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Urban trees left high and dry – Modelling urban trees water supply and evapotranspiration under drought

Björn Kluge and Margit Kirmaier

Technische Universität Berlin, Chair of Ecohydrology and Landscape Evaluation, Institute of Ecology, Ernst-Reuter-Platz 1, 10587 Berlin, Germany

E-mail: bjorn.kluge@tu-berlin.de**Keywords:** urban tree evapotranspiration (ET), water supply, water stress, urban environment, sealing, modellingSupplementary material for this article is available [online](#)

Abstract

Long-lasting extreme weather conditions are expected to occur more frequently in the future owing to climate change, as demonstrated by the recent heat waves. In particular, the decrease in precipitation during the summer months had a significant impact on urban tree water availability. Therefore, it is imperative to develop methodologies for determining the available water supply and evapotranspiration rates for urban trees. We mapped data from 49 urban small-leaved linden trees with varying characteristics including groundwater levels, shading situations, tree pit sizes, pavement materials, and sealing ratios. By combining these data with an adapted Penman-Monteith method to calculate evapotranspiration, we simulated the soil water storage and evapotranspiration rates of these trees during the very dry year of 2018 as an example. Model validations were performed using lysimeter and sap-flow studies on *Tilia cordata* trees in 2022. During the growing season, most trees experienced water stress on > 85% of the days because of weak precipitation events that failed to refill soil water storage. In contrast, trees with additional water supply through capillary rise reached water stress approximately 45 days later. The model results suggest that many trees will require additional water supply during predicted droughts in the future, which could have significant implications for urban forestry management. This model approach can be used to test and refine future water supply management strategies, making it a useful planning tool for improving the water efficiency of trees in urban areas and blue-green infrastructure.

List of Abbreviations

$\beta_{s,w}$	Runoff coefficient (summer, winter)
Ca	Capillary rise
$Ca_{0.3}$	Capillary rise rate of 0.3 mm d ⁻¹
$Ca_{2.8}$	Capillary rise rate of 0.3 mm d ⁻¹
De	Depth of evaporation from the soil surface
DP	Deep percolation
DSM	Digital Surface Model
DG	Soil heat flux
HTW	Hochschule für Technik und Wirtschaft, Berlin
ET	Evapotranspiration
ET_0	Reference evapotranspiration
ET_c	Crop evapotranspiration under ideal conditions

<i>ETc adj</i>	<i>Adjusted crop evapotranspiration under water stress conditions</i>
<i>FAO</i>	<i>Food and Agriculture Organization of the United Nations</i>
<i>Kc</i>	<i>Crop coefficient</i>
<i>Kcb</i>	<i>Crop transpiration coefficient</i>
<i>Ke</i>	<i>Soil water evaporation coefficient</i>
<i>Kr</i>	<i>Soil evaporation reduction coefficient</i>
<i>Ks</i>	<i>Water stress coefficient</i>
<i>RAW</i>	<i>Readily available water</i>
<i>Rn</i>	<i>Net radiation</i>
<i>Roff</i>	<i>Runoff</i>
<i>Si s, w</i>	<i>Crown interception coefficient (summer, winter)</i>
<i>SVF</i>	<i>Sky View Factor</i>
<i>T.</i>	<i>Tilia cordata</i>
<i>TAW</i>	<i>Total available soil water in the root zone (equals aFC)</i>
<i>Wn</i>	<i>Soil water storage</i>
<i>Zr</i>	<i>Rooting depth</i>

1. Introduction

The effects of unusually high temperatures and prolonged dry periods have occurred within the last couple of years, not only in Berlin, but also in many other European regions (Blauhut *et al* 2015, 2021). Berlin experienced its hottest summer in 2018, with a prolonged drought lasting from April to December, following the warmest decade since 1861 (Gerstengrabe 2014). Owing to climate change, periods of drought are expected to occur more often during the vegetation period (April—October) in the region of Berlin-Brandenburg, as summer precipitation is expected to shift to winter months (Reyer *et al* 2012, IPCC 2013). This trend has been observed in recent years, particularly until 2022.

In July 2018, Berlin residents were called upon to help with the irrigation of street trees, (Der Regierende Bürgermeister 2018) and the State of Berlin spent an additional 2.3 million Euro for irrigation measures (Abgeordnetenhaus von Berlin 2019a, 2019b). Such supplementary watering has become increasingly important for sustaining the manifold ecosystem services of urban trees: mitigation of urban heat island effects (Bowler *et al* 2010, Lee *et al* 2016, Rahman *et al* 2017a, 2017b), reduction of stormwater runoff (Armson *et al* 2013), improvement of air quality, offset of greenhouse gas emissions and reduction of nutrient leaching into groundwater. Furthermore, trees in cities can significantly affect mean radiant temperature and physiologically equivalent temperature (PET) (Lai *et al* 2023), and strongly influence pedestrian thermal comfort, depending on site selection and tree species (Vatani *et al* 2024). However, all these benefits can only be realised if urban trees are sufficiently supplied with water (Livesley *et al* 2016).

In urban areas, impervious surfaces and drainage infrastructure lead to high amounts of runoff and reduced infiltration, which decrease the water available to plants in urban soils (Nowak *et al* 2004, Xiao *et al* 2007, Gaffin *et al* 2012, Shields and Tague 2015, Hanel *et al* 2018, Fini *et al* 2022). Additionally, increasing drought and extreme heat waves may reinforce water stress of urban trees (Teskey *et al* 2015, Van Loon *et al* 2016). Different studies have shown that an insufficient water supply negatively influences the annual growth rate, tree vitality, and ecosystem services of urban trees (Bolund & Hunhammar 1999, Nowak *et al* 2004, Bréda *et al* 2006, Vico *et al* 2014, Konarska *et al* 2015, Moser *et al* 2016, Haase and Hellwig 2022). To avoid the risk of vitality loss and mortality of urban trees, the prediction of water balance and water deficit under different meteorological and characteristic urban conditions is crucial and will become increasingly important in the future (McDowell *et al* 2008, Asawa *et al* 2017, Schütt *et al* 2022).

The water supply of urban trees originates from a number of sources, including infiltrated precipitation, direct or indirect irrigation (including lateral inflow from nearby sites), and capillary rise from groundwater (Larcher 2003, Wessolek and Kluge 2021). Tree water loss encompasses interception, runoff, deep percolation, or leakage below the root zone as well as the evaporation of water from the soil and transpiration of the tree (Stål 1998, Randrup *et al* 2001, Winbourne *et al* 2020). To ascertain the water balance of a tree, these parameters must be measured, derived, or estimated.

In the case of precipitation, data from nearby climate stations should be available, and runoff can be determined using data on soil sealing and runoff coefficients (e.g., Timm *et al* 2018). Data on capillary rise may be derived from soil texture databases or pedo-transfer functions (e.g., Wessolek *et al* 2011).

Because the processes of evaporation and transpiration are difficult to distinguish, they were considered and estimated together as evapotranspiration (ET) (Amelung *et al* 2018). In principle, there are two ways to obtain evapotranspiration data: measuring or computed modelling (Rana and Katerji 2000). Evapotranspiration measurements comprise hydrological concepts (e.g., weighing lysimeter), micro-meteorological concepts (e.g., measurement of the latent heat flux) or plant physiological concepts e.g., sap flow or porometer measurements (Granier 1987, Bartens *et al* 2008, Pataki *et al* 2011, Konarska *et al* 2015, Rahman *et al* 2018). Because of the high effort required to obtain measurements, evapotranspiration is usually derived through the application of models.

One of the most common is the FAO Penman-Monteith model, which is recommended as the sole standard method by the FAO (Allen *et al* 1998). The FAO Penman-Monteith method computes evapotranspiration, referred to as the reference evapotranspiration (ET_0), for a constantly moist grass area. To describe evaporation from a defined soil area (e.g., tree pit, tree catchment area), transpiration from a defined plant other than grass (e.g., a tree), and from areas with certain conditions, such as sealing and shading, additional coefficients must be applied to the reference evapotranspiration. A series of authors have measured or modelled (evapo-) transpiration and balanced tree water to estimate the transpiration of urban trees (Pataki *et al* 2011, Vico *et al* 2013, Volo *et al* 2013, Litvak *et al* 2017, Nouri *et al* 2019, Pace *et al* 2021, Rambhia *et al* 2023), only a few studies have focused on evapotranspiration and water demand on a daily or hourly basis (see Rambhia *et al* 2023). Furthermore, only a few studies have considered heterogeneous urban conditions, such as sealing and shading (e.g. Rötzer *et al* 2019, Hörschemeyer *et al* 2021, Wessolek and Kluge 2021, Tams *et al* 2023).

The aims of this study were (i) to map heterogeneous urban site characteristics, including sealing and shading, of 49 individuals, the most common urban tree species, small-leaved lime (*Tilia cordata* sp.) in Berlin, Germany, and (ii) to develop a model to describe the urban tree water balance by coupling tree characteristics with site properties based on the classical Penman-Monteith equation to determine the FAO reference crop evapotranspiration standard. Using this model (iii), we quantified water stress and daily evapotranspiration rates for the exceptionally dry year of 2018 in Berlin, Germany. The model was validated using sap-flow and lysimeter studies of two young linden trees in 2022.

2. Material and methods

2.1. Study area

This study was conducted in Berlin (52°31'N, 13°24'E), the capital of Germany. Berlin is in a temperate transitional zone between maritime and continental climates, with a 9.7 °C long-term average temperature (1991–2020). In summer, the mean maximum air temperature was 26.6 °C.

