weight will be increased (ClimateChangeAdaptation, 2014). These effects need to be taken into account during the planning of the implementation of this measure.

Photo credits: Gaida, M. / pixabay.com

Products/services covered: Civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this solution is expected to be high as the protection it can offer against sea level rise is equal to the height of the quay.

Typical co-benefits

No co-benefits identified

Cost information

No cost information could be found

Potential disadvantages / negative impacts/ trade-offs

This solution might limit the use of the harbour by vessels that are lower, since they will not be able to reach the increased height to load and unload their cargo or passengers. Moreover, higher quays might limit the view to the sea, lowering the aesthetic value of the area.

Challenges / requirements for implementation

Since the construction of higher quays will result in increased weight on the existing quays, this solution requires extensive engineering work. In addition, the increase of a quay's height will have consequences on the various types of vessels using the harbour, which need to be taken into consideration in the planning of the project.

References

ClimateChangeAdaptation (2014). Higher quays [online] Available at: http://en.klimatilpasning.dk/technologies/sea-level-rise/higher-quays.aspx

Photo source: https://pixabay.com/en/port-port-facility-transport-water-2467837/

15. Quay walls / sheet pile walls

Description

Quay walls are long port structures built on the coast. A quay wall across the harbour area can keep seawater from invading the city in the event of a storm surge or high tide. They can also make space for new activities in the harbour area (ClimateChangeAdaptation, 2014). The material usually used for the construction of these walls can be concrete, plastic sheet piles, steel sheet piles, or wood structures (ClimateChangeAdaptation, 2014).

Photo credits: ClimateChangeAdaptation (2014)

Products/services covered: Construction of flood control infrastructure; civil engineering

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Quay walls have a fixed height and they are expected to effectively protect the harbour area against sea water elevation of equal height.

Typical co-benefits

No co-benefits identified

Cost information

The cost of quay walls / sheet pile walls is directly related to their retaining height and length. De Gijt and Vinks (2011) collected costs of quay walls from around the world and estimated that the contribution of the retaining height of the quay wall to the total costs is more than 75%.

Potential disadvantages / negative impacts/ trade-offs?

Since quay walls are constructed in harbours, where the area is already developed, no negative impacts are foreseen.

Challenges / requirements for implementation

No specific challenges were identified in the literature.

References

ClimateChangeAdaptation (2014). Quay walls / sheet pile walls [online] Available at: http://en.klimatilpasning.dk/technologies/sea-level-rise/quay-walls-sheet-pile-walls.aspx [Accessed 07 May 2018]

De Gijt, J. & Vinks, R. (2011). Cost of quay walls including life cycle aspects. In Proceedings of the International Maritime-Port Technology and Development Conference, MTEC2011, April, Singapore. MTEC

Photo source: ClimateChangeAdaptation (2014). Quay walls / sheet pile walls [online] Available at: http://en.klimatilpasning.dk/technologies/sea-level-rise/quay-walls-sheet-pile-walls.aspx [Accessed 07 May 2018]

16. Sluices and pumping stations

Description

Photo credits: Heaysman, D./commons.wikimedia.org

Sluices are water channels established in the port entrance or in watercourses that run through the city to protect the city from intruding sea and river water (ClimateChangeAdaptation, 2014). The flow of water in and out of the sluice is controlled through sluice gates. Pumping stations often accompany the sluices to pump the water from the watercourse into the port when the sluices are closed (ClimateChangeAdaptation, 2014). Sluices are open during normal sea-water levels and close when the sea level is above the defined height, so that the sea-water is prevented from flowing up the river (ClimateChangeAdaptation, 2014). The sluice gates should also be closed when the river-water level is above normal and the pumping stations should pump water out of the watercourses and into the sea, preventing the river from overflowing its banks (ClimateChangeAdaptation, 2014).

Products/services covered: Sluices and pumping stations; civil engineering; construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
	■		■							

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
					■	■	

Effectiveness

No indication of the effectiveness of this solution was identified.

Typical co-benefits

No co-benefits identified.

Cost information

No cost information was found.

Potential disadvantages / negative impacts/ trade-offs?

When sluices are closed, the passing of fish from the sea to the watercourse is prevented (ClimateChangeAdaptation, 2014). Therefore, the sluices should remain closed only for a limited amount of time.

Challenges / requirements for implementation

No specific requirements from implementation were identified.

References

ClimateChangeAdaptation (2014). Sluices and pumping stations [online] Available at: http://en.klimatilpasning.dk/technologies/sea-level-rise/sluices-and-pumping-stations.aspx [Accessed 07 May 2018]

Photo source: https://commons.wikimedia.org/wiki/File:Abbey_Mill_Sluice_Tewkesbury_-_panoramio.jpg
Licence: CC BY 3.0

17. Dry flood-proofing

Description

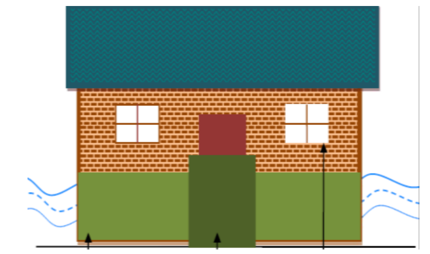


Figure source: Xianli et al. (2010)

Dry flood-proofing refers to making a structure watertight below the expected flood level, preventing water from entering the structure in the first place (Xianli et al., 2010). This would require the sealing of its walls with waterproof coating, installation of impermeable membranes, the development of a supplemental layer of masonry or concrete, installing watertight shields, and complementary measures to prevent sewer backup (Xianli et al., 2010), similarly to the way depicted in the figure on the right, where the green parts represent the sealing material. The advantage of this solution is that it is more affordable than other more elaborate flood protection works and more cost-effective (Xianli et al., 2010). Moreover, dry flood-proofing will make it easier and faster to clean up and repair building-level flood damages.

