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Integrative Design Solutions for Connecting Street Trees to the Urban Water Cycle

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1 ABSTRACT

Climate change adaptation and the need to improve micro-climates in cities bring urban forestry into focus. Street trees are important nature-based solutions (NBS) with multiple functions. But only large, well-developed trees that are at least a few decades old can provide the necessary range of ecosystem services and perform the tasks required. There are two essential criteria for trees to grow old: (1) the qualities of the site, in particular the adequate supply of water, air, and nutrients to the root zone, and (2) the choice of tree species. This links tree planting in the urban environment to the improvement of the urban water cycle, which is a goal of NBS in its own right.

In this paper, we explore how tree planting and the urban water cycle can be combined by means of integrated design solutions in different types of open spaces in cities. Based on a qualitative analysis of built design projects using NBS in Austria and scholarly literature, we explore the requirements for and the range and combinations of different design solutions for NBS.

In the design of urban rainwater management based on the "sponge city" principle, NBS can be used for the "collection of water", "retention of water", "purification of water", and "discharge of water to the atmosphere or water bodies". Three different design approaches for water management are possible: "concealment" (diverting rainwater rapidly from the surface to underground systems), "integration" (leaving the water visible, but unobtrusive, and integrating it into the overall design of the site), and „showcasing" (transforming stormwater measures into water-based amenities).

The analysis of 24 projects showed that implementing NBS by using the sponge city principle for trees has become an important element in stormwater management cascades and has been applied in a range of different types of urban open spaces. The sponge city principle for trees is primarily a NBS with low design impact: strategies of "concealment" and "integration" predominate. "Showcasing" has only occurred in conjunction with sunken planters for purification. Incorporating NBS into the overall design of an open space has untapped potential.

The projects under analysis also show that while the water conditions for trees are being improved, the choice of species is also changing. The focus now is on species that are able to cope with hotter and drier conditions. Native species are being replaced with trees from appropriate climatic regions.

The conclusion is that finding synergies between landscape design and engineering provides a rich source of innovation for new urban open spaces. The overall design goal is to achieve an integrative solution serving technical, ecological, social, and economic needs. Designing nature-based solutions means taking a site-specific, integrative approach and connecting with a citywide network of green infrastructure.

keywords: street tree, urban water cycle, urban design, sponge city, nature-based solutions

2 INTRODUCTION

2.1 NBS connecting stormwater management and street trees

Stormwater management in urban planning and site planning is increasingly becoming an issue (Kruse 2014). On the one hand, quantitative changes in the water cycle caused by surface sealing – in conjunction with a climate change-related increase in heavy rainfall events –have brought existing sewer systems to the limits of their capacity. On the other, urban heat islands created by enlarged structures and surfaces, increased waste heat, and reduced evaporative cooling in connection with the climate change–induced aggravation of heat periods are becoming a public health problem. This problem can be counteracted through shading by vegetation and adiabatic cooling caused by increased evaporation (Schmidt 2010). This requires many strong, healthy, and well-irrigated trees providing evapotranspiration in built-up areas.

Summarizing the two EU Commission strategies (EC Energy, Climate Change, Environment n.d.& European Research Executive Agency n.d.), green infrastructure is the strategically planned network of green structures, while nature-based solutions are the concrete measures to address specific challenges that can be integrated into a strategic network. NBS can thus be seen as modules of green infrastructure. Many of them address water management or at least have an influence on the water balance (Fig. 1).

