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# Optimization of a Tree Pit as a Blue–Green Infrastructure Object

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**Abstract:** Trees in dense urban environments are often planted in bioretention cells with an underlying trench (BC-T) providing both stormwater pretreatment and storage. The BC-T design is based on a water balance; however, some input data (tree water uptake and water-holding capacities of soil filter and trench substrate) are difficult to obtain. The goals of this paper were (i) to study the sensitivity of such data in the BC-T design (i.e., their effect on the size of the drained area which may be connected to the tree pit), and (ii) to recommend a possible simplification of the water balance for engineering practice. Global sensitivity analysis was performed for the setup of a BC-T used in Prague, Czech Republic, assuming three different trench exfiltration rates. The most sensitive variable affecting the size of the drained area is the available water-holding capacity in the trench. The simplification of the water balance is highly dependent on exfiltration conditions. At high exfiltration rates (18 mm·h$^{-1}$ and more) or for a trench with an underdrain, the water-holding capacity in the soil filter and the tree water uptake can be omitted; whereas, at low trench exfiltration rates (1.8 mm·h$^{-1}$, without an underdrain), both the water-holding capacity of the trench substrate and the potential tree water uptake have a significant influence and cannot be omitted.

**Keywords:** blue–green infrastructure; water balance; sustainable stormwater management; tree pit; bioretention cell; global sensitivity analysis; Morris method

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## 1. Introduction

A paradigm shift in urban stormwater management started in the 1960s to mitigate the impacts of draining stormwater out of cities as fast as possible [1]. The Sustainable Drainage Systems (SuDS) concept evolved over decades; however, it was connected mainly with water-related problems in cities such as flood protection, surface water quality and ecology protection, restoration of natural local water balance, and stormwater harvesting [2]. Microclimate improvement as a reaction to climate change impacts was later incorporated as an additional goal of SuDS. The concept of blue–green infrastructure emerged [3].

Blue-Green Infrastructure (BGI) can be defined as a package of measures supporting ecosystem functions to deliver multiple benefits connected not only with water but also with urban microclimate, biodiversity, urban aesthetics, and social wellbeing. One of its major goals is to adapt urban areas to climate change [4]. Key elements of BGI are trees and other vegetation (providing the climate function [5]) as well as water retention spaces (providing water flow control). To provide the above-mentioned ecosystem functions, the elements are often combined in one BGI structure: an open terrain vegetated depression (bioretention cell) with an underlying trench (referred to as BC-T). Stormwater runoff from the surrounding paved area is conveyed to the terrain depression and infiltrates through a soil filter to the underground trench which also serves as a tree pit. The soil filter serves as the stormwater treatment [6] to prevent clogging of the underground trench [7] and protect the quality of underground and/or surface waters [8].

BC-T has to be optimized for both tree habitat criteria and water management criteria. The tree habitat criteria consist mainly of the sufficient volume of root space provided by the tree pit [9], type of substrate [10], and prevention of root system waterlogging [11]. The stormwater management criteria aim mainly at discharge regulation, stormwater pretreatment [12], and the duration of the retention space emptying [13].

To reach an optimal BC-T setup, the above-mentioned criteria must be related to performance criteria and site-specific conditions. Performance criteria consist of:

- Contributing to the restoration of the natural water regime by reducing runoff frequency and total runoff volume [14]; reducing the frequency of runoff events to around 15 days per year has been proposed as a target in southeastern Australia [15]. In the same region, a target of retaining 77–93% of the annual runoff volume has been proposed by [16];
- Providing enough water for trees; computing a tree water balance is a complicated task with many uncertainties and depends on many factors including tree species and its climatic region [17];
- Sufficient pretreatment of stormwater; at least 80% of stormwater runoff volume is recommended to be captured and pretreated through the soil filter in the bioretention cell [18–20];
- Prevention of waterlogging tree roots; various authors [18,21,22] recommended between 24 and 48 h as the trench emptying duration.

Site-specific conditions consist mainly of:

- Groundwater level;
- Exfiltration rate from the underground trench (i.e., permeability of the native soil);
- Space availability for BC-T.

The urban environment has limited space available space for BGI both on the surface and underground [23]. Conflicts of interest with transport, buried infrastructure, and historic preservation are common and lead to constrictions of the BGI design [24]. Thus, the use of the bioretention cell with the open retention space near the tree trunk is often the only possible solution in dense urban environments and/or historical parts of cities. The excess stormwater can be drained directly into the underground trench by a rainfall gully; however, this means that the stormwater is not pretreated by the soil filter in the bioretention cell. The lack of pretreatment increases the risk of groundwater pollution and underground trench clogging [25]. Therefore, an adequate ratio of the drained area (reduced by the runoff coefficient) $A_{red}$ to bioretention cell area $A_{BC}$ is a crucial parameter for BC-T performance [26].

Various authors studied a suitable $A_{red}/A_{BC}$ ratio, usually for specific conditions, in selected case studies. The bioretention cell area is considered 2.5% of the impervious drained area when the exfiltration rate from a trench is 34 mm per hour and 8.4% when the exfiltration is limited to 1 mm per hour [11]. A 100 mm ponding depth in the bioretention cell was considered. It equals an $A_{red}/A_{BC}$ ratio between 11 and 36, considering the runoff coefficient of paved surfaces at 0.90. Biofilter performance in Melbourne, Australia was studied in [27]. The authors considered a ponding depth in the bioretention cell of 200 mm and recommended its area to be at least 2% of the drained area ($A_{red}/A_{BC}$ ratio of 45 considering the value of the runoff coefficient of paved surfaces to be 0.90) to ensure treatment of 90% of the mean annual runoff. Christchurch City, New Zealand [18], analyzed several scenarios with a goal to capture 80% of stormwater runoff. They found that 350 $m^2$ of a drained area can be connected to a bioretention cell with a ponding area of 8.05 $m^2$ and a depth of 150 mm (i.e., an $A_{red}/A_{BC}$ ratio of 39 considering the runoff coefficient of paved surfaces to be 0.90). Simulations of bioretention cell performance with 10-year rainfall data in Kansas City, Missouri, USA, proved that if bioretention cell surface area is only 5% of $A_{red}$ (i.e., an $A_{red}/A_{BC}$ ratio of 18 considering the runoff coefficient of paved surfaces to be 0.90), the cumulative runoff volume is reduced by 53% [22]. Hamburg City, Germany, recommends connecting 15–21 $m^2$ of the drained area to 1 $m^2$ of bioretention cell area [28] (i.e., $A_{red}/A_{BC}$ ratio 13.5–19 considering the runoff coefficient of paved surfaces to be 0.90). Having a bioretention cell area equaling 2–10% of the drainage area is sufficient for stormwater purification. In cases where it is supplemented by an underlying trench (as in the case of BC–T), a sufficient area is 2–5% according to [29], resulting in an $A_{red}/A_{BC}$ ratio of 18–45 (considering a 0.90 runoff coefficient for paved surfaces). The authors of [26] declared that the $A_{red}/A_{BC}$ ratio for bioretention cells should be between 5 and 15, because a higher value may lead to faster clogging of the soil filter.