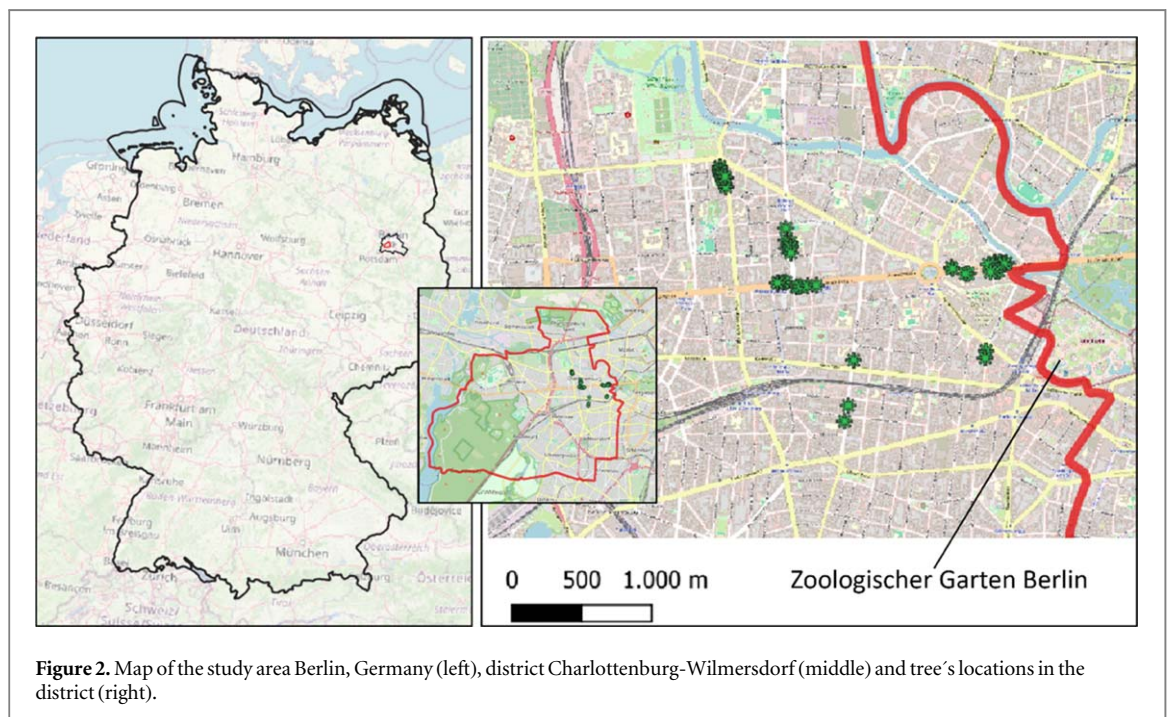
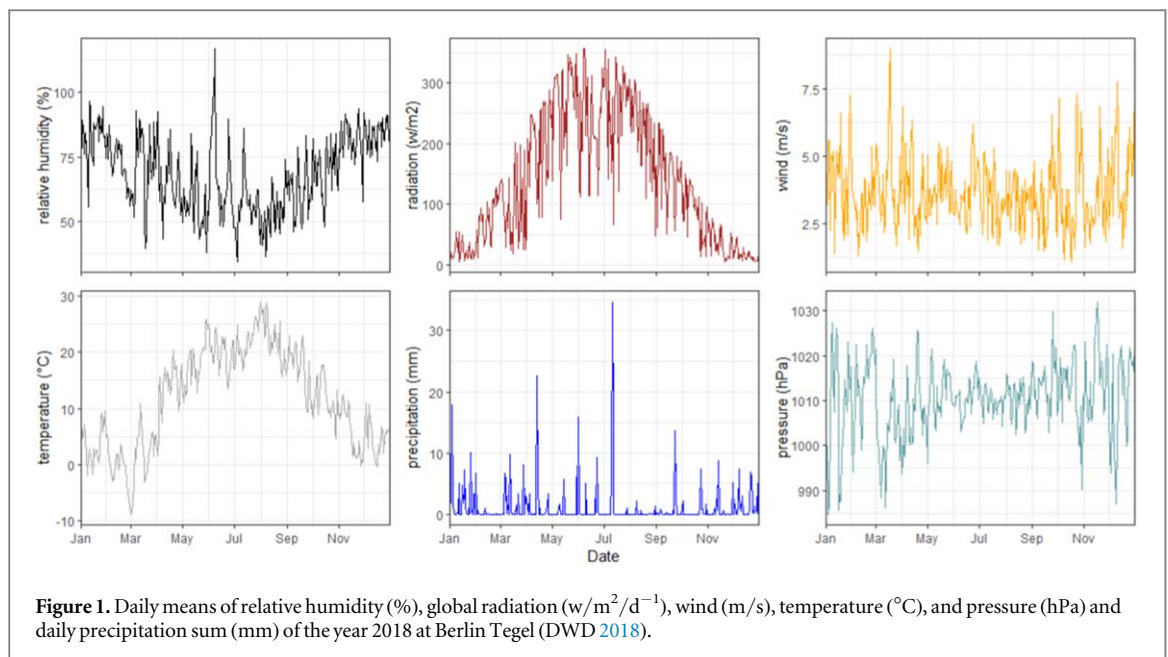
The annual precipitation fluctuates between 510 and 580 mm, with a long-term average of 579 mm (DWD 2024). In 2018, the weather was characterized by new records, with an annual average air temperature of 11.4 °C and 2,165 sunshine hours (long-term average 1,635 h) (DWD 2018). The total precipitation in 2018 was 375 mm, with only 155 mm occurring during the vegetation period (01.04–30.09). Berlin is one of the driest federal states in Germany (figure 1). Berlin's aquifer layers range between 0.5 m and more than 40 m. The center, located in the glacial valley of Berliner Urstromtal, along the Spree and Landwehrkanal rivers, shows relatively high levels of 0.5 m to 4.0 m (Umweltatlas Berlin 2009).

2.2. Model data collection

Hourly climate data were obtained from the climate station Berlin, Tempelhof (DWD station ID 433, DWD 2019). As global radiation data were not available for this station, hourly and daily global radiation data were obtained from the climate station of the HTW located in Berlin, Schöneeweide (HTW 2019). To ensure the availability of data for the entire period under consideration, namely, from June 4 to June 12, the hourly climate data were interpolated. Net precipitation was calculated using hourly data, and for all further calculations (reference evapotranspiration, crop evapotranspiration, soil water balancing, etc.), hourly data were converted to daily data.

2.3. Tree characteristics, site properties and sealing degree

A total of 49 trees of varying ages and differing characteristics were mapped in the district of Charlottenburg-Wilmersdorf (figure 2), which contains approximately 45,000 street trees (Bezirksamt Charlottenburg-Wilmersdorf 2019).



Street widths (building to building) ranged from 20 m to 50 m, with one location (Straße des 17. Juni) with a broad width of approximately 110 m (Google Earth Engine 2019). The criteria for tree site selection were as follows: I) sites with varying groundwater levels, II) sites with varying shading, and III) trees of varying heights. During the field campaign, images of each tree were captured and the dimensions of the tree pits were mapped using a folding rule (figure 3).

The ratio of the pavement categories—asphalt, large pavers, and cobblestones within the catchment area (vertically projected tree crown area minus 30%)—was estimated using field mapping and photography. To investigate how the degree of sealing within the catchment affected the total amount of infiltrated water from precipitation, the tree sites were clustered according to the proportion of sealing: two trees with 38%–59% sealing (mean sealing 49%), 12 trees with 67%–80% sealing (mean sealing 78%), and 35 trees with 81%–95% sealing (mean sealing 90%). These clusters were referred to as P_{in} cluster 1, P_{in} cluster 2, and P_{in} cluster 3, respectively.



Figure 3. Examples of different tree catchment areas (left to right = Richard-Wagner-Straße 41 (ID30), Straße des 17 Juni 23 (ID34) and Fasanenstraße 98 (ID49) with different tree pit and catchment area sizes (details see table S1, supplementary material).

The stand age, age at planting, and groundwater water levels were determined using geospatial data from the Berlin Digital Environmental Atlas. The crown area (i.e., the projected crown area) was calculated using Google Earth Engine and additional verification at the tree sites (Google Earth Engine 2019, Umweltatlas Berlin 2019). Further details on the trees and tree sites can be found in supplementary material (table S1, supplementary material).

2.4. Modell description

The most important equations and parameters to estimate the urban trees water balance and evapotranspiration are described in detail in the following section. All the additional model equations and parameters used are listed in the supplementary material file (tables S1 to S5, supplementary material).

2.4.1. Calculation of the trees water balance

In the applied model approach, the water supply to trees originates either from precipitation (P) or capillary rise from groundwater (C_a); whereby C_a only occurs on non-rainy days (Wessolek *et al* 2009). Moreover, lateral inflow or inflow from sealed surfaces into the catchment area and irrigation were not considered. In contrast, water loss occurs through deep percolation, D_p and evapotranspiration (ET). To estimate the amount of water available for the tree, the proportion of infiltration (P_{in}), the amount of groundwater reaching the effective root zone (Z_r) through capillary rise C_a , the amount of water evaporated from the soil surface (E_e), and the amount of water transpired by the tree (ET_c), were calculated (figure 4).

The infiltration of precipitation (P_{in}) into the tree catchment area equals the gross precipitation minus the intercepted crown storage loss (S) minus the amount of runoff (R_{off}) and can be described as follows:

$$P_{in} = P_{net} - R_{off} \quad (1)$$

where

P_{net} = net precipitation (mm) and R_{off} = runoff, including evaporation from the paved surface (mm).

Net precipitation is calculated as:

$$P_{net} = P_{gross} - S \quad (2)$$

with P_{gross} = gross precipitation (mm) and S = interception storage (-).