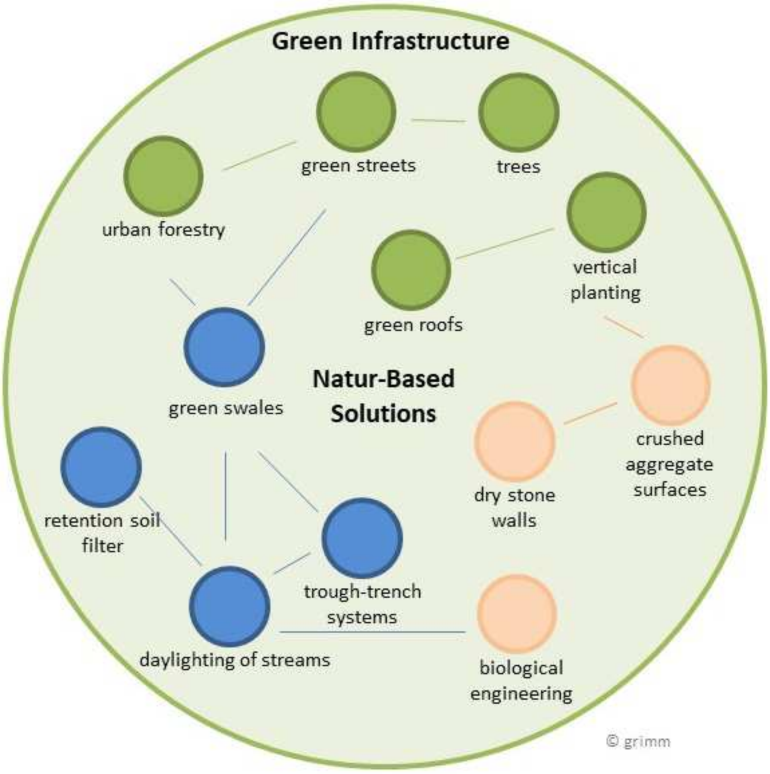

Fig. 1: Nature-Based Solutions –Modules of Green Infrastructure (source: Karl Grimm)

Seen from a climate and water-management perspective, increasing the evaporation of stormwater has the highest priority, ahead of infiltration for groundwater recharge. Stormwater management in combination with urban greening measures can also support biodiversity, offer an experience of nature, and enhance recreational value in urban areas. Accordingly, stormwater management implemented on roofs and facades and in open space is increasingly interlinked with landscape architecture. The transformation of urban drainage systems includes opportunities to enhance the quality of open space in existing urban structures as well as in new urban developments in terms of a network of green infrastructure (Grimm 2018). The living elements of open-space design – trees, planting, permeable surfaces – are themselves NBS. To effectively deploy the multiple functions and services of NBS, a precise development and integration of NBS into high-quality designs is a major task for the future. This implies a paradigm shift in planning for infrastructure and in designing open space, moving towards integrative solutions that are also customized for specific sites.

2.2 Research question and aim of the paper

The focus of this paper is on NBS in the context of trees and water. We investigated which NBS have been implemented in public space in Austria and how water was integrated in the design of the open space.

It is the aim of the research to identify the status of NBS realizations in Austrian projects and to build a knowledge base on tree planting and the urban water cycle. It was important to identify the scope and trends of implementation.

3 MATERIAL AND METHODS

A literature analysis covered the topics urban rainwater management and design, the sponge city principle for trees, and the tree species suitable for urban environments, so-called climate-fit trees. The literature review set out to identify criteria for the analysis of the built projects taking into account the various functions of the realized NBS in connection with a design approach for rainwater.

Based on lists from AK Schwammstadt (the sponge city working group), we conducted a survey in May and June 2023 and identified 60 sponge city projects in Austria focusing on tree planting and the urban water cycle, which varied in terms of their stage of completion, size, and complexity. All the projects are either in a public space or publicly accessible. The list does not claim to be complete. We excluded projects that are still in preparation or planning or in which construction is not yet complete. We also excluded built projects where no information was available that could be analysed. We included projects focusing on rainwater management to cover a broader scope of NBS. This resulted in a list of 24 projects (Tab. 1) for further analyses. We conducted a qualitative analysis of the 24 cases aiming at complementary rather than comparable information (Yin 2010) to get an overview of the range and state of implementation.