Based on the cited studies, it can be concluded that the recommended $A_{red}/A_{BC}$ ratio varies substantially from 5 to 45. The reasons for this may be the different study locations, climatic data, different setups of bioretention cells, ambient soil characteristics, and/or the performance criteria used for analysis. The methods used (where declared) are based on experimental studies and do not provide general methodical guidance that can be used in engineering and landscaping practice.

Generally, the quantification of an adequate $A_{red}/A_{BC}$ ratio is based on the calculation of the BC-T water balance. Data needed for the calculation consist of BC-T structural data (e.g., dimensions, used materials, and their characteristics), drainage area data (e.g., initial losses, runoff coefficient), geological data (e.g., exfiltration rate from underground trench), rainfall data (historical rainfall series), and tree water uptake data. Some of these data are easy to obtain (e.g., rainfall data are provided by national hydrometeorological institutes or the exfiltration rate can be measured on-site before the BC-T construction) or are subject to the design process (e.g., dimensions of the B-CT or the drainage area size). However, there are data that are not readily available for an arbitrary location and/or are the subject of scientific research. Examples of these data are the tree water uptake (consisting of transpiration and tree water storage [30]) and the available water-holding capacity of the soil filter and structural substrates (stone–soil media used for the growth of tree roots) used in the underground trench [31].

The uptake of water by a tree is a complex problem. At a single root scale, root hydraulic properties and planting media are of main concern; however, at the whole tree root system scale, single root processes affect each other and are integrated [32]. The primary source of water for a tree in BC-T is water held by the soil or substrate the tree is planted in [9]. The maximum amount of the held water available to the tree is limited by available water-holding capacity. It is defined as the amount of water held between the field capacity and the permanent wilting point of the soil [33].

The tree water uptake data are site-specific (e.g., climatic conditions, site conditions, degree of shading by adjacent buildings) and differ by tree species; the size of the tree must also be considered. The tree water uptake can be calculated theoretically, but the calculation is based on many data and parameters (such as radiation, air temperature, air humidity, wind, soil water content and the ability of the soil to conduct water to the roots, waterlogging, soil water salinity, water stress, growing season length, and tree characteristics—type of tree, size of tree, diameter of crown, canopy structure, internal water storage, etc. [34–36]) that are difficult to obtain and quantify. This leads to a high level of uncertainty in the quantification of tree water uptake.

Water-holding capacity in structural substrates was analyzed in several studies, both in the laboratory and in situ. The available water-holding capacity in compacted stone–soil media was estimated by [37] as 7–11% by volume, which is comparable to loamy sand.

Adding biochar to structural substrates can increase the available water-holding capacity by 25% in coarse-textured soils [38], by 50% (2–5% of biochar in the soil, [39]), or even by 100% (9% of biochar in the soil, [40]). However, the mentioned studies were not carried out with structural substrates, and therefore the increase in the available water-holding capacity by adding biochar under such conditions remains rather uncertain.

The effect of using or omitting tree water uptake and available water-holding capacity data in the calculation of the water balance is unknown.

The goals of this paper are (i) to study the sensitivity of the tree water uptake rate and water-holding capacity in the water balance calculation used for the BC-T design (permissible $A_{red}/A_{BC}$ ratio), and (ii) to recommend a possible simplification of the water balance used for the BC-T design in engineering and landscaping practice.

## 2. Methods

### *2.1. BC-T Experimental Design and Local Conditions*

The BC-T design used in the study is composed of four elements (Figure 1): (i) an open storage, (ii) a soil filter, (iii) an underground trench, and (iv) a tree. A surrounding area (e.g., street, sidewalk) is drained to the BC-T open storage.

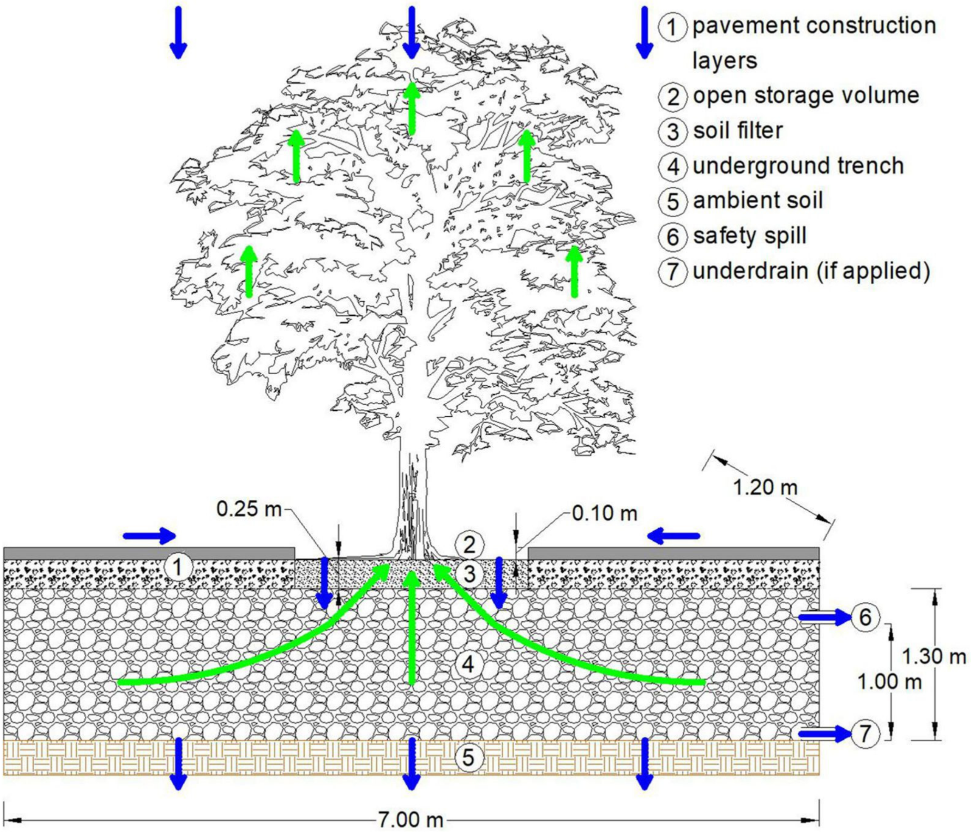


**Figure 1.** Scheme of a BC-T used for the water balance calculation; blue arrows depict rainfall input and stormwater pathways through the BC-T, green arrows highlight the tree water uptake and transpiration.

