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How to safely retain stormwater in the city: technical tools

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Before 1990, the industrial area of Dahlwitz-Hoppegarten located east of Berlin covered an area of 40 ha. During the most intense rainfall, runoff speed to the Werner-Graben stream reached 360 litres per second. The area was due to be expanded by another 120 ha after 1990. According to the permit, total runoff from the extended area could not exceed 400 l/s. In other words, although the combined area was going to increase 4-fold, runoff could increase only by 10%. This goal was achieved with the use of best stormwater management practices. What is more, water quality in the river improved as did the aesthetics of the industrial area with the costs of stormwater management 25% lower compared to traditional systems. During the last 15–20 years, on-site stormwater management has become the standard procedure in urban catchments in Germany.

Keywords: blue-green infrastructure, stormwater and snowmelt management, infiltration, retention

Introduction: on-site stormwater management

New way of thinking

Precipitation is the primary source of water in the city that initiates a number of positive processes in the urban space, such as cleaning the air, attenuating microclimate and improving residents' living conditions. Precipitation allows greenery and small aquatic ecosystems to survive in the heavily transformed urban environment, shaping a healthy living environment for residents. Well-planned areas of greenery prevent flooding and urban drought and create safe space for stormwater collection (Wagner et al. 2013).

At the same time, stormwater management is one of the fundamental challenges for most modern cities where development density is constantly increasing. This process leads to residents being deprived of biologically active areas: green space and water. Surfaces sealed by grey infrastructure (streets, sidewalks, parking lots, buildings, squares, hardened and degraded soil) do not allow excess water to infiltrate the ground. Rain or thawing snow/ice flows over the surface causing flooding and local inundations that paralyze the city. In traditional water management, these were to be avoided through the use of combined and stormwater sewer systems. However, practice has shown that these systems often only exacerbate the problem. During intense rainfall, the overloaded stormwater system cannot drain rainwater quickly enough and streets are flooded. Occasionally, backflows occur causing water to flow up in other parts of the city. However, the effective removal of water from the city also has its downside: urban drought. Surface and groundwater levels decline, the urban heat island effect gets worse, green areas and human living conditions deteriorate (cf. chapter on the links between water in the city and residents' health: Kupryś-Lipińska et al. in this volume).

Integrated stormwater (rainwater and snowmelt) management based on on-site management offers an alternative to traditional management systems. Here, the goal is not draining water from the city as quickly as possible, but retaining it where it fell or in the nearby surroundings. Water is then gradually released during dry weather (or once the flood risk is gone), mostly through evaporation and infiltration, and to a lesser degree through surface runoff and into sewer systems. This requires a shift in the perception of the city: from seeing the need to desiccate it and perceiving water as a threat to understanding the benefits of increasing the presence of water in a controlled way and seeing water as a resource and an essential element of high quality of life.

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Concepts and solutions applied around the globe

Countries that are world leaders in terms of the technical knowledge, implementation, establishment of guidelines as well as legal, organizational and economic tools for on-site stormwater management include the USA, Canada, Australia and New Zealand. These countries were faced with the problems associated with intensive urbanization, flooding and drought much earlier than Europe and have been applying best practices for 50 years. In Europe, Germany, Scandinavian countries, the UK and France have the most experience.

New ways of rainwater and snowmelt management have been described in multiple concepts (see box) and solutions which have a lot in common:

- acknowledge the importance of water as the basis of a fully functioning natural system that provides urban residents with a wide range of benefits (ecosystem services);
- accept the presence of water in the city and design space for it;
- use technical (construction) solutions that enhance dispersed stormwater infiltration and retention in the urban drainage basin, and its treatment;
- allow the use of best practices in stormwater management alone or in combination with traditional methods (combined or stormwater sewer systems);

- allow stormwater management to be combined with urban and landscape architecture and with the city's natural system.

The use of best practices provides a multitude of benefits, such as:

- avoiding or minimizing flooding or urban drought and the associated effects;
- creating an integrated infrastructure system (grey, green and blue infrastructure) that can adapt to changing conditions (climate change, urban spatial development, demographic and economic changes);
- stormwater purification and limiting the spread of pollutants;
- reducing the pressure on receiving water bodies by reducing the number of pollutants and hydraulic stress caused by sewer systems (best practices allow to reduce peak flow, attenuate and lengthen the duration of high flows, increase baseflow and groundwater levels);
- reducing the load on stormwater and combined sewer systems and improving their performance in extreme conditions;
- reducing the costs of stormwater management and other operating costs in cities (less need for irrigation, lower environmental fees, less flood damage etc.);
- societal benefits derived from ecosystem services and multifunctional space (the application of sustainable solutions allows to use land for a park, space for recreation or education, and even a playing field or urban square. Renaturalized rivers not only have enhanced retention capacity, but can become attractive places for residents to spend their free time).

Concepts associated with rainwater and snowmelt management

Low Impact Development (LID): an approach that emerged in the USA and consists of the spatial design of new and revitalized urban areas whereby landscape features (such as terrain, geological structure, aquatic and land ecosystems) determine the framework for urban development. This approach reduces the negative impact of development on newly built and neighbouring space and on the natural system. Rainwater is used on-site based on retention in the landscape supported by technical solutions.