Name / Location	Type of open space	Planning and Design	Consultancy	Year of realization
8020, Graz, Eggenberger Allee	street	Freiland ZT	Stefan Schmidt, Erwin Murer	2018
2103, Langenzersdorf	street	3:0 Landschaftsarchitekten	Stefan Schmidt, Erwin Murer	2019
1220, Wien, Quartier am Seebogen	street	3:0 Landschaftsarch., Stoik ZT	Stefan Schmidt, Erwin Murer	from 2020
3730, Eggenburg, Pulkauer Straße	street	NÖ Straßenbauabteilung 1, Hollabrunn	Karl Grimm, Erwin Murer	2021
2011, Sierndorf, Wiener Straße	street	Karl Grimm Landschaftsarchitekten	Erwin Murer	2021
3340, Waidhofen/Ybbs, Freisinger Berg	street	Karl Grimm Landschaftsarchitekten	Erwin Murer	2021
4020, Linz, Kroatengasse	street	3:0 Landschaftsarchitektur		2021
6020, Innsbruck, Ing.-Etzelstraße	street	Stadtgartenverwaltung Innsbruck,	Stefan Schmidt, Erwin Murer, Grimm	2021
1160, Wien, Thaliastraße	street	D\D Landschaftsplanung	City of Vienna, MA 42	2022
8010, Graz, Leonhardgürtel	street	3:0 Landschaftsarchitektur	Stefan Schmidt, Erwin Murer	2022
8742, Obdach	parking area	lichtblauwagner architekten	Karl Grimm Landschaftsarchitekten	2021
3580, Horn	parking area	Held & Franke	Karl Grimm Landschaftsarchitekten	2023
6020, Innsbruck Wallnöferplatz	urban plaza	LAAC		2010
8020, Graz, Lendhotel	urban plaza	Studio Boden / LAM	Freiland ZT	2018
4880, Attnang-Puchheim	urban plaza	Arch. Peter Gilhofer	studioblaugrün	2020
1180, Wien, Johann-N.-Vogl-Platz	urban plaza	Karl Grimm Landschaftsarchitekten	Erwin Murer (substrate)	2020
2821, Lanzenkirchen	urban plaza	3:0 Landschaftsarchitektur	Stefan Schmidt, Erwin Murer	2020
1020, Wien Praterstern	urban plaza	D\D Landschaftsplanung	Stefan Schmidt, Erwin Murer	2022
1190, Wien Leopold-Ungar-Platz	urban plaza	FCP Fritsch, Chiari & Partner ZT GmbH	Karl Grimm Landschaftsarchitekten	2022
1100, Wien Neues Landgut	urban plaza	Arge SimZim Grimm	Karl Grimm Landschaftsarchitekten	2023
1220, Wien, Süssenbrunnerstraße	residential UGS	Jakob Fina Landschaftsarchitekt	Karl Grimm Landschaftsarchitekten	2013
1100, Wien, Biotope City	residential UGS	Knollconsult		2019
1220, Wien Leben am Langen Felde	residential UGS	Arge SimZim Grimm	Karl Grimm Landschaftsarchitekten	2019 -2022
6020, Innsbruck, Campus Technikerstraße	campus	Karl Grimm Landschaftsarchitekten		2018

Tab. 1: List of analysed projects

4 BACKGROUND

4.1 Urban rainwater management

Traditional urban drainage was developed in the 19th century (Brombach et al. 2011) and is based on end-of-pipe solutions (Geiger&Dreiseitl 1995). Water is primarily regarded as a problem and is rapidly removed into the sewers, into surface waters, or into the groundwater via dry wells. Green infrastructure seeks integrative solutions, and water is recognized as a resource. It aims to rehabilitate natural water cycles, harvest rainwater, protect against urban flooding caused by stormwater and cloudbursts, and reduce pollution. Furthermore, rainwater can also be regarded as an amenity (Grimm 2018). It is necessary to distinguish between these goals, as there is some conflict between them, and they require different solutions. As a result, water-sustainable urban design cannot be separated from open-space design.

4.1.1 Functions of NBS on site-level

When implementing NBS as design elements in an urban open-space context, the functioning of green infrastructure in more natural landscapes may serve as a model. The principles of hydrological systems are well researched. Surface runoff is determined by topology, geology, and land cover. The extent of tree canopies plays an important role. In the design of urban rainwater management based on the sponge city principle, NBS are used for various functions in different stages of the water cycle:

- Reduction of runoff
- Collection of runoff
- Retention of water
- Purification of water
- Discharge of the water to the atmosphere or water bodies (surface water or groundwater).

The systematic arrangement of these elements is referred to as a “management train” (Roehr&Fassmann-Beck 2015).

4.1.2 Design strategies for rainwater

Water features are a traditional topic in landscape architecture, but the creation of multifunctional systems based on green infrastructure principles requires a new taken design approaches, incorporating the various functions and benefits of NBS.

Following an analysis of literature and case studies in Europe and North America, three major design strategies for designing rainwater-based NBS were identified (Grimm 2017):

“Concealment” means that rainwater is removed from view as rapidly and unobtrusively as possible and diverted to underground systems, e.g. in downpipes and gutters.