Products/services covered: Dry flood-proofing measures

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this solution depends on the flood depth and thus it is most effective when applied in areas of low flood depth. If the flood level is higher than the height of the flood-proofing, the effect of the flood will be as if there was no protection at all.

Typical co-benefits

No co-benefits identified.

Cost information

According to Xianli et al. (2010), the costs of dry flood-proofing measures in the USA are as follows:

- Sprayed cement on the structure: $55.10 per meter of wall covered
- Waterproof membrane: $18.70 per meter of wall covered
- Asphalt: $39.36 per meter of wall covered
- Drainage line around perimeter of the house: $101.68 per meter
- Plumbing check valve: $1060 each
- Sump and sump pump: $1710 lump sum

- Metal flood shield: $1230 per meter of shield surface
- Wood flood shield: $383.76 per meter of shield surface

The presented costs refer to flood-proofing of approximately 0.9 m and are presented in 2009 $US.

Potential disadvantages / negative impacts/ trade-offs?

A disadvantage of this solution is that flood shields should be permanently on display and are not aesthetically pleasing and thus might lower the aesthetic value of a building (Xianli et al., 2010). Moreover, continuous maintenance of flood-proofing materials is required, which increases the cost of implementing this solution (Xianli et al., 2010). In addition, if flood waters exercise pressure on the structure above the design loads, the walls of the building might collapse, the floors might buckle, and even the building might float, which would cause more damage than if it was allowed to flood (Xianli et al., 2010).

Challenges / requirements for implementation

Dry flood-proofing requires precursory flood hazard mapping studies and installation of flood warning systems, so that the risk of flooding can be known and communicated to the public (Xianli et al., 2010). Through this, residents will have time to close the barriers of their flood-proofed buildings and evacuate them in a timely fashion. Moreover, since residents will have to evacuate their houses in a flooding event, facilities that provide shelter and accommodation to these people need to be provided in advance (Xianli et al., 2010).

References

Xianli, Z., Linham, M. and Nicholls, R.J. (2010) Technologies for Climate Change Adaptation - Coastal erosion and flooding. TNA Guidebook Series. UNEP/GEF.

18. Wet flood-proofing

Description

In contrast to dry flood-proofing of buildings, wet flood-proofing does not aim to keep floodwater out of the structure, but rather to easily flow in and out of it. In order for this to be achieved, wet flood-proofing measures involve the use of waterproof materials below the expected flood level, the elevation of important utilities, the anchoring of structures against flood flows, and the use of openings and breakaway walls that allow easy passage of floodwater (Xianli et al., 2010). The advantage of this solution is that it is significantly cheaper than other more elaborated solutions.

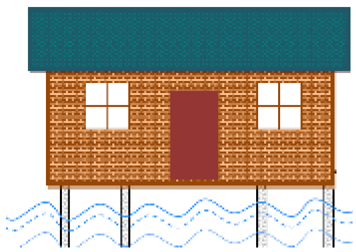


Figure source: Xianli et al. (2010)

Products/services covered: Wet flood-proofing

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this solution depends on the flood depth and thus is most effective when applied in areas of low flood depth. If the flood level is higher than the height of the flood-proofing, the effect of the flood will be as if there was no protection at all.

Typical co-benefits

No co-benefits identified

Cost information

Costs of wet flood-proofing measures in the USA were collected by Xianli et al. (2010). These costs include elevating a structure above flood depth, which is between $29 and $96 per square foot of house footprint, and additional measures, such as wall openings for floodwater entry and exit, pump installation, relocating utility systems, moving appliances, and coating surfaces, which is likely to cost between $2.2 and $17 per square foot of house footprint.

Potential disadvantages / negative impacts/ trade-offs?

Since floodwater is allowed to enter the structure in case of a flood incident, significant clean-up will be required when the water recedes (Xianli, et al., 2010).

Challenges / requirements for implementation

Wet flood-proofing requires precursory flood hazard mapping studies and installation of flood warning systems, so that the risk of flooding can be known and communicated to the public (Xianli et al., 2010). Moreover, since residents will have to evacuate their houses in a flooding event, facilities that provide shelter and accommodation to these people need to be provided in advance (Xianli et al., 2010).

References

Xianli, Z., Linham, M. and Nicholls, R.J. (2010) Technologies for Climate Change Adaptation - Coastal erosion and flooding. TNA Guidebook Series. UNEP/GEF.

19. Floating and amphibious housing

Description

Photo credits: Unknown/ flickr.com

Floating and amphibious houses are built in water bodies and are designed to adapt to rising and falling waters. Floating houses are permanently in the water, while amphibious buildings are built above the water and can float once the water level rises (Climate-ADAPT, 2015). Such applications can be found mainly in inland surface waters, but it would be possible to be built in marine environments as well (Climate-ADAPT, 2015). To ensure an adequate stability of the structures, amphibious houses are usually fastened to flexible mooring posts and rest on concrete blocks, and when water level rises they move upwards (Climate-ADAPT, 2015). Both types of houses are popular in highly populated areas where available land is scarce and the demand for houses near or in the water is high. Such buildings have a great potential to mitigate the effects of flooding, but can also reduce the negative effects of heat (Climate-ADAPT, 2015). The scale of these building vary from individual houses to big groups of dwellings and even theoretically reach the size of a floating city (Climate-ADAPT, 2015).

Products/services covered: Floating and amphibious housing; construction of buildings

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
	■		■							

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
					■	■	

Effectiveness

Since these houses can rise as much as the water level, they are considered as highly effective against flooding.

Typical co-benefits

No co-benefits identified.

Cost information

Housing development costs are greatly affected by the price of the land on which they are built, and water surface area is considerably cheaper than the urban ground (Climate-ADAPT, 2015). However, the rest of the factors that affect the price of a dwelling, such as materials, design, and technology, are typically more expensive, which drive the building costs higher. The return on investment of such buildings is less than ten years and the protection from flood damages can increase their value (Climate-ADAPT, 2015). Nevertheless, the rocking of the buildings with the sea and their limited accessibility and distance from the city can lower their value (Climate-ADAPT, 2015). In addition, services such as water supply, sewage disposal, and electricity are likely more expensive than in conventional houses (Climate-ADAPT, 2015).

