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Ecohydrological consequences of tree removal in an urban park evaluated using open data, free software and a minimalist measuring campaign

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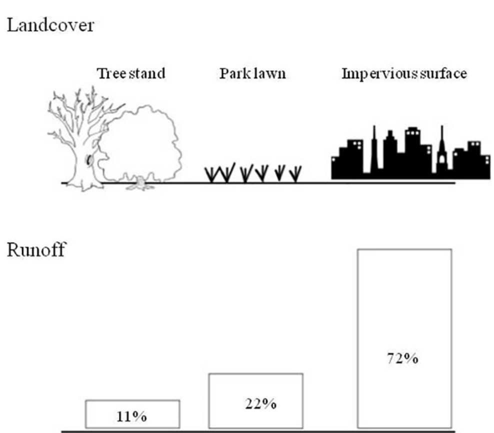
HIGHLIGHTS

- Ecohydrological aspects of urban green areas are increasingly important.
- Minimalist approach confirmed to yield sufficient results.
- Trees in urban parks offer higher quality ecohydrological services than lawns.
- Easily applicable approach to ecohydrological assessment of urban parks

GRAPHICAL ABSTRACT



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ABSTRACT

With ongoing global climate change and an increasingly urbanized population, the importance of city parks and other forms of urban vegetation increases. Trees in urban parks can play an important role in mitigating runoff and delivering other ecosystem services. Park managers, E-NGOs, citizen scientists and others are increasingly called upon to evaluate the possible consequences of changes in park management such as, e.g., tree removal. Here, we present an unorthodox approach to hydrological modelling and its potential use in local policy making regarding urban greenery. The approach consists of a minimalist field campaign to characterize vegetation and soil moisture status combined with a novel model calibration using freely available data and software. During modelling, we were able to obtain coefficients of determination (R^2) of 0.66 and 0.73 for probe-measured and simulated soil moisture under tree stand and park lawn land covers respectively. The results demonstrated that tree cover had a significant positive effect on the hydrological regime of the locality through interception, transpiration and effects on soil moisture. Simulations suggested that tree cover was twice as effective at mitigating runoff than park lawn and almost seven times better than impervious surfaces. In the case of a potential replacement of tree vegetation in favour of park lawn or impervious surfaces an increase in runoff of 14% and 81% respectively could be expected. The main conclusion drawn from our study was that such an approach can be a

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very useful tool for supporting local decision-making processes as it offers a freely available, cheap and relatively easy-to-use way to describe the hydrological consequences of landcover change (e.g., tree removal) with sufficient accuracy.

1. Introduction

Urban areas around the world are increasingly subject to extreme climatic and hydrological conditions. These climate and hydrologic extremes, combined with the growth in urban living and an increasing percentage of the population moving to cities impose ever greater demands on parks and other urban green infrastructures (Wang et al., 2008). Urban parks are increasingly seen as multifunctional environments. In addition to the aesthetic demands placed on them (Klemm et al., 2017), urban green areas are increasingly expected to provide climate mitigation and water retention related ecosystem services. In light of the aforementioned pressures, the importance of the hydrological aspects of green urban area functionality has increased and is being subject to greater discussion and scrutiny during project planning and as part of park management. At the same time, an increased frequency of extreme climatic events is to be expected, as are changes in the temporal distribution of precipitation and temperature (Trenberth et al., 2003; IPCC, 2007; Bates et al., 2008). All of these factors increase the vulnerability of existing green infrastructure in urban areas and simultaneously highlight their importance for the stabilization of urban environmental conditions.