“Integration” describes designs in which the water flow is open, but the system and its components are not highlighted. It is an unobtrusive integration of the infrastructure in the overall design of the site and everyday use of the open space. The elements involved can include green roofs, green swales, or sunken planters.

“Showcasing“ means that the design not only addresses stormwater management but transforms these measures into stormwater-based amenities. Designs create site-specific features and interactions. The term “artful rainwater design” was coined by Stuart Echols and Eliza Pennypacker (2015) to describe this approach. A major consideration when designing for rainwater is that open space is used less when it rains, so showcasing rainwater should also make a feature of the system in dry weather. A planting design approach is called a “rain garden”, when swales or sunken planters are designed as herbaceous or mixed borders. The planting design can be naturalistic or explicitly horticultural. It is a popular design approach in the USA that originated as a concept for making infiltration in front or back yards popular, but the term is now applied to any infiltration measure using specific planting.

On-site, a combination of “integration” and “concealment” is usually applied, and “showcasing” is the exception. The overall goal is to achieve an integrative solution serving social, technical, ecological, and economic needs by combining these three design approaches with functions of NBS.

4.2 From urban greenery to green infrastructure

4.2.1 Sponge city principle for trees

The use of structural soils (Bassuk et al. 2015) as root space for trees that are mostly under impermeable surfaces in combination with the infiltration of rainwater is referred to in Austria as a "sponge city principle for trees" (Grimm et al. 2022). This method has been developed and successfully applied in Sweden for about 15years. The pioneer was the city of Stockholm (Embrén et al., 2009). A defined grading of the mineral components of the soil ensures the long-term preservation of pores for the supply of soil air and soil water to the tree roots (Zeiser et al. 2023). A basic structure of uniformly sized crushed stones makes the substrate suitable for carrying traffic loads, so it can be used under public traffic areas. The Swedish recommendations have been further developed for application in Austria. The first results were published in 2021 (Grimm et al. 2021;Zeiser et al. 2021). Comparable systems have also been developed in Germany (Richter et al. 2021). However, the German solutions rely more on an impermeable trough in the subsoil for water storage and less on plant-available water retention in the substrate through field capacity. There are also current developments in Germany to realize the two infrastructural functions of the „improvement of the root space of trees" and "infiltration of rainwater", only in separate constructions (GALK 2023; Helmreich 2022).

In 2022 the Austrian Standards Institute published a revised national standard L 1112 "Requirements for the Irrigation of Vegetation Areas" (ÖNORM L 11122022), which includes a definition that reads "3.3 Sponge city principle for trees – Construction method of root spaces for trees that simultaneously functions as a base layer for vegetation, a water storage and distribution medium, and a subterranean infiltration system, and that can be installed under paved surfaces so that large-volume root space is made available."

The system is described as a storage medium for irrigation water as follows: "When the sponge city principle is applied to trees, the use of available surface water forms the basis of the water supply, with the substrate in the subsoil being the storage medium. A distribution system shall be provided under impermeable surfaces for the introduction of water and air. For surface water that cannot be absorbed directly by the storage medium, infiltration or drainage must be provided."

Our analysis of the projects is based on the description in standard L 1112.