Crown interception is a highly dynamic parameter that is influenced by both meteorological parameters and morphological features of the trees (Zabret *et al* 2018). In this study, we used the data from Smets *et al* (2019).

The authors measured S for small-leaved lime trees and determined different interception coefficients based on the total amount of precipitation per rainfall event (table 1). To include the dependence of interception on temperature further, the values of Smets *et al* (2019) were adapted using Turc's (Turc 1961) empirical evaporation equation (equation (3)):

$$S = P_{gross} \frac{T/T + 15}{14^\circ\text{C}/14^\circ\text{C} + 15} S_i \quad (3)$$

with S_i = crown interception coefficient, P_{gross} = gross precipitation (mm) and T = temperature ($^\circ\text{C}$)

To estimate runoff and evaporation from the paved areas, the coefficients of Wessolek *et al* (2008) and Rim (2011) for three different pavement categories and two different coefficients for summer and winter (table 2) were applied (equation (4)).

$$R_{off} = P_{net} \beta \quad (4)$$

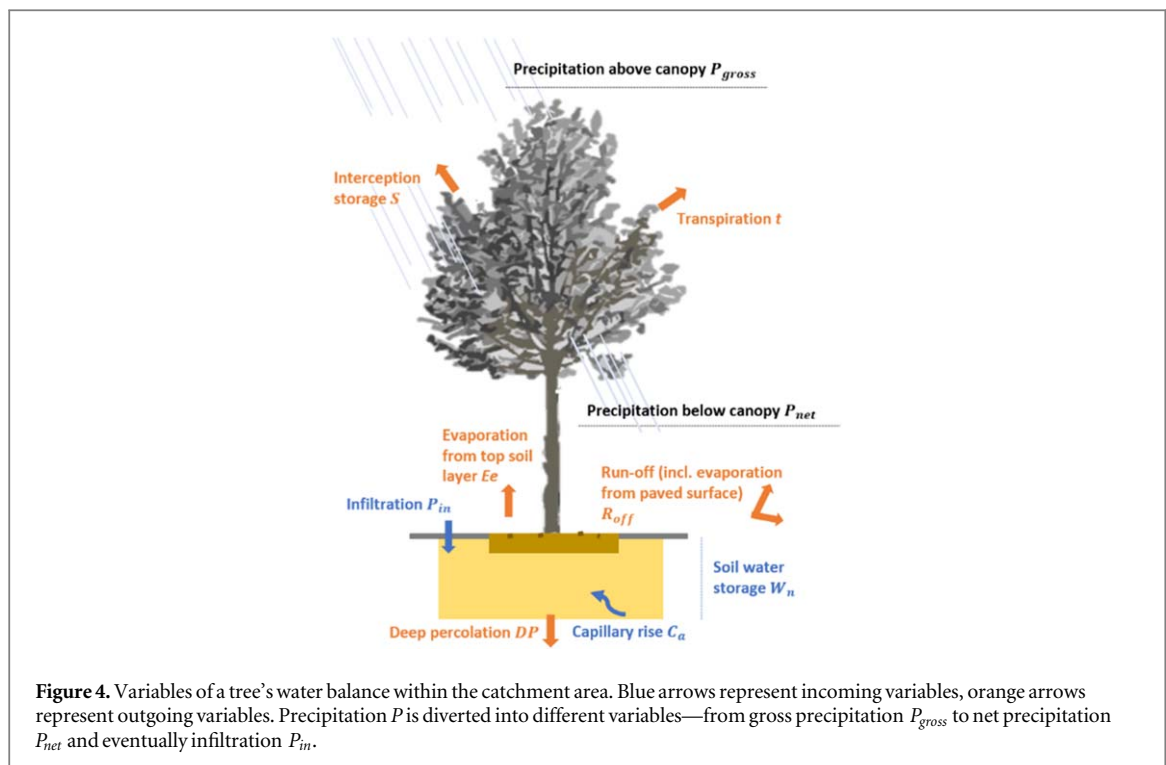


Table 1. Crown interception coefficients S_i according to Smets *et al* (2019) for summer and winter.

Events	Crown interception coefficient S_i	
	Summer S_i	Winter S_i
<5mm	0.44	0.13
5–10mm	0.57	0.26
>10mm	0.23	0.0

Table 2. Runoff coefficients inclusive evaporation for asphalt for summer and wintertime according to Wessolek *et al* 2008, Timm *et al* 2018 and Rim 2011.

Pavement category	Runoff (incl. evaporation) coefficients β	
	Summer β_s	Winter β_w
Road (asphalt)	0.92	0.91
Concrete pavers	0.46	0.25
Cobblestone	0.40	0.19

where

P_{net} = net precipitation (mm)

and the runoff coefficient β (–), including evaporation from the paved surface (mm).

2.4.2. Estimating evapotranspiration

Daily evapotranspiration of the trees, both under the condition of ideal water supply, referred to as ET_0 (potential evapotranspiration), and under water stress conditions, referred to as $ET_{c\ adj}$ (actual evapotranspiration), was calculated using the Penman-Monteith method according to the 'FAO Guideline to compute crop water requirements' (Allen *et al* 1998). An additional step was taken, which was not given by the FAO guideline, namely, from the reference evapotranspiration ET_0 to an adjusted tree individual

Table 3. Reference evapotranspiration ET_0 , individual reference evapotranspiration ET_{0i} , crop evapotranspiration ET_c and adjusted crop evapotranspiration $ET_{c\ adj}$. The $\sim$ symbol points out which elements predict the assigned ET rate. When the soil water storage reaches a certain threshold, the tree suffers water stress and decreases its ET rates— ET_c turns to $ET_{c\ adj}$ (adapted from Allen *et al* 1998).

	ET_0	ET_{0i}	ET_c	$ET_{c\ adj}$
Weather parameters	$\sim$	$\sim$	$\sim$	$\sim$
Actual incoming radiance	Standard (non-limiting)	$\sim$	$\sim$	$\sim$
Plant (tree) characteristics	Reference	Reference	$\sim$	$\sim$
Water stress	Standard (non-limiting)	Standard (non-limiting)	Standard (non-limiting)	$\sim$

evapotranspiration ET_{0i} . ET_{0i} here is defined as the reference evapotranspiration under limited incoming radiation, and represents an easily applicable shading factor (table 3 and equation (5)).

ET_{0i} was calculated using the Penman-Monteith equation (Allen *et al* 2005):

$$ET_{0i} = \frac{0.408\Delta(R_{ni} - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (5)$$

with ET_{0i} = individual reference evapotranspiration of the tree,

R_n = net radiation at the tree surface $\frac{MJ}{m^2}$, e_s = saturation vapor pressure kPa,

e_a = mean actual vapor pressure at 1.5 to 2.5 m height kPa,

Δ = slope of the saturation vapor pressure – temperature curve $\frac{kPa}{^\circ C}$,

γ = psychrometric constant $\frac{kPa}{^\circ C}$, C_n = numerator constant $66\ K\ mm\ s^3/Mg/h$,

C_d = denominator constant $0.25 \frac{s}{m^2}$,

units for the 0.408 coefficient are $m^2\ mm/MJ$.

Because ET_0 was calculated using climate data from the nearest weather station, the atmospheric demand was the same at each tree site. However, it is assumed that ET_0 is not equal at all tree sites because street trees are shaded by surrounding buildings and are not exposed to total radiation. To adjust the actual incoming radiation, the Sky View Factor (SVF) for each tree was determined, applying the corresponding function of the QGIS plugin UMEP (Urban Multi-scale Environmental Predictor, Lindberg *et al* 2018). Using a Digital Surface Model (DSM) of the catchment area of the trees and surrounding buildings as input data, the yearly factor for each tree was calculated. This dimensionless factor describes the ratio of the radiation received by the tree surface to the radiation emitted by the entire hemispheric environment (Watson and Johnson 1987). The incoming solar radiation was multiplied by each SVF, resulting in an individual incoming short-wave radiation for each tree (equation (6)), with

$$R_{ni} = K_i R_n \quad (6)$$

where K_i = sky view factor and R_n = Net radiation MJ/m^2

Therefore, the individual reference evapotranspiration, ET_{0i} for each tree was calculated (see supplementary material table S3, equation T3).