Water Sensitive Urban Design (WSUD): an interdisciplinary approach developed in Australia that is based on the cooperation of experts in water management, architecture, spatial planning and environmental protection. It deals with all elements of the urban water cycle (precipitation, water supply, waste water collection, aquatic ecosystems) and incorporates their functionality into urban design. The goal is for the urban water cycle (especially rainwater) to mimic the natural cycle as closely as possible. Cf. the example of Mordialloc Industrial Precinct in the section of good practices at the end of this guidebook.

Sustainable Urban Drainage Systems (SUDS): these comprise technical solutions for urban stormwater collection that are more environmentally-friendly than traditional engineering solutions. Combining different modes of action allows pollution and hydraulic stress in rivers and lakes to be minimized. This UK-based approach is illustrated by the SUDS for Schools project described in the section of good practices at the end of this guidebook.

Best Management Practices (BMPs): stormwater BMPs comprise structural activities aimed at retaining water and eliminating pollutants, as well as non-structural activities to limit surface runoff and prevent pollution. The technical solutions of BMPs form part of all of the concepts mentioned above and therefore sustainable stormwater management is often referred to as best practices or BMPs.

Green and blue infrastructure, ecohydrology

The European Commission (EC 2013) defines green infrastructure as a strategically planned network of natural areas that is designed and managed so as to provide a wide range of ecosystem services. The Commission also makes reference to blue infrastructure i.e. aquatic ecosystems (rivers and their valleys, lakes, artificial reservoirs or wetlands). Both systems combined, blue and green, are a crucial tool for the natural processes of stormwater retention and purification. Green infrastructure is particularly important for the urban landscape (land ecosystems): it helps improve water cycling, supports the functioning of grey infrastructure and reduces the load on stormwater and combined sewer systems.

Both types of infrastructure remain in close cooperation: plants are biological water reservoirs whereas water is indispensable for plant growth. The acknowledgment of this functional cohesion fits in with the concept of ecohydrology (Zalewski 2011). This concept is based on the understanding of the interrelationships between hydrological processes (such as precipitation, infiltration, runoff, interception, evaporation, river flow, water retention) and ecological processes (the biological, physical and chemical processes associated with the cycle of matter, transpiration, biodegradation, primary production, denitrification etc.). These interrelationships are applied in practice in environmental management, including that of the urban environment (Wagner and Breil 2013). Ecohydrological regulation enhances and optimizes the performance of blue-green infrastructure which is of particular importance in densely built urban areas where a desired effect (such as high water retention, high purification efficiency) is to be achieved on a small area. For instance, the choice of tree species with a higher transpiration coefficient[1] can help attenuate the urban microclimate more efficiently. Ecohydrological activities may be coupled with urban (hydro)technical infrastructure. Such combinations help to control hydrological parameters such as water flow velocity and direction to regulate e.g. sedimentation processes and water purification rates or enhance/inhibit the growth of particular plant species in aquatic ecosystems.

The proposed methods of regulating the cycle of water and matter (e.g. nutrients and pollutants) in the urban landscape support the traditional functions of grey infrastructure, such as water purification or flood prevention. From this perspective, ecosystems and their services may be viewed as valuable urban management tools. The reduced implementation, maintenance and operating costs of urban systems that actively use green and blue infrastructure are an additional advantage (EPA 2007; cf. also the chapter on integrated management: Krauze and Wagner in this volume).

Structural solutions

Structural solutions within best stormwater management practices include constructions that enhance dispersed infiltration and retention of stormwater in the urban catchment as well as its treatment. In practice, this includes the construction of facilities and investment-related activities such as the construction, expansion, redevelopment and adaptation of grey infrastructure (e.g. green roofs, changes in street contours, new designs of greenery or pervious surfaces).

Structural solutions are classified in a number of ways. This guidebook uses the classification proposed by the European DayWater project and the guidelines of the US Environmental Protection Agency to select the following: pervious surfaces, plant buffer strips, and facilities for stormwater retention and infiltration. Some papers make a separate distinction for pre-treatment systems located immediately before the receiving water bodies.

The choice of structural solutions and facilities is determined primarily by the amount of runoff from a given area and the possibilities for its retention. These depend on the land use and physiographic features of the catchment, and precipitation properties. Land use in a catchment comprises mainly the development density of a given area and its surroundings, the presence and location of green spaces, the route and load of the sewer system and the presence of underground infrastructure. The physiographic features of land include inclination (which determines the volume and speed of surface runoff formation), the geological structure and soil conditions (which determine natural infiltration capacity), the presence of aquifers, water

> Stormwater management provides ample space for architects' and urban planners' imagination and creativity, and allows for the creation of multiple links between the proposed solutions, elements of architecture and the urban fabric.

[1] The amount of water that a plant transpires to produce a weight unit of dry matter.

relations, and overall climatic conditions. In engineering practice, precipitation properties (which determine the dimensions of structural facilities) typically include intensity and volume. The correct assessment of the amount of rainwater received by retention or infiltration facilities helps to prevent flooding. Emergency overflows can be designed that will safely direct excess water to the sewer system should such a threat emerge. The dimensioning of sewer systems and structural facilities presents many challenges to the good practices in urban catchments. These and dimensioning methods have been widely discussed in Polish literature (e.g. Edel 2010; Geiger and Dreiseitl 1999; Królikowska and Królikowski 2012). These papers also include detailed descriptions, technical guidelines and conditions for the choice of the proposed structural solutions.