Potential disadvantages / negative impacts/ trade-offs?

A potential disadvantage of such structures is that they can lower the aesthetic value of an area since they would block off the view and restrict the access to the water body in which they are built.

Challenges / requirements for implementation

The development of such project would require the involvement of governments or local authorities. They would have to assign the location and conditions under which these types of houses would be allowed to be built and arrange the access and the provision of services (Climate-ADAPT, 2015).

References

Climate-ADAPT (2015). Floating and amphibious housing [online] Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/floating-and-amphibious-housing [Accessed 07 May 2018]

Photo source: https://www.flickr.com/photos/pierrotcarre/4168841609/in/photostream/ Licence: CC BY-SA 2.0

20. Floating or elevated roads

Description

Photo credits: TNO Traffic and Transport (2003)

Floating roads consist of a series of floating pontoons enabling them to float on water and support the weight of vehicles (Climate-ADAPT, 2015). Ideally floating roads are flexible both in time and space, meaning that they are able to float and move to accommodate changing water levels (Climate-ADAPT, 2015). Such a road could be used in areas where water is allowed to overflow regularly or where the ground is weak, such as peat (Climate-ADAPT, 2015). Due to their flexibility, these roads can be used as bypass in cases of road blockages by reasons other than flooding. This is an innovative idea developed as part of the “Floating roads” consortium consisting of TNO, Bayards, DHV, and XX Architects (TNO Traffic and Transport, 2003). The consortium demonstrated this idea by building and installing a 70m floating road (see picture) near the North Brabant town of Hedel, Netherlands. Although several years have passed, we could not find evidence that this solution has been picked up and implemented elsewhere in Europe.

Elevated roads might look like a fixed bridge, but are typically longer, forming a network of streets that leads to higher grounds or can be on top of a bank elevated with sand (Climate-ADAPT, 2015). These roads are useful for evacuation purposes when the rest of the streets have been flooded.

Products/services covered: Floating and elevated roads; construction of transport infrastructure; civil engineering

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

Both floating and elevated roads are considered effective against all three types of flooding. Elevated roads are situated higher than the floodwater’s reach and thus remain unflooded under any circumstances. Attached to both ends of floating roads there are ramps that can accommodate fluctuations of the water level and as such they are an effective adaptation option (Climate-ADAPT, 2015).

Typical co-benefits

No co-benefits identified

Cost information

Floating roads are less expensive than bridges and after construction there is no need for regular maintenance (Climate-ADAPT, 2015). Similarly, elevated roads on top of banks are cheaper than bridge-like roads and maintenance requirements are limited (Climate-ADAPT, 2015). However, the return on the investment in both solutions will occur only once flooding occurs (Climate-ADAPT, 2015).

Potential disadvantages / negative impacts/ trade-offs?

No negative impacts identified.

Challenges / requirements for implementation

No challenges identified.

References

Climate-ADAPT (2015). Floating or elevated roads [online] Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/floating-or-elevated-roads [Accessed 07 May 2018]

Photo source: TNO Traffic and Transport (2003). Staying afloat – a road to the future. Available at: http://www.iiinstitute.nl/sites/default/files/FloatingRoad_343.pdf [Accessed 07 May 2018]

21. Raising coastal land

Description

Raising coastal land using rock and soil to protect communities from coastal floods is a practice used for centuries, however, only few examples of this solution can be seen these days (Climate-ADAPT, 2015). Older examples of this solution include the building of small settlements on small man-made hills in order to protect from storm surges. A contemporary example is the raising of the level of many embankments and streets of Venice to enhance the protection of the city against coastal flooding (Climate-ADAPT, 2015). As part of a broader project aiming to renew water and sewage conduits, additional sand and other material was added under the streets, after the conduits maintenance work was over, before the paving stones were put back in place. This raised the streets and embarkments by as much as 110 cm above sea level (Climate-ADAPT, 2015).

Products/services covered: Construction of flood control infrastructure

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

This solution raises the height of land and specific types of infrastructure which can protect inland areas from sea level rise or storm surges of the same height. Above this level, the solution does not offer any protection.

Typical co-benefits

No co-benefits identified

Cost information

The cost of this solution depends on the adaptation needs and location (Climate-ADAPT, 2015). Moreover, if undertaken together with other construction work in public infrastructure, the costs could be significantly reduced (Climate-ADAPT, 2015).

Potential disadvantages / negative impacts/ trade-offs?

Such street-raising work would be very difficult to implement in urban and industrial areas as well as historical areas, due to the surrounding buildings (Climate-ADAPT, 2015). In addition, raising land using landfill materials can lead to soil compaction and subsidence (Climate-ADAPT, 2015).

Challenges / requirements for implementation

Raising urban land might require public consultation under national or local law (Climate-ADAPT, 2015).

References

Climate-ADAPT (2015). Raising coastal land [online] Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/raising-coastal-land [Accessed 07 May 2018]

22. Upgrading drainage systems / increasing pipe capacity

Description

Cities' piped drainage infrastructure can be upgraded to accommodate larger amounts of stormwater entering the network.

Products/services covered: Construction of drainage and sewage systems; water management

Photo credits: Castelazo, T./commons.wikimedia.org

Problems addressed (climate hazards)

Heat	Floods			Water	
	River	Surface water	Coastal	Scarcity	Quality

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

No specific information found, but effectiveness should in principle be high since the upgrades are specifically designed to accommodate much higher inflows of water during extreme rainfall.

Typical co-benefits

No co-benefits identified

Cost information

The costs are highly dependent on the location and extent of the works, but are generally very high (in the order of millions of euro).