Urban green infrastructures (e.g. trees, forests, lawns and parks) behave as functional counterparts to urban impervious surfaces. It is recognized that even single trees provide environmental and ecological benefits, as they affect the urban hydrological cycle through interception, evaporation, transpiration and infiltration and have a positive impact on microclimate and storm water runoff (Berland et al., 2017). In return, the ecosystem services provided by trees reduce the financial demands on urban gray infrastructure and wastewater treatment systems (Gonzalez-Sosa et al., 2017). City planners, park managers and others are increasingly given responsibilities for green infrastructure planning (e.g., Hansen and Pauleit, 2014). One aspect of green infrastructure planning is exploring the hydrological consequences of retaining or removing existing trees. Therefore, it is of great importance for political and societal decision-making (Olsson and Andersson, 2007) to have a tool to enable simulations of hydrological responses to potential vegetation/surface changes.

There are several models capable of providing simulations of soil moisture status and other potential hydrologic responses to changing vegetation and/or land surface properties. These include (but are not limited to): HYDRUS 1D (Šimůnek et al., 2016), Mike SHE (Sahoo et al., 2006), SWAT (Gassman et al., 2007; Douglas-Mankin et al., 2010), HYPE (Lindström et al., 2010), numerous versions of HBV (Lindström et al., 1997; Sælthun, 1996; Seibert and Vis, 2012) and PERSiST (Futter et al., 2014). All of the aforementioned models can provide daily (or sub-daily) estimates of, e.g., soil moisture at one or more depths in the soil profile. With the exception of Mike SHE, all these models are available at no cost to the user. All of the freely available models except HYPE (Lindström et al., 2010) and the "Nordic" HBV model (Sælthun, 1996) have a graphical user interface which simplifies model use. Both PERSiST (Futter et al., 2014) and HBV-Light (Seibert and Vis, 2012) are used in undergraduate teaching, where experience has shown that students are able to set up and parameterize the model in a half day or less. The time to set up and parameterize either SWAT or HYDRUS 1D is significantly longer. While both HBV-Light and PERSiST have all the desired properties, i.e. simulation of soil moisture status, freely available and easy to use, we chose to use PERSiST as it has been shown to perform comparably to HBV-Light (Ledesma and Futter, 2017) and offers the possibility to simulate multiple hydrological response units (HRUs) simultaneously.

Hydrological modelling of rainfall-runoff processes using any of the aforementioned models is capable of providing information about the consequences of changing vegetation and/or land cover if the correct input data, adequate model structure and necessary calibration are all provided (Beven, 2006; Renard et al., 2010). In the case of PERSiST, the correct input data includes catchment properties, e.g., total area, impervious area, vegetation and its properties, forcing data, e.g., temperature and precipitation as well as hard calibration data such as runoff measurements and 'soft' (Seibert and McDonnell, 2002) calibration data such as soil moisture estimates. Acquiring instrumental measurements of environmental parameters including weather (temperature and precipitation), runoff and soil moisture status for such an analysis can be time consuming, potentially expensive, require a certain level of expertise, and be subject to many uncertainties (Wang et al., 2008; Ledesma and Futter, 2017). These uncertainties may be especially acute in frequently visited urban parks where the risk of instrument disturbance is great, and where the timeline of the decision making process may rule out long term data collection. Therefore, we strived to come up with an alternative approach that would provide scientifically credible answers about the hydrological benefits of tree cover and give realistic insight into the potential consequences of tree removal or land cover change. We wanted an approach that would only require freely available and easy to use hydrological modelling software, readily available data and minimal fieldwork so as to be accessible to park planners, other municipal staff, as well as citizens' organizations and environmental non-governmental organizations (E-NGOs). Furthermore, we wanted an approach that would not require the user to be an expert in the field of hydrology but which would maintain reasonable model performance and have sufficient scientific validity as to be acceptable to an expert in hydrology. Thus, here we model the effects of different vegetation cover on surface and subsurface hydrology in a urban park using a novel calibration to soil moisture measurements.

2. Methodology and study site description

The study was composed of three steps - field work, data processing and hydrological modelling. The study period was defined by available soil moisture data obtained from a measurement campaign that took place from October 2015 to March 2018. The study period includes two full hydrologic years in 2016 and 2017.

