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Article

Optimization of a Tree Pit as a Blue-Green Infrastructure Object

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Abstract: Key elements of Blue-Green Infrastructure are vegetation and stormwater storage. A combination of a bioretention cell with an underlying trench (BC-T) serving as a tree pit is often used in dense urban environments. An adequate ratio of drained area to bioretention cell area is a crucial design parameter. The ratio is derived from the hydrological balance; however, input data are often difficult to obtain or uncertain. The goal is to study the sensitivity of such data (tree water uptake and water holding capacities of soil filter and trench substrate) in the BC-T design. Sensitivity analysis is performed for the setup of a BC-T used in Prague, Czech Republic. A 10-year rainfall series (1 hour resolution) is used as an input. Data that are subject to the sensitivity analysis are changed for different trench exfiltration rates, and the effect on the size of the drained area is studied. At low trench exfiltration rates (1.8 $mm.h^{-1}$), both the water holding capacity of the trench substrate and potential tree water uptake have a significant influence (more than a 20% change in the size of the drained area) and cannot be neglected. At good exfiltration rates (more than 18 mm.h-1) or when the trench is equipped with an underdrain, all studied parameters can be neglected. However, it is recommended to reduce the size of the drained area by 10-20%.

Keywords: Blue-Green Infrastructure; hydrological balance; stormwater management; tree pit; tree water uptake; water holding capacity

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 well-being. Its primary goal 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, i.e., a portion of stormwater runoff retained by BC-T; this portion should be between 77 and 93% of the total stormwater runoff [14];
- providing enough water for trees; computing a tree water balance is a complicated task with many uncertainties, depending on many factors including tree species and its climatic region [15];
- sufficient pretreatment of stormwater; at least 80% of stormwater runoff is recommended to be pretreated through the soil filter in the bioretention cell [16];
- prevention of waterlogging tree roots; various authors [16, 17] recommended between 24 and 48 hours 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 is specific, especially regarding the available space for BGI both on the surface and underground [18]. Conflicts of interests with transport, buried infrastructure, and historic preservation are common and lead to constrictions of the BGI design [19]. Thus, the use of the bioretention cell with the open retention space in close proximity to the tree trunk is often the only possible solution in dense urban environments and/or historical parts of cities. The area of the bioretention cell might be limited to 3-6 m^2 per tree. This means that the open storage area is limited and the retained stormwater volume is reduced. 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 [20]. Therefore, an adequate ratio of drained area (reduced by the runoff coefficient) A_{red} to bioretention cell area A_{BC} is a crucial parameter for BC-T performance [21].

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 the 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 [22]. 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 45 considering the value of the runoff coefficient of paved surfaces of 0.90) to ensure treatment of 90% of the mean annual runoff. Christchurch City, New Zealand [16] analyzed several scenarios with a goal to capture 80% of stormwater runoff. They found that 350 m^2 of 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). Hamburg City, Germany recommends connecting 15-21 m^2 of the drained area to 1 m^2 of bioretention cell area [23] (i.e., A_{red}/A_{BC} ratio 13.5-19 considering the runoff coefficient of paved surfaces of 0.90). The 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 [24], resulting in an A_{red}/A_{BC} ratio of 18-45 (considering the runoff coefficient of paved surfaces of 0.90). The authors of [21] declared that the A_{red}/A_{BC} ratio for bioretention cells should be between 5 and 15, as 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 reason for this may be different locations of the studies, climatic data, different setups of bioretention cells, ambient soil characteristics, and 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 hydrological balance. A common practice is to calculate the hydrological balance using IDF (Intensity-Duration-Frequency) rainfall curves (i.e., uniform rainfalls) [25]. However, it is suitable for stand-alone BGI structures only [21]. For BGI structures connected in series (as in the case of BC-T, where the bioretention cell is connected in series with an underground trench), a more detailed description of the performance dynamics is necessary.

Data needed for the calculation of the hydrological balance of a BC-T 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 is 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; [26]) 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 [27].

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, tree characteristics – type of tree, size of tree, diameter of crown, canopy structure, internal water storage, etc. [28-30]) 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 [31] 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 [32], by 50% (2-5% of biochar added to soil, [33]), or even by 100% (9% of biochar added to soil, [34]). 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 neglecting tree water uptake and available water holding capacity data in the calculation of the hydrological balance is unknown.

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

2. Materials and Methods

A BC-T consists of three separate elements (Figure 1): (i) an open storage volume, (ii) a soil filter, and (iii) an underground trench.