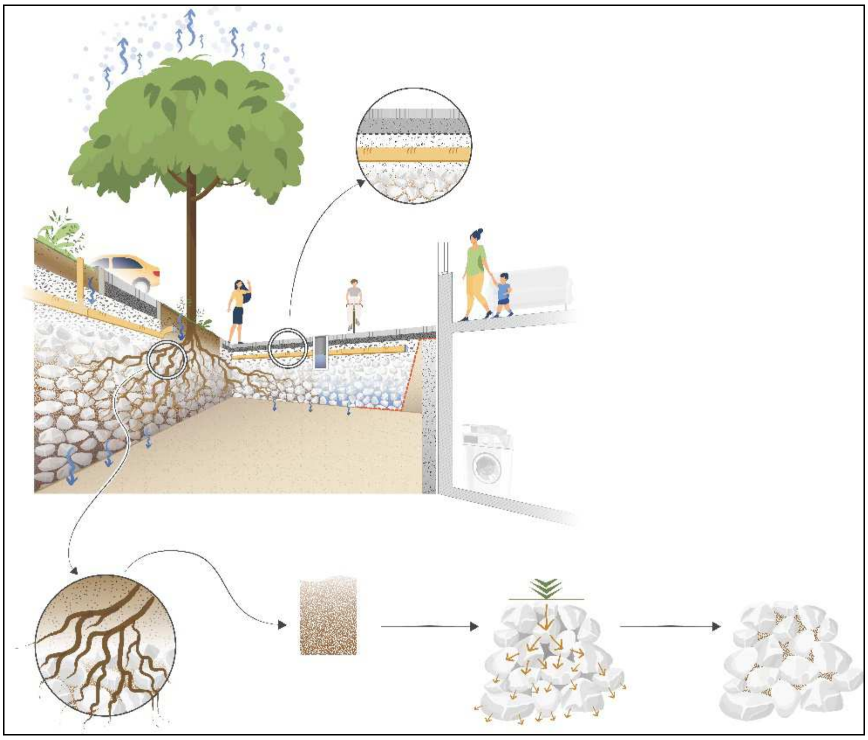

Fig. 2:Sponge city principle for trees (source: Grimm, Murer, Schmidt 2021)

The method is disseminated in Austria through landscape architects and engineers to municipalities and in the larger cities to garden administrations, city planning, and environmental departments. Non-profit

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organizations such as Climate Alliance and Soil & Land Alliance play an important role in informing smaller municipalities.

The number of design projects using the technique was estimated at 16 in 2021 (Grimm et al 2021). Currently there are about 60 projects that are completed, under construction, or planned.

4.2.2 Tree species

Moisture availability and temperature potentially have a significant effect on the growth, development, and fitness of plants in the urban public landscape (Alizadeh&Hitchmough 2020). Plants make species-specific demands on their environment. If these are not met, they will deteriorate, be more susceptible to diseases and pests, and ultimately die. Choosing the right plant for the site becomes more important the longer the life span, the greater the investment in the plant, and the more significant the functions assigned to it. Full ecosystem services are provided by large, well-developed trees that are at least a few decades old. A tree planted today will reach its full potential in about 50 years – if it reaches that age. It is a fact that in urban streetscapes our native trees struggle to cope with extreme radiation climates, drought, pollutant inputs, and mechanical damage (Moser et al. 2017). Few native tree species survive in these locations. In accordance with climate change scenarios, the choice of tree species and varieties is changing.

For several years, experts have been addressing the question of which tree species do well in urban environments. In 1976, the German Conference of Garden Officials (GALK) decided to support municipalities and planning offices in the selection of trees for streets and squares with a list based on experience and observation. This “GALK Street Tree List” has been available as an online tool since 2012 and has become a sound source of information (GALK-Straßenbaumliste n.d.). The varieties and their ratings are regularly discussed and published in professional journals. Since 2009, the Bavarian State Institute for Viticulture and Horticulture (LWG) in Veitshöchheim has investigated 30 tree species at three Bavarian sites in the “Stadtgrün 2021” project (Schönfeld 2022). In 2022, a “climate tree grove” was planted out for research purposes at the “Höhere Bundeslehr- und Forschungsanstalt für Gartenbau” in Schönbrunn, Vienna (Grimm et al. 2022). The aim is to identify so-called future trees. These are tree species and varieties that can not only cope with the current adverse conditions in urban areas but are also expected to be able to endure future conditions exacerbated by climate change.

New varieties of trees and species that have been rarely used in the past are in demand. The search is focused on deciduous tree species from climatic regions that are warmer and drier than we are currently experiencing but also have cold winters (Schönfeld 2022; Bund deutscher Baumschulen n.d.). In forestry, this approach relies on what are called “climate analogues” (Mette et al. 2021).Such comparable regions, characterized by a continental climate, can be found in South-eastern Europe and Anatolia, East Asia, and North America, for example. Another way is to breed new varieties. For example, Resista® elms are largely immune to Dutch elm disease and well suited as street trees in Central Europe.

The adaptation and diversification of tree species, together with the creation of suitable site conditions through larger root spaces with improved air and water supply, are the key to future-proof urban forests. Therefore, in addition to studying the design approaches, we also looked at whether the selection of tree species in projects applying the sponge city principle for trees was based on traditional urban trees or whether new tree species and varieties were used that are considered fit for the future.

5 RESULTS AND DISCUSSION

In the 24 projects selected for further investigation, three groups of projects were identified by using the criteria function of NBS, design approach and tree irrigation:

Group A: 7 projects – the sponge city tree principle is applied, but there is no integration in an overall design.