The minimalist field work consisted of catchment land cover and vegetation assessment, soil analysis and continuous soil moisture measurements. Daily temperature and precipitation estimates for hydrological model forcing were obtained from the freely available European high resolution gridded climate dataset "E-OBS" (Haylock et al., 2008) provided by The European Climate Assessment & Dataset project (ECA&D). The E-OBS dataset offers fine-scale gridded estimates of daily weather parameters derived from actual meteorological observations. This data set covers all of Europe from 1950 onwards and is similar to, e.g., North American data sets such as Daymet (Thornton et al., 2016) or Asian APHRODITE precipitation (Yatagai et al., 2012) and temperature (Yasutomi et al., 2011) data sets. Parameterization of the PERSiST model was performed using interception and evapotranspiration values consistent with literature (more on this below) and soil parameters obtained from own on-site measurements. Given that there were limited possibilities to monitor surface water discharge in the city park where we conducted our study (which might be the case in many other urban parks and other small discharge areas) the model was not calibrated against observed streamflow which is the common way to do it (Photiadou et al., 2011; Futter et al., 2014). Instead, a "soft" calibration (Seibert and McDonnell, 2002) was performed in which PERSiST generated estimates of soil moisture were compared to time series soil moisture measurements made at the study site. To our knowledge, this is the first time such a calibration strategy has been used for the PERSiST model.

2.1. Study site and land cover

The study was conducted in the Northern Terraces city park in Hradec Králové, Czech Republic (Fig. 1) The 6.2 ha park is located on the slopes of the Northern Terraces locality in the city of Hradec Králové, which has a population of just under 93,000 people, in the north-central region of the Czech Republic. The average temperature during the last 70 years (from 1950) approaches 9 °C and the mean annual precipitation is 563 mm. The Northern Terraces locality is a city park located directly in the city centre (Fig. 1). It is situated on a steep slope of up to 45% with a northern to east-northern orientation. The vegetation can be characterized as a mosaic of trees and park lawns of different origin on artificial slopes. The main tree species are autochthonous *Tilia cordata*, *Acer platanoides* and *Quercus petrea* of 40–60 years of age. Within the locality, the boundary of the functional discharge basin was identified using a combination of air photo analysis and direct observation (i.e., walking the catchment area and identifying flow pathways). The identified boundary was then used as the basis for the delineation of the catchment divide (Fig. 1). This was a key step for the future analysis because the basin would represent the effective area for the rainfall-runoff process of the whole locality with a direct link to the factors influencing the hydrological regime. Using only the terrain morphology for catchment delineation turned out to be insufficient, as a number of roofs on the southern border of the park basin had to be included as well because they had no rainwater drainage systems. Air photo analysis was used to divide the catchment into a series of hydrologically relevant land cover types defined by vegetation and runoff processes: pavement, roofs, lawn, gardens, and tree vegetation (Fig. 1, Table 1). No attempt was made to separate land cover types by slope. In green urban planning, the main challenge usually lies in the delineation of functional green areas into park lawns and woody vegetation (Brown et al., 2015). Therefore, the abovementioned land cover categories were merged into three functional land cover categories according to their expected behaviour in the runoff generation process – park lawn, tree stand and impervious surface (Table 1).

2.2. Soil survey

Acquisition of pedological data and their interpretation was focused on the description of the soil body in terms of its hydrological regime in association with vegetation. Two soil probes under different functional land cover categories were analysed (Zbíral, 2003). Soil probe 1 was deployed in a park lawn and soil probe 2 was deployed in a tree stand. To assess soil hydrological properties and obtain some PERSiST model parameters including maximum water capacity, retained water depth and hydraulic conductivity, four replicates of undisturbed soil samples in physical cylinders of 100 cm^3 volume were analysed in each soil horizon. At both the park lawn and tree stand soil probe locations,