Potential disadvantages / negative impacts / trade-offs

Replacement of underground pipes is a costly endeavour and entails significant disruption in the city.

Challenges / requirements for implementation

Requires extensive works which can disrupt transport and economic activities for significant periods of time.

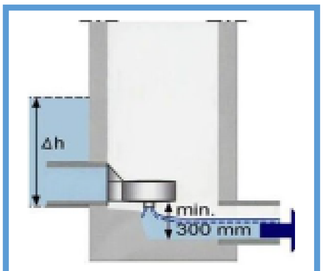
References

EEA (2012). Urban adaptation to climate change in Europe: Challenges and opportunities for cities together with supportive national and European policies.

Photo source: https://commons.wikimedia.org/wiki/File:Pipe_installation_2.jpg Licence: CC BY-SA 3.0

23. Flow regulators

Description



Source: ClimateChangeAdaptation (2014)

Flow regulators control the flow to the sewer system. The water is stored behind the flow regulator and it is released in a controlled manner. Flow regulators can be used to control the flow to the sewer from roofs and paved areas, as well as to control the flow within the sewer and even out the load on the treatment plants (ClimateChangeAdaptation, 2014).

To regulate drainage in the pipelines, flow regulators detain water such that the unused pipe volumes can be utilized. Most often, during a heavy rainfall, the pipelines that become overloaded are found in the lower part of the system where all the water is concentrated while leaving the remaining parts of the system upstream with extra capacity (ClimateChangeAdaptation, 2014). Flow regulators utilize these parts of the system by storing run-off water in them and gradually release it. Flow regulators do not need an energy source to function and they do not contain moving parts in the mechanism (ClimateChangeAdaptation, 2014).

Products/services covered: flow regulators; water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
		■								

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
	■						

Effectiveness

This solution is available in a variety of versions; each can accommodate different magnitudes of run-off, depending on a number of factors. Their proper installation and use can ensure a more balanced distribution of run-off in the sewage system, which can mitigate overflows.

Typical co-benefits

No co-benefits identified

Cost information

According to Carr et al. (2001), who studied the implementation of a project aimed at mitigating basement flooding and sewer overflows in Skokie, Illinois, US, the estimated cost of the installation of 2900 flow regulators together with berms was $6 million in 2000 prices.

Potential disadvantages / negative impacts/ trade-offs?

No negative impacts identified.

Challenges / requirements for implementation

Since run-off is detained by the flow regulators, there might be a need to install subsurface storage tanks which will receive the detained water (Carr, et al., 2001).

References

ClimateChangeAdaptation (2014). Flow regulators. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/flow-regulators.aspx [Accessed 07 May 2018]

Carr, R. W., Esposito, C., & Walesh, S. G. (2001). Street-surface storage for control of combined sewer surcharge. Journal of Water Resources Planning and Management, 127(3), 162-167.

Photo source: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/flow-regulators.aspx

24. Smart regulation of the sewage system

Description

This is a 'smart regulation' technology described on the Danish portal 'ClimateChangeAdaptation'. It has been developed and tested collaboratively by Avedøre Wastewater Services, the Lynettefællesskabet treatment plants, HOFOR and Krüger, in the framework of the METSAM project ('Environmentally efficient technology for intelligent coordinated control of the wastewater system').

The smart regulation of the sewage system requires the use of weather radars, which are deployed to predict the intensity of precipitation and its location one to two hours in advance of a rainfall event so as to utilize the full capacity of the sewage system (ClimateChangeAdaptation, 2014). This is done by the utility companies who are able to adjust both the sewerage and the treatment plants to receiving excessive loads of stormwater combined with wastewater. The sewage system is adjusted by gates that can permit and restrict the passage of water or by pumps that can send stormwater to other parts of the system with higher capacity (ClimateChangeAdaptation, 2014). The treatment plants at the same time adjust their capacity so that they are able to accommodate higher loads of water. By keeping stormwater in the sewage system and utilizing its full capacity, the risk of surface water flood as well as the amount of sewage water discharged untreated to a water body are minimized. Moreover, in case the sewerage becomes overloaded, this smart system can direct the discharge of water to areas where it leads to the least damage (ClimateChangeAdaptation, 2014).

Products/services covered: water management; smart regulation technologies for water management; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The smart regulation of the sewage system is still a novel solution that has not been tested at city level; therefore, inferences about its effectiveness are not yet possible.

Typical co-benefits

No co-benefits identified

Cost information

No cost information identified for this solution. However, the total cost of implementation would include the cost of installing and using weather forecast technologies, construction and maintenance of gates and installation of pumps, and installation of smart sensors in the sewage system. The latter would also include the development of a software, which will analyse in real-time the data provided by the sensors that would permit the instantaneous coordination of different parts of the smart system. Other costs relate to planning of this solution, namely the costs of engineering studies, scientific research, and modelling of the sewage system.

Potential disadvantages / negative impacts/ trade-offs?

No negative impacts identified.

Challenges / requirements for implementation

Requirements to be met in order for this solution to be implemented include firstly the willingness of different stakeholders that participate in the sewage regulation to collaborate. Secondly, such a solution would require civil engineering and scientific studies to be undertaken before implementation.

References

ClimateChangeAdaptation (2014). Smart regulation of the sewage system. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/smart-regulation-of-the-sewage-system.aspx [Accessed 07 May 2018]

25. Flood control channels

Description

Photo credits: Cbl62/ commons.wikimedia.org

Flood control channels are channels that convey rainwater towards a receiving water body. Flood control channels are generally large earth or concrete lined channels that remain dry or with low water flow, designed to receive and convey stormwater in order to decrease the risk of surface water flooding (Wong, 2014).

