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Project Report

Tree Infiltration Trenches in the City of Leipzig—Experiences from Four Years of Operation

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Abstract

Increasing climate change requires cities to adapt to changing weather conditions. New elements for decentralized stormwater management must be installed to protect the sewer system from overloading during heavy rainfall events and to keep water in the city for irrigation use. A pilot project was implemented in Leipzig in 2020, in which infiltration tree trench systems with three different designs were installed and equipped with measuring technology during a road renovation project. The catchment areas of these three tree trenches are between 215 and 300 m² each. In two of the systems, water retention was included to supply the tree with water during drought periods. The retention elements are sealed with clay in tree trench TT1 and bentonite in tree trench TT3. For tree trench TT2, no retention capacity was provided. This article presents the design, construction, and scientific monitoring of the three tree infiltration trenches. The conclusions after four years of operation from the perspective of two departments of the City of Leipzig are summarized. The tree trench TT1 with the clay pan for water storage shows the best performance in terms of water retention and tree fitness. For the next generation of such infiltration systems, improvements in the design of the street runoff inlets and the surface of the tree trench system's interior are discussed.

Keywords: tree trench; water-sensitive urban design; blue-green infrastructure; urban climate adaptation; stormwater management

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1. Introduction

As climate change progresses, cities face the challenge of protecting their citizens and infrastructure from evolving climatic conditions. This primarily involves rethinking how rainwater is handled. Up to now, rainwater has been rapidly drained from urban areas, typically via the municipal combined sewer system and routed to centralized wastewater treatment plants. However, due to the shift in precipitation patterns in the future, heavy rain events will occur statistically more frequently [1]. Existing sewer networks and treatment facilities are not designed to handle such volumes, resulting in the discharge of untreated wastewater into receiving water bodies during storm events due to overflow. This effect is further amplified by the increasing surface sealing of urban areas [2]. In future, rainwater

management in cities should therefore increasingly take place at the local level and on a small scale with elements of Water-Sensitive Urban Design (WSUD) [3].

So-called blue-green infrastructures are considered a suitable instrument for a water-sensitive city as stormwater control measures. These are characterized by their function as water management sites and habitats for plants. In the street space, for example, this means linking a water retention system to a tree site. In this way, the incoming rainwater is retained on site and cleaned by passing through the soil and is available to the tree in dry periods. Such a system is called a tree-integrated infiltration trench [4], or simply tree trench. Infiltration trenches consist of a water storage that may be located in small spaces, such as a grassed verge, receiving runoff from a nearby urban surface (e.g., a road or roof) [4]. Several publications show experiences acquired with such constructions. Burge et al. [3] described the installation and operation of bioretention tree pits in Melbourne docklands, Australia. The authors demonstrated diverse types of installed tree trenches with various inlet structures that are used for the treatment of street runoff before it is collected in the lower areas and lead into a river, specifically addressing the challenges that are connected with the construction and operation of the infiltration systems. Another study from Melbourne, Australia, described the functionality of infiltration trenches to provide irrigation water for street trees, although the tree location was not directly part of the infiltration system [5]. The authors showed that the inlet design has a significant effect on successful runoff retention. Caplan et al. [6] presented the monitoring of a tree trench in Philadelphia, USA, containing several trees in one trench. The street runoff inlet occurred at one end of the trench and the water was distributed through it via a perforated pipe. The goal was to provide the trees with consistent irrigation during dry periods. The tree trenches described by Caplan et al. [6] were also the subject of a study conducted by Tu et al. [7], who studied the hydrological dynamics of these systems. The authors pointed out the possible overdesigning of the tree trench systems, which may lead to physiological stress on the trees in the trenches.

The potential benefits of such infiltration systems connected with a tree location are better irrigation status of the trees during dry periods [6], connected with higher evapotranspiration during hot days compared to conventional tree installations, as well as stormwater retention during heavy rain [5]. However, some risks are feared, such as waterlogging, which harms the trees in the trenches [8] or, conversely, too low substrate moisture due to enhanced infiltration for young, still not established trees [6] or due to overdesign with respect to the capacity to store water [7]. In this case, the installation of a capillary column between the water retention and the tree could be a solution. Moreover, appropriate tree species should be selected that cope well with varying amounts of water [8], and especially with prolonged periods of increased substrate moisture.

In the city district Gohlis in Leipzig, the municipality installed three tree trench systems of varying designs as part of a road renovation in 2020. These three locations were equipped with sensors by the Helmholtz Centre for Environmental Research and monitored for a period of four years. This was the first location of such systems in a streetscape in Germany. The aim of this project report is to provide a description of the design of the tree trenches in Leipzig and to outline the comprehensive monitoring concept including the estimation of water-related parameters, tree vitality, and concentrations of pollutants. Finally, the experience gained from four years of operation is described to highlight the opportunities and the challenges involved in installing such innovative systems directly in street spaces.