A surface setup of BC-T is prescribed in the historical part of the city because Prague is under UNESCO World Heritage protection. An unpaved area around a tree (bioretention cell) has an area of 3 $m^2$ and is either vegetated or covered by a grate with slits to allow water to flow to the tree; the tree span is usually 7 m. The underground trench is continuous (when permitted by buried infrastructure). Characteristics of the open storage, soil filter, underground trench, tree, and drained area of the BC-T used in the study are in Table 1.

**Table 1.** Characteristics of the BC-T used in the study.

| Characteristic | Value | Comment |
|---|---|---|
| Open storage | | |
| Area | 3.0 $m^2$ | |
| Ponding area | 2.8 $m^2$ | a tree with a 0.5 m trunk diameter is considered |
| Depth | 0.10 m | |
| Storage volume | 0.28 $m^3$ | |
| Overflow | included | in case open storage is surcharged the excess water is diverted directly to the underground trench |

**Table 1.** *Cont.*

| Characteristic | Value | Comment |
|---|---|---|
| Soil filter | | |
| Area | 2.8 $m^2$ | the same as ponding area of the open storage |
| Thickness | 0.25 m | |
| Material | manufactured soil | soil with ca. 10% of clay and 3% of moisture-containing matter (humus, biochar) |
| Infiltration rate | 180 $mm \cdot h^{-1}$ | recommended by [26] |
| Water-holding capacity | 5 to 20% | difficult to obtain, thus subject to the sensitivity analysis |
| Underground trench | | |
| Area | 8.4 $m^2$ | width 1.2 m × length 7 m |
| Depth | 1.3 m | effective storage depth from the trench bottom to the level of its safety spill is considered 1.0 m |
| Material | manufactured substrate | structural stone–soil substrate |
| Porosity | 30% | |
| Storage volume | 2.52 $m^3$ | |
| Exfiltration rate | four scenarios studied | 180 $mm \cdot h^{-1}$, 18 $mm \cdot h^{-1}$ and 1.8 $mm \cdot h^{-1}$ without underdrain and 1.8 $mm \cdot h^{-1}$ with underdrain (maximum capacity of 0.5 $l \cdot s^{-1}$) |
| Ground water level | 4.65 m below terrain | i.e., 3 m below trench bottom |
| Water-holding capacity | 5 to 20% | difficult to obtain, thus subject to the sensitivity analysis |
| Tree planted in BC-T | | |
| Trunk diameter | 0.5 m | at ground level |
| Crown diameter | 7 m | |
| Crown area | 38.48 $m^2$ | |
| Tree type | broad leaved, mature | Juglans and some other species used in the cities (e.g., Acer, Tilia, Platanus, and Quercus) [41] |
| Interception of rainfall | 1.1 mm | interception in tree crown area according to [42] |
| Crop coefficient | 0.15–1.10 | changing by the season (lowest from November to February, highest from June to August), according to [34] |
| Tree water uptake | 10.1 to 26.3 $m^3 \cdot y^{-1}$ | difficult to obtain, thus subject to the sensitivity analysis |
| Drained area | | |
| Area | unknown | target variable in water balance calculation |
| Initial losses | 0.5 mm | according to [43] |
| Runoff coefficient | 0.90 | typical for urban paved surfaces in city centers |

### *2.2. Performance Criteria*

The BC-T shall be designed to provide the required stormwater management functions. The performance criteria used and their values are listed in Table 2.

### *2.3. Water Balance*

The overall water balance of BC-T is budgeting the following items:

- Input: stormwater inflow to BC-T from the drained area;
- Outputs: (i) evapotranspiration, (ii) exfiltration to ambient soil, (iii) discharge via underdrain, (iv) tree water uptake, and (v) overflow of safety spill;

- Volume of water retained in (i) open space, (ii) soil filter, and (iii) underground trench.

**Table 2.** Performance criteria and their requested values.

| Criterion | Value | Comment |
|---|---|---|
| Maximum permissible frequency of underground trench surcharge | 1 per 5 years | according to Czech standard [26] |
| Minimum ratio of stormwater runoff volume treated by soil filter | 85% | according to [18–20] |
| Maximum duration of the full underground trench emptying | 48 h | according to [18,21,22] |

The overall water balance of the BC-T consists of sub-balances of its individual components, i.e., open storage, soil filter, underground trench, and tree. Individual terms of the water balance are described below.

2.3.1. Stormwater Inflow

Stormwater is collected from the impervious area in the vicinity of BC-T. Stormwater runoff is affected by initial and continuous losses [44]. Initial losses consist of interception of rainfall by vegetation cover, wetting loss on paved surfaces, and depression storage. Continuous losses are infiltration (e.g., by joints or cracks in drained surface), evapotranspiration, and unspecific losses (e.g., traffic or wind effects). Inflow volume can be written as:

$$V_{runoff} = (h_{rainfall} - IL - IC) \times RF \times A_{dr}, \tag{1}$$

where

$V_{runoff}$—is the volume of stormwater inflow to open storage from the drained area in $m^3$;
$h_{rainfall}$—is rainfall depth in m;
IL—is the initial loss depth on drained surfaces in m (i.e., it represents wetting and depression storage);
IC—is initial loss depth by an interception in tree canopy in m;
RF—is the dimensionless runoff coefficient of the drained area (i.e., it represents continuous loss);
$A_{dr}$—is the area of drained catchment in $m^2$.

2.3.2. Open Storage

The open storage collects water from the drained area and infiltrates it into the soil filter. A small amount of water is evaporated from the ponded water in the open storage. In case of excess inflow, the stormwater overflows directly to the underground trench via a street gully. The open storage sub-balance can be written as:

$$V_{runoff} = V_{OS} + E_{OS} + INF_{SF} + V_{OS\_OF}, \tag{2}$$

$$INF_{SF} = A_{SF} \times IR_{SF}, \tag{3}$$

where

$V_{OS}$—is the volume of water stored in open storage in $m^3$;
$E_{OS}$—is the volume of water evaporated from ponded water in soil filter area in $m^3$;
$INF_{SF}$—is the volume of water that infiltrates to soil filter in $m^3$;
$V_{OS\_OF}$—is the volume of water that overflows the open storage when it is full in $m^3$;
$A_{SF}$—is the area of soil filter in $m^2$;
$IR_{SF}$—is the soil filter median infiltration rate in $m \cdot s^{-1}$.