In city centres, solutions such as green roofs or underground retention facilities can be used. The collected water can subsequently be used e.g. for irrigation or in urban water fountains. In densely built areas, infiltration is typically hampered by technical barriers such as building foundations and underground infrastructure, and is applicable only in specific locations, such as stadiums or parks. Outside of the city centre and along its borders, infiltration facilities can be used that are commonly combined with pervious surfaces, greenery and even tall trees. Small retention can be used in parks, in combination with urban green spaces and street furniture. Areas located outside of city boundaries offer much wider possibilities: here, surface infiltration and retention may be used freely, both in combination with open public spaces and recreational areas, as well as on private property. In the case of new investments, on-site stormwater management allows to save on the costs of sewage infrastructure as well as to improve the quality and attractiveness of these areas. In practice, stormwater management provides ample space for architects' and urban planners' imagination and creativity, and allows for the creation of multiple links between the proposed solutions, elements of architecture and the urban fabric. The ultimate prerequisite is to apply these solutions in such a way that the designed space is safe for all users.

Below is a collection of examples of sustainable stormwater management solutions that most efficiently contribute to the improvement of microclimate and the urban natural system.

Pervious surfaces

Pervious pavements, asphalt and grass pavers

Large surfaces devoid of greenery, such as parking lots, roads and sidewalks cause the most trouble in terms of uncontrolled surface runoff. Green infrastructure is often impossible to apply. However, it is possible to use materials that allow water to infiltrate, i.e. pervious paving and asphalt. Concrete grids or synthetic reinforcement grids allow the

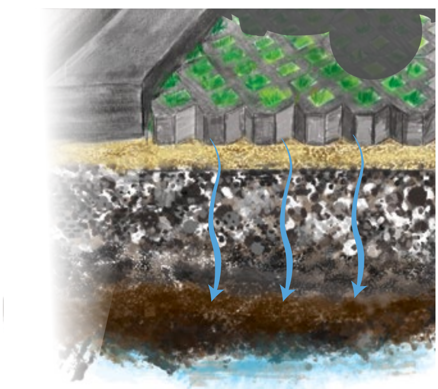

Photo: Chesapeake Stormwater Network

Figure 1. Pervious surfaces: schematic representation of a concrete grid with grass on a bedding, and water percolating through a pervious surface layer

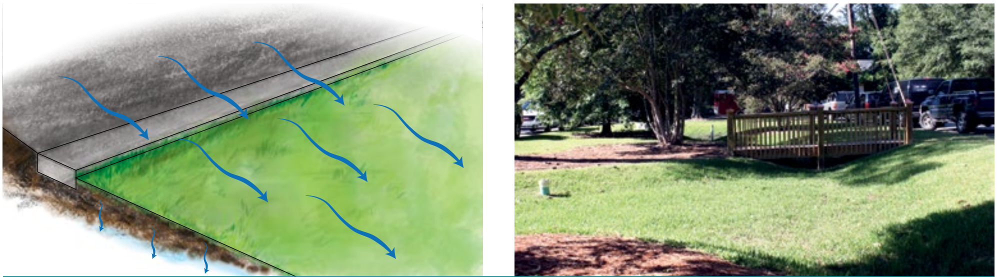

Photo: Clemson University

Figure 2. Grass buffer strips along communication routes: schematic representation and real-world application in combination with an infiltration basin and footbridge in Aiken, USA

growth of grass within the grid system (figure 1). Pervious surfaces are placed on a sub-base that allows further infiltration, such as bedding made of natural material (crushed rock, sand, gravel, stones) or infiltration boxes.

Plant buffer strips

Green roofs and walls

Increasing the coverage of biologically active areas by preserving or expanding green areas (lawns, squares, green spaces, streetside greenery etc.) is vital to restore the urban water cycle. Green roofs and walls covered with vegetation (on specially prepared growing media) fit in well with this strategy, particularly in densely built areas (Kaźmierczak 2013). Depending on the construction and rain intensity, green roofs can retain all of the rain that falls on them. Other benefits include thermal insulation of buildings, increased evaporation, increased biodiversity and coverage of biologically active areas as well as providing additional space for residents to use. Green walls also help regulate temperatures, improve buildings' thermal insulation and aesthetics; the plants can feed on rainwater.

Vegetated buffer strips

Vegetated grass buffer strips are a good solution in areas with looser development, especially near roads. These slightly inclined vegetated surfaces allow the slow (horizontal and lateral) flow of stormwater from adjacent land (figure 2). Plant buffer strips effectively trap sediment and associated pollutants and are therefore commonly used for pre-treatment and as protective areas for other solutions (e.g. basins).

Contouring of streets and green infrastructure

Green areas (and infiltrating facilities) must be located below communication routes in order to capture stormwater from the streets and sidewalks. The simplest way of draining a street is by allowing water to flow freely through indentations in curbs (figure 3).