Group B: 4 projects – there is a focus on designing rainwater management without sponge city trees.

Group C: 13 projects – the sponge city tree principle is integrated in an overall design of the open space.

5.1 Group A: 7 projects – the sponge city tree principle is applied but there is no integration in an overall design.

The projects are realized in three different types of open space:

4 streets

2 parking areas

1 urban plaza

The projects were constructed between 2018 and 2023. In all seven cases, the sponge city trees are a single infrastructure element. The effective part, the structural soil, lies underground and is invisible. The focus is on road infrastructure without any further creative claims. All seven projects investigated address the same NBS functions, which are the collection, retention, and discharge of rainwater. The same design approach – "concealment" – is applied in all the projects. The source of irrigation for trees is always rainwater collected on the surface. In group A, the "purification" function is mostly not applied. This keeps the design simple. The omission of purification is possible because only stormwater from areas without motorized traffic is collected, which is permissible for underground infiltration. Often trees were added into ongoing projects. The trees were either implemented separate from the open space design or there was no design at all: for example, when it involved the replacement of single trees, or new rows of trees were planted in a streetscape in the course of road reconstruction.

5.2 Group B: 4 projects – there is a focus on designing rainwater management without sponge city trees.

2 residential open spaces

1 urban plaza

1 university campus

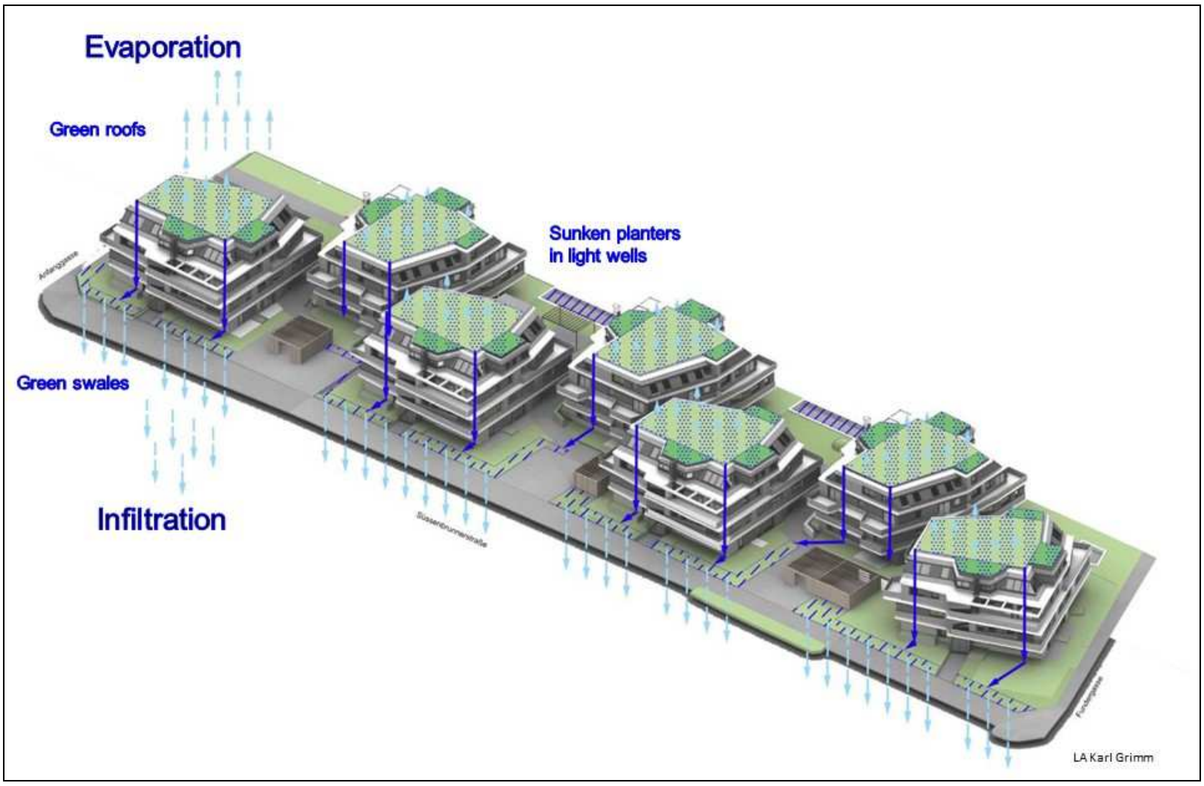

Fig. 3: Pilot project for rainwater management within the cost frame of affordable housing, Süßenbrunner Straße, Vienna, Austria. (Open-space planning: Jakob Fina; Rainwater management: Karl Grimm; Architecture: Thomas Moosmann).