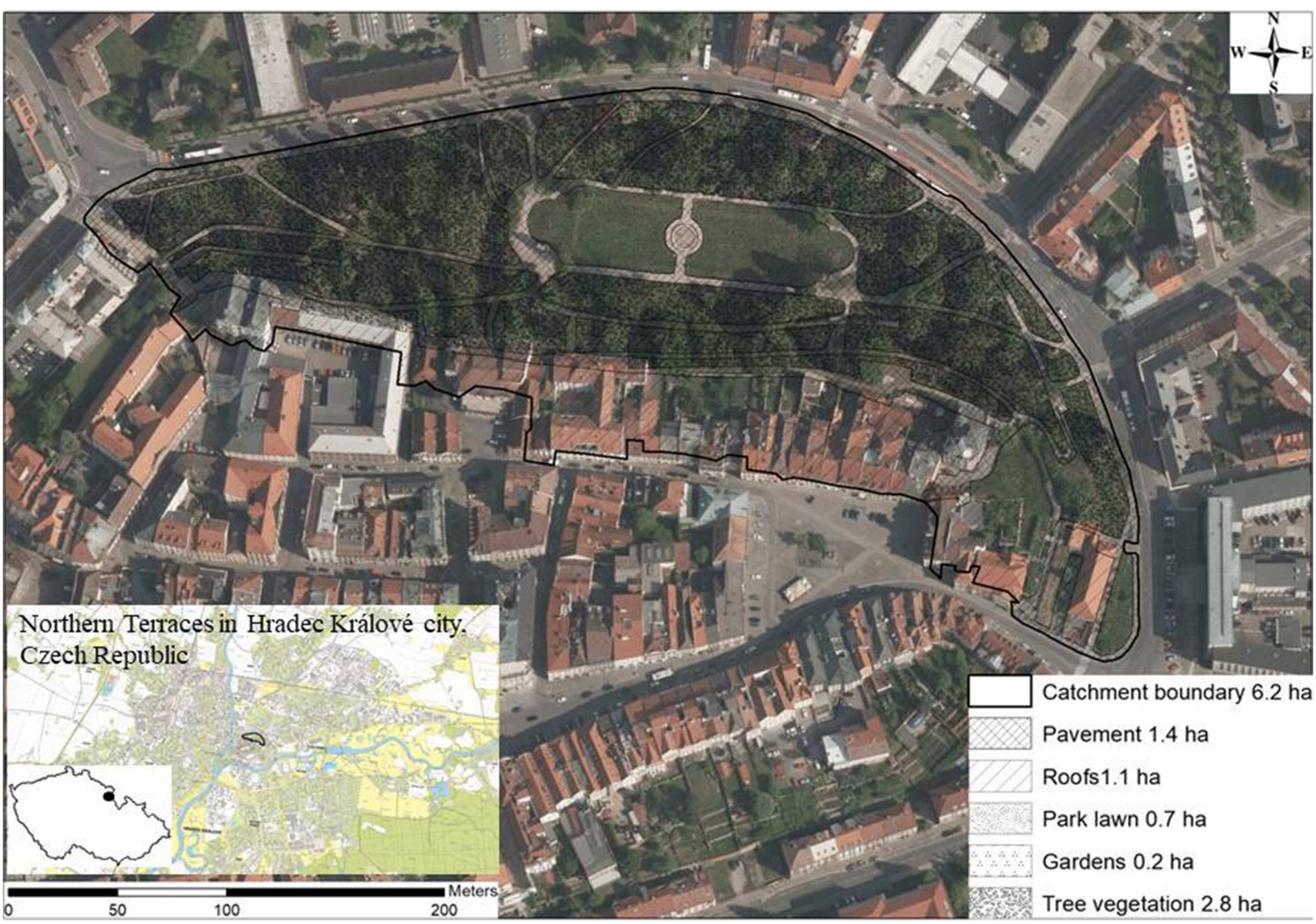

Fig. 1. The localization of the Northern terraces in Hradec Králové city. The aerial photograph shows the park locality. The inset maps show the location of the park in Hradec Králové and the location of Hradec Králové in the Czech Republic.