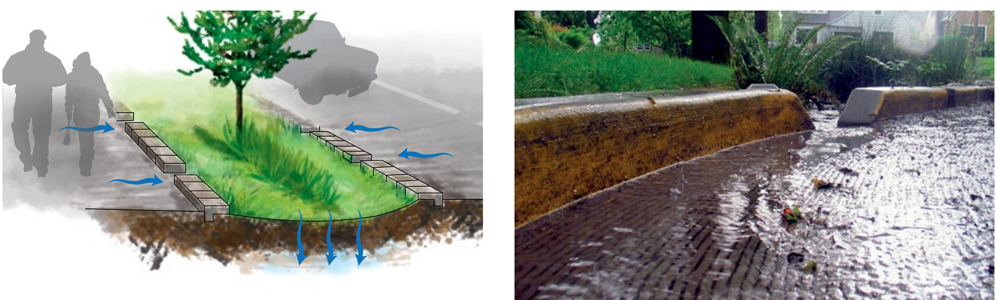

Photo: Kevin Robert Perry, City of Portland

Figure 3. Curb indentations channel water, allowing it to flow from the streets and sidewalks. The photo shows runoff water flowing down NE Siskiyou street in Portland, Oregon, USA

Stormwater infiltration facilities

Stormwater infiltration facilities are used on land with sufficient permeability, where the proportion of biologically active or pervious areas cannot be increased or larger quantities of water need to be managed despite the use of such areas. In principle, water that flows into these facilities leaves them by infiltrating to the ground. Other ways of discharging water (such as into the sewer system or directly to the river) are used as emergency overflows only in case of overloading.

Infiltration basins

Infiltration basins are depressed landforms covered by vegetation and characterized by high infiltration capacity and low water flow velocity (<0.15 m/s). Ideally, the slopes should be only slightly inclined and the underlying soil must be permeable. Infiltration can also be enhanced with additional infiltration layers. Infiltration basins are effective at removing pollutants and may therefore be used for the pre-treatment of water before it is diverted to other areas with blue-green infrastructure. Weirs can be constructed to increase retention capacity, sedimentation and infiltration, and to reduce the drainage rate by reducing inclination. Infiltration basins may be located in areas with varied development density (figure 4). Their irregular shape and diversified depth support the growth of assorted plants.

Photo: <greenworkspc.com>

Figure 4. Infiltration basin in open land (schematic representation) and densely built land (photo): in addition to retaining water this is the main element of landscape architecture in a housing estate in Portland

Detention basins

Photo: <www.sudswales.com>

Figure 5. Detention basin used for recreation during dry weather (schematic representation) and to collect water from the streets and parking lot

Photo: J. Coleby-Williams

Figure 6. Cross section through a drainage well (Burszta-Adamiak 2011) and drainage well in a homeside garden in Bellis, Wynnum, Queensland, Australia

Detention basins display similar features and mode of action to infiltration basins but are larger, deeper and used to drain larger areas (above 1 ha) (figure 5). Detention basins are suitable for areas with varied development density and for road drainage (especially highways). Where allowed by the quality of the conveyed waters, these basins may also serve recreational and aesthetic purposes. In catchments with significant amounts of sediment, initial sedimentation of inflowing water prevents the detention basin floor from silting up during exploitation.

Infiltration wells

In densely built areas where water cannot be retained on the surface, subsurface infiltration systems may be used. Many prefabricated products made of plastics for underground retention and infiltration are available on the market. Infiltration wells offer a more affordable alternative (figure 6): wells filled with infiltration material covered with soil, stones or other material that receive water from surrounding impervious surfaces. Infiltration wells can occupy dozens of square metres, but are typically small (<4 m^2) and no more than 2 m deep. Lining the floor of the drainage well with geotextile fabric separates the adjacent soil from the filling material and prevents soil collapse. Water infiltrates through the floor or both the floor and sides of the well.

Photo: <www.csc.temple.edu>

Figure 7. Cross-section through an infiltration ditch (schematic representation) and infiltration ditch near Einstein hospital in East Norriton, Pennsylvania, USA

Infiltration ditches and grass ditches

Infiltration ditches are linear sections of land typically located along roads (figure 7), filled with infiltration material (similarly to a drainage well) and covered with stones, rock or vegetation. Rainwater percolates to the soil or a perforated pipe, and excess water may be diverted to traditional overflows. A popular alternative to the classic

Photo: <expo2010.freiburg.de>

Figure 8. Grass ditch along tramway tracks in the city centre of Freiburg, Germany

ditches made of concrete are grassed ditches, which are triangular in cross-section with gentle slopes (typically an inclination of 1:3 on the side of the road, 1:3–1:5 on the external side) that collect stormwater; part of it infiltrates and the rest is conveyed elsewhere over the surface (figure 8).

Stormwater tree trenches

Stormwater tree trenches integrate underground retention with tall greenery, e.g. streetside greenery (figure 9). In densely built areas, trees can also evaporate water collected directly from specially designed underground retention systems. In each case, a strip of tree plantings is connected with a cohesive underground retention, infiltration or combined retention/infiltration system that allows the flow of the retained water between plants. During heavy rainfall, excess stormwater can be captured by traditional sewer systems.

Photo: SvR Design Company

Figure 9. Example of streetside greenery combined with an infiltration system, and cascade of greenery fed with water from roofs, Maynard Avenue Green Street, Seattle, Washington, USA

Above ground stormwater retention systems

Stormwater retention systems are designed to hold excess runoff from urban drainage basins and may be temporarily or permanently filled with water. Part of the water may infiltrate and evaporate, but

Photo: De Urbanisten

Figure 10. Dry detention pond of Benthemplein water square in Rotterdam, the Netherlands: photo during dry weather and visualization during wet weather

most of it flows to receiving water bodies in the form of surface runoff or via underground pipe systems.