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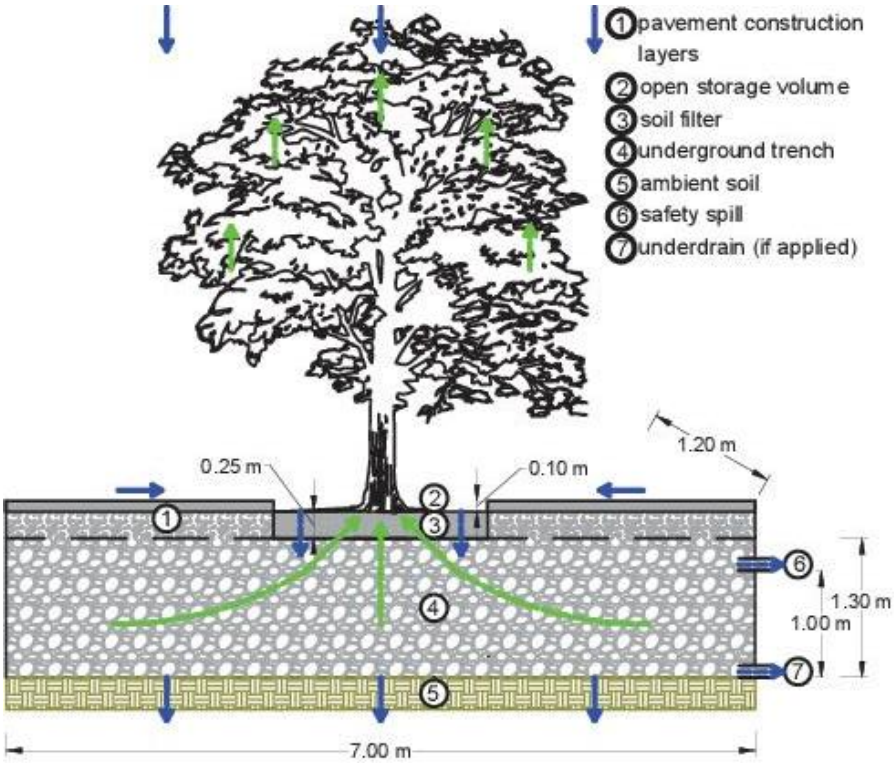

Figure 1. Scheme of a BC-T used for the hydrological balance calculation.

2.1. Subsection

The hydrological balance for each element can be written as follows.

2.1.1. Open storage volume

$$V_{runoff} = V_{open\_storage} + E_{open\_storage} + INF_{soil\_filter} + V_{open\_storage\_OF}, \quad (1)$$

where

V_{runoff} is volume of inflow to open storage from drained area in m^3 calculated as:

$$V_{runoff} = (h_{rainfall} - IL - IC) \times A_{drained} \times RF, \quad (2)$$

where

$h_{rainfall}$ is rainfall depth in m;
IL is initial loss depth on paved surfaces in m;
IC is initial loss depth by interception in tree canopy in m;
$A_{drained}$ is area of drained catchment in m^2;
RF is dimensionless runoff coefficient;
$V_{open\_storage}$ is volume of open storage used for retention of inflow in m^3;
$E_{open\_storage}$ is volume of water evaporated from ponded water in soil filter area in m^3;
INF_{soil_filter} is volume of water that infiltrates to soil filter in m^3 and is calculated as:

$$INF_{soil\_filter} = A_{soil\_filter} \times INF_{rate}, \quad (3)$$

where

A_{soil_filter} is area of soil filter in m^2;
INF_{rate} is median infiltration rate in $m.s^{-1}$;
$V_{open\_storage\_OF}$ is volume of water that overflows from the open storage when it is full in m^3.

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2.1.2. Soil filter

$$INF_{soil\_filter} = PER_{trench} + ET_{soil\_filter} + WHC_{soil\_filter}, \quad (4)$$

where

PER_{trench} is volume of water that percolates to underground trench in m^3;

ET_{soil_filter} is volume of evapotranspiration from soil filter and vegetation planted in soil filter in m^3;

WHC_{soil_filter} is volume of water held by soil filter in m^3.

2.1.3. Underground trench

$$PER_{trench} + V_{open\_storage\_OF} = EXF_{trench} + V_{outflow} + WHC_{trench} + TWU + V_{trench\_OF}, \quad (5)$$

where

EXF_{trench} is the volume of inflow to the open storage from the drained area in m^3 and is calculated as:

$$EXF_{trench} = A_{exf} \times EXF_{rate}, \quad (6)$$

where

A_{exf} is the effective area of exfiltration in m^2 and is calculated as:

$$A_{exf} = (b + 0.5 \times h_{trench}) \times (l + 0.5 \times h_{trench}), \quad (7)$$

where

b is the width of the underground trench in m;

l is the length of the underground trench in m;

h_{trench} is the depth of water in the underground trench in m;

EXF_{rate} is the median exfiltration rate in $m.s^{-1}$;

$V_{outflow}$ is the volume of water drained by the flow control element (underdrain) in m^3 (if applied);

WHC_{trench} is the volume of water held by the structural substrate in m^3;

TWU is the tree water uptake in m^3;

V_{trench_OF} is the volume of water overflowing the trench when it is full in m^3.