Based on this idea, existing infrastructure, such as roads or pathways, can be modified so that they can be used as flood control channels in case of flooding. Such channels can be established in the form of V-shaped profile roads that do not allow stormwater to spill over their sides, or roads with trenches or drains together with raised kerbing, or roads whose kerbing and pavements are hollow (ClimateChangeAdaptation, 2014). The dimensioned road profiles and kerbing ensure that if stormwater builds up over the entire road, the basements, houses and stores alongside the emergency flood channels will not be flooded (ClimateChangeAdaptation, 2014). In addition, emergency flood channels can be designed in such a way that they not only convey water during extreme rainfall events, but also collect the water during normal precipitation, preventing it from entering the sewer systems (ClimateChangeAdaptation, 2014). Furthermore, the emergency flood channels can be combined with spaces that detain stormwater to decrease the amount that reaches the channels, such as infiltration basins, permeable paving, or trenches with overflow drains (ClimateChangeAdaptation, 2014).

Products/services covered: Landscape architecture; civil engineering; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The flood control channels are built with a specified capacity of stormwater conveyance and until this level is reached they are considered a reliable solution that can contribute to the mitigation of surface water flooding (Wong, 2014).

Typical co-benefits

No co-benefits identified

Cost information

The cost of this solution is directly related to the length of the channel as well as to the materials used for its construction. The cost of such projects include the design of the channel, its construction, and its maintenance, which might be particularly important as such channels tend to convey water with high sediment content that can seriously impact the functioning of the channel (Wong, 2014).

Potential disadvantages / negative impacts/ trade-offs

The disadvantages of this solution are mainly related to the single-purpose objective of the channel and its ecological impact. Flood control channels are usually lengthy constructions with the single purpose of conveying floodwater in case a flood occurs, serving no other purpose the rest of the time. In other words flood control channels (excluding the emergency flood channels) occupy a place that the vast majority of time is not used. More importantly, flood control channels have been detrimental to ecological conservation since their design does not include ecosystem patterns, processes and concepts (Greco & Larsen, 2014)

Challenges / requirements for implementation

The development of flood control channels would require the involvement of governments or local authorities. They would have to assign the location and conditions under which this solution can be implemented and probably involve stakeholders, including citizens, in the process.

References

ClimateChangeAdaptation (2014). Emergency flood channels. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/emergency-flood-channels.aspx [Accessed 07 May 2018]

Wong, P. L. R. (2014). Federal Flood Control Channels in San Francisco Bay Region-A Baseline Study to Inform Management Options for Aging Infrastructure (Doctoral dissertation, UC Berkeley).

Greco, S. E., & Larsen, E. W. (2014). Ecological design of multifunctional open channels for flood control and conservation planning. Landscape and Urban Planning, 131, 14-26.

Photo source: https://commons.wikimedia.org/wiki/File:Tujunga_Wash.JPG; Licence: CC BY-SA 3.0

26. Surface water storage

Description

Photo credits: Foivos Petsinaris

Climate change will lead to more frequent and heavier extreme rainfalls in many parts of Europe. This will increase the risk of damages caused by surface water flooding, particularly in densely built-up, paved urban areas where it is often difficult to find room for rainwater retention. Surface water storage constructions, such as water-squares, can store rainwater during extreme precipitation events and thus contribute to protecting against surface flooding (Urban green-blue grids, undated). Water squares are public spaces that normally function as playing areas or sports grounds, which are connected with run-off from the surrounding district and collect and store water during high rainfall. This way the city's sewage system is not excessively stressed during peak rainfall events.

The main benefit of such solutions, apart from lowering the risk of surface flooding, is that they combine different functions, creating spaces with multiple purposes, which enhances their value. Other benefits include the enhancement of the aesthetic value, by making visible the dynamics of water in the city (Urban green-blue grids, undated). This solution also helps the city avoid the substantial costs associated with upgrading sewers (C40 Cities, 2014).

Products/services covered: water management; water storage

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					
		■								

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						
	■						

Effectiveness

The effectiveness of this solution is solely determined by the storage capacity of the construction as well as its location. The Benthemplein square in Rotterdam, for example, which is designed as a combination of a basketball and skateboarding and performance arts pits, can hold up to 1.7 million litres of rainwater (C40 Cities, 2014). The Benthemplein is also strategically located in an area that is characterized by paved urban areas, quite densely built.

Typical co-benefits

Social	Recreation
	Enhanced amenity value
	Enhanced space for social gathering

Cost information

The costs of this solution include the construction of the surface reservoir, the installation of all the necessary equipment for the reservoir to be transformed to a square or whatever else its non-flooded use will be, and maintenance costs. Additional costs derived from the disconnection of the surrounding buildings' wastewater pipes from the city's central sewage system may also arise. As an indication, the total costs of the Benthemplein project in Rotterdam were EUR 4.5 million.

Potential disadvantages / negative impacts / trade-offs

No potential disadvantages identified

Challenges / requirements for implementation

A key requirement for this solution to be implemented is stakeholder engagement. People from the broader neighbourhood need to be consulted and encouraged to actively participate in the planning and design of the square so that the multiple uses of this construction can be identified.

References

Urban green-blue grids (undated). Water squares. Available at: http://www.urbangreenbluegrids.com/measures/water-squares/#cite-0

C40 Cities (2014). Benthemplein Water Square: An innovative way to prevent urban flooding in Rotterdam. Case study. Available at: https://www.c40.org/case_studies/benthemplein-water-square-an-innovative-way-to-prevent-urban-flooding-in-rotterdam

Photo source: Author's own.

27. Underground water storage

Description

Climate change will lead to more frequent and heavier extreme rainfalls in many parts of Europe. This will increase the risk of damage caused by surface water flooding, particularly in densely built-up, paved urban areas where the available capacity of rainwater storage is limited. At the same time, collection of rainwater in some European countries will be key to limit water scarcity. For areas with little open space, the underground storage of water is considered a promising solution. The objective of this solution is to capture and store rainwater close to where it falls and delay drainage avoiding sewage system overload. This solution includes various forms of water storage in and around buildings (in basements, or even walls and garden fences). A technically different and smaller application of this solution is the underground installation of big water tanks of various volumes ranging from 300 to 10 000 litres. These tanks, except for reducing the surface flooding exposure of a building, also give the opportunity to utilize the collected water at a later time.