2.4.3. Evapotranspiration with sufficient water supply

The crop evapotranspiration ET_c refers to the evapotranspiration of a specific tree under an ideal water supply under the given climatic conditions, and is therefore also called potential evapotranspiration (figure 5, left). To incorporate the effects of various climatic conditions and tree characteristics on ET_{0i} , a combination of two coefficients (dual crop coefficient), crop transpiration K_{cb} and soil evaporation K_e , (equation (7)) were multiplied by ET_{0i} (Allen *et al* 1998):

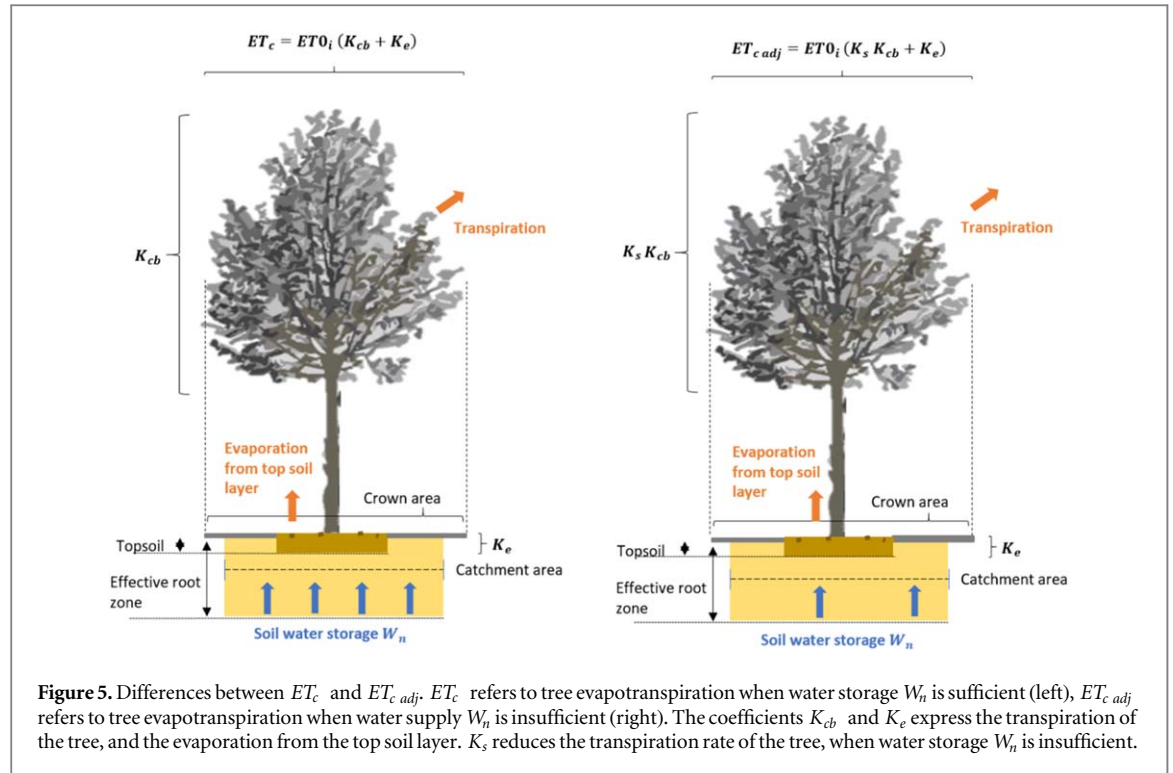
$$ET_c = ET_{0i}(K_{cb} + K_e) \quad (7)$$

with ET_c = potential crop evapotranspiration (mm),

ET_{0i} = tree individual evapotranspiration (mm), K_{cb} = basal crop coefficient,

K_e = soil evaporation coefficient.

The K_{cb} coefficient describes ‘the ratio of the crop evapotranspiration to the reference evapotranspiration (ET_c / ET_{0i}) when the soil surface is dry but transpiration occurs at a potential rate’ (Allen *et al* 1998). It represents the difference between the reference crop and the referred crop (trees, in this case) for albedo, plant height, aerodynamic, and leaf and stomatal properties. The K_e coefficient represents a reduction in evaporation owing to the decreasing amount of water in the surface soil layer. The coefficient K_e oscillates between the



maximum evaporation rate of the exposed wetted topsoil layer (upper 10 cm of the tree catchment area) and zero (dry topsoil, no evaporation).

The calculation of K_e (equation T 5.3, table S5 supplementary material) requires the determination of the maximum value for evaporation and transpiration after rainfall events $K_{c\ max}$ (equation T 5.4, table S5 supplementary material) and the topsoil layer evaporation reduction coefficient K_r (equation T 4.5 to 4.7, table S4 supplementary material). Ultimately, to determine K_e , a daily water balance computation for the surface soil layer was carried out (equations T 4.8 to T 4.9, table S4 supplementary material).

2.4.4. Evapotranspiration with insufficient water supply

The adjusted crop evapotranspiration ($ET_{c\ adj}$) refers to the evapotranspiration of a specific plant facing water shortages under given climatic conditions (also actual evapotranspiration) (figure 5, right). In the soil water balance model, the potential evapotranspiration (ET) and adjusted evapotranspiration ($ET_{c\ adj}$) were determined for each examined tree (equation (8)). Although the meteorological factors, temperature, wind, and relative humidity, which influence the ET rate, were equal in all model runs, the adjustment of the reference evapotranspiration, as well as the determination of the amount of infiltration, allowed us to approach the ET rate of the trees. The water shortage state is expressed by the water stress coefficient K_s , which has a value between one and zero.

$$ET_{c\ adj} = ET0_i(K_s K_{cb} + K_e) \quad (8)$$

where $ET_{c\ adj}$ = potential crop evapotranspiration under water shortage (mm),
 $ET0_i$ = tree individual evapotranspiration (mm), K_s = Water stress coefficient, K_{cb} = basal crop coefficient,
 K_e = soil evaporation coefficient.

$$K_s = \frac{TAW - D_r}{(1 - p)TAW} \quad (9)$$

with K_s = water stress coefficient(–), D_r = root zone depletion(mm)
 and TAW = total available soil water in the root zone (mm).

Root zone depletion at the end of the day (mm) was calculated as follows:

$$D_r = \begin{cases} TAW; & \text{if } D_{r-1} - P_{in} - C_a + ET_c + DP > TAW \\ D_{r-1} - P_{in} - C_a + ET_c + DP & \\ 0; & \text{if } D_{r-1} - P_{in} - C_a + ET_c + DP < 0 \end{cases} \quad (10)$$

with D_r = root zone depletion at the end of day (mm),
 D_{r-1} = water content in the root zone at the end of the previous day (mm),
 P_{in} = infiltration of the precipitation into the tree catchment area (mm/d),

C_a = capillary rise from the groundwater (mm/d), ET_c = evapotranspiration (mm/d),
 DP = water loss out of the root zone by deep percolation (mm/d),
 TAW = total available soil water in the root zone (mm).

TAW was defined as the total available soil water in the root zone. The used TAW value (equation T 5.3, table S5 supplementary material) was derived from the data of Wessolek *et al* (2009), where the rooting depth depends on the stand age of the tree. In this study we used $Z_r = 1.5\text{ m}$ and $Z_r = 0.8\text{ m}$ for old and young trees, respectively. Water stress was defined as readily available soil water RAW (equation T 5.4, table S5 supplementary material). In this study, RAW equals 50% of TAW as mean of all tree values given by Allen *et al* (1998). If the water storage is close to TAW , the water uptake of the plant is equal ET_c .

As soon as the potential energy of the soil water drops below RAW (compare equations T 5.2 to T 5.5, table S5 supplementary material), a plant experiences water stress (Allen *et al* 1998).

2.4.5. Daily soil water storage in the trees' catchment areas

Following the FAO guidelines (Allen *et al* 1998), the daily soil water storage (W_n) is expressed in terms of depletion (D_r) at the end of the day (equation (11) and equation T 3.1, table S3 supplementary material). The change in soil water storage is the sum of positive change = inflow and negative change = outflow (equation (11) and equation T 3.2, table S3 supplementary material). The soil water model started on April 1st (start of the vegetation period) to the end of the vegetation period on September, 30st. It was assumed that at the beginning of the vegetation period, the soil water storage in the root zone equaled TAW (Larcher 2003). Water storage oscillates between TAW and PWP , defined as the permanent wilting point, which is the share of soil water inaccessible to plants (equation (11)).

$$W_{n+1} = \begin{cases} TAW, & \text{if } W_{n+1} + P_{in} + C_a - ET_{c\ adj} - DP > TAW \\ W_{n-1} + P_{in} + C_a - ET_{c\ adj} - DP \\ PWP; & \text{if } W_{n+1} + P_{in} + C_a - ET_{c\ adj} - DP < PWP \end{cases} \quad (11)$$

where W_n = daily soil water storage (mm), TAW = total available soil water in the root zone (mm),
 PWP = permanent wilting point,
 DP = water loss out of the root zone by deep percolation (mm/d),
 $ET_{c\ adj}$ = adjusted crop evapotranspiration. W_{n+1} is an individual value for each tree.

2.4.6. Capillary rise

We focused on geospatial data from the Berlin Digital Environmental Atlas, analyzing trees with root depths of up to 150 cm. Trees with root depths less than 80 cm were excluded, as they were assumed to lack access to water via capillary rise. We identified 31 trees with no access to groundwater and 10 trees with access to groundwater via capillary rise. Owing to the varying soil textures, these trees were grouped into two categories based on their capillary rise rates: 0.3 mm per day (eight trees) and 2.8 mm per day (two trees).

2.5. Model validation

2.5.1. Lysimeter measurements

To evaluate the performance of the model, we conducted weighing lysimeter and sap flow measurements on two young little-leaf linden (*Tilia cordata*) trees, Tc1 and Tc2, which were planted in 2016 in weighing lysimeters in a suburban area of Berlin Marienfelde, Germany (52°23'48.21°N, 13°22'4.04°E). Before the commencement of the growing season in 2022, crowns of the trees in the lysimeters were trimmed to a circumference of 1 m². The lysimeters were made of steel, with a surface area of 1 m² and a depth of 1.5 m. Each lysimeter was equipped with a 30-liter weighted tank designed to measure the groundwater recharge (exfiltration) of the system. The weighing precision was 100 g for the soil monolith, and 5 g for the tank. Data were recorded every minute using a data-logging system of UGT, Germany. The lysimeters were filled with three soil horizons. The subsoil consisted of 15 cm of gravel followed by 35 cm of sand, which ensured efficient discharge of infiltrated rain and irrigation water. The topsoil, is a sandy layer, 100 cm deep, with an organic content of approximately 15% (table 4).

To account for fluctuations in lysimeter data caused by wind, maintenance, and other factors, we processed our data using the Savitzky–Golay filter routine (AWAT) developed by Peters *et al* (2014). AWAT is specifically designed for processing field lysimeter data, and employs an adaptive threshold to distinguish between significant and insignificant mass changes. This ensured that the precipitation (P) and evapotranspiration (ET) were not overestimated. The filter also uses step interpolation between significant mass changes to improve the accuracy. Additional information on the AWAT filter routine can be found in Peters *et al* (2014).