2. Structure of Tree Trenches

The tree trenches are situated along Kasseler Straße (51°21′46.4″ N 12°21′33.2″ E) in Leipzig-Gohlis and were constructed in the course of a regular road renovation project

in 2020 with several new tree planting locations (Figure 1). They were planned by Ingenieurgesellschaft Prof. Dr. Sieker mbH and put into operation in 2020. The trees were planted in late November 2020.

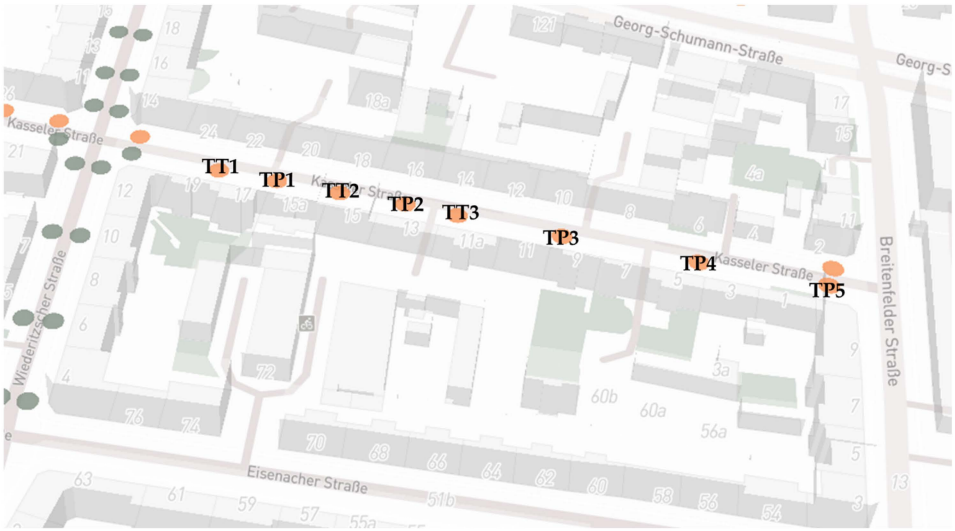


Figure 1. Location plan of tree trenches (TT1–TT3) and tree pits (TP1–TP5) in the street Kasseler Straße, Leipzig, Germany (based on [9]).

The tree trenches are constructions with a total surface area of 16.1 m^2 (7.00 m × 2.30 m) and an inner infiltration area of 12.9 m^2 (6.50 m × 1.99 m) that collect rainwater from the adjacent sidewalk through direct influence (the schemes of the tree trenches are displayed in Figure 2; site photographs are provided in Figure 3). On the road-facing side, there are seven perforated curbstones (each with a length of 0.99 m and a width of 0.25 m) on the long side, with a total of 28 holes (4 holes per curbstone) with a diameter of 50 mm each, enabling road runoff to enter the tree trench. The catchment area was 235 m^2 for TT1, 300 m^2 for tree trench TT2, and 215 m^2 for TT3, including the road surface, parking spaces, and adjacent sidewalks. There is no curb between the sidewalk and the tree trench, allowing unhindered lateral runoff from the pavement directly into the tree trenches. In the center of each tree trench, a ten-year-old small-leaved linden (*Tilia cordata* MILL.), cultivar 'Greenspire', was planted.

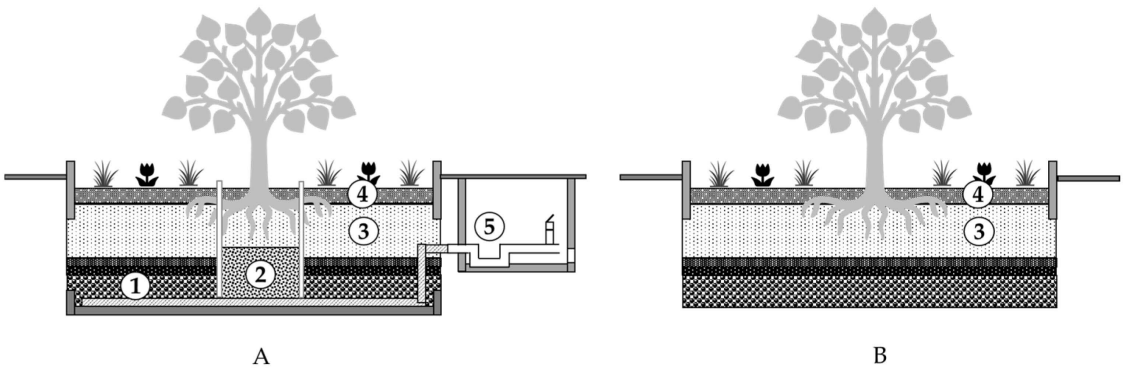


Figure 2. Schemes of the tree trenches TT1 and TT3 (**A**) and TT2 (**B**) with a water retention (1) (sealed with clay (TT1) and bentonite (TT3)), capillary column (2), tree substrate (3), topsoil (4), and overflow pipe (5).