In these projects, the function as a usable open space is in the foreground of design decisions, but the projects also focus on the water cycle and stormwater management. The time of realization spans from 2010 to 2019. These projects are older than the ones in group A and group C. The focus was on rainwater collection, retention, and discharge, and to some extent on purification too. In this group there are three different types of open spaces (residential open space, urban plaza, and campus). These open spaces have to cater to a wide range of uses and provide a variety of open-space qualities, like shade, light, protection from wind, ventilation, diversity of use and equipment, and communicative and aesthetic qualities. There are no streets in this group.

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Owing to the size of the projects, several NBS were implemented, and they fulfil various functions, e.g. green swales for purification or green roofs for water retention. The aim in many cases is to develop "management trains" (Roehr&Fassmann-Beck 2015).

This approach can be best explained with the project Süßenbrunner Straße. It was a pilot project in Vienna for rainwater management within the cost frame of affordable housing.

The design combines NBS in a management train, and various functions and elements are integrated in the architecture and open-space design: retention of the runoff by green roofs, downpipes on the outside walls, retention in the planters, runoff in open flumes, retention and infiltration in infiltration trenches, and sunken planters in the light wells to provide daylighting in the garage. The project was the winner of the City of Vienna Environmental Prize 2017.

5.3 Group C: 13 projects –the sponge city tree principle is integrated in an overall design of the open space.

6 plazas

6 streets

1 residential open space

All 13 projects were constructed between 2018 and 2023. Two projects were in the course of urban expansion, but most of the projects were realized in the context of redevelopments in the existing city. All of them are design projects integrating diverse open-space needs and multiple functions. Trees are important design elements and NBS, and long-term tree health and the water supply of trees are key topics. During this period, climate-change adaptation became an important issue (BMNT 2017) and was considered in design projects. In one project, the financing was supported with an EU programme aimed at supporting the creation of micro open spaces, cooling measures, and tree planting to improve the quality of the open space.

Quality improvement of open space was achieved in almost all projects by redistributing the available space. The implementation of NBS is closely connected with the design of open spaces, although even in these projects the sponge city principle for trees is not necessarily a basic design approach but a subsequent functional addition.

The attitude towards the urban water cycle has changed from primarily integrating rainwater by infiltration to evaporation and the provision of water to urban trees. In all projects, the sponge city tree principle was applied. The water is collected from streets, plaza surfaces, and roofs. In five projects, water features were integrated as a new design element for play and for cooling the surroundings. The runoff is used for watering the trees.

Even in these projects, the design approaches regarding water are restrained. Purification of rainwater is often necessary in connection with street runoff. "Showcasing" and "integration" are only applied for sunken planters in connection with purification. Sponge city trees, whether they are fed by unpolluted stormwater or by a water feature, practically always follow the design approach "concealment" (Fig. 4).

The applied NBS are almost invisible, and the users of the open spaces cannot experience and comprehend the complex interplay of the NBS and the qualities of the open space.