Note: $V_{open\_storage\_OF}$ is applied only when the open storage is connected directly to the underground trench (e.g. by a street gully).

2.2. Sensitivity analysis

Sensitivity analysis is performed for the setup of a BC-T commonly used in Prague, Czech Republic. 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 meters. The underground trench is continuous (when permitted by buried infrastructure).

Sensitivity analysis overview is presented in Table 1.

Table 1. Overview of groups of data used in sensitivity analysis procedure.

Data groups	Data used
Given characteristics and inputs	BC-T physical setup
	Tree physical characteristics
	Soil filter infiltration rate
	Initial and interception losses, runoff coefficient of drained area
	Historical rainfall series

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Variable local conditions	Exfiltration rates from underground trench to ambient soil Use/non-use of underdrain for emptying of underground trench
Performance criteria	Frequency of underground trench surcharge Minimum amount of stormwater treated by soil filter Duration of underground trench emptying
Target variable [1]	Size of area drained to BC-T ($A_{drained}$) that can be connected to BC-T, can be also expressed as A_{red}/A_{BC} ratio
Subject to sensitivity analysis	Water holding capacity of soil filter (WHC_{soil_filter}) Water holding capacity of underground trench substrate (WHC_{trench}, can be substituted by available water holding capacity $AWHC_{trench}$) Potential tree water uptake ($TWU_{potential}$)

[1] Result of hydrological balance calculation.

2.2.1. BC-T physical characteristics

Characteristics of open storage, soil filter, underground trench and tree are in Table 2, Table 3, Table 4, and Table 5.

Table 2. Open storage characteristics.

Characteristic	Value / Comment
Area	3 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	In case open storage is surcharged the excess water is diverted directly to the underground trench

Table 3. Soil filter characteristics.

Characteristic	Value / Comment
Area	2.8 m^2
Thickness	0.25 m
Material	Soil with ca. 10% of clay and 3% of moisture-containing matter (humus, biochar)
Infiltration rate	180 $mm.h^{-1}$ (recommended by [21])
Water holding capacity	Subject to the sensitivity analysis

Table 4. Underground trench characteristics.

Characteristic	Value / Comment
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 the safety spill is considered 1.0 m)
Material	Structural stone-soil substrate
Porosity	30%
Storage volume	2.52 m^3
Exfiltration rate	Scenarios: 180 $mm.h^{-1}$, 18 $mm.h^{-1}$ and 1.8 $mm.h^{-1}$ without underdrain and 1.8 $mm.h^{-1}$ with underdrain (regulated outflow at the bottom of the trench with maximum of 0.5 $l.s^{-1}$)
Ground water level	3 m below trench bottom
Water holding capacity	Subject to the sensitivity analysis

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Table 5. Tree characteristics.

Characteristic	Value / Comment
Trunk diameter at ground	0.5 m
Crown diameter	7 m
Tree type	Broad leaved, mature
Interception of rainfall	1.1 mm in tree crown area (according to [35])
Tree water uptake	Subject to the sensitivity analysis

2.2.2. Performance criteria

Performance criteria used for calculation of the drained area size $A_{drained}$ that can be connected to the BC-T are based on Czech technical standards [21] and are listed in Table 6.

Table 6. Performance criteria and their requested values.

Criterion	Value / Comment
The maximum permissible frequency of underground trench surcharge	1 per 5 years
The minimum amount of water infiltrating to the soil filter ensure the restoration of the natural water regime and proper pretreatment of stormwater	85%
The maximum duration for emptying the underground trench when it is full (prevention of tree roots waterlogging)	48 h

2.2.3. Hydrological balance

A 10-year historical rainfall series with a time resolution of 1 hour is used as an input to the hydrological balance; see equation (2). Characteristics of used rainfall series are given in Table 7; characteristics of drained area are given in Table 8.

Table 7. Historical rainfall series characteristics.

Characteristic	Value / Comment
Location	Prague, Czech Republic
Length of the record	10 years (from 2006 to 2015)
Time resolution	1 hour
Average rainfall depth	532 $mm.y^{-1}$

Table 8. Drained area characteristics.