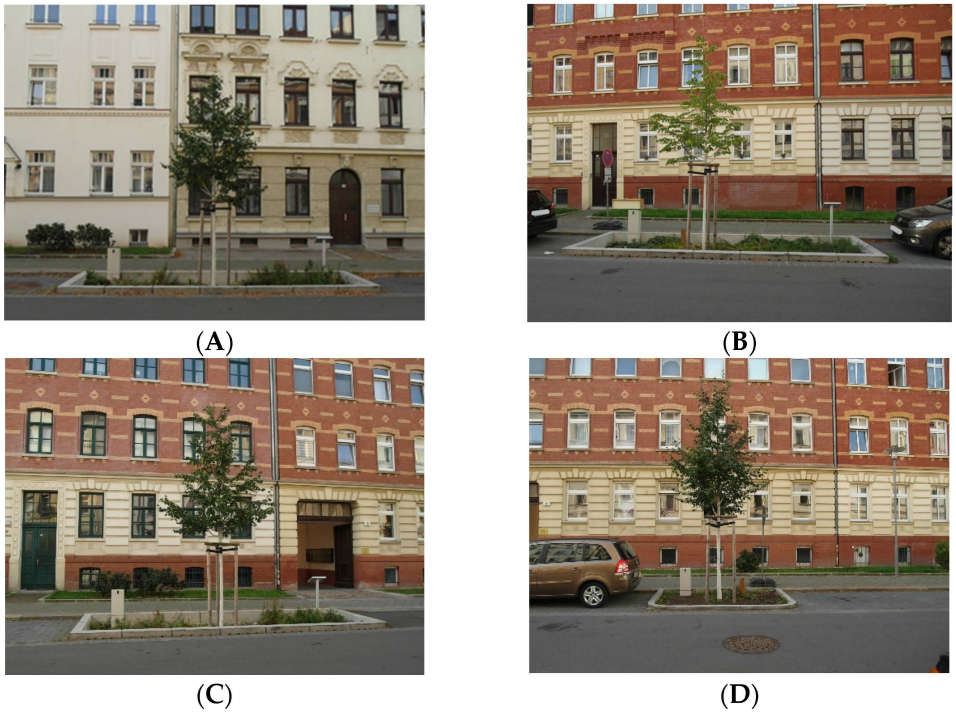


Figure 3. Site photographs of the tree infiltration trenches TT1 (**A**), TT2 (**B**), and TT3 (**C**), as well as the conventional tree pit TP2 (**D**) (taken on 18 October 2023 by author Katy Bernhard).

The substructure of the three tree trenches was designed differently. TT1 was optimized for water retention using a 0.3 m high clay pan with a wall thickness of 0.15 m at a depth of 2.4 m (measured from the top of the curb) that enables water accumulation (Figures 2A and 3A). Between the clay pan at the bottom and curb at the surface, a 0.98 m vertical space is available for infiltration within the trench. On the clay pan, a drainage pipe (DN200) was installed, allowing overflow to connect to the sewage system at a height of approximately 1.0 m above the trench bottom, thus preventing road flooding during heavy rainfall events. The overflow outlet is protected against sewer backflow by a non-return flap. Furthermore, a clayey (SI2) capillary column (1.5 m × 1.3 m × 0.9 m wdh) was placed on the clay pan directly under the future position of the tree to enable the tree to be supplied with water from the clay pan during dry periods. The area surrounding the capillary column was filled with a granite gravel (8/16 mm) layer with a thickness of 0.7 m, forming the primary water retention body. On top of this layer, a separating layer with granite gravel (3/8 mm) with a thickness of 0.2 m was placed. The subsequent layer comprised 0.68 m of tree substrate FLL Type 2 ("substrates of the planting pit construction method 2—covered planting pit", according to FLL [10]; selected specifications are summarized in Table 1), covered with 0.3 m of humus-rich topsoil. In the first year, lawn grass was seeded in the tree trenches around the linden tree; in the second year, it was replaced by a ground cover mat. The mats contained the following plants with 75% coverage by delivery: *Buglossoides purpurcaeruleum* (L.) HOLUB, *Convallaria majalis* L., *Lysimachia punctata* L., *Epimedium* × *versicolor* C. MORREN, *Hemerocallis* sp. L. (three varieties of early, mid-, and late flowering in different shades), *Euphorbia cyparissiens* L., *Gypsophila repens* L., *Bergenia cordifolia* (HAW.) STERNB., *Geranium renardii* TRAUTV., *Allium hollandicum* R.M.FRITSCH, and *Crocus flavus* WESTON.