Table 4. Soil texture, pH, and other physical parameters of the lysimeter soil substrates.

Depth (cm)	Texture	C _{org} (%)	pH (CaCl ₂)	Dry bulk density (g/cm ³)	pF 0	pF 1.8
0–100	Loamy sand	15.2	7.2	0.9	63.1	40.8
100–135	Fine sand	0.2	4.4	1.5	42.4	8.8
135–150	Gravel	n.m	n.m	n.m.	n.m	n.m

2.5.2. Sap-flow measurements

Sap-flow measurements were conducted in addition to lysimeter measurements. A detailed description of sap flow measurements and calculations can be found in Wessolek and Kluge (2021).

2.5.3. Soil moisture measurements

Soil moisture sensors (Decagon 5TM) were installed at two depths (40 cm and 90 cm) in each lysimeter ($n = 4$). The trees received supplementary irrigation in addition to natural precipitation. The model used precipitation and irrigation data as well as climate data as the input parameters.

2.5.4. Model performance

The modelled evapotranspiration (ET) rates were compared with measured lysimeter and sap flow data from two young linden trees. The model parameters were matched to the specific trees planted in the lysimeter, including tree crown area, precipitation amount, soil texture, and SVF. The model performance was evaluated using the mean absolute error (MAE) and root mean square error (RSME) for the period from June 1st to July 30, 2022.

To further validate our results, we compared the mean ET rates of all 41 trees ($Z_r = 150$ cm) with the measured ET data from small-leaf linden trees in urban areas reported in the literature. Additionally, we compared the evapotranspiration data for an example tree (ID 34, see table S1 supplementary material) during the 2018 growing season with the results of a model run using the approach of Wessolek and Kluge (2021). This model allows the calculation of evapotranspiration for street trees in sealed urban areas on a yearly basis. The input parameters for tree ID 34 were matched to those used in this study, including the tree crown area, precipitation amount, soil texture, SVF, sealing material, and degree of sealing.

3. Results

3.1. Tree characteristics, site properties and sealing degree

The median crown area of all investigated trees was 43.0 m^2 , with a range of 10.2 m^2 to 113.1 m^2 . Stand ages ranged from 16 to 70 years, with a median age of 44 years. The median height of the trees was 12 m, with a range of 7–25 m (with the largest tree being an outlier). The sky view factor (SVF) ranged from 0.59 to 0.99, with a median SVF of 0.85. Most trees were planted between 1977 and 1989 (32 trees), with plantations dating back to 1953, and as recently as 2008. On average, the catchment area was sealed by 84%, the average size of the tree pit was 4.12 m^2 , with a minimum of 2.8 m^2 and a maximum of 8.05 m^2 . On average, more than 70% of the catchment area is sealed with asphalt and large pavers, which is attributed a much lower infiltration rate than cobblestone (figure 6; see also table S1 supplementary material).

3.2. Model evaluation for the year 2022

3.2.1. Evapotranspiration

A comparison of the daily evapotranspiration data obtained from lysimeter and sap flow measurements revealed a similar trend with deviations of 11% and 5.7% from the total sum for the period June 1st to July 30th, 2022 (table 5 and figure 7). However, the daily deviations are higher, with mean absolute errors (MAE) of 2.7 and 2.9 mm day^{-1} and root mean square errors (RSME) of 3.3 and 3.6 mm day^{-1} , respectively. A weak linear correlation was observed between the model and sapflow data, with an R^2 value of 0.24, and between the model and lysimeter data, with an R^2 value of 0.18. The model captures the general trends observed in the data but may not accurately represent underlying patterns, such as soil moisture and evaporation from soils and leaves, as well as interception following precipitation or irrigation events. This was particularly evident when comparing the lysimeter measurements with the model output (figure 7). A linear regression through the origin resulted in R^2 value of 0.87 and 0.83, respectively (table 5 and figure S1 supplementary material).

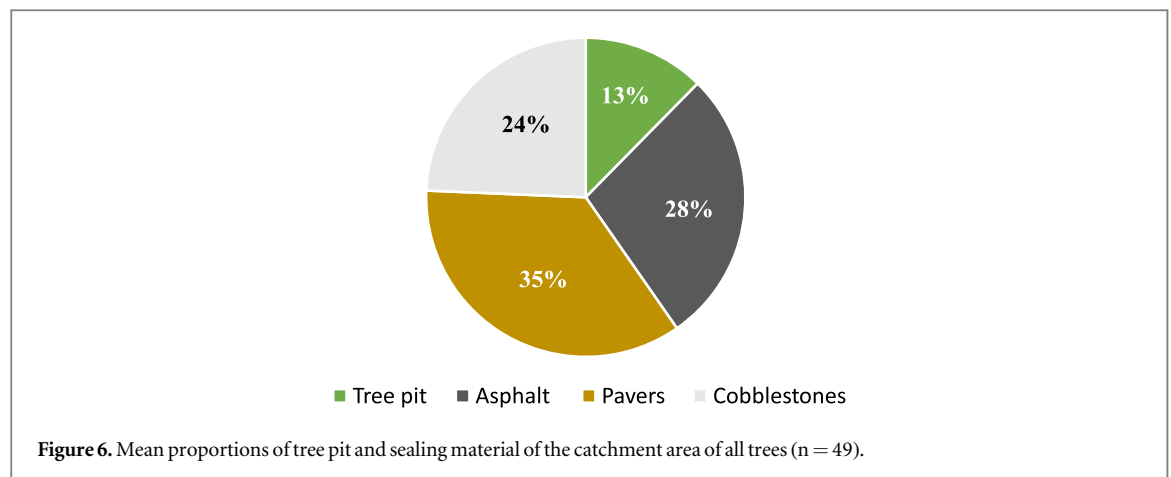


Table 5. Comparison of modelled and measured ET by lysimeter as well as T by sapflow, deviation, MAE, RSME, and R^2 to describe the differences between predicted and observed values (01.06–31.07.2022).

results Modelled/measured	ET mm/period	Deviation of mm/period %	MAE mm/d	RSME mm/d	R^2
Modelled ETc	306	—	—	—	—
Measured Sapflow T*	326	5.7	2.7	3.3	0.24 (0.87')
Measured Lysimeter ET*	352	13.0	2.9	3.6	0.18 (0.83')
Modelled/Measured SM**	—	—	14	17	0.78 (0.99')

*mean (n = 2); *** mean (n = 4); 'linear regression through origin.

3.2.2. Soil moisture

During the investigated period, both modelled and measured soil moisture curves showed similar patterns, with slight deviations on days with high precipitation. The measured soil moisture was generally higher than the simulated soil moisture, particularly on days of high precipitation. The differences between the modelled and measured soil moisture values were quantified using metrics such as the Mean Absolute Error (MAE) and Root Mean Square Error (RSME), which yielded values of 14 and 17 mm/d, respectively. Linear regression analysis revealed a strong correlation between the measured and simulated daily soil moisture values with an R^2 value of 0.78, indicating a moderate level of correspondence. A linear regression through the origin resulted in R^2 value of 0.99 (figure S2 supplementary material).