### 2.3.3. Soil Filter

Stormwater infiltrated to the soil filter partially percolates to the underground trench and partially is held by the soil itself. The held portion of water evapotranspires from the soil filter and vegetation. The soil filter sub-balance can be written as:

$$INF_{SF} = V_{SF} + PER_{TR} + ET_{SF}, \tag{4}$$

where

$V_{SF}$—is the volume of water stored in the soil filter in $m^3$;
$PER_{TR}$—is the volume of water that percolates to an underground trench in $m^3$;
$ET_{SF}$—is the volume of evapotranspiration from the soil filter and vegetation planted in soil filter in $m^3$.

The volume of water stored in the soil filter is limited by the water-holding capacity ($WHC_{SF}$) that corresponds to the soil field capacity, i.e., it is the maximum amount of water held by soil after drainage (water contained in the macropores by gravity action) [45].

### 2.3.4. Underground Trench

Inflow to the underground trench consists of the water percolating from the soil filter and the overflow of the open storage that is connected to the trench via a street gully. Part of the water is held by the trench structural substrate and used by the tree, part exfiltrates to the ambient soil. In some cases, the underground trench is equipped with an underdrain that helps to empty it. In case of excess inflow of stormwater, it overflows the trench and is connected directly to the sewer system or receiving waters. The underground trench sub-balance can be written as:

$$PER_{TR} + V_{OS\_OF} = V_{TR} + EXF_{TR} + V_{UD} + TWU + V_{TR\_OF}, \tag{5}$$

$$EXF_{TR} = A_{TR} \times ER_{TR}, \tag{6}$$

$$A_{TR} = (b + 0.5 \times h_{TR}) \times (l + 0.5 \times h_{TR}), \tag{7}$$

where

$V_{TR}$—is the volume of water stored in the underground trench in $m^3$;
$EXF_{TR}$—is the volume of water that exfiltrates from the underground trench to ambient soil in $m^3$;
$V_{UD}$—is the volume of water drained by the underdrain in $m^3$ (if applied);
TWU—is the tree water uptake volume in $m^3$;
$V_{TR\_OF}$—is the volume of water overflowing the trench when it is full in $m^3$;
$A_{TR}$—is the effective area of exfiltration in $m^2$;
$ER_{TR}$—is the median exfiltration rate from the trench to ambient soil in $m \cdot s^{-1}$;
b—is the width of the underground trench in m;
l—is the length of the underground trench in m;
$h_{TR}$—is the depth of water in the underground trench in m.

The volume of water stored in the underground trench is limited to its retention volume. Part of the retention volume is used for long-term storage of water limited by the substrate water-holding capacity ($WHC_{TR}$) in a similar way as in the case of the soil filter.

### 2.3.5. Tree

The tree is considered to take water for its needs from the underground trench exclusively. The maximum amount of water taken by the tree is defined by a theoretical value of water the tree claims for its wellbeing. A tree water deficit arises when there is not enough water stored in the underground trench. The deficit should be covered by additional watering; otherwise, the tree suffers. Tree water deficit can be calculated as:

$$WD_{tree} = TWU_{pot} - TWU, \quad (8)$$

where

$WD_{tree}$—is the volume of tree water need that is not provided in $m^3$ (i.e., water deficit);
$TWU_{pot}$—is the theoretical volume of water the tree claims for its wellbeing in $m^3$.

The extent to which the water claimed by the tree is covered by BC-T can be calculated as:

$$TWU_{cov} = TWU/TWU_{pot} \times 100, \quad (9)$$

where

$TWU_{cov}$—is the extent to which the water claimed by the tree is covered by rainfall runoff stored in BC-T in %.

Reference tree transpiration must be estimated prior to $TWU_{pot}$ calculation. The Hargreaves equation (1985 version) [46] was used:

$$ET_o = 0.0023 \times R_a \times (T_C + 17.8) \times T_R^{0.50}, \quad (10)$$

where

$ET_o$—is reference crop transpiration in $mm \cdot d^{-1}$;
$R_a$—is extraterrestrial radiation in $mm \cdot d^{-1}$ (converted from $MJ \cdot m^{-2} \cdot d^{-1}$, according to [34]);
$T_C$—is the daily average temperature in degrees Celsius;
$T_R$—is the daily temperature range in degrees Celsius.

$TWU_{pot}$ calculation based on $ET_o$ is described in [34,35] with the crop coefficient used to describe plant transpiration considering the needs of the tree during the year:

$$TWU_{pot} = ET_o \times K_c \times A_{tree} \times d/1000, \quad (11)$$

where

$K_c$—is a dimensionless crop coefficient;
$A_{tree}$—is a tree crown area in $m^2$;
d—is the number of days.

#### 2.3.6. Assumptions

Several assumptions were introduced when calculating the water balance:

- Interception in the tree canopy and initial loss are applied when rainfall starts after a 24 h dry period or longer;
- Evaporation from the open storage ponding area is neglected as evaporation during rainfall is negligible; the same applies for the emptying period of the open storage after the rainfall (ca. 0.5 h when full);
- The capillary rise in the soil filter is not considered as the underground trench percolation rate is much higher than the one in the soil filter;
- The permanent wilting point in the soil filter (expressed as a fraction) is 0.1 (according to [47]) and the soil filter is allowed to dry out completely;
- Water held in the soil filter is considered to dry out in 7 days [48], it is assumed to be the result of evaporation from the soil filter surface and transpiration by vegetation planted in the soil filter (if present); tree is not considered to take water up from the soil filter;
- The capillary rise in the underground trench is not considered because the groundwater level is 3 m below the trench bottom and is less than 0.5 $mm \cdot d^{-1}$ (according to [17]);

- The structural substrate cannot dry completely as it is placed under the soil filter with no capillary rise (i.e., the amount of water in the substrate cannot be lower than the permanent wilting point); therefore, the trench water-holding capacity $WHC_{TR}$ can be substituted by the available water-holding capacity $AWHC_{TR}$;
- The covering of the trench's available water-holding capacity is considered as shown in Figure 2; when water from the soil filter percolates downwards through the trench at a 45° angle, the available water-holding capacity is primarily covered in the corresponding volume of substrate only; when the water level in the trench rises, the capacity takes up the full area of the trench to the instant retention depth (up to the level of the safety spill);
- The uptake of water held in the structural substrate in the trench is attributed to the tree only;
- Controlled outflow from the underground trench (underdrain) is considered as 50% of its maximum value;
- A surcharge event of the underground trench is considered to be an event preceded by a minimum of 6 h without an overflow.