Table 1
Land cover in the catchment area of the urban park in the Northern terraces locality. Land cover categories were combined into functional groups for modelling.

Landcover category	Description	Area (m^2)	Percentage	Functional landcover	Area (m^2)	Percentage
Pavement	Paved areas with no infiltration nor transpiration. Runoff takes solely the form of surface runoff, or the water overflows and infiltrates in neighbouring landuse types.	13,723	22.2%	Impervious surface	24,345	39%
Roofs	Parts of roofs of houses on the southern border of the model catchment that gravited towards it. There is no infiltration nor transpiration. The surface runoff gravitates towards neighbouring landuse types.	10,622	17.2%			
Lawn	Areas covered with short grass with limited or no woody vegetation. During the season, the lawn is intensivly managed (approximately each 14 days). Interception and transpiration are limited due to the intense management. Infiltration and subsurface runoff can occur just below ground as the root do not reach to deep.	7493	12.1%	Park lawn	7493	12%
Gardens	Areas of a combination of lawn and woody vegetation on private land on the borders of the catchment. Some interception, transpiration and infiltration occurs.	2052	3.3%	Tree stand	30,069	49%
Tree vegetation	Areas of trees with dense canopy. Interception and transpiration are the highest. Some infiltration occurs. Subsurface runoff is limited due to intense water uptake up to one meter depth.	28,017	45.3%			
Total		61,907	100%		61,907	100%

triplicate measurements of volumetric soil water content were continuously monitored from October 2015 to March 2018 at 15, 50 and 80 cm soil depths using CS616 probes (Campbell Scientific, Logan, UT, USA). Data were acquired every hour and stored in a data logger (F3 T3, EMS Brno, Czech Republic). Manually measured soil water content was later used in comparison to continuous data to verify the accuracy of the probes.

2.3. Interception and evapotranspiration

When comparing tree stands and park lawns, the amount of water retained by interception depends on the properties of the vegetation and on the temporal dynamics of the rainfall events. Usually, tree stands can retain 1–3 mm of rain per event by interception, which in Central European conditions corresponds to 15–50% of total precipitation during the growing season (Bréda et al., 1995; Alavil et al., 2011). The interception of park lawns can be up to five times lower than that of tree stands, depending on the management and intensity of mowing (Thurow et al., 1987).

The evapotranspiration of tree stands is also higher than that of park lawns, usually by up to 30% (Zhang et al., 2001). There are two main reasons for the high transpiration of tree stands as compared to park lawns. The first one is the high surface conductance of aerodynamically rough tree crowns, compared to the relatively smooth grass (Allen et al., 1998). The aerodynamical conductance of a tree canopy is an order of magnitude higher than that of grass (Kelliher et al., 1993). Therefore, trees are better aerodynamically coupled to the atmosphere than grass (Jarvis and McNaughton, 1986) and able to exchange moisture more efficiently. The second reason relates to the rooting depth. While grasslands have 90% of their roots in the top 30 cm (Jackson et al., 1996), trees root significantly deeper with maximum rooting depths several times greater than those of grasses (Canadell et al., 1996). Deeper rooting allows trees access to water even when the topsoil is dry. In a comparative experiment conducted in Sweden, grass transpired 419 mm year^{-1} while forest transpired between 497 and 516 mm year^{-1} (Persson, 1997). For various tree dominated sites, evapotranspiration is usually 20% to 40% higher than reference evapotranspiration of grass (Allen et al., 1998). As a result of lower evapotranspiration, water discharge from most watersheds can be expected to increase after tree cover is reduced (Bosch and Hewlett, 1982).

2.4. E-OBS Gridded climate data

Daily values of total precipitation and mean daily temperature were obtained from the European high resolution gridded dataset "E-OBS" which was developed as part of the EU FP6 project ENSEMBLES (2017) and contains daily meteorological data back to 1950 for 0.25 × 0.25° grids over Europe (Haylock et al., 2008). In the E-OBS system, raw data is obtained from more than 11,000 stations all over Europe and is tested for quality (Haylock et al., 2008; Hofstra et al., 2009). Data for the study period were obtained from the cell of the grid were the city is located (50.125 N; 15.875 E).