TT2 was designed to optimize the infiltration of the road runoff (Figures 2B and 3B). The construction of this tree trench was simpler than TT1 and TT3: in a 1.7 m deep pit, 0.7 m granite gravel 8/16 mm, 0.2 m granite gravel 3/8 mm, 0.7 m tree substrate FLL Type 2 [10], and 0.3 m humus-rich topsoil were placed. Compared to TT1 and TT3, no water

retention layer, no capillary column, and no drainage pipe connected to the sewage system were installed in TT2.

Table 1. Selected specifications for the substrates of tree pits (Type 1) and tree infiltration trenches (Type 2).

Parameter	Type 1	Type 2
Grain size [mm]	0/16	0/32
pH value [-]	5.0–8.5	6.0—7.0
Organic matter [mass %]	2.1–4.2	1.5–2.0
Total pore volume [vol %]	n.s. [1]	45–50
Maximum water capacity [vol %]	Min. 25	Min. 25
Salt content [mg/100 g DM [2]]	n.s. [1]	10–50

[1] n.s.: not specified; [2] DM: dry matter.

TT3 was constructed according to TT1 with a single difference: the bottom of the water retention pan was made from bentonite layer with a wall thickness of less than 0.01 m (Figures 2A and 3C). All tree trenches were designed to perform on a five-year rain event without overflow into the tree substrate. Assuming that the porosity of 8/16 mm gravel is 35% (equivalent to 350 L of water per cubic meter of gravel), each of TT1 and TT3 can be expected to have a storage capacity of 1.16 m^3 of water in their retention pans. On top of that, due to the deepness of the tree trenches (approximately 190 mm vertical distance between the inlet hole and the substrate layer), extended detention on the soil surface is possible to maximize the volume of stormwater that passes through the soil substrate.

All newly planted trees in the location were maintained by a contracted service provider until autumn 2023. Maintenance included irrigation with approximately 100 L per tree, applied in two intervals (2 × 50 L), performed seven times in 2021, four times in 2022, and eleven times in 2023. Moreover, in June 2022 the trees were fertilized. After three years, maintenance was transferred to the City of Leipzig. Watering was carried out four times in 2024. This watering regime is planned to be continued until 2030.

3. Monitoring of Diverse Functions of the Tree Trenches

The installation and operation of the tree trenches was organized by the City of Leipzig, Mobility and Civil Engineering Office. The Helmholtz Centre for Environmental Research used this opportunity to monitor the functions of the TTs. A common tree pit (3.3 m × 2 m × 1.20 m wdh) with the same tree species and tree substrate layer FLL Type 1 ("Substrate of the planting pit construction method 1—open, non-built-over planting pit", according to FLL [10]; selected specifications are summarized in Table 1) was used as a reference (Figure 3D).

3.1. Installed Sensors

Two vertical pipes (0.05 m in diameter) were installed in each tree trench at a distance of approximately 0.85 m to the left and right sides of the tree as seen from the street. The pipes serve to ventilate the lower layers of the trenches. A level sensor was placed in each right pipe to estimate the water level in the retention space (for TT1 and TT3) or in the lower space (in the case of TT2) of the trenches (Figure 4). Each tree trench and the reference were equipped with five soil moisture (SM) measuring sensors (SMT 100, Truebner GmbH, Neustadt, Germany). Three sensors were placed directly under the tree at depths of −1.4 m (SM1), −1.1 m (SM2), and −0.8 m (SM3) (if the surface of the topsoil is taken as the zero point), and two more sensors were placed at the same depth as SM3 at distances of 0.8 m (SM4), and 1.4 m (SM5) from the tree (Figure 4). In the cases of TT1 and TT3, therefore,

SM1 and SM2 were positioned directly in the capillary column. A rain sensor was installed in a private garden on Kasseler Straße to estimate the amount and intensity of rainfall.