Characteristic	Value / Comment
Area	Target variable
Initial losses	0.5 mm (according to [36])
Runoff coefficient	0.90 (typical for urban paved surfaces in city centers)

Several assumptions were introduced when calculating the hydrological balance:

- interception in the tree canopy and initial loss are applied when rainfall starts after a 24-hour 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);

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- retention volume in the soil filter pores and capillary rise 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 [37]) and the soil filter is allowed to dry out completely;
- water held in the soil filter is considered to dry out in 7 days [38], 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); trees are not considered to take water up from the soil filter;
- the capillary rise in the underground trench is not considered because the ground water level is 3 m below the trench bottom and is less than 0.5 $mm.d^{-1}$ (according to [15]);
- the structural substrate cannot dry completely as it is placed under the soil filter with no capillary rise (the amount of water in the substrate cannot be lower than the permanent wilting point; therefore, WHC_{trench} can be substituted by the available water holding capacity $AWHC_{trench}$ in the hydrological balance);
- the covering of $AWHC_{trench}$ is considered as shown in Figure 2; when water from the soil filter percolates downwards through the trench at a 45^0 angle, $AWHC_{trench}$ is primarily covered in corresponding volume of substrate only; when the water level in the trench rises, $AWHC_{trench}$ is covered in the full length of the trench to the actual 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;
- regulated outflow from the underground trench (underdrain) is considered as 50% of its maximum value;
- a surcharge event of the underground trench is an event preceded by a minimum of 6 hours without an overflow;
- data on the potential tree water uptake, $TWU_{potential,}$ (i.e., the amount of water the tree theoretically claims for its wellbeing) are monthly average values for a mature broad leaf tree; $TWU_{potentional}$ is calculated using the procedure described in [28, 29] with the basal crop coefficient used to describe plant transpiration taking into account the needs of the tree during the year (reference crop evapotranspiration is estimated using the Hargreaves equation [39] based on data from the nearest meteorological station; monthly transpiration data are assumed to vary between - 50% and + 30% according to available data in central Europe [40-44]); used $TWU_{potential}$ scenarios represent average (20.2 $m^3.y^{-1}$), low (10.1 $m^3.y^{-1}$) and high (26.3 $m^3.y^{-1}$) annual tree water uptake (Table 9).

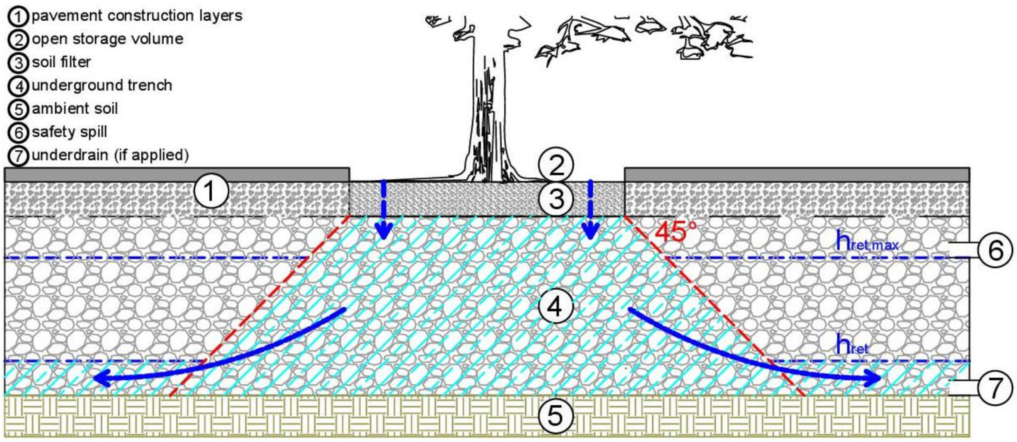

Figure 2. Schematization of $AWHC_{trench}$ calcuation in hydrological balance (h_{ret} is depth of retained water in time t, $h_{ret,max}$ is a maximum depth of retained water).

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Table 9. Potential tree water uptake $TWU_{potential}$ data used in the hydrological balance.

Month	Average air temperature in ^{0}C	$TWU_{potential}$ in $l.d^{-1}$		
		Average	Low	High
January	0.9	1.3	0.7	1.7
February	1.6	2.6	1.3	3.3
March	5.8	19.6	9.8	25.5
April	11.7	50.5	25.3	65.7
May	15.3	98.6	49.3	128.2
June	19.0	138.2	69.1	179.6
July	21.6	147.1	73.5	191.2
August	20.2	118.6	59.3	154.2
September	15.5	57.6	28.8	74.9
October	10.1	21.3	10.6	27.7
November	6.3	2.1	1.1	2.7
December	2.3	1.2	0.6	1.6

2.2.4. Subject to sensitivity analysis

Parameters that are subject to sensitivity analysis are listed in Table 10.