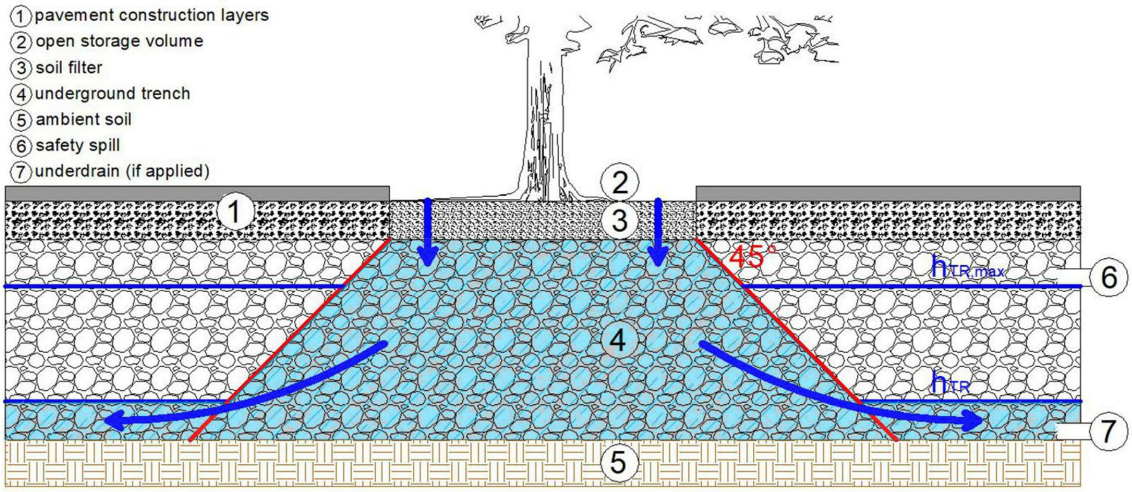


**Figure 2.** Schematization of $AWHC_{TR}$ calculation in water balance ($h_{TR}$ is the depth of stored water in time t, $h_{TR,max}$ is the maximum depth of retained water); arrows depict how the the trench's water-holding capacity is covered.

### 2.3.7. Rainfall and Temperature Data Used in Water Balance

A 10-year historical rainfall series (from 2006 to 2015) with a time resolution of 1 h was used as an input to the water balance calculation. The series was measured by a tipping bucket rain gauge Fiedler SR03 located in Prague, Czech Republic; the average annual rainfall depth is 532 mm.

A historical temperature series of the same period with a time resolution of 1 day (daily average, minimum, and maximum temperatures) was used as an input to the $TWU_{pot}$ calculation. The series was measured by Vaisala Radiosonde RS92-SGP located in Prague, Czech Republic; the average annual temperature is 10.9 degrees Celsius.

### 2.3.8. Water Balance Outcomes

The target value calculated by the water balance model is the maximum area $A_{dr}$ which can be drained to BC-T. The size of the drained area was iterated to meet the performance criteria given in Table 2. As additional information, the ratio of the amount of water taken up by the tree from the underground trench to its potential water need $TWU_{cov}$ was calculated. This value shows the extent to which the tree's water need is covered by rainfall runoff drained to the BC-T.

### *2.4. Sensitivity Analysis*

#### 2.4.1. Sensitivity Analysis Method

The Morris method was used to perform global sensitivity analysis [49]. It is based on the randomization of the one-at-a-time method [50]. Input design space is created where the number of its dimensions is defined by a number of studied variables, k. The space is limited to given ranges of variables and discretized into p intervals of step Δ. Within the input space R random trajectories are defined; each trajectory has k + 1 points, i.e., one starting point (random combination of variables values), the consecutive point is defined randomly changing variable i value by Δ, then the trajectory continues by changing remaining variables one by one by corresponding Δ. It means that R(k + 1) simulation runs are carried out. At each trajectory, an elementary effect EE on model outcome is calculated (each outcome is compared to the previous one, i.e., k elementary effects are calculated for one trajectory). From elementary effects belonging to each studied variable i, sensitivity measures are calculated as follows:

$$\mu_i = \frac{1}{R}\sum_{j=1}^{R} EE_i^j, \tag{12}$$

$$\mu_i^* = \frac{1}{R}\sum_{j=1}^{R} \left|EE_i^j\right|, \tag{13}$$

$$\sigma_i = \sqrt{\frac{1}{R}\left(\sum_{j=1}^{R} EE_i^j - \mu_i\right)} \tag{14}$$

While σ deals with μ, $\mu^*$ mitigates the problem arising from possible different signs (plus/minus) in elementary effects. Therefore, $\mu^*$ is used as a measure of total sensitivity in the study.

#### 2.4.2. Studied Variables

Three variables were subject to sensitivity analysis: (i) water-holding capacity of the soil filter ($WHC_{SF}$), (ii) water-holding capacity of the trench substrate ($AWHC_{TR}$), and (iii) potential tree water uptake ($TWU_{pot}$).

The ranges of studied variables are listed in Table 3.

**Table 3.** Variables that are subject to sensitivity analysis and their ranges.

| Statistics | Variables | | |
|---|---|---|---|
| | $WHC_{SF}$ (%) | $AWHC_{TR}$ (%) | $TWU_{pot}$ ($m^3 \cdot y^{-1}$) |
| Min | 5 | 5 | 10.1 |
| Max | 20 | 20 | 26.3 |

Ranges of water-holding capacities were set according to [47]. The range of the potential tree water uptake was calculated as monthly average values for a mature broadleaf tree (Table 4) according to [46]; monthly transpiration data were assumed to vary ±50% according to available data in central Europe [51–55].

**Table 4.** Potential tree water uptake $TWU_{pot}$ data used in the water balance.

| Statistics | Monthly Values of TWUpot ($l \cdot d^{-1}$) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Min | 0.7 | 1.3 | 9.8 | 25.3 | 49.3 | 69.1 | 73.5 | 59.3 | 28.8 | 10.6 | 1.1 | 0.6 |
| Max | 1.7 | 3.3 | 25.5 | 65.7 | 128.2 | 179.6 | 191.2 | 154.2 | 74.9 | 27.7 | 2.7 | 1.6 |

2.4.3. Application of Sensitivity Method

Within the presented work, studied variables are discretized into four intervals, creating the input space with $4^3$ = 64 possible combinations of variable values. Five trajectories are used, i.e., 15 elementary effects are calculated in total (five for each variable).

Sensitivity is studied for two model outcomes: (i) the maximum size of drained area $A_{dr}$ that can be connected to BC-T and (ii) the extent to which the water claimed by the tree is covered by BC-T ($TWU_{cov}$). Four scenarios of local conditions (in terms of exfiltration rate from the underground trench to ambient soil and presence of underdrain) are analyzed: (i) $ER_{TR}$ = 180 mm·h$^{-1}$ without underdrain, (ii) $ER_{TR}$ = 18 mm·h$^{-1}$ without underdrain, (iii) $ER_{TR}$ = 1.8 mm·h$^{-1}$ without underdrain, and (iv) $ER_{TR}$ = 1.8 mm·h$^{-1}$ with underdrain.