Products/services covered: water management; water storage

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this solution is determined by the storage capacity and the location of the storage place. The capacity of underground water storage spaces can vary significantly from a few cubic metres of a private basement to a 10 000 m^3 for a public space. This is the case with the Museum Park's underground car park in Rotterdam, which has been designed to receive, retain, and store 10 000 m^3 of water in case of extreme precipitation that can be discharged later, reducing substantially drainage peaks (Oppla, undated). It is also important for the effective implementation of this solution that the storage space be strategically placed in areas where excessive runoff occurs with which the available drainage system cannot cope.

Typical co-benefits

No co-benefits identified

Cost information

Since the cost of this solution depends primarily on the amount required to build the underground rainwater storage space, an accurate cost estimation is not possible. The total costs involve the planning and design of the solution, the construction of the storage space, and the construction of the pipeline system which would transport rainwater to the reservoir. This also requires maintenance costs, especially for the pipeline system. Moreover, in case the water collected is intended for reuse, additional costs will arise for the construction and maintenance of the system that would allow that. It should be noted that part of the construction and maintenance costs can be recovered when the space is used for other purposes (i.e. when it does not store runoff water), as is the case with the Rotterdam museum car park mentioned above.

Potential disadvantages / negative impacts/ trade-offs

No negative impacts identified

Challenges / requirements for implementation

No challenges for implementation is required

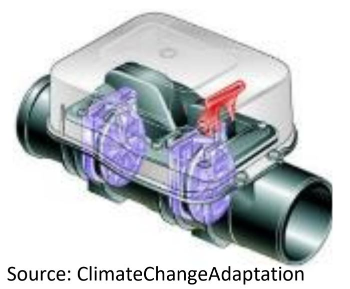
References

Oppla (undated). Rotterdam - NBS for building a waterproof city. Available at: https://oppla.eu/rotterdam-nbs-building-waterproof-city

28. Backflow blocker

Description

A backflow blocker is used to prevent sewage water from flowing back up in the house through drains in the event of heavy rainfall. The valves serve as gates, opening when sewage water runs out from the house and closing if sewage water is pressed into the house (ClimateChangeAdaptation, 2014).



Source: ClimateChangeAdaptation (2014)

According to ClimateChangeAdaptation (2014), there are three types of backflow blockers:

- Built into a floor drain;
- Fitted on pipes where two floor drains are coupled together;
- Fitted on toilet drain pipes.

Products/services covered: Backflow blocker; water management

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

This solution is designed to protect individual buildings from backflow of sewage water caused by surface water flooding. For this function they are considered very efficient. However, this solution cannot prevent buildings from flooding from other entry points, such as doors, windows, and other openings.

Typical co-benefits

No co-benefits identified

Cost information

The price of backflow blockers including their installation ranges from several hundred to thousands of Euros (FEMA, 2010).

Potential disadvantages / negative impacts/ trade-offs

The disadvantage of this solution is that drainage installations, such as toilets, wash basins, and similar cannot be used until the sewage system is unblocked.

Challenges / requirements for implementation

No specific requirements for implementation identified.

References

ClimateChangeAdaptation (2014). Backflow blocker. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/backflow-blocker.aspx [Accessed 07 May 2018]

FEMA (2010). Two Solutions To Consider For Sewage Backflow Problems. Release number: 1895-040. Available at: https://www.fema.gov/news-release/2010/05/07/two-solutions-consider-sewage-backflow-problems [Accessed 07 May 2018]

Photo source: ClimateChangeAdaptation (2014). Backflow blocker. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/backflow-blocker.aspx

29. Pump well with check valve

Description

Pump wells installed in the drainage pipes between the basement and the sewage system prevent the backflow of sewage water from drainage installations in basements in low-lying areas during heavy precipitation (ClimateChangeAdaptation, 2014). Pump wells have usually a volume of 0.5 to 1 m^3, which allows for the use of drainage installations in a building when the public main sewer has limited capacity and is thus unable to meet demand in cloudburst situations (ClimateChangeAdaptation, 2014). These pump wells have a preinstalled non-return check valve that faces the public sewerage system ensuring that there will not be a backflow of sewage from the main network (ClimateChangeAdaptation, 2014).

Products/services covered: Pump well with check valve; water management

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

This solution is designed to protect individual buildings from backflow of sewage water caused by surface water flooding. For this function they are considered very efficient. However, this solution cannot prevent buildings from flooding from other entry points, such as doors, windows, and other openings.

Typical co-benefits

No co-benefits identified.

Cost information

No cost information identified.

Potential disadvantages / negative impacts/ trade-offs?

No negative impacts identified.

Challenges / requirements for implementation

No specific requirements for implementation identified.

References

ClimateChangeAdaptation (2014). Pump well with check valve. Available at: http://en.klimatilpasning.dk/technologies/normal-rainfall-and-cloudbursts/pump-well-with-check-valve.aspx [Accessed 07 May 2018]

30. Separate sewers

Description


Photo credits: Castelazo, T./commons.wikimedia.org

Separate sewers involve separating sewage and rainwater into two different pipe systems. A separate sewer system minimizes the risk of flooded basements during extreme rainfall events for people living in low-lying areas. In the event that heavy rainfall leads to flooding, it is rainwater not sewage from kitchens and bathrooms that rises into basements. Separation also means that sewage can be led away via a closed system to the treatment plant instead of ending up in the environment, while rainwater can be led to detention basins and watercourses (ClimateChangeAdaptation, 2014).

The surface run-off and rainwater can be reused (e.g. for irrigation) after a simplified treatment (Stauffer and Spuhler, 2018).