3.3. Model results for the dry year 2018

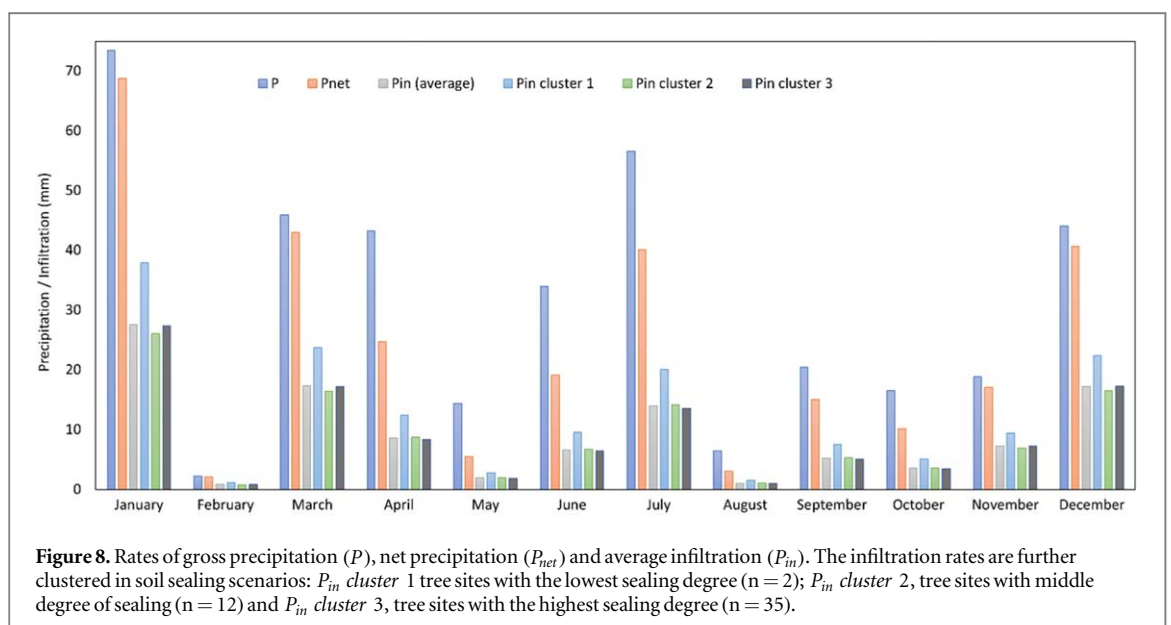
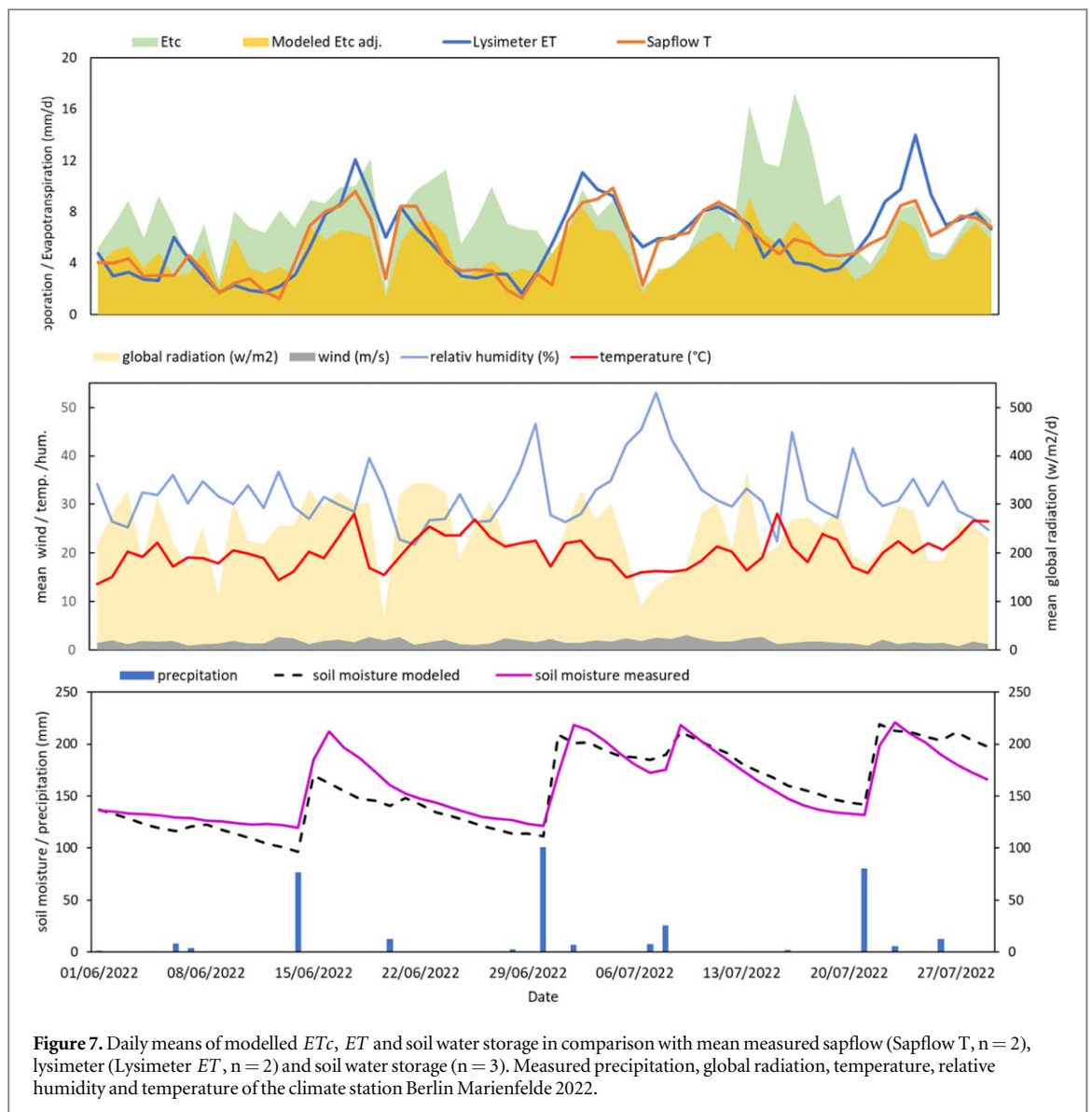
3.3.1. Precipitation, infiltration and interception year

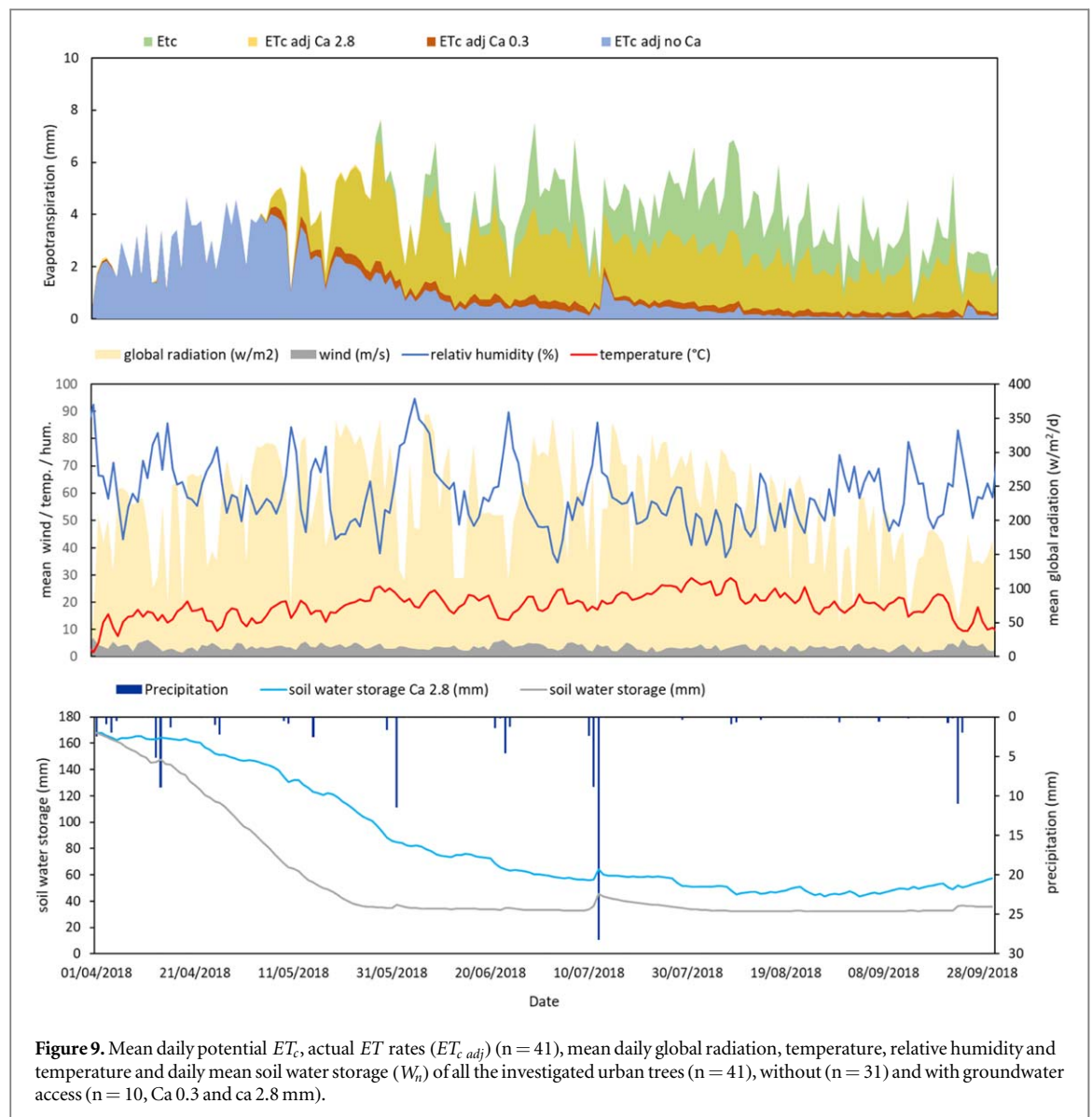
In 2018, the total amount of precipitation was 375.9 mm (DWD 2018, weather station Tempelhof) (figure 1 and figure 8), during the vegetation period, gross precipitation was 191.5 mm (which equals 51% of total precipitation). The total number of precipitation events was 129. Most of the precipitation occurred in January and July (20% and 15% of total precipitation, respectively), and the least precipitation occurred in February and August (1% and 2% of total precipitation, respectively). model results showed that on average 97.6 mm (26%) of the precipitation (P) was lost by crown interception (S) throughout the year, leaving a total of 289.2 mm (77%) to net precipitation. A mean sum of 111.2 mm (30%) infiltrated into the soil, which corresponds to a value of 53% of precipitation leading to runoff (figure 8).

The infiltration rate of tree sites with the lowest sealing degree (P_{in} cluster 1) was 53% for net precipitation, 37% for trees with middle-sealing degree (P_{in} cluster 2), and 38% for trees with the highest sealing degree (P_{in} cluster 3). A decrease in sealing within the catchment area by 41% led to an increase in infiltration by 40% during the vegetation period compared to the average infiltration rate of all examined trees, with an average proportion of sealing of 84%. A decrease from 84% sealing to 78% only led to an increase in infiltration of 1%, whereas an increase in sealing from 84% to 90% led to a decrease in infiltration of 4%.

3.3.2. Evapotranspiration and depletion of the soil water storage

During the vegetation period (01.04–30.09), the mean potential evapotranspiration (ET_c) without water limitations was 3.8 mm d⁻¹. The highest potential evapotranspiration was observed in May, with a rate of 7.6 mm d⁻¹, while the lowest rate was recorded in April, at 0.3 mm d⁻¹ (figure 9). The mean actual





evapotranspiration ($ET_{c\ adj}$) for all trees ($n = 41$) were as follows: April, 2.60 mm d^{-1} ; May, 3.3 mm d^{-1} ; June, 1.6 mm d^{-1} ; July, 1.4 mm d^{-1} ; August, 0.93 mm d^{-1} ; and September, 0.70 mm d^{-1} , with a mean of 1.1 mm d^{-1} .