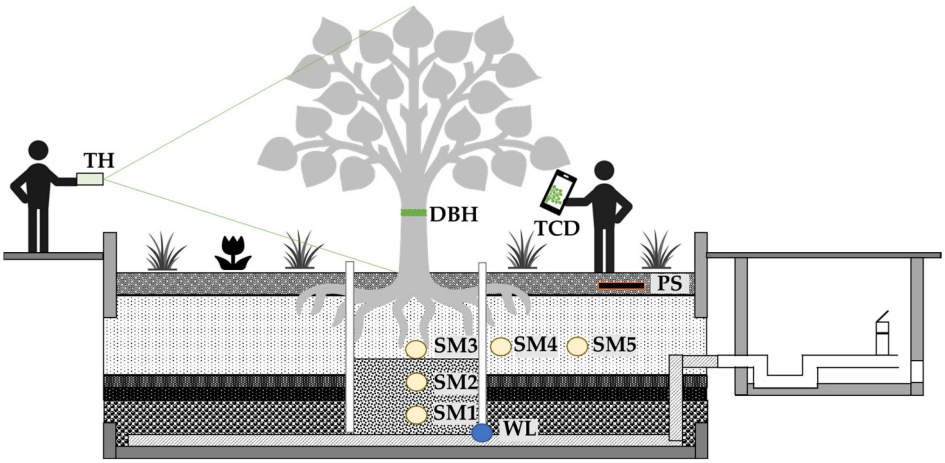


Figure 4. Locations of the passive sampler (PS) and the installed sensors for estimating soil moisture (SM, yellow circles) and water level (WL, blue circle) in the water retention pan. Positions of estimations of stem diameter at breast height (DBH), tree height (TH), and tree crown density (TCD).

3.2. Tree Vitality

All small-leaved linden trees planted as part of the road renovation in 2020—eight in total—were assessed for their vitality. Stem diameter at breast height, mean crown radius, and tree height were measured twice a year (except for 2023) (Figure 4). In addition, during the vegetation periods since their planting, the tree crowns were regularly photographed with a smartphone using a method developed by Sippel et al. [11] for this purpose.

As an example, we show the stem diameter (diameter at breast height, DBH) in this study (Figure 5). The stem diameter of trees in tree trenches that contain water retention is the same or slightly smaller than that of most linden trees in tree pits. However, the stem diameter of the tree in TT2 shows only a small increase throughout the estimated period. The reason for this bad growth is discussed in Section 4. It should be mentioned that tree pit TP4, which had the second-best increase in stem diameter, died in 2024 and had to be replaced.

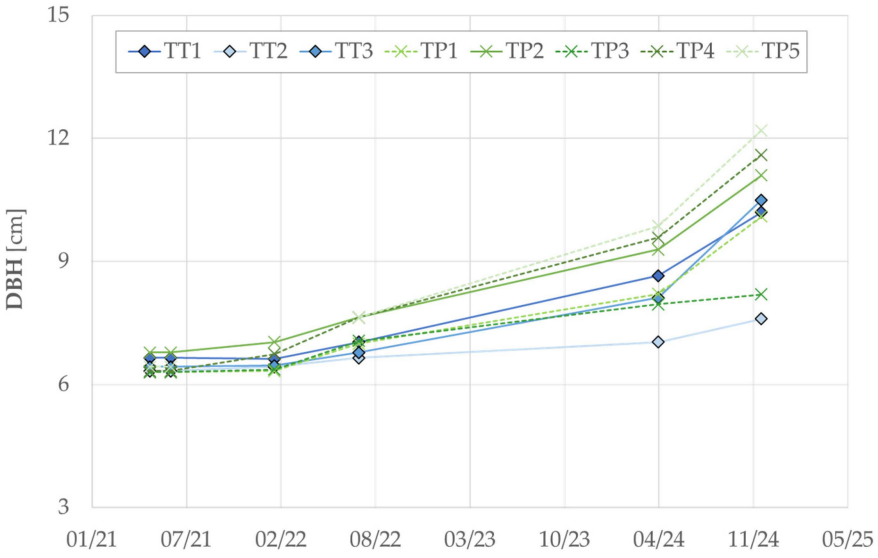


Figure 5. Stem diameter at breast height (DBH) for small-leaved linden trees in tree trenches (TT; curves with diamond symbols) and regular tree pits (TP; curves with cross symbols); TP2 is the reference tree equipped with soil moisture sensors.

3.3. Soil Pollution

The infiltration of surface runoff from an extended catchment area into tree trenches is also associated with an increased input of urban pollutants. As the tree trenches receive runoff from both roadways and pavements, including runoff from building surfaces, a variety of typical urban pollutants can be expected, such as traffic-related chemicals from car bodies, exhaust of combustion engines, tire wear particles, and leachate chemicals, as well as biocides from the paint and plaster of building surfaces [12]. Similarly to natural soils, the plant–soil system in the tree trenches acts as a natural barrier against the infiltration of pollutants into urban groundwater (TT2 type) or their release into the sewer system (TT1 and TT3 types). This barrier function is related to the filtration and sorption functions of the soil, as well as microbial transformation and degradation processes, depending on the biodegradability of the chemical and the actual microbial ecology and habitat function of the system [13]. Long-term experience regarding the transport and fate of urban runoff pollutants in tree trench systems and other blue-green infrastructures is still scarce [12]. The tree trenches in Kasseler Straße offer a valuable opportunity to investigate the retention and potential accumulation of contaminants, such as heavy metals or persistent organic pollutants, in the soils of tree trench systems over extended periods of time and in comparison to conventional street tree pits.