Table 10. Parameters that are subject to sensitivity analysis and their studied values.

Parameter	Reference value	Tested range	Increments	Neglected
WHC_{soil_filter}	10%	5 – 20%	5%	parameters
$AWHC_{trench}$	10%	5 – 20%	5%	neglected in
$TWU_{potential}$	Average	Low to High	-50%; +30%	hydrological balance

2.2.5. Sensitivity analysis evaluation

Parameter sensitivity was evaluated by comparing the calculated $A_{drained}$ (which can also be expressed as the A_{red}/A_{BC} ratio).

As supplementary information, the ratio of the amount of water taken up by the tree from the underground trench to $TWU_{potential}$ (Table 2) was calculated. This value shows the extent to which the tree's water need is covered by rainfall runoff drained to the BC-T. It is calculated as:

$$TWU_{cover} = TWU / TWU_{potential} \times 100, \quad (8)$$

where

TWU_{cover} is the extent to which the water claimed by the tree is covered by rainfall runoff in %;

TWU is the tree water uptake based on the hydrological balance calculation in m^3;

$TWU_{potential}$ is the theoretical value of water the tree must claim for its wellbeing in m^3.

3. Results

3.1. Calculation with reference values

At first, $A_{drained}$ is optimized for different exfiltration rates from the underground trench and reference values of parameters that are subject to the sensitivity analysis. Results are summarized in Table 11.

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Table 11. Summary of results for different exfiltration rate scenarios with reference values of parameters that are subject to the sensitivity analysis (both WHC_{soil_filter} and $AWHC_{trench}$ are set to 10%, average $TWU_{potential}$ is used); determining performance criterion shows which of the three performance criteria used (Table 6) is critical for the optimization (i.e., two other criteria are fulfilled).

Exfiltration rate in mm.h^{-1}	Determining performance criterion	$A_{drained}$ in m^2	A_{red}/A_{BC} in m^2.m^{-2}	TWU_{cover} in %
180	Frequency of surcharge	167	54.6	73.1
18	Frequency of surcharge	69	23.1	59.9
1.8	Emptying duration	14	5.5	16.4
1.8 + underdrain	Frequency of surcharge	112	37.0	68.1

It is obvious that with the decreasing exfiltration rate, the maximum size of the drained area, $A_{drained}$, is rapidly decreasing. Therefore, the tree water need, $TWU_{potential}$, is covered to a smaller extent as well. For exfiltration rates lower than 18 mm.h^{-1}, it might be helpful to speed up the emptying of the underground trench by incorporating an underdrain with regulated outflow (e.g., by an orifice). In cases where the regulated outflow of 0.5 l.s^{-1} is applied for exfiltration rates of 1.8 mm.h^{-1}, the drained area can be increased from 14 to 112 m^2, and as a result TWU_{cover} increases from 16 to 68%.

3.2. Sensitivity of water holding capacity in soil filter

Results of the sensitivity analysis of the water holding capacity in the soil filter WHC_{soil_filter} are shown in Figure 3.