The mean actual evapotranspiration rates for specific tree sites were: 2.9 mm d^{-1} for trees with capillary rise of 2.8 mm d^{-1} ; 1.27 mm d^{-1} for trees with capillary rise of 0.3 mm d^{-1} ; and 1.1 mm d^{-1} for tree's without capillary rise, with maximum values of 6.78 , 4.67 , and 4.26 mm d^{-1} , respectively, and minimum values of 0.3 , 0.1 , and 0.1 mm d^{-1} , respectively (figure 9). The actual evapotranspiration rates varied across tree sites, except in April. Trees without capillary rise had the lowest evapotranspiration rates, whereas those with a capillary rise of 2.8 mm per day had the highest. By early May, evapotranspiration at tree sites without and those with an additional capillary rise of 0.3 mm had fallen below potential evapotranspiration rates and remained below them for the rest of the vegetation period.

In contrast, tree sites with an additional capillary rise of 2.8 mm d^{-1} experienced a decline in actual evapotranspiration rates 23 days later but recovered by the end of October. The mean soil water storage of all trees was the highest at the beginning of April and steadily decreased throughout the summer (figure 9). However, the rates of soil water depletion and refilling differed between trees with no capillary rise and with capillary rise (table 6). Trees without capillary rise fully depleted their soil water storage in August, whereas those with capillary rise did so in September. By the end of September, soil water storage had declined to 20% of total available soil water in the root zone for trees without capillary rise and more than 50% of those with capillary rise. The critical threshold (RAW), which induces water stress and causes trees to lower their evapotranspiration rate, is exceeded in May. Trees with and without capillary rise experienced water stress that persisted until the end of the vegetation period. This resulted in an insufficient water supply for 182 and 176 days. Trees with

Table 6. Average monthly means of soil water storage (W_n) for trees with Ca 0.3 and Ca 2.8 and without groundwater supply (no Ca) and share of total available soil water in the root zone (TAW) and readily available water (RAW) = average monthly threshold below which water stress is experienced.

Month	W_n no Ca (mm)	TAW (%)	W_n Ca 0.3 (mm)	TAW (%)	W_n Ca 2.8 (mm)	TAW (%)	RAW mean (mm)
April	138.9	83	140.2	83	160.5	96	91.5
May	56.9	34	59.4	35	122.2	73	77.7
June	34.3	20	31.7	19	72.8	43	81.3
July	36.7	22	34.3	20	57.6	34	76.8
August	32.6	19	31.5	19	47.8	28	80.3
September	33.5	20	32.6	19	50.0	30	90.2
October	36.7	22	36.0	21	71.0	42	100.2
November	42.9	26	43.5	26	118.3	70	109.0
December	56.6	34	57.0	34	162.5	97	108.7
Mean Apr-Oct	52.8	31	52.3	31	83.1	49	85.4
Mean year	52.1	31	51.8	31	95.8	57	90.6

capillary rise at a rate of 2.8 mm d^{-1} had a comparable soil water supply to total available soil water in the root zone (TAW) in April, but exhibited a less pronounced decline in May. Water stress lasted from June 2nd onwards, totaling 147 days of insufficient water supply.

4. Discussion

4.1. Model evaluation and tree (evapo-) transpiration

An evaluation of the adapted FAO56 approach to predict tree water supply and evapotranspiration rates showed good agreement with the measured lysimeter and sapflow data from 2022 on a daily scale, even when the measured evapotranspiration rates were generally higher. Green and Clothier (1999) and Green *et al* (2003) used an adapted Penman-Monteith model to calculate the evapotranspiration of apple trees. The modelled actual evapotranspiration corresponded well with the measured sap flow data. Pereira *et al* (2006) concluded that the daily evapotranspiration of trees, in this case walnut and apple trees, could be estimated using the conventional grass reference evapotranspiration parameterized by the FAO-56 bulletin (Allen *et al* 1998), provided that the input data of nearby weather stations were measured and the canopy was well irrigated. However, a comparison between the modelled and measured values demonstrated that the method employed was also capable of depicting actual evapotranspiration of urban trees under dry soil conditions (figure 7; e.g., June 19th – 29th or July 15th–20th).

The model results for the very dry year 2018 showed that the actual evapotranspiration of the investigated urban trees without an additional water supply sharply decreased at the beginning of May, whereas the other trees showed nearly potential evapotranspiration until mid-June. In comparison with the potential evapotranspiration, the mean actual evapotranspiration of trees without additional water supply was reduced by more than one-third. Several studies have indicated that different tree species exhibit reduced transpiration in response to drought (e.g., Hogg *et al* 2002, 2008, Gartner *et al* 2009). The latter authors determined reduced transpiration of birch and spruce growing in southeastern Austria, amounting to more than half of the original transpiration under persistent drought. This is in line with the reduction in ET determined by sapflow and lysimeter measurements from 2022. In contrast, our modelled results from 2018 showed a greater reduction in evapotranspiration rates, which could be mainly due to low precipitation and the associated lower soil moisture.

In a drought experiment conducted on the *Tilia* sp. in Guangzhou, Zhang *et al* (2023) simulated the evapotranspiration of controlled (well-watered) and drought-simulated *Tilia cordata* using the city-tree model (Rötzer *et al* 2019). The simulation study demonstrated a significant decrease in evapotranspiration rates, with a more than three-fold reduction in evaporation rates (from 2.5 to $0.7 \text{ m}^3 \text{ tree}^{-1}$).

Only a limited number of studies have reported measured transpiration data from urban trees, making it possible to compare ET values obtained in this study (table 7). In a study by Gillner *et al* (2015), transpiration of a *Tilia cordata* ‘Greenspire’ was measured during June, July, and August of 2013 in the city of Dresden, Germany, which includes a long period of heat and drought between June and August. the mean transpiration rate was 1.87 mm , whereas the mean evapotranspiration rate between June and August of the present study was 50% lower (0.9 mm). Despite the periods of drought in both years, in Dresden 2013, the evaporative demand and aridity index were much lower during spring (DWD 2013a), and precipitation was roughly doubled (DWD 2013b), which might explain the higher transpiration rates in Dresden.

Rahman *et al* (2019) determined the transpiration of 10 street trees of *Tilia cordata* in May, June, and July 2017 in Munich, Germany using sapflow measurements. The trees were located on a lawn 1.5 m away from an

Table 7. Comparison of (evapo-) transpiration rates of linden trees with data of other authors.

	Present study 2018	Wessolek/Kluge 2021 ^b	Rahman <i>et al</i> 2019 ^a	Gillner <i>et al</i> 2015
Location	Berlin, Germany	Berlin, Germany	Munich, Germany	Dresden, Germany
Mean temp. precipitation sum	9.1 °C	9.1 °C	9.7 °C	9.2 °C
Method	379 mm Penman-Monteith	379 mm Penman approach and lysimeter studies	944 mm Thermal dissipation probes	< 700 mm Gas-exchange measuring system
Period	May - August 2018	May - August 2018	May - July 2017	June - August 2013
Tree species (n)	41 x <i>T. cordata</i>	1 x <i>T. cordata</i>	10 x <i>T. cordata</i>	1 x <i>T. cordata</i>
Mean height (m)	12	Tree ID 34	10.6	10.9
Mean stand age (y)	38	7 15	36	30
ET (mm d ⁻¹)	(mean/period) 1.1	(mean/period) 1.0	(mean) 1.4	(mean) 1.9
ET (l per tree)	Tree ID 34 2701	Tree ID 34 2380	— —	— —

^a Rahman *et al* 2019 = 1500 l month⁻¹ divided by 30.5 days and 35 m² projected crown area.

^b Wessolek and Kluge 2021 = model results of tree ID 34 of this study with same data input; ET (mm/d) of vegetation period divided by 180 days.

asphalt street. Transpiration of *Tilia cordata* was specified as approximately 1500 l m⁻¹, which is equal to a mean transpiration rate of 1.4 mm d⁻¹. The average (evapo-) transpiration within the period of May-July in the present study was 1.4 mm, as well. The mean actual evapotranspiration rate for all trees (n = 41) in this study was 1.1 mm d⁻¹. It is expected that the evapotranspiration rate in the Munich study was higher because of differences in meteorological factors and presumably more favorable water supply conditions, as the precipitation amounts were much higher in Munich in 2017 than in Berlin in 2018 (DWD 2017, 2018). However, the evaporative demand was lower (DWD 2017), which could explain the similarities between the evapotranspiration in the Munich study to a certain extent.

Evapotranspiration, especially under drought, of tree ID34 (see table S1 supplementary material) was also modelled using the Hydro-Pedo-Transfer-Functions (HTPFs) described in Wessolek and Kluge (2021). The total evapotranspiration of tree ID34 from April 1 to September 30 was 2541 l tree⁻¹, whereas the total evapotranspiration calculated in this study was 2701 l tree⁻¹, resulting in a deviation of 6.3%.