Some classifications consider this as a hybrid or NBS solution, since it can be combined with certain SuDS components; we nonetheless include it alongside the grey solutions as it only involves engineering methods to be developed and applied.

Type of intervention: N/A

Products/services covered: water management; civil engineering; environmental engineering; construction of drainage and sewage systems

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

No quantified information on performance could be found, but the solution should in principle be effective at tackling surface flood risk since it avoids combined sewer overflow.

Typical co-benefits

Economic	Avoided cost of sewage treatment
	Water provision (as the rainwater entering the separate sewer can potentially be reused for non-potable purposes)

Cost information

No specific cost information found, but the capital costs of the solution are generally high (Stauffer and Spuhler, 2018).

Potential disadvantages / negative impacts/ trade-offs

A separate sewer network may lead to an increase in pollutant concentrations in receiving water bodies, due to an increase in the discharge of untreated surface run-off (Stauffer and Spuhler, 2018)..

Challenges / requirements for implementation

It is generally difficult to change the existing sewer network in a city.

References

ClimateChangeAdaptation (2014). Separate sewers. Available at: https://en.klimatilpasning.dk/knowledge/technologies/normal-rainfall-and-cloudbursts/separate-sewers/ [Accessed 07 February 2019]

Stauffer, B. and Spuhler, D. (2018). Separate sewers. Available at: https://sswm.info/sswm-university-course/module-2-centralised-and-decentralised-systems-water-and-sanitation/further/separate-sewers [Accessed 08 February 2019]

Photo source:

https://commons.wikimedia.org/wiki/Commons:Featured_picture_candidates/File:Large_diameter_pipe_installation.jpg#/media/File:Large_diameter_pipe_installation.jpg; License: CC BY-SA 3.0

31. Greywater recycling systems

Description

Photo credits: ErVeVe / Pixabay.com

Where fresh water is limited, the recycling of greywater and its reuse can be an adaptation measure. Greywater is wastewater that is discharged from showers, bathtubs, sinks, kitchen, dishwashers, laundry tubs, and washing machines, but excluding 'blackwater' (toilet water) (fbr, undated). Greywater can be directly recycled by piping treated greywater into water supply or it can happen indirectly by mixing the treated water with another water supply before re-use (Climate-ADAPT, 2015). The water can be used for agriculture, industry, households, recreational and environmental purposes including aquifer recharge (Wintgens et al., undated). Treated greywater can also be infiltrated into groundwater aquifers. Greywater recycling reduces pressure on freshwater resources from lakes, streams and ground water and protects ecosystems. It prevents water scarcity and helps to cope with drought situations. Therefore, greywater recycling is not dependent on season or variability of rainfall (fbr, undated).

The countries with the largest uptake of greywater recycling reported in Europe are Spain and Italy, although the measure is applicable almost everywhere and allows centralised (e.g. national water authority) and decentralised (e.g. industrial plant, farmers, regional) approaches (Campling et al., 2008). Greywater recycling exists at scales ranging from very small (<0.1 Mm^3/a), to small (0.1-0.5 Mm^3/a), medium (0.5-5 Mm^3/a) and large (>5 Mm^3/a).

Type of intervention: intervention in an existing ecosystem

Products/services covered: Greywater recycling; environmental engineering; water management

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The substitution of potable water with recycled greywater for applications that do not require potable water saves directly freshwater and is an effective measure. In particular, it is a reliable resource during dry spells.

Typical co-benefits

Environmental	Regulation of the water cycle
	Improvement of water quality
	Biodiversity
	Resource efficiency
Social	Health and quality of life
Economic	Local employment

References: Campling et al. (2008); MED WWR WG (2007)

Cost information

The costs vary depending on the treatment needs, intended use of greywater and technology used. The capital costs are low to medium for most greywater re-use systems and are recoverable in a very short time. However, additional costs are associated with the need for a second distribution network in order to keep greywater separate from potable water (Campling et al., 2008).

If greywater is used for households, the costs of equipment of water recycling facilities are high and the payback period is longer compared to other water efficiency measures. A case study of a hotel in Birmingham city centre (Styles at al., 2013) shows that the payback period for the installation of rainwater recovery was 14 years. Greywater recovery systems require a separate distribution system which is difficult to retrofit. Styles et al. (2013) found payback periods for such systems to vary from 2 to 15 years depending on the type of system and the cost of potable water saved. Relatively high maintenance costs, of EUR 2,000 to EUR 3,000 per year, were found in another hotel case study (Styles et al., 2013).

Potential disadvantages / negative impacts/ trade-offs?

Insufficiently treated greywater poses the following risks:

- to human health via the indirect consumption of or exposure to pathogens, heavy metals and harmful organic chemicals contained within it;
- to groundwater due to heavy metals, increased loads of nitrate and organic matter contained in it in areas where reuse for irrigation is practiced;
- to the soil due to heavy metals and salt accumulation and acidification;
- to crops due to the presence of certain substances in the greywater in concentration levels that are toxic;
- to the environment due to high concentration of toxic substances (Campling et al., 2008).

Using recycled water in households requires a second distribution system in parallel to the one for potable water, which increases the costs substantially. The costs are a main barrier for higher uptake, as the costs of recycled water may exceed that of fresh water, if the additional benefits for resource efficiency and the protection of fresh water is not taken into account (Climate-ADAPT, 2015; Wintgens et al., undated).

Users may refuse to consume products that are associated with greywater reuse (Campling et al., 2008).

Challenges / requirements for implementation

For use in households or industry, a second water distribution network needs to be built if it does not yet exist.

Water prices should reflect the full cost including the benefits for the environment to overcome the barrier that conventional fresh water supply is much cheaper than the recycled greywater (Wintgens et al., undated; Armstrong et al., undated).