2.4.4. Supplementary Evaluation

Global sensitivity analysis provides information about the importance of the variables in question in the water balance model. For practical application, it is useful to supplement the sensitivity analysis results for the information on absolute changes in the model outputs for a specific range of studied variables. Therefore, a reference combination of the variables values was set as follows: $WHC_{SF}$ to 10%, $AWHC_{TR}$ to 10%, and $TWU_{pot}$ to 20.2 m$^3$·y$^{-1}$. The individual variables were changed within the range in Table 3 by $\pm\Delta$ increments ($\pm\Delta$ was set to 5% in the case of water-holding capacities and to 5.4 m$^3$·y$^{-1}$ in the case of potential tree water uptake). Then, $A_{dr}$ was calculated for different exfiltration scenarios and the results were compared.

In another situation, all three variables were omitted from the water balance to study the maximum possible simplification of the water balance model for practical design purposes. Combinations of studied variables resulting in the minimum and maximum size of the drained area, respectively, were identified at first (Table 5). Subsequently, $A_{dr}$ was calculated with all tree variables omitted and the results were compared. Omitting $AWHC_{TR}$ from the water balance means that the tree is assumed to take up water only during the rainfall runoff and shortly after it (until the trench is emptied, i.e., within 48 h). Therefore, $TWU_{cov}$ is not evaluated in this scenario.

**Table 5.** Combinations of variables resulting in the minimum and maximum drained area $A_{dr}$.

| Exfiltration Scenario | | Variables Values Resulting in the Minimum and Maximum $A_{dr}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Minimum | | | Maximum | | |
| $ER_{TR}$ (mm·h$^{-1}$) | Underdrain | $WHC_{SF}$ (%) | $AWHC_{TR}$ (%) | $TWU_{pot}$ m$^3$·y$^{-1}$ | $WHC_{SF}$ (%) | $AWHC_{TR}$ (%) | $TWU_{pot}$ m$^3$·y$^{-1}$ |
| 180 | no | 20 | 5 | 26.3 | 5 | 20 | 10.1 |
| 18 | no | 20 | 5 | 26.3 | 5 | 20 | 10.1 |
| 1.8 | no | 20 | 20 | 26.3 | 5 | 5 | 10.1 |
| 1.8 | yes | 20 | 5 | 26.3 | 5 | 20 | 10.1 |

*2.5. Calculation Tool*

The MS Excel environment was used to calculate the water balance model using VBA language. The Morris method calculations were carried out in the same environment.

**3. Results**

*3.1. Global Sensitivity Analysis*

The average value μ, standard deviation σ, and coefficient of variation (σ/μ) of model outcomes are provided in Table 6 for the studied exfiltration scenarios.

**Table 6.** Averages, standard deviations, and coefficients of variation of water balance outcomes.

| Exfiltration Scenario | | Model Outcomes | | | | | |
|---|---|---|---|---|---|---|---|
| $ER_{TR}$ ($mm \cdot h^{-1}$) | Underdrain | $A_{dr}$ in $m^2$ | | | $TWU_{cov}$ in % | | |
| | | μ | σ | σ/μ | μ | σ | σ/μ |
| 180 | no | 161 | 10.0 | 0.062 | 78.8 | 12.4 | 0.158 |
| 18 | no | 64 | 6.5 | 0.102 | 64.5 | 12.4 | 0.192 |
| 1.8 | no | 15 | 2.5 | 0.169 | 19.9 | 6.6 | 0.330 |
| 1.8 | yes | 105 | 8.4 | 0.079 | 73.6 | 12.7 | 0.172 |

It is obvious that with the decreasing exfiltration rate, the maximum size of the drained area, $A_{dr}$, is rapidly decreasing. Therefore, the tree water need, $TWU_{pot}$, is covered to a smaller extent as well. For exfiltration rates lower than 18 $mm \cdot h^{-1}$, it might be helpful to speed up the emptying of the underground trench by incorporating an underdrain with controlled outflow (e.g., by an orifice). In cases where the controlled outflow of 0.5 $l \cdot s^{-1}$ is applied for exfiltration rates of 1.8 $mm \cdot h^{-1}$, the drained area can be increased from 15 to 105 $m^2$, and as a result, $TWU_{cover}$ increases from 20 to 74%.

Values of the coefficient of variation show that the model outcomes vary substantially, and the variation increases with a decrease in the exfiltration rate. It confirms the need for sensitivity analysis of studied variables.

The results of the sensitivity analysis are presented in Tables 7 and 8.

**Table 7.** Sensitivity analysis results for $A_{dr}$.

| Exfiltration Scenario | | Variable | | | | | |
|---|---|---|---|---|---|---|---|
| $ER_{TR}$ ($mm \cdot h^{-1}$) | Underdrain | $WHC_{SF}$ RV = 10% | | $AWHC_{TR}$ RV = 10% | | $TWU_{pot}$ RV = 20.2 $m^3 \cdot y^{-1}$ | |
| | | μ* | Rank | μ* | Rank | μ* | Rank |
| 180 | no | 0.000 | 2–3 | 2.080 | 1 | 0.000 | 2–3 |
| 18 | no | 0.000 | 3 | 1.440 | 1 | 0.037 | 2 |
| 1.8 | no | 0.040 | 3 | 0.560 | 1 | 0.259 | 2 |
| 1.8 | yes | 0.040 | 2 | 1.680 | 1 | 0.037 | 3 |

**Table 8.** Sensitivity analysis results for $TWU_{cov}$.

| Exfiltration Scenario | | Variable | | | | | |
|---|---|---|---|---|---|---|---|
| $ER_{TR}$ ($mm \cdot h^{-1}$) | Underdrain | $WHC_{SF}$ RV = 10% | | $AWHC_{TR}$ RV = 10% | | $TWU_{pot}$ RV = 20.2 $m^3 \cdot y^{-1}$ | |
| | | μ* | Rank | μ* | Rank | μ* | Rank |
| 180 | no | 0.164 | 3 | 1.620 | 1 | 1.504 | 2 |
| 18 | no | 0.388 | 3 | 1.080 | 2 | 1.956 | 1 |
| 1.8 | no | 0.680 | 2 | 1.140 | 1 | 0.626 | 3 |
| 1.8 | yes | 0.256 | 3 | 1.500 | 2 | 1.685 | 1 |

The sensitivities of studied variables rank differently for different model outcomes. In the case of the drained area, the most sensitive parameter is the available water-holding capacity in the underground trench in all four studied scenarios. The sensitivity of the water-holding capacity of the soil filter is none to very low, which is also true for the potential tree water uptake, except for the lowest exfiltration scenario (without underdrain), where its sensitivity is more significant.