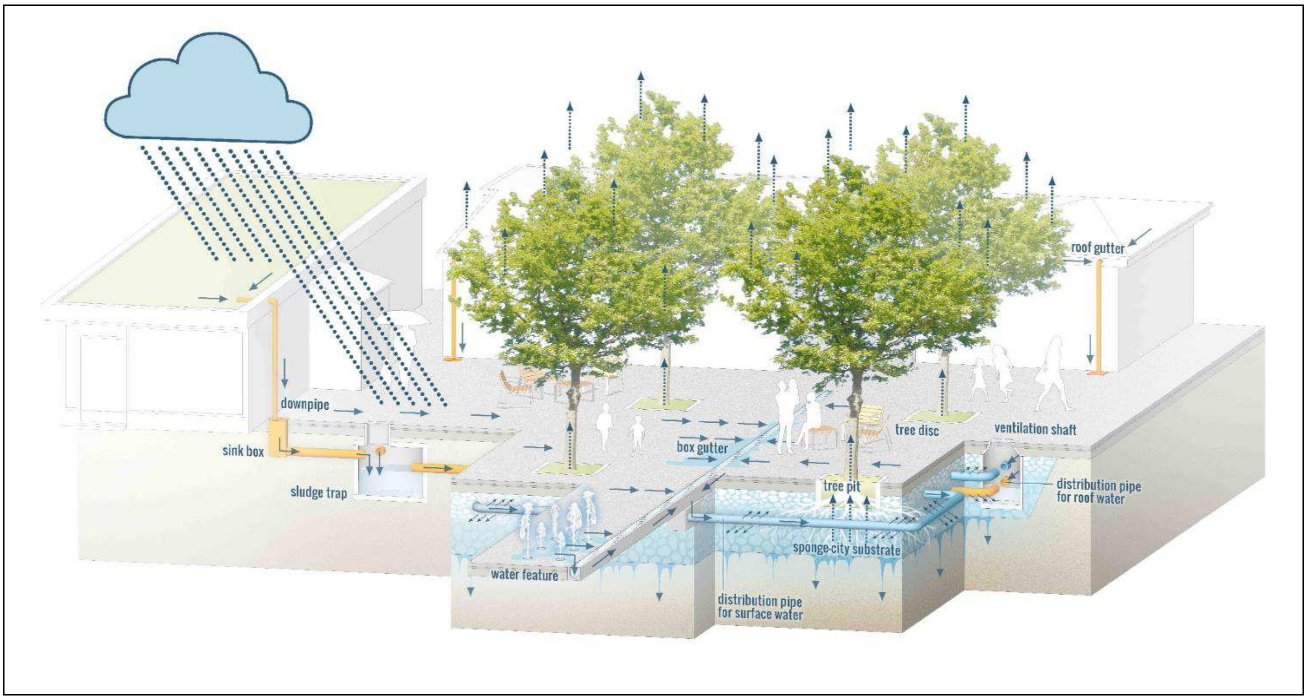

Fig. 4: Using rainwater and a water feature to improve the site conditions for urban trees and create an open space for the neighbourhood. Example: Johann-Nepomuk-Vogl-Platz, Vienna. Design: Karl Grimm Landscape Architects

The 13 projects in this group incorporate the findings of research on climate-fit trees. In some cases, use is made of traditional tree species (i.e. those already used in recent decades) whose suitability for urban climates has been confirmed. Alternatively, "new" tree species or varieties are planted that have been identified as climate-fit and have never or seldom been planted in the past. Classic street tree species that are not considered climate-fit were not used in these projects.

6 CONCLUSION

Until the mid-2010s, it was the aim of rainwater management to close the water cycle by infiltration and groundwater recharge. Subsequently transpiration through trees became important as part of urban heat island measures for improving the microclimate. Now the focus is moving to water retention in the soil for supplying water to vegetation in increasingly longer dry periods. Following the shift in targets the "sponge city principle for trees" emerged as a design solution. Its main characteristic is the use of structural soils to improve site conditions for urban trees, including water storage. It can reasonably be assumed that the sponge city principle for trees will play an important role in tapping and storing different on-site sources of water (stormwater, water features) for the irrigation of trees. This helps close the local water cycle with increased evapotranspiration and improve heat-affected microclimates through adiabatic cooling. Infiltration to the aquifer is also strengthened as a side effect, because surplus water from the supply of vegetation seeps into the groundwater.

The sponge city principle for trees has the potential to become an essential NBS in future urban green infrastructure systems and stormwater management cascades. The systems implemented so far have a certain experimental character and serve to gather experience. Two projects are being monitored.

Investigation shows that the sponge city principle for trees is a NBS with low design impact: "concealment" and "integration" strategies predominate. "Showcasing" has only occurred in conjunction with sunken planters for purification. This powerful NBS with development potential deserves to be made more visible in order to have a public presence. Although stormwater management is integrated in the design of several projects, incorporating NBS into the overall design of an open space has untapped potential, in particular for raising awareness of the connectedness of the urban water cycle and urban vegetation, especially trees.

Landscape architecture merges rainwater management, planting design, and irrigation planning. This means optimizing an NBS system for various functions, incorporating these in a design concept, and – usually – working within a tight cost frame. However, it is not a stand-alone challenge but rather a task for landscape architects, urban designers, architects and engineers, who can combine to mobilize the full potential of NBS.

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