Dry detention ponds

Dry detention ponds are filled with water only during torrential rain. Water flowing down from roads (typically highways) or densely built up land is retained until the flood risk is gone, and subsequently discharged to a receiving water body or sewer system. The size, capacity and features of these reservoirs is variable; from the point of view of ecosystem services, the most valuable are those semi-natural dry detention ponds that integrate elements of green and blue infrastructure. In addition to their retention capacity, these areas offer attractive, open, green space for residents in rain-free periods and may be used for sports and recreation, e.g. the Liourat à Vitrolles stadium in France. Dry detention ponds may also be combined

Photo: Center for Watershed Protection

Photo: I. Wagner

Figure 11. Detention ponds with continuous flow zones: reservoir in the Sokolowka river in Lodz and in Virginia, USA

with urban architecture. An interesting and bold example is Benthemplein water square in Rotterdam (figure 10). It serves as attractive public space during dry weather and can accommodate nearly 2 million litres of water during rain. Since its construction in 2013, maximum capacity has not been reached.

Detention ponds with continuous flow zone

Detention ponds with a continuous flow zone (figure 11) are a variant of dry detention ponds, often located within aquifers. These are made up of a wider, dry upper level which is submerged only in cases of intense rain and a bed with standing water or shallow marsh (0.2–0.5 m deep). These aesthetic landscape elements are also biodiversity safe havens. Their efficacy in removing solids and heavy metals is high and comparable with retention ponds and stormwater wetlands, and may be further increased with increasing retention periods.

Retention ponds

Retention ponds are solutions used in the riverbed itself or its immediate neighbourhood (figure 12). Their role is to hold water that was already conveyed to the river through direct surface runoff and via stormwater or combined sewer systems. These reservoirs attenuate extreme storm flows, thereby increasing the retention capacity of the river. Stormwater is purified primarily through intensified sedimentation. Plantings may be added to aid in the biological removal of pollutants. Retention ponds are often important elements of the urban landscape that enhance the natural value of a city and serve aesthetic, educational and recreational purposes. Maintaining short retention times (<2 weeks) helps prevent colonization by cyanobacteria which can form toxic blooms in the summer.

Photo: Barbara Gortat

Figure 12. Retention pond by the Sokolowka river in Lodz in 2006 when it was constructed and 6 years later, with established vegetation

Biological stormwater treatment systems

Biological stormwater treatment systems use macrophytes (such as the common cattail, miniature cattail, calamus, yellow iris, tule and the common reed) for stormwater purification at the edge of a receiving water body (river, reservoir, lake). Their performance can be enhanced with pre-treatment facilities: separators and sediment forebays, especially when inflowing water is heavily polluted, e.g. from the streets, parking lots or service stations. This helps maintain the proper functioning of biological systems.

Stormwater wetlands

Perhaps the most popular solution for the retention and purification of stormwater immediately before its release into aquatic ecosystems are stormwater wetlands (figure 13). These are vegetated systems with extended retention periods that are permanently filled with varying levels of water. Most urban stormwater wetlands use horizontal surface flow and are most suitable during rapid stormwater flows due to their large capacity and throughput.

[2] A system of this kind was created in the Sokolowka river in Lodz as part of EU's SWITCH project (FP6 EU, GOCE 018530) and POIG.01.01.02-10-106/09-04 "Innovative resources and effective methods of safety improvement and durability of buildings and transport infrastructure in the sustainable development" financed from the European Regional Development Fund within the framework of the Innovative Economy Operational Programme.

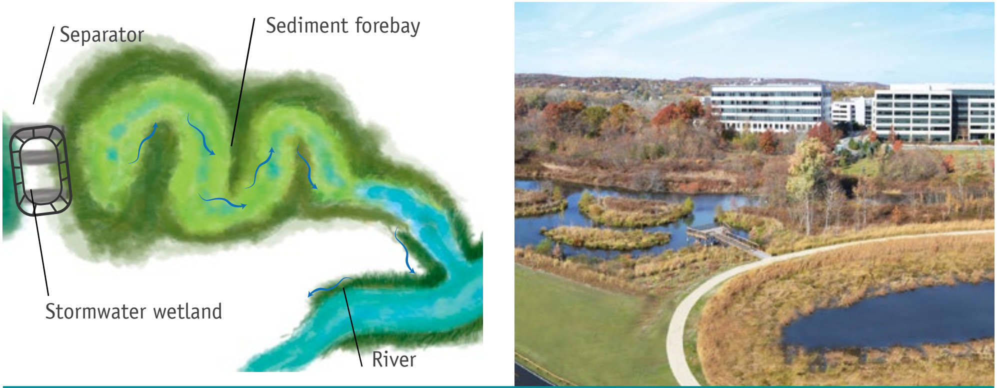

Figure 13. Schematic representation of a treatment wetland used for stormwater purification and photo showing a large stormwater wetland in Massachusetts, USA

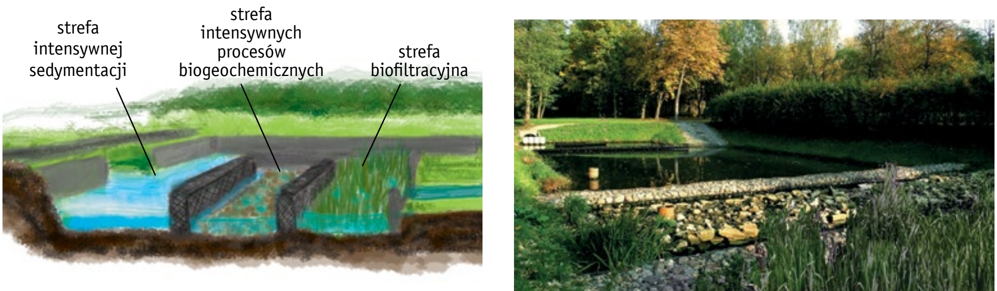

Figure 14. Sequential sedimentation – biofiltration system: schematic representation and pilot project in the Sokolowka river in Lodz

Submerged and floating vascular plants effectively remove pollutants and enhance sedimentation.