Solutions require the involvement of many different stakeholders like different authorities, investors, utility companies, building and land owners as well as a re-orientation of the water governance towards integrated water management (Climate-ADAPT, 2015; Wintgens et al., undated; Armstrong et al., undated). Strict quality controls for greywater treatment are required to minimise pollution risks to human health and the environment. National and local standards for wastewater treatment need to be met (Campling et al., 2008). In some cases, they might be too strict to allow the use of greywater for irrigation (Climate-ADAPT, 2015).

If treated greywater is used for irrigation, it needs – depending on the source and management - to be stored in non-irrigation times (Campling et al., 2008).

To overcome public resistance, awareness campaigns and stakeholder involvement are needed in order to make potential users aware of the benefits of reusing greywater, but also of the potential risks and how to avoid them (Campling et al., 2008; Climate-ADAPT, 2015).

References

Armstrong, A., Bartram, J., Lobuglio, J., Elliott, M. (undated). Water reclamation and reuse. In: ClimateTechWiki. Available at: http://www.climatetechwiki.org/content/water-reclamation-and-reuse [Accessed 17 August 2018]

Campling, P., De Nocker, L., Schiettecatte, W. , Iacovides, A.I., Dworak, T., Kampa, E., Álvarez Arenas, M., Cuevas Pozo, C., Le Mat, O., Mattheiß, V., Kervarec, F. (2008). Assessment of alternative water supply options. Available at: http://ec.europa.eu/environment/water/quantity/pdf/Summary%20Report_extended%20version.pdf [Accessed 06 August 2018]

Climate-ADAPT (2015). Water recycling. Available at: http://climate-adapt.eea.europa.eu/metadata/adaptation-options/water-recycling [Accessed 10 August 2018]

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Photo source: https://pixabay.com/en/spraying-irrigation-agriculture-294628/

32. Desalination

Description

Photo credits: Starsend/ commons.wikipedia.org

Desalination is the process of removing salt and other dissolved constituents from saltwater, brackish water, wastewater, or contaminated freshwater in order to make it potable or generally 'fit for use' for other purposes (Armstrong et al., undated). Due to the projected worsening of water scarcity in some parts of the world, this solution has the potential to significantly contribute to climate change adaptation in those areas. Although desalination plants exist worldwide, only 10% of the total global operating capacity is currently used in Europe, with 70% used in Middle east and North Africa (Climate-ADAPT, 2015).

There are several desalination techniques that could be broadly divided into two categories; thermal and membrane processes (Armstrong et al., undated). The thermal desalination processes involve heating the saltwater at a boiling temperature, which then evaporates leaving dissolved constituents behind. The water vapour then cools down and condenses as pure liquid water. The membrane technologies, on the other hand, utilize very dense membranes through which the water is filtered. High pressure forces the water to pass through semi-permeable membranes which can trap salt and other constituents (Climate-ADAPT, 2015).

The desalination process, irrespective of the technology used, produces a by-product, a concentrated salt solution called brine. This solution can negatively affect the local marine ecosystems as it can significantly increase the salinity of the seawater (Climate-ADAPT, 2015). Moreover, brine and other waste produced during the desalination process contain chemicals which are used during the seawater pretreatment process. When brine is released into the marine environment, it ends up in the seabed, as it is heavier than water, and threatens seabed species.

Products/services covered: desalination plant; environmental engineering; water management

Problems addressed (climate hazards)

Heat	Floods			Water		Land-slides	Forest fire	Storms	Hail	Extreme cold days
	River	Surface water	Coastal	Scarcity	Quality					

Scale

Urban		Transport infrastructure	Peri-urban	Rural	Coastal	Water bodies	Adjacent to water bodies
Building-level	Public space						

Effectiveness

The effectiveness of this solution is considered to be high since it can produce water on demand and usually the water produced is pure and of high quality. Desalination can be an important climate change adaptation measure that can mitigate the effect of water scarcity by diversifying water supply. The diversification of water supply sources can make water management more flexible against inadequate water quantity or quality (Armstrong et al., undated).

Typical co-benefits

No co-benefits identified

Cost information

According to a review of desalination literature (Armstrong et al., undated), the cost of this solution is site-specific and the cost per volume of water produced can vary significantly. The factors with the greatest influence on the cost include the energy cost, the desalination plant scale, construction costs, and the salt concentration in the treated water.

For membrane technologies, the cost of desalination increases sharply as the concentration of salt increases in the seawater. For a large plant that produces 5,000-60,000 m^3/day of water with the Reverse Osmosis technology (the most widespread desalination method) from brackish water that contains 1,000-10,000 mg of salt per litre, the cost is between \$0.26 to \$0.54 per m^3 (Armstrong et al., undated). For the same type of brackish water and the same technology, the cost would increase to \$0.78-\$1.33/m^3 if the plant only produced 1,000m^3/day (Armstrong et al., undated).

For thermal technologies, the cost of desalination generally follows the same economies of scale (Armstrong et al., undated). For a production of 1,000-1,200m^3/day of water, the cost is between \$2 and \$2.60 per m^3, and for more than 12,000m^3/day the cost decreases to \$0.52-\$1.95/m^3 (Armstrong et al., undated).

Potential disadvantages / negative impacts / trade-offs

The most important disadvantages of this technology are the high cost, the high energy requirements, and the environmental impacts. As described above, the environmental impact in marine ecosystems can be important affecting both plant and animal life alike found in the water as well as in the seabed. Moreover, the greenhouse gas emissions can be significant due to the energy requirements.

Challenges / requirements for implementation

According to the World Bank (2005), desalination alone cannot lead to improved water supply if other inefficiencies of the water sector are not addressed first. In order for the water sector to work appropriately and the desalination solution to make sense governments need to:

- Develop a water policy according to the Integrated Water Resource Management (IWRM) approach, which would exploit the conventional water resources efficiently;
- Implement policies of water conservation and demand management in all sectors; and
- Consider desalination in combination with other non-conventional water sources, such as treated wastewater, water importation, rainwater harvesting, etc.

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