4.2. Soil water storage

The modelled mean soil water of all investigated trees without additional water supply in 2018 was highest at the beginning of the vegetation period but dropped to low values by the end of May. Soil moisture measurements conducted by the Plant Protection Agency in Berlin (Pflanzenschutzamt Berlin 2018) revealed a sharp decline in soil water content, dropping below 30% of the total available soil water in the root zone (TAW) at a tree pit in mid-May, 2018. This decline persisted throughout the summer months, reaching less than 5% in June and July. Scharnweber *et al* (2020) measured soil moisture at various depths in old-growth mixed broadleaved forests in NE Germany, close to the city of Greifswald. Although the data were not directly comparable, as they were measured in the forest stands of beech and oak trees rather than in urban areas, a similar trend of decreasing soil moisture (sand to loamy sand, similar to Berlin) was observed. The measured soil moisture decreased sharply with a slight delay from the beginning to the middle of June, reaching 0.1 m³/m³. Both studies yielded results consistent with the soil moisture values in the tree pits, as shown in figure 9. However, they also demonstrated that despite significant water stress, there was no mortality in these trees.

4.3. Implications and further research directions

The results of our model indicate that trees in Berlin's inner city, without supplementary irrigation during the 2018 very dry year, exhibited significant water stress throughout the vegetation period. The following years, from 2019 to 2022, were distinguished by markedly lower precipitation rates in Berlin, ranging from -72 to -148 mm, in comparison to the long-term average annual precipitation (1991-2020), with the exception of 2021, which saw an increase of 27 mm (Meteoplus 2024). The reduction in precipitation was particularly evident during the growing season (April-October), when trees require more water because of increased transpiration and photosynthesis. These findings suggest that urban trees can access additional water sources. They also exhibit certain adaptations to dry conditions, such as drought tolerance and deep fine root growth, which enhance their water uptake capacity (e.g. Zhang *et al* 2019). Despite showing signs of decline, the investigated

trees remained alive. However, the longevity of these trees under these conditions remains unclear. Several studies have demonstrated that a lack of water negatively affects the annual growth rate, vitality, and ecosystem services of urban trees (Vico *et al* 2014, Moser *et al* 2016, Haase & Hellwig 2022). Furthermore, the increasing frequency of drought and extreme heat waves may exacerbate water stress experienced by urban trees (Teskey *et al* 2015, Van Loon *et al* 2016). Scharnweber *et al* (2020) concluded that there would be a significant decline in the growth of deciduous tree species in northern Central Europe in the event of a future characterized by drier and warmer climatic conditions. This could result in the further deterioration of tree health and ecosystem function, ultimately causing trees to decline or even die. This trend was also reflected in the increasing degree of tree damage and massive tree mortality among the street trees. In recent studies, Haase and Hellwig (2022) found that trees in Leipzig experienced a significant decline, whereas initial analyses of tree population data from Berlin suggested similar trends (Umweltatlas Berlin 2023). Therefore, it is imperative to understand the effects of water demand, drought, and heat stress on urban trees to ensure long-term resilience and health of urban ecosystems. This necessitates the diverse and comprehensive monitoring of soil water content, evapotranspiration rates, and the health status of urban trees to identify early warning signs of stress. Furthermore, it is necessary to develop more sophisticated models to predict water stress and water demand to optimize site conditions in terms of water supply and uptake. By integrating data from field monitoring and modelling, we can gain a deeper understanding of the complex relationships among water availability, tree health, and ecosystem function, which will ultimately inform strategies for improving urban tree management and resilience.

4.4. Study limitations and sources of error

The comparability of our results is limited by various factors including differences in meteorological conditions, study areas, site properties, and tree species. Additionally, methodological differences may have affected our findings. Our results are strongly limited to the FAO Penman-Monteith method (Allen *et al* 1998) with the adaptation described in section 2.4 and tables S2 to S5 supplementary material. Therefore, our results restricted to this approach for determining the reference evapotranspiration (ET_0). This method is widely recommended for calculating ET_0 , but it also has some flaws. For example, the method could lead to an overestimation of net radiation (R_n) and aerodynamic factors, which might result in an overestimation of ET_0 (Hlaváčiková & Novák 2013, Hao *et al* 2018). We also observed this overestimation at our validation period from July 13 to July 20, 2022 by comparing it with lysimeter and sap-flow data (figure 7).

The present study was conducted in the Cfb climate zone and is limited to the tree species *Tilia cordata*, which is the most common tree in the city of Berlin, Germany, and is also prevalent in Central European cities. Consequently, the results may not be representative of the broader region and other tree species. It would, therefore, be advisable to test and validate the model results for other regions and species. This is particularly important for crop transpiration coefficients for trees in urban areas.

Crop transpiration coefficients have a great influence on the transpiration rate and are challenging to determine due to both inter-species and intra-species variability. We selected a crop transpiration value of $K_{cb} = 0.85$ and $K_{c_{adj}} = 0.46 - 1.18$ which is similar to the coefficient ($K_{cb} = 0.83$, $K_{c_{adj}} = 0.31 - 1.59$) reported by Montague *et al* (2004). This value was determined based on transpiration measurements of young *Tilia cordata* 'Greenspire' in Texas, U.S. Environmental factors, such as those identified by Allen *et al* (1998), can also influence these coefficients.

We calculated the amount of infiltration from net precipitation using infiltration coefficients from the literature, considering differences in surface material and season. Soil compaction may have prevented infiltration at the beginning of the rainfall event, leading to waterlogging in the tree pit, increased evaporation, and potentially lower infiltration rates.

This study did not consider several factors that affect interception loss, including wind direction and tree crown shape, as described by Huang *et al* (2017). To incorporate these factors, we could consider using an alternative model such as that developed by Huang *et al* (2017). Stemflow, which is particularly important for isolated urban trees, has been shown to play a crucial role in both interception and infiltration processes (Schooling and Carlyle-Moses 2015, Carlyle and Schooling 2015, Rahman *et al* 2019). Given the disparity between our calculated interception rates and those reported in the literature (table S6 supplementary material), we recommend incorporating additional parameters into the models proposed by Huang *et al* (2017) and the proposed method.

In our approach, soil water supply was the primary driver of ET throughout the vegetation period. Trees with higher soil water storage due to groundwater supply can maintain ET levels for longer periods than those without groundwater supply. In this study, we defined RAW as 50% of TAW based on the mean of all tree values reported by Allen *et al* (1998). This value may vary, influencing the ET rates accordingly. One trait of *Tilia cordata* that is not included in our water balance model is that it is anisohydric, meaning that it could keep stomata open and photosynthetic rates high for longer periods, even in the presence of decreasing leaf water

potential (Sade *et al* 2012). *Tilia cordata* transpired almost three times more than an isohydric tree species during summer in a residential area (Rahman *et al* 2018).

When the water supply is sufficient, transpiration of urban trees, in general, is mainly driven by radiation, wind, and vapor pressure deficits. This effect is reflected in our model in that SVF was significantly correlated with *ET* only in April, when water storage was not limited. Owing to the lack of small-scale data, we assumed that the wind, temperature, and humidity parameters were the same for all tree locations. However, owing to the heterogeneous building structures in urban areas, such as street canyons (wind corridors), these parameters can vary significantly on a small scale and strongly affect evaporation results. The calculation can be supplemented with 3D urban structures and climate models to increase accuracy, such as QGIS with UMEP (Lindberg *et al* 2018); however, this is mostly very time consuming, especially for larger areas.

5. Conclusions

Our approach combines urban tree catchment soil water storage with an adapted Penman-Monteith model to analyze and predict water supply and evapotranspiration, thereby enabling us to better understand the impact on street trees. The determination of the soil water storage, evapotranspiration rate, and further tree characteristics and site properties of 49 small-leaved lime trees, located in different streets in Berlin, has come to the concerning result that severe water stress started early in the year and persisted throughout the above-average dry and hot summer of 2018. Precipitation events are too weak to refill soil water storage, making groundwater the only source of water supply. However, only a few of the examined street trees benefited from the groundwater via capillary rise. Without capillary rise, trees were predicted to experience up to 182 d of water stress during the growing season. In contrast, trees that were attributed to a capillary rise rate of 2.8 mm d^{-1} reached the critical threshold approximately one and a half months later, with 35 fewer days of water stress. In Berlin, 35% of all street trees are lime trees, which provide valuable ecosystem services during heat waves by shading and cooling through transpiration, even when water supply shortens. The model results highlight the need for proactive water management strategies to ensure the health and well-being of urban trees under future climate change scenarios.

During dry summers, such as in 2018, an increase in infiltration solely within the catchment area may not be sufficient to meet the water requirements of trees. Moreover, it is necessary to improve water supply to trees, particularly during drought periods. Therefore, a combination of water catchment area enlargement (e.g., using small cobblestones or water-permeable pavement) and a controlled direct and/or delayed water supply by stormwater runoff should be developed, designed, and promoted. Run-off water from adjacent sealed areas, such as sidewalks and bike paths across residential areas with low pollutant load potential, would be suitable. In new building areas, additional water supply through cisterns should be encouraged, whether above or below ground.

More research is needed to test and calibrate the model and adapted coefficients, such as the parameters for the individual soil water balance of the trees (e.g., different soil types and *RAW*), individual tree evapotranspiration (crop transpiration coefficients), and radiation reduction factors to describe shading in urban canyons (e.g., sky view factor and shading models). The model should be tested and validated in other cities and climatic regions. Furthermore, the model must be verified using empirical data obtained from street trees in different urban environments. This could then provide better insights into future water supply management, making it a useful planning tool for improving water-efficient street tree design and maintenance. This can help to identify areas where trees may be at risk of water stress, which can subsequently impact their health and ability to provide essential ecosystem services. This will be a worthwhile topic for future research.

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Data availability statement

The full set of model formulas and data for the investigated trees can be found in supplementary material. The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest declaration

The authors declare that they have no conflicts of interests.

Ethical approval

Not applicable.

ORCID iDs

Björn Kluge  <https://orcid.org/0000-0003-3010-2270>

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