Sequential sedimentation – biofiltration systems

Sequential sedimentation/biofiltration systems (figure 14) are stormwater treatment systems that use ecohydrological regulation. These are applied at the inflow of stormwater into a receiving water body or in the aquifer itself.[2] The system is made up of 3 zones: intensive sedimentation (where a combination of fixed and mobile constructions modify the hydrodynamics of the chamber, increasing sedimentation); intensive biogeochemical processes (where the coarse limestone fraction captures phosphorus compounds); and biofiltration (where biogenic substances are eliminated by macrophytes). The zones are separated by gabions of coarse gravel which additionally filter the water.

Shoreline vegetated buffer strips with biogeochemical barrier

Sedimentation – biofiltration systems can be combined with plant buffer strips on the periphery of water bodies[3] (figure 15). Pollutants are removed through intensive sedimentation and assimilation by aquatic plants, as well as adsorption on biogeochemical barriers in the form of gabions filled with dolomite or limestone rock covered with a coconut mat. This solution may be applied for the pre-treatment of stormwater conveyed to rivers and other water bodies via stormwater outlets but only when the drained surface is small and water flow velocity during rain is not high enough to damage the plants.

[3] This solution was applied in the project entitled "Ecohydrological rehabilitation of Arturowek recreational reservoirs (Lodz) as a model approach to the rehabilitation of urban reservoirs" (EH-REK; LIFE08 ENV/PL/000517).

Photo: Tomasz Jurczak

Figure 15. Buffer zone with biogeochemical barrier for the pre-treatment of water conveyed directly to the reservoir: schematic representation and pilot project in the ponds of Arturowek in Lodz

Non-structural solutions

The implementation of sustainable stormwater management solutions is not limited to technical activities but requires the establishment of a wider background. This background is formed by a wide range of non-structural (soft) measures in the following areas (EPA 2005):

- education/awareness: educating residents and information campaigns on the alternative ways of stormwater management;
- planning and management: vehicle emissions control, conscious design of the urban space, plant design, reducing the coverage of impervious surfaces and separating these from the stormwater sewer system;
- stormwater system maintenance: street cleaning, cleaning of manholes and drains, water jetting the sewer system, road and bridge maintenance, maintenance of stormwater channels as well as ditches and aquifers;
- pollutant spill prevention and cleanup: control of oil leakage from vehicles and tankers, tightness control of sanitary sewers and cesspits;
- control of waste storage: stormwater sewer labelling, collection of hazardous waste from households, collection and recycling of used oil;
- control of illicit connections: prevention, detection and elimination of illegal connections to the stormwater sewer network;
- stormwater reuse: non-consumptive use of stormwater (e.g. for toilet flushing, irrigation of municipal greenery).

The experience of the USA's National Pollutant Discharge Elimination System (NPDES) suggests that non-structural activities that engage and include multiple stakeholders (residents, schools, entrepreneurs, decision makers, politicians, artists & the media) can actually be more effective at solving stormwater-related problems than structural activities. Non-structural activities are grounded in a common understanding of the challenges of traditional urban stormwater management, the effects of decisions and activities taking place in the urban space, the need for a new approach and the associated benefits. These constitute the starting point for the creation of a platform of cooperating institutions, the establishment of guidelines, legal frameworks and procedures, as well as the creation of a culture of responsibility for common activities in both public areas (e.g. spatial planning, architecture, environmental protection, infrastructure design) and private areas (e.g. the need to retain runoff generated on one's own property).

Non-structural planning measures: using the potential of blue-green infrastructure

Spatial planning is crucial for the creation of conditions that will encourage sustainable stormwater management. Design goals should include the functional connection of blue-green infrastructure and its coherent incorporation in the dense urban development, which is often a great challenge. However, this approach is vital to preserve the high potential of a city's natural system that translates into its ability to provide ecosystem services, including stormwater retention. This may be achieved by integrated thinking on the city and its natural system (cf. chapter on integrated management: Krauze and Wagner in this volume). The optimum use of the natural potential of blue-green infrastructure requires diversifying its forms and ensuring spatial links between these, thereby increasing urban infiltration.

Reducing the proportion of sealed surfaces

Reducing the proportion of sealed surfaces in the urban space is one of the fundamental measures for retaining water in the city. This can be achieved in several ways. The basic measure is indicating areas that naturally retain water through natural retention, infiltration and surface runoff processes and protecting these from development. These are often wetland areas and therefore exclusion from development also reduces the chances for an investment with a high risk of flooding or temporary inundation. Rivers and river valleys should be placed under special and absolute protection as receiving water bodies for stormwater, as well as corridors that link the urban natural system with its surroundings.

A subsequent step is determining the development conditions for new investments and revitalized areas in particular zones of the city. There are two possibilities here. The first is associated with determining the type of development, i.e. the minimum size of a parcel and development density, the maximum admissible proportion of impervious surfaces or minimum proportion of biologically active areas. Detailed technical requirements and guidelines can also be specified concerning the use of best practices and materials for the construction and hardening of large surfaces (e.g. pervious surfaces of streets, driveways, parking lots). A good practice that helps increase local water retention is the requirement of maintaining diversified terrain near investments (depressions, diversified slopes, land irregularities that retain water) instead of flat land covered with grass.