So far, two soil sampling events (12 August 2022 and 26 June 2023) have been carried out in the three tree trenches and one tree pit in the road, in which soil samples were taken from different horizontal (pavement and roadside at a distance of approximately 30 cm from the inflow side for upper-layer samples and 50 cm for lower-layer samples, respectively) and vertical positions (surface layer: soil directly under the plant mat for tree trenches or the gravel layer for tree pits; lower layer: 15 cm below the soil surface). These samples were analyzed for the presence of polycyclic aromatic hydrocarbons (PAHs), which are pollutants resulting from incomplete combustion processes, mainly from the exhaust gases of internal combustion engines and typical tire wear chemicals. Fiber mats, consisting of a commercially available activated carbon fiber felt (dimensions: 10 cm × 10 cm; felt thickness: 2 mm; fiber diameter: 10 µm) in a stainless-steel grid frame for stabilization, were placed at similar positions in the tree trenches (Figure 4) and the reference tree pit TP2. They serve as passive samplers to compare chemical concentrations in the different horizons of the tree trenches and tree pit, providing more integrated information than soil samples taken at different times.

Figure 6 presents selected results from the soil sampling events in the tree trenches and the tree pit in 2022 and 2023. A large number of pollutants typical of road runoff were included in the study. Here, only the detected concentrations of benzo[*a*]pyrene in the soil samples are presented as an indicator compound for PAH. At all sampling points, benzo[*a*]pyrene concentrations were found to be below the limit for residential areas (1 mg/kg) of the German Federal Soil Protection Ordinance [14], while the soil sampled from the surface layer of TT1 on the roadside is close to the limit for children's playgrounds (0.5 mg/L). The example of benzo[*a*]pyrene demonstrates that there can be enrichment effects in soil material over time that are especially relevant to infrastructural units collecting roadside runoff from a larger catchment area. This emphasizes the need to adjust the design of tree infiltration trenches and prevent the leaching of accumulated pollutants into receiving water bodies through structural adaptations. Investigations into this are underway, and the results will be presented in a separate paper.

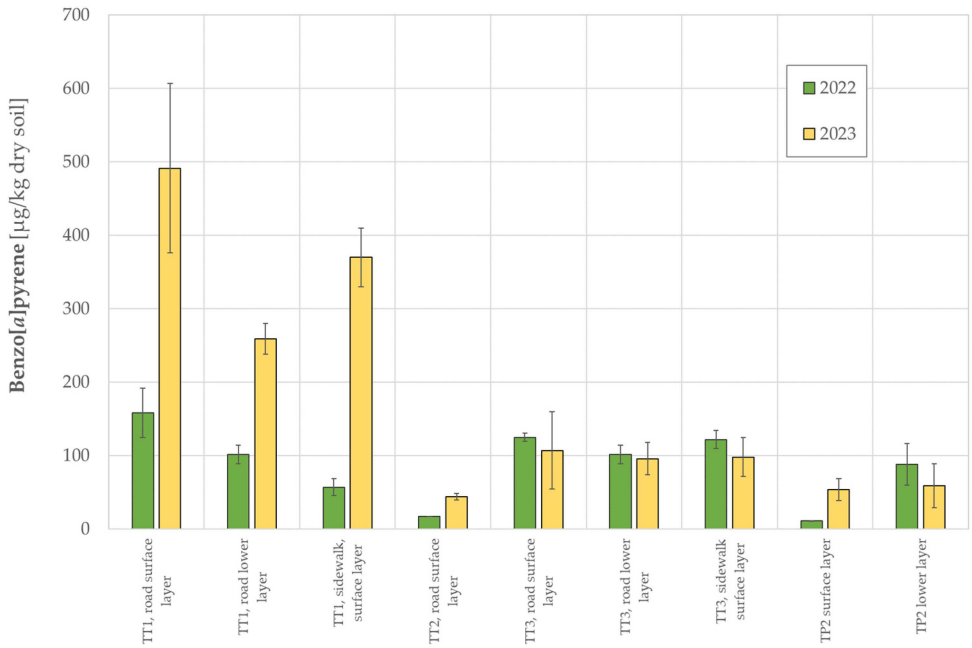


Figure 6. Concentrations of benzo[*a*]pyrene in soil determined at various sampling points of three tree trenches (TT1, TT2, and TT3) and a tree pit (TP2) in Kasseler Straße. The locations of sampling are explained in the text.

4. Lessons Learned

The tree trenches in Kasseler Straße were the first of their kind to be installed in a streetscape in Germany. For this reason, their construction and operational monitoring revealed a range of challenges that are important for the further spread of tree infiltration systems of this type and are summarized in this chapter.