Results of the extent to which the water claimed by the tree is covered by BC-T are more diverse. For high exfiltration rates and underdrain scenarios, the available water-holding capacity of the trench and potential tree water uptake has the highest sensitivity, the remaining variable is much less sensitive. Both variables play an important role in medium and low exfiltration rate scenarios as well; however, the importance of the water-holding capacity of the soil filter increases and its sensitivity in the lowest exfiltration scenario is higher than the potential tree water uptake.

It is possible to deduce that if the drained area is the only model outcome sought, the available water-holding capacity in the trench is the most important variable to be quantified accurately. If coverage of tree water need is to be calculated, a quantification of the potential tree water uptake must be a subject of interest as well. The water-holding capacity of the soil filter plays an important role in very low exfiltration conditions only.

### *3.2. Supplementary Evaluation*

#### 3.2.1. Specific Cases

Results for specific cases are summarized in Table 9. Determining the performance criterion shows which of the three performance criteria used (Table 2) is critical for the optimization (i.e., two other criteria are fulfilled).

**Table 9.** Summary of results for different exfiltration rate scenarios with reference values of variables.

| **Exfiltration Scenario** | | **Determining Performance Criterion** | **$A_{dr}$ in $m^2$** | **$A_{red}/A_{BC}$ in $m^2 \cdot m^{-2}$** | **$TWU_{cov}$ in %** |
|---|---|---|---|---|---|
| **$ER_{TR}$ ($mm \cdot h^{-1}$)** | **Underdrain** | | | | |
| 180 | no | Frequency of surcharge | 167 | 54.6 | 73.1 |
| 18 | no | Frequency of surcharge | 69 | 23.1 | 59.9 |
| 1.8 | no | Emptying duration | 14 | 5.5 | 16.4 |
| 1.8 | yes | Frequency of surcharge | 112 | 37.0 | 68.1 |

Comparison of results calculated with variables reference values and those changed by ±Δ are presented in Tables 10 and 11.

**Table 10.** Effect of changing the values of the studied variables on $A_{dr}$. RV stands for reference value, Δ for change in reference value.

| **Exfiltration Scenario** | | **Change in $A_{dr}$ Compared to Reference Value (%)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **$WHC_{SF}$ RV = 10%** | | **$AWHC_{TR}$ RV = 10%** | | **$TWU_{pot}$ RV = 20.2 $m^3 \cdot y^{-1}$** | |
| **$ER_{TR}$ ($mm \cdot h^{-1}$)** | **Underdrain** | **−Δ** | **+Δ** | **−Δ** | **+Δ** | **−Δ** | **+Δ** |
| 180 | no | 0.0 | 0.0 | +7.2 | −7.2 | 0.0 | 0.0 |
| 18 | no | −1.4 | 0.0 | +7.2 | −13.0 | −1.4 | 0.0 |
| 1.8 | no | −7.1 | 0.0 | −21.4 | +14.3 | −21.4 | +7.1 |
| 1.8 | yes | 0.0 | 0.0 | +6.3 | −10.7 | 0.0 | 0.0 |

**Table 11.** Effect of changing the values of the studied variables on $TWU_{cov}$. RV stands for reference value, Δ for change in reference value.

| **Exfiltration Scenario** | | **Change in $TWU_{cov}$ Compared to Reference Value (%)** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **$WHC_{SF}$ RV = 10%** | | **$AWHC_{TR}$ RV = 10%** | | **$TWU_{pot}$ RV = 20.2 $m^3 \cdot y^{-1}$** | |
| **$ER_{TR}$ ($mm \cdot h^{-1}$)** | **Underdrain** | **−Δ** | **+Δ** | **−Δ** | **+Δ** | **−Δ** | **+Δ** |
| 180 | no | +1.4 | −1.2 | −23.4 | +11.5 | +25.2 | −11.5 |
| 18 | no | +2.8 | −3.3 | −22.5 | +7.3 | +37.7 | −15.2 |
| 1.8 | no | +11.0 | −17.7 | −36.0 | +25.0 | +38.4 | −14.6 |
| 1.8 | yes | +2.2 | −2.1 | −23.8 | +10.4 | +30.8 | −12.6 |

Changing the value of the $WHC_{SF}$ has a negligible effect on $A_{dr}$, which can be connected to the BC-T, as the soil filter deals only with a small amount of stormwater in comparison to the underground trench. A small effect can be seen in scenarios with lower exfiltration rates, in which even the small amount of water released from the soil filter into the underground trench can affect the duration of the trench emptying. However, the change is in the range of 1 $m^2$ of connectable drained area.

Changing the $AWHC_{TR}$ has a significant effect on $A_{dr}$, which can be connected to the BC-T. For higher exfiltration rates (and the trench with the underdrain), the amount of water held in the structural substrate of the trench decreases the available retention volume for stormwater inflow. It is especially important during heavy rainfall events that have the potential to surcharge the underground trench more often. Therefore, when $AWHC_{TR}$ is decreased, the connectable drained area $A_{dr}$ increases by 6–7% compared to the reference value of $AWHC_{TR}$. Accordingly, with the increasing $AWHC_{TR}$ value, the maximum drained area $A_{dr}$ decreases by 7–13%. The opposite situation occurs in the case of a very low exfiltration rate when the duration of the trench emptying plays a major role. A lower value of $AWHC_{TR}$ means that more water exfiltrates to ambient soil, and $A_{dr}$ must be significantly decreased (by 21% compared to the reference values). When $AWHC_{TR}$ is higher, a larger area may be connected (increase by up to 14%).

$A_{dr}$ is slightly increasing with an increase in $TWU_{pot}$ as the tree water uptake helps to empty the underground trench faster. It is not so important in cases of very good exfiltration rates (the volume of water taken up by the tree is of little significance in the overall water balance of BC-T). However, in cases of very low exfiltration conditions, $A_{dr}$ increased by 7%. A decrease in $A_{dr}$ of 21% is observed when $TWU_{pot}$ is changed to a lower value.

It is possible to state that the studied variables do not affect the results of the BC-T optimization in terms of $A_{dr}$ significantly when the exfiltration rates from the underground trench are moderate to high. On the contrary, in the case of the lowest exfiltration rate, values of $AWHC_{TR}$ and $TWU_{pot}$ can lead to a more substantial change in $A_{dr}$. However, at low exfiltration rates, it should be preferred to equip the underground trench with an underdrain to increase $TWU_{cov}$.

$TWU_{cov}$ is affected more significantly than $A_{dr}$. With the decreasing water-holding capacity of the soil filter, even small rainfall events have a chance to percolate to the trench and contribute to its available water-holding capacity and tree water uptake. The difference is more significant for very low exfiltration rates, as the amount of stormwater potentially held in the soil filter plays a more significant role in the overall water balance.