The second possibility consists of the introduction of a requirement to maintain a specific amount of runoff once the investment is finalized. Surface runoff can be expected to remain unchanged compared with pre-investment values or to constitute a specific amount after the construction is finished (e.g. a runoff coefficient of 0.1 would mean that 90% of rainwater is retained in the analysed area). Solutions of this kind have been successfully used in Germany and are now being implemented in Poland as well (Krakow).

Ensuring the diversity of blue-green infrastructure

The preservation of the diversity and high quality of blue-green infrastructure consists primarily of preserving the diversity of its elements in the urban landscape (rivers, river valleys, reservoirs, natural and artificial wetlands, parks, squares, orchards, gardens, community gardens, greened cemeteries, streetside greenery, areas of particular ecological value etc.). It is good practice to use indigenous species and plant assemblages that are adjusted to the physiography of the area. Not only is this a way to increase the natural value and importantly, the health value of a city, but to create original and pleasant landscape elements that shape residents' natural identity as well. Still, this solution is rarely found in Poland.

From the point of view of blue infrastructure, it is essential to take on actions aimed at preserving the existing aquatic and water-related ecosystems (that favour water retention) together with their vegetated buffer zone (that helps improve the quality of water and the condition of ecosystems) unchanged to the extent possible. The concept of zone-based development of small river valleys established and used in Lodz can serve as an example. Here, the assumption is that every urban river should be surrounded by three zones:

zone 1: absolute protection of the riverbed and valley from being built up. This zone assumes the restoration of degraded rivers where technically possible. These are areas used for the collection and treatment of stormwater and for recreation. Zone 1 is designated on the edge of the 100-year floodplain with the inclusion of natural habitat zones and

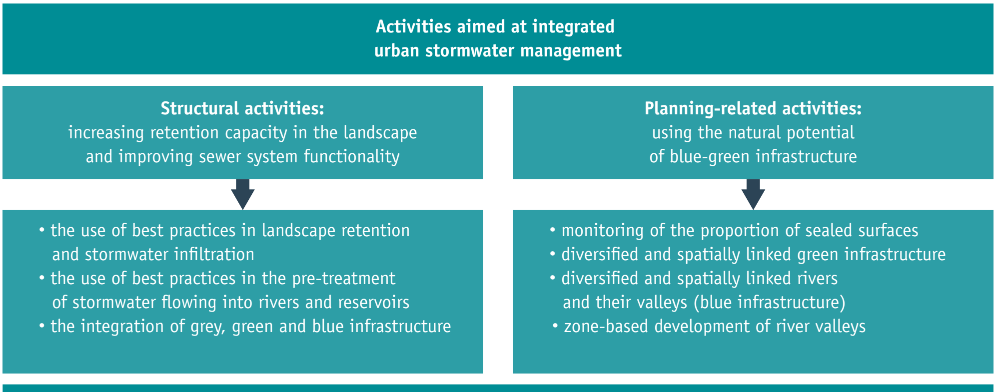

Figure 17. The use of blue-green infrastructure for integrated urban stormwater management

ecological corridors where these coincide with the 100-year floodplain and where allowed by current development.

zone 2: areas temporarily inundated. This zone provides for development with light recreational infrastructure (grassed fields, picnic areas, running paths). This zone is established within 50–100 m from the boundaries of zone 1, including natural landscape and natural/cultural landscape areas where these are continuously linked with the designated zone.

zone 3: zone of low development with strictly defined parameters, a significant proportion of biologically active areas and on-site water retention. This zone is established between the boundaries of zone 2 and the existing development in river valleys or their neighbourhood, and based on the guidelines concerning the natural conditions of the valley and its surroundings.

Ensuring spatial continuity of the urban natural system

Ensuring spatial links between the elements of the urban natural system increases their resilience to external factors and enhances their capacity to provide ecosystem services. This is a challenging task in densely built urban space where "hard" investments are often preferred over the creation of blue-green infrastructure due to competition and the high price of land. However, some rules must be followed when designing the natural system of a city. Green areas should be as big, compact and located as close to one another as possible. Their integration with the structural solutions of best management practices will improve their functioning as more water will be available to plants. If continuity of green infrastructure cannot be ensured, it may be compensated by adequately planned street greenery (cf. previous guidebook in the *Sustainable Development Applications* series), the creation of "green islands" (green roofs or squares located close to one another), and increasing the coverage of pervious surfaces or the use of structural solutions aimed at water retention and infiltration.

Summary

The functioning of blue-green infrastructure in the city is based on sustainable stormwater management. This can be achieved by integrating multiple fields of action that make use of both structural and design solutions (figure 17). Such combinations lead to increased retention capacity in the landscape (even under the pressure of climate change and progressing urbanization), which helps reduce the load on stormwater sewer networks as well as the risk of flooding, temporary inundations and drought (including the heat island effect) and the effects of these. Water accessibility is one of the fundamental prerequisites for the proper functioning of urban ecosystems. The high natural potential of blue-green infrastructure also translates into the ecosystems' ability to provide a wide range of services that are crucial for the quality of life of residents and their ecological safety.