1. Water inflow: The time series of the water levels in the bottom area of all three tree trenches during the entire operation time, from the beginning of the measurements until May 2025, are displayed in Figure 7. In TT1, the water level in the retention zone remained stable throughout the entire investigation period, showing peaks associated with the rainfall events. In contrast, the water level in TT3 over time indicates that the joints in the retention room were not properly sealed during construction, resulting in a reduced water-holding capacity. The water level in TT2 only shows small peaks during rainfall events, which disappear very quickly. In the case of both TT1 and TT3, water level reached heights of more than one meter during stormwater events, three times in the case of TT1 and twice for TT3 (Figure 7). This means that there was most likely overflow into the sewage system (no flow meter is installed in the overflow pipe). A rapid increase in water level was found in the period when the street side inlet holes were manually cleaned by UFZ staff using a bottle brush. The holes tend to become clogged by leaf litter and street debris so that no rainwater enters the tree trenches during smaller rainfall events. Therefore, in a future construction of such trench systems for road runoff, the problem of the water inflow into the tree trench needs to be addressed. For example, curb edges with wider interruptions (approx. 17 cm wide) are conceivable, which would allow for the free inflow of water into the infiltration trench. Problems with the inflow were also reported by Szota et al. [5]. The authors compared two types of inlet systems (lintel and pit) to divert stormwater from the curb and channel into the infiltration trenches. Initially, however, stormwater did not enter some of the trenches, particularly those with pit inlets, indicating that the inlets were restricted. To solve the problem, changes were made to the inlet design by replacing the permeable paver filters installed in the pit inlets with stainless steel

mesh, and to the regular maintenance by cleaning the inlets through emptying the basket filters in all inlets every six weeks.

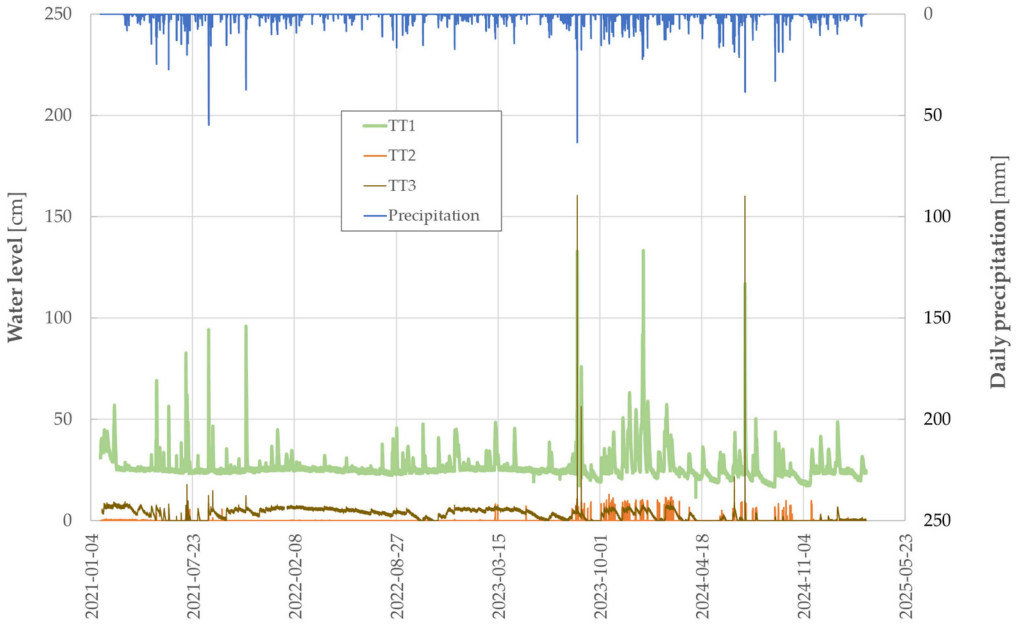


Figure 7. Water levels in the tree trenches and precipitation for the time period from 21 January 2021 to 7 March 2025. Target values of 30 cm (height of water storage layer) and levels of overflow of 100 cm (position of drainage pipe for the connection to the sewage system) are shown for TT1 and TT3 containing retention pans.