Coverage of potential tree water need is obviously increasing with the increase in the trench available water-holding capacity. Even a small change of $AWHC_{TR}$ affects the $TWU_{cov}$ by tens of percents (up to 36%).

The same applies to $TWU_{pot}$ (change up to 38%); however, the proportionality is inverse instead of direct. The reason for such a significant change is that $A_{dr}$ does not increase substantially with the $TWU_{pot}$ increase.

#### 3.2.2. Omitting the Variables

The results of omitting the studied variables from water balance are in Table 12; $A_{dr}$ is compared to combinations of variables that allow for connection of the smallest and the largest drained area.

**Table 12.** Effect of omitting variables from water balance.

| Exfiltration Scenario | | $A_{dr}$ ($m^2$) | | | Change in $A_{dr}$ (%) | |
|---|---|---|---|---|---|---|
| $ER_{TR}$ ($mm \cdot h^{-1}$) | Underdrain | Min | Max | Omitted | Min | Max |
| 180 | no | 143 | 179 | 179 | +25.2 | 0.0 |
| 18 | no | 51 | 75 | 78 | +52.9 | +4.0 |
| 1.8 | no | 9 | 21 | 7 | −22.2 | −66.7 |
| 1.8 | yes | 88 | 120 | 119 | +35.2 | −0.8 |

It is apparent that the simplified water balance (i.e., when variables in question are omitted) provides a close approximation to the results calculated with the combination of variables allowing the maximum drained area to be connected (with the exception of the lowest exfiltration rate). In case future research enables quantifying the studied variables accurately, this knowledge can be used in the design of BC-T for maximizing the drained area size and the simplified water balance can be used. Nevertheless, if the variable values remain as unsure as they are today, the water balance simplification must be limited to specific situations identified by the sensitivity analysis described above.

## 4. Discussion

Several counteracting factors affect the optimization of BC-T: (i) volume of water held by the soil filter, (ii) volume of water held by the trench substrate, (iii) water needed for the tree uptake $TWU_{pot}$, and (iv) exfiltration rate from the underground trench to the ambient soil.

The volume of water held by the soil filter $WHC_{SF}$ decreases as a higher amount of water percolates into the underground trench and is available to cover the $AWHC_{TR}$. On the other hand, more water in the trench must be exfiltrated. A higher volume of water held by the trench substrate $AWHC_{TR}$ means more water is available for tree uptake and less water is exfiltrated from the trench. However, less retention volume is available during heavy rainfall events. A higher value of the amount of water needed for the tree uptake $TWU_{pot}$ helps to restore the free retention volume in the underground trench. However, it is a slow process so it is significant only under very low exfiltration conditions. The exfiltration rate from the underground trench to the ambient soil determines which of the above-mentioned processes will be crucial during the optimization procedure.

The $A_{red}/A_{BC}$ ratio was found to be in the range of 4.5–58 which is consistent with the studies [11,18,26–29] (identified $A_{red}/A_{BC}$ in the range 5–45). However, it is highly dependent on exfiltration conditions (48–58 when the exfiltration rate is 180 $mm \cdot h^{-1}$, 18–23 when the exfiltration rate is 18 $mm \cdot h^{-1}$, 4.5–7 when the exfiltration rate is 1.8 $mm \cdot h^{-1}$, and 31–39 when an underdrain is applied). It corresponds with the findings of [11,56].

$A_{red}/A_{BC}$ should be 36 when the exfiltration rate is 34 $mm \cdot h^{-1}$ and only 11 when the exfiltration rate is 1 $mm \cdot h^{-1}$ [11]. However, the $A_{red}/A_{BC}$ value for 1 $mm \cdot h^{-1}$ stated by [11] is substantially higher than our finding for the exfiltration rate of 1.8 $mm \cdot h^{-1}$ (11 compared to 4.5–7). This difference can be explained by different climatic data used for the analysis. While the annual rainfall depths in Melbourne, Australia, and Prague, Czech Republic, are similar (515 vs. 532 $mm \cdot y^{-1}$), the rainfall distribution during the year is different (Melbourne: minimum 33, maximum 60 mm per month; Prague: minimum 23, maximum 77 mm per month); thus, the retention space of BC-T has to be accommodated accordingly.

Further, the risk of the soil filter clogging must be discussed [26]. A higher $A_{red}/A_{BC}$ leads to faster clogging and, therefore, higher costs associated with its more frequent replacement.

## 5. Conclusions

This paper studied the sensitivity of input data which are difficult to obtain in the water balance that is used for the BC-T design. It appears that the most sensitive variable affecting the size of the drained area connected to the BC-T is the available water-holding capacity in the underground trench $AWHC_{TR}$. The sensitivity of the water-holding capacity of the soil filter $WHC_{SF}$ is none to very low. It is also true for the potential tree water uptake $TWU_{pot}$, except for very low exfiltration rates and the tree pit without underdrain, where its sensitivity is more significant.

The practical implication of the analysis performed is a possible simplification of the water balance for engineering practice. This simplification and the resulting $A_{red}/A_{BC}$ ratio are highly dependent on exfiltration conditions:

- At high exfiltration rates (18 mm·h$^{-1}$ and more) or when the trench is equipped with an underdrain, the water-holding capacity in the soil filter $WHC_{SF}$ and the tree water uptake $TWU_{pot}$ can be omitted in the water balance;
- At low trench exfiltration rates (1.8 mm·h$^{-1}$; without an underdrain), both the water-holding capacity of the trench substrate $AWHC_{TR}$ and the potential tree water uptake $TWU_{pot}$ have a significant influence and cannot be omitted;
- If $TWU_{cov}$ is subject to calculation, $AWHC_{TR}$ and $TWU_{pot}$ should not be omitted; in the case of low exfiltration rates, $WHC_{SF}$ cannot be omitted either.

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## Abbreviations

| | |
|---|---|
| AWHC | available water-holding capacity |
| BC | bioretention cell |
| BC-T | bioretention cell with underground trench |
| BGI | blue–green infrastructure |
| E | evaporation |
| EE | elementary effect |
| ER | exfiltration rate |
| ET | evapotranspiration |
| EXF | exfiltration |
| IC | interception loss |
| IL | initial loss |
| INF | infiltration |
| IR | infiltration rate |
| OF | overflow |
| OS | open storage |
| PER | percolation |
| RF | runoff coefficient |
| SF | soil filter |
| SuDS | sustainable drainage systems |
| TR | trench |
| TWU | tree water uptake |
| UD | underdrain |
| WD | water deficit |
| WHC | water-holding capacity |

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