Case study: ecohydrological reclamation of Arturowek recreational reservoirs in Lodz

Small rivers and reservoirs are an inseparable feature of the landscape of Lodz, a city located on the watershed divide between the Vistula and Oder rivers. This location coupled with the lack of any large water body that would receive stormwater, forces the city to seriously consider the use of sustainable stormwater management solutions and the multifunctional use of space (such as combining water retention with recreational and landscape functions and the protection of biodiversity).

The three ponds on the Bzura river in Arturowek together with the surrounding forest complex are one of the most valuable and openly accessible recreational areas for city residents, and even a holiday destination. Designated bathing areas are a popular attraction. However, water quality used to be low due to the inflow of stormwater and the reservoirs' internal load of biogenic substances in the bottom sediments that accumulated over the years. Toxic cyanobacterial blooms that formed on hot summer days posed the biggest threat: bloom intensity significantly exceeded WHO guidelines for bathing waters. Due to the health threat to residents, the bathing areas were closed down on numerous occasions. The improvement of water quality and ecological conditions of the ponds became the prerequisite for maintaining the attractiveness of the site, creating safe public space and recreating ecosystem services.

Within the framework of the ecological reclamation project for the ponds in Arturowek,[4] the threats and opportunities were examined for the restored area (Jurczak et al. 2012). This served to establish action plans aimed at improving water quality where one of the challenges was the pretreatment of stormwater flowing into the ponds. The following solutions were applied (figure 16):

- The ponds in Arturowek are fed by a river with a cascade of seventeen small, dammed reservoirs. Two of these were subject to ecohydrological adaptation: sediments were removed, plants that accelerate water purification were planted and hydrotechnical engineering used to force water flow through the vegetated zones.
- The last reservoir upstream of the ponds in Arturowek receives stormwater from the street. A construction described in this chapter (the sequential sedimentation – biofiltration system) reduces the inflow of pollutants carried by the river to the ponds in Arturowek.
- Most inflowing sediments accumulated in the upper part of the first pond in Arturowek. Therefore, the upper part of its basin was also transformed into a sequential sedimentation/ biofiltration system.
- There are also stormwater outlets that convey stormwater to the reservoirs in Arturowek directly from small stormwater basins (such as a hotel, sports centre). At the inlets, plant buffers zones with biogeochemical barriers described earlier in this chapter, were set up.
- In the lowest pond, sediments were removed and floating plant islets were set up that additionally purify the water.

In the first year after the investment was completed (2014), the concentrations of biogenic substances fell 10-fold for the first time in many years, there were no cyanobacterial blooms and the water is now so clear that the bottom can be seen.

The innovative quality of the solutions proposed here is associated mainly with the comprehensive use of multiple, complementary solutions along the entire river system. The application of ecohydrological solutions allowed the achievement of significant benefits at relatively low cost. The natural areas became the basis for the creation of attractive and safe space in line with the city's strategic goals laid out in the Integrated Development Strategy for Lodz 2020+ and the Blue-Green Network concept (Wagner et al. 2013).

[4] The project entitled "Ecohydrological rehabilitation of Arturowek recreational reservoirs (Lodz) as a model approach to the rehabilitation of urban reservoirs" (EH-REK; LIFE08 ENV/PL/000517) is carried out by the Department of Applied Ecology of the University of Lodz in cooperation with Lodzka Spolka Infrastrukturalna and the City of Lodz Office represented by the Municipal Sports and Recreation Center. The project is financed from the European Commission, the National Fund for Environmental Protection and Water Management, co-financed from the Regional Fund for Environmental Protection and Water Management in Lodz and project beneficiaries' own contribution.

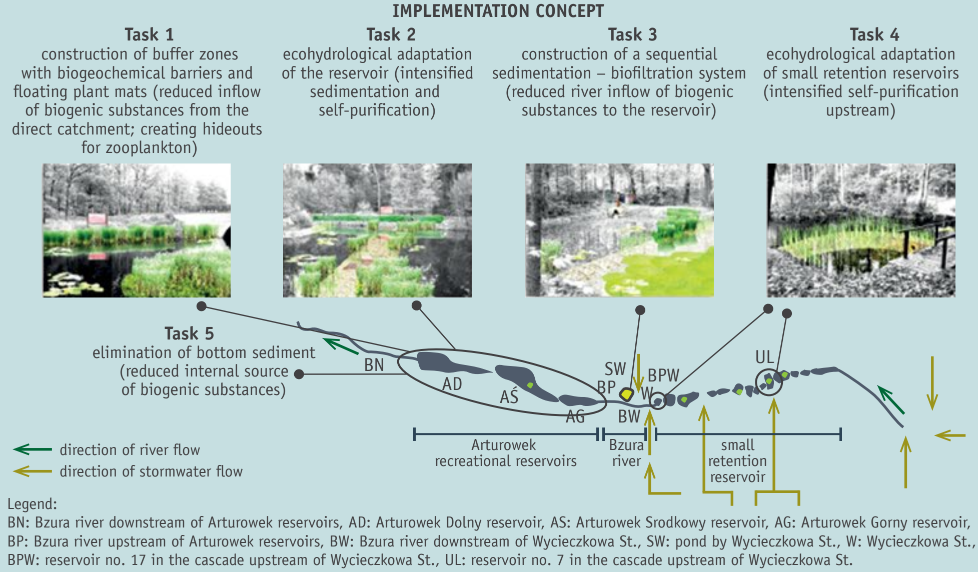

Figure 16. Solutions applied for the reclamation of ponds in Arturowek

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