2. Construction defects: In addition to the suboptimal performance of the roadside inlets to the tree trenches, design flaws were also identified during operation. In the case of TT3, the bentonite layer was apparently not tested for impermeability, resulting in a significantly reduced water retention capacity within the storage space of the tree trench. For TT2, a very slow water infiltration was observed in infiltration tests carried out in 2021, during which the tree trenches were artificially filled to the top with water and the infiltration capacity was assessed (0.58 cm/h in comparison to 9.41 cm/h in the case of TT1 and 6.14 cm/h for TT3). This situation is caused by excessive compaction during the construction of TT2. A commissioned expert opinion determined very low water permeability coefficients of 8.2×10^{-8} and 9.1×10^{-8} m/s in the lower layers of -95 cm and -110 cm, respectively. In contrast, at the position of -70 cm, a water permeability coefficient of 3.7×10^{-6} was measured, indicating easier infiltration conditions in this layer. As a result of the poor infiltration in the lower part of TT2, the water was retained in the upper layer. This is also reflected in the average values measured by the soil water content sensors: $12.8 \pm 0.5\%$ in the case of SM1 vs. $25.9 \pm 0.5\%$ for SM3 (average values were calculated for the entire estimated period). Accordingly, the tree in TT2 visibly suffered from waterlogging, as already described by Sippel et al. [11]. The stem diameter of this tree is the smallest of all the trees assessed in Kasseler Straße (Figure 5). However, this tree was not the only one with vitality problems. A tree in a common tree pit in the same street (TD4 in Figure 5), which was planted at the same time as the trees in the infiltration trenches, dried out in its fourth year and had to be replaced. Tu and al. [7] reported that the implications of limited water availability in soil pits to the trees are strongly species-dependent; in their study, *Acer x freemanii* was more sensitive against water stress than *Plantanus x acerifolia*. Vitality problems in trees are also frequently reported as a consequence of road treatment in winter (e.g., in Ordóñez-Barona et al. [15]). Kasseler Straße is a

relatively quiet side street with low traffic volumes and parking spaces for cars on both sides of the road. As a result, there is no winter maintenance and therefore no use of de-icing salt, which could be detrimental to the vitality of the trees. Problems with design errors were also reported by Hanley et al. [4]: only one of three infiltration trenches receiving stormwater from a car park was functioning as designed. The authors showed that trees planted adjacent to the infiltration trenches grew larger than trees planted close to trenches without infiltration. Several issues could probably be solved through more targeted construction supervision, as classic road works (i.e., high soil compaction) are often not compatible with blue-green infrastructures.

3. Character of the pit: The lack of curbstones between the sidewalk and the tree trenches is criticized by residents who see the tree trenches as a potential accident site. To counter this, it would be important to adapt the groundcover vegetation planting accordingly, e.g., by using shrubs. This would also prevent the trees from being misused as bicycle racks and the trenches as rubbish dumps. The current planting using vegetation mats turned out to be suboptimal because the plants on the mats do not properly root into the depth. Another way to prevent accidents and the contamination of the infiltration trenches would be to cover them with a grate, panels, or lids, as described in Burge et al. [3].
4. Costs: As prototypes, the tree trenches in Kasseler Straße cost about 40k Euros each (without monitoring), much more than their successor models would be.
5. Communication: The first communication problems apparently occurred already during the construction. It is common practice to strongly compact all layers in the street space. In the case of TT2, however, this had detrimental consequences. Burge et al. [3] also emphasized: "Clear communication with construction contractors is important to ensure that the design intent of WSUD systems is captured in the built form." The second challenge was to clarify the responsibility for the maintenance of the tree trenches, which are in fact a combination of a tree site and an urban water management facility. A compromise had to be found that will also be a base for future WSUD constructions. Similar experiences have been reported by others. Burge et al. [3] described bioretention tree pits, similar to TT2, where the tree is planted into bioretention filter media and the treated stormwater is then collected via perforated pipes at the base of the cell, before being discharged into stormwater pipes that also act as an overflow. The authors concluded that strong communication between constructors and designers is important to ensure that the functional intent of the WSUD system is transferred from the design to the built form. They also found that in Melbourne, the maintenance responsibilities for the tree pits lie with a number of different departments, and thus the exact responsibility for a particular maintenance task is not always clear.

5. Conclusions

On the way to water-sensitive urban development, local pilot projects are very important for learning how to deal with stormwater through blue-green infrastructure. There are many aspects that can only be assessed using real objects and therefore such projects are of enormous importance. The present article shows the opportunities and challenges involved in implementing new structures in existing road areas. The inlet systems have to be designed in such a way that the runoff can fully enter the infiltration areas. During the construction process, the impermeability of the retention pans should be checked before filling, and the tree substrate should not be excessively compacted. Particular attention should be paid to the underground vegetation, which should cover the entire infiltration area and fill the pit optically. This would support the residents' acceptance of such new

features in their street. New pilot systems are planned for the near future, which will be used to retain road runoff in combination with urban tree irrigation in Leipzig. The results of the monitoring outlined here will be used for the improvement of the design of future installations.

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Abbreviations

The following abbreviations are used in this manuscript:

DBH	Diameter at breast height
DM	Dry matter
n.s.	Not specified
PAHs	Polycyclic aromatic hydrocarbons
PS	Passive sampler
SM	Soil moisture
TCD	Tree crown density
TH	Tree height
TP	Tree pit
TT	Tree trench
UFZ	Helmholtz Center for Environmental Research
WL	Water level
WSUD	Water-Sensitive Urban Design

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