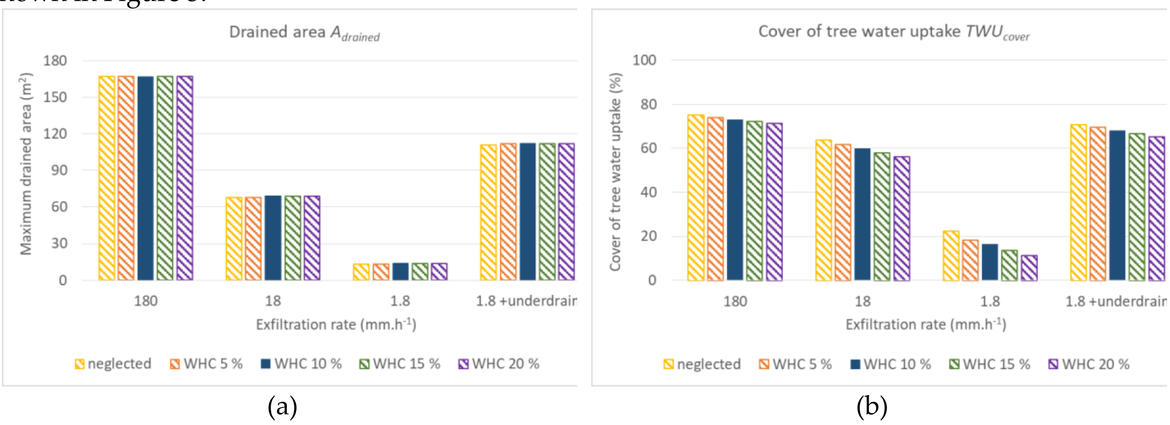


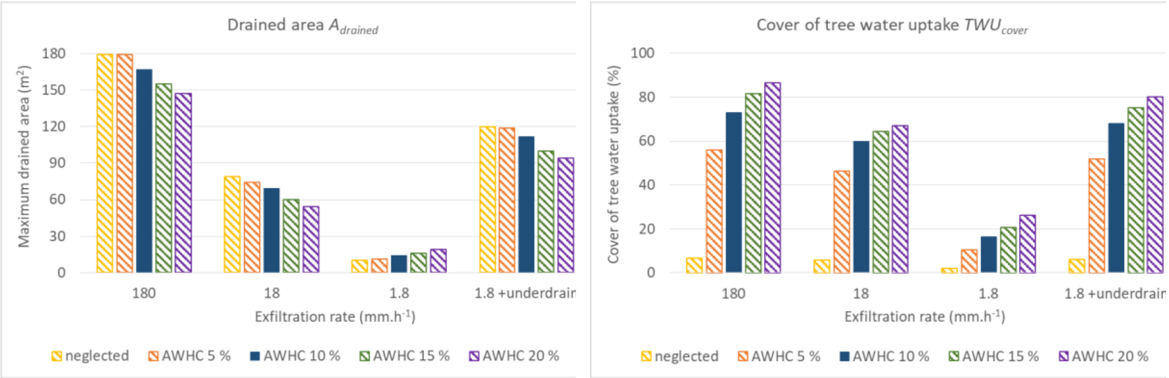
Figure 3. Effect of water holding capacity of the soil filter WHC_{soil_filter} on: (**a**) $A_{drained}$; (**b**) TWU_{cover}.

Changing the value of the WHC_{soil_filter} has a negligible effect on $A_{drained}$, 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.

TWU_{cover} varies more. 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.

3.3. Sensitivity of available water holding capacity of underground trench

Results of the sensitivity analysis of the available water holding capacity in the underground trench $AWHC_{trench}$ are shown in Figure 4.



(a) (b)

Figure 4. Effect of available water holding capacity of underground trench $AWHC_{trench}$ on: (**a**) $A_{drained}$; (**b**) TWU_{cover}.

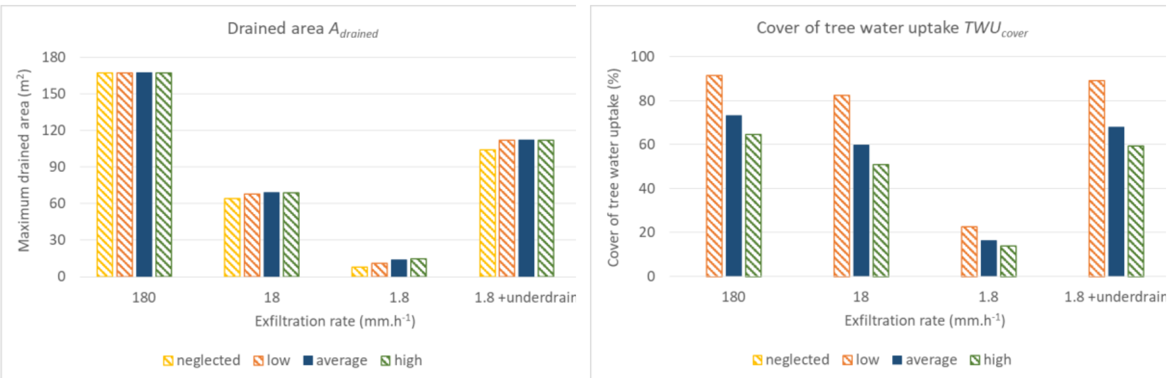
Changing the $AWHC_{trench}$ has a significant effect on $A_{drained}$, which can be connected to the BC-T. For higher exfiltration rates (and the trench with the underdrain), the amount of water held in the structural substrate of the trench decreases the available retention volume for stormwater inflow. It is especially important during heavy rainfall events that have the potential to surcharge the underground trench more often. Therefore, when $AWHC_{trench}$ is neglected, the connectable drained area $A_{drained}$ increases by 7-15% compared to the reference value of $AWHC_{trench}$ (note: in the 180 mm.h^{-1} exfiltration scenario, $A_{drained}$ for both the neglected and the 5% $AWHC_{trench}$ is the same as percentage of water treated by the soil filter determines the result of calculation). Accordingly, with the increasing $AWHC_{trench}$ value, the maximum drained area $A_{drained}$ decreases by 12-22%.

The opposite situation occurs in cases of very low exfiltration rates when the duration of the trench emptying plays a major role. A lower value of $AWHC_{trench}$ means that more water exfiltrates and $A_{drained}$ must be significantly decreased (by 30% compared to the reference values); when $AWHC_{trench}$ is higher, a larger area may be connected (increase by up to 35%).

TWU_{cover} is increasing with the increase of $AWHC_{trench}$ in all studied exfiltration scenarios. Omitting $AWHC_{trench}$ from the hydrological balance means that the tree can take up water only during the rainfall runoff and shortly after it (until the trench is emptied, i.e., within 48 h). Therefore, TWU_{cover} is very low (2-7%). Even the small value of $AWHC_{trench}$ (5%) increases TWU_{cover} by tenths of a percent. Coverage progress with further increases in $AWHC_{trench}$ is still significant (15-30%).

3.4. Sensitivity of potential tree water uptake

Results of the sensitivity analysis of tree water uptake claim $TWU_{potential}$ are in Figure 5.



(a) (b)

Figure 5. Effect of potential tree water uptake $TWU_{potential}$ on: (**a**) $A_{drained}$; (**b**) TWU_{cover}

$A_{drained}$ is slightly increasing with an increase in $TWU_{potential}$ as the tree water uptake helps to empty the underground trench faster. It is not so important in cases of very good exfiltration rates

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(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, $A_{drained}$ doubles (from 8 m^2 in the case of $TWU_{potential}$ to a neglected 15 m^2 in the case of ´high´ $TWU_{potential}$).

TWU_{cover} decreases because $A_{drained}$ does not increase substantially with the $TWU_{potential}$ increase.

3.5. Summary of the sensitivity analysis

Summary of the sensitivity analysis results are shown in Table 12 and Table 13.

Table 12. Effect of changing the studied parameters values (WHC_{soil_filter}, $AWHC_{trench}$ and $TWU_{potential}$) on $A_{drained}$.

	Tested parameters					
	WHC_{soil_filter}		**$AWHC_{trench}$**		**$TWU_{potential}$**	
Reference value	10%		10%		Average	
Tested values	5%	15%	5%	15%	Low	High
Exfiltration	Change in $A_{drained}$ compared to reference value in %					
180 mm.h^{-1}	0.0	0.0	+7.2	-7.2	0.0	0.0
18 mm.h^{-1}	-1.4	0.0	+7.2	-13.0	-1.4	0.0
1.8 mm.h^{-1}	-7.1	0.0	-21.4	+14.3	-21.4	+7.1
1.8 mm.h^{-1} + underdrain	0.0	0.0	+6.3	-10.7	0.0	0.0

The most noticeable change in $A_{drained}$ was caused by a change in $AWHC_{trench}$; however, the change in $A_{drained}$ is generally within 10% in the case of good exfiltration conditions. Therefore, it is possible to state that the uncertainty in the value of the $AWHC_{trench}$ (as well as the other two parameters) does not affect the results of the BC-T optimization significantly. Cases of very low exfiltration rates are a different situation, where values of $AWHC_{trench}$ and $TWU_{potential}$ can lead to more than a 20% change in $A_{drained}$. However, at such exfiltration rates it should be preferred to equip the underground trench with an underdrain to increase TWU_{cover}.

Table 13. Effect of changing the studied parameters values (WHC_{soil_filter}, $AWHC_{trench}$ and $TWU_{potential}$) on TWU_{cover}.

	Tested parameters					
	WHC_{soil_filter}		**$AWHC_{trench}$**		**$TWU_{potential}$**	
Reference value	10%		10%		Average	
Tested values	5%	15%	5%	15%	Low	High
Exfiltration:	Change in TWU_{cover} compared to reference value in %					
180 mm.h^{-1}	+1.4	-1.2	-23.4	+11.5	+25.2	-11.5
18 mm.h^{-1}	+2.8	-3.3	-22.5	+7.3	+37.7	-15.2
1.8 mm.h^{-1}	+11.0	-17.7	-36.0	+25.0	+38.4	-14.6
1.8 mm.h^{-1} + underdrain	+2.2	-2.1	-23.8	+10.4	+30.8	-12.6

TWU_{cover} results are mainly affected by the parameters $AWHC_{trench}$ and $TWU_{potential}$. Within their usual range of values, the effect on TWU_{cover} is 10–40% for all exfiltration scenarios studied. If TWU_{cover} is required for decision-making, these parameters should be quantified as accurately as possible. WHC_{soil_filter} has only a small effect on TWU_{cover} (1-3%), especially in good exfiltration conditions. In the case of very low exfiltration rates, it might be up to 20%; however, the same conclusion as in the case of $A_{drained}$ applies (i.e., the necessity to equip the underground trench with an underdrain).

3.6. Neglecting the parameters

A situation of neglecting all three studied parameters in the hydrological balance was also studied. To get an idea of to what extent it affects the result of optimization, the maximum drained

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area $A_{drained}$ is calculated with WHC_{soil_filter}, $AWHC_{trench}$ and $TWU_{potential}$ neglected. The results, including their comparison with the above-presented results, are in Table 5.

Table 14. Summary of results for different exfiltration scenarios with values of WHC_{soil_filter}, $AWHC_{trench}$ and $TWU_{potential}$ neglected.

	Tested parameters		
	WHC_{soil_filter}	**$AWHC_{trench}$**	**$TWU_{potential}$**
Reference value	10%	10%	Average
Tested value	neglected	neglected	neglected
Exfiltration:	Change in $A_{drained}$ compared to reference value in %		
180 mm.h^{-1}		+7.2	
18 mm.h^{-1}		+13.0	
1.8 mm.h^{-1}		-50.0	
1.8 mm.h^{-1} + underdrain		+6.3	

The standard design procedure overestimates $A_{drained}$ by 6-13% under good exfiltration conditions and in the scenario with the underdrain. The overestimation would be more significant with an increase in the $AWHC_{trench}$ reference value (22% in the case where the $AWHC_{trench}$ reference value is set to 20%). The other two parameters are not of such importance. In the case of a very low exfiltration rate, the $A_{drained}$ is significantly underestimated by 50%; the underestimation would be more significant with an increase in the $AWHC_{trench}$ reference value (63% when the $AWHC_{trench}$ reference value is set to 20%) and less significant in the case of a decrease in $TWU_{potential}$ (36% when the $TWU_{potential}$ reference value is set to ´low´).

4. Discussion

Several counteracting factors affect the optimization of BC-T:

- volume of water held by the soil filter WHC_{soil_filter}: its decrease means that a higher water volume percolates into the underground trench and is available to cover the $AWHC_{trench}$. On the other hand, more water in the trench must be exfiltrated;
- volume of water held by the trench $AWHC_{trench}$: a higher volume held in the substrate of the trench 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;
- amount of water needed by the tree for uptake $TWU_{potential}$: a higher value 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;
- exfiltration rate from the underground trench to the ambient soil: it determines which of the above-mentioned processes will be crucial during the optimization procedure.

Based on the analysis, it is possible to state that water holding capacities in the soil filter WHC_{soil_filter}, the trench $AWHC_{trench}$, and the tree water uptake TWU_{claim} can be neglected in the following situations:

- all three parameters can be neglected under good exfiltration rates from the underground trench or when the trench is equipped with an underdrain; however, if $AWHC_{trench}$ is omitted, it is recommended to reduce $A_{drained}$ by 10-20%;
- $AWHC_{trench}$ and $TWU_{potential}$ should not be neglected under very low exfiltration rates (without an underdrain) and should be expressed as accurately as possible;
- if TWU_{cover} is a subject of calculation, $AWHC_{trench}$ and $TWU_{potential}$ should not be omitted.

Also, further findings can contribute to the design process of BC-T:

- in cases of very low exfiltration rates, it is recommended to equip the underground trench with an underdrain because it significantly increases $A_{drained}$ and thus TWU_{cover};

- $AWHC_{trench}$ is the most important factor for satisfying the tree water need. Further research should be focused on developing structural substrates with high values of available water holding capacity,
- A_{red}/A_{BC} ratio was found to be in the range of 4.5-58 which is consistent with the studies [11, 16, 21-24] (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 $mm.h^{-1}$, 18-23 when exfiltration rate is 18 $mm.h^{-1}$, 4.5-7 when the exfiltration rate is 1.8 $mm.h^{-1}$, and 31–39 when an underdrain is applied). It corresponds with the findings of [11] that A_{red}/A_{BC} should be 36 when the exfiltration rate is 34 $mm.h^{-1}$ and only 11 when the exfiltration rate is 1 $mm.h^{-1}$. However, the A_{red}/A_{BC} value for 1 $mm.h^{-1}$ stated by [11] is substantially higher than our finding for the exfiltration rate of 1.8 $mm.h^{-1}$ (11 compared to 4.5-7). This difference 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 $mm.y^{-1}$), the rainfall distribution during the year is different (Melbourne: minimum 33, maximum 60 $mm.month^{-1}$; Prague: minimum 23, maximum 77 $mm.month^{-1}$); thus, the retention space of BC-T has to be accommodated accordingly. Further, the risk of the soil filter clogging must be discussed [21]. A higher A_{red}/A_{BC} leads to faster clogging and therefore higher costs associated with its more frequent replacement.

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