2.5. PERSiST model and calibration strategy

PERSiST (Futter et al., 2014) is a semi distributed, bucket-type model for daily flow simulations. It consists of a flexible framework that allows the modeller to specify the perceptual representation of the runoff generation process, which is based on a number of interconnected buckets within a mosaic of landscape units in the basin. The catchment is divided into a series of subcatchments according to different land cover types (Wade et al., 2001). The individual land cover units consist of a number of soil layers (buckets) that define the hydrological behaviour by simulating the movement of rainfall water through the buckets towards the discharge outlet. PERSiST requires daily time series of air temperature and precipitation as input data, which were obtained from E-OBS gridded data. In this case, the area of the functional catchment, the land cover categories and their respective areas were the main inputs to the model. The soil buckets were set up to best describe the physical characteristics and the stratigraphy of the soils based on the results of our soil survey.

In the simulations here, we were most interested in modelling daily changes in soil moisture storage which was simulated based on a water balance:

$$\Delta S = P - I - ET - R \quad (1)$$

where the change in storage (ΔS, mm day^{-1}) is equal to precipitation (P, mm day^{-1}) minus interception (I, mm day^{-1}), evapotranspiration (ET, mm day^{-1}), and runoff (R, mm day^{-1}).

The three horizons described by the soil stratigraphy and physics were used for the definition of three corresponding soil buckets in the model setup. Relevant model parameters are presented in Table 2. Retained water depth was calculated as the gravitation water in the depth of the horizon minus skeleton and maximum capacity was

Table 2
Typical sensitive parameters identified during PERSiST model calibration.

Typical sensitive PERSiST parameters	Tree stand	Park lawn	Impervious surface
Degree day evapotranspiration mm/°C	0.3	0.18	0.05
Canopy inteception mm/day	1.5	0.5	0
Maximum capacity B2	277	207	200
Retained water depth B2	190	137	100

Table 3
Basic properties of the soils underlaying "tree stand" and "park lawn" land cover types.

Functional landuse	Horizon	Bucket Number	Depth (cm)	Average values SD - standard deviation	Porosity (%)	Gravitation water (%)	Skeleton (%)	Hydraulic conductivity (mm/day)	Hydraulic conductivity -clasification
Park lawn	A	1	35	Mean	49.82	35.41	13	1993	highly permeable
				SD	2.70	0.57			
	M1	2	55	Mean	50.96	33.67	26	1454	permeable
				SD	4.56	2.44			
	M2	3	50	Mean	58.92	36.32	33	1993	highly permeable
				SD	2.71	1.20			
Tree stand	A	1	30	Mean	57.89	33.63	7	1993	highly permeable
				SD	0.22	3.82			
	M1	2	73	Mean	53.40	36.71	29	1273	permeable
				SD	3.14	2.67			
	M2	3	30	Mean	53.80	46.33	80	931	permeable
				SD	1.22	0.59			

calculated as the porosity in the depth of the horizon minus skeleton (Table 3). These values were used as given during the model calibration and were never changed as they were deemed as being as close to the real environment as possible. Other important parameters (Table 2) were changed during the calibration process to obtain the best fit with the measured soil moisture data while retaining their expected values and ratios according to literature. This way, the canopy interception parameter value for park lawn was approximately three to five times less than that of tree stand during all steps of the calibration. In a similar manner, the degree day evapotranspiration parameter in the tree stand land cover type was approximately 30% higher than that for the park lawn throughout the simulations. Transpiration was set up to only occur in the second bucket which represented the depth range where most roots were found and it was considered to be the rooting zone for both park lawn and tree stand. As such, the second bucket was thus the most important for the model.

3. Results

3.1. Soils

The soil profiles at the park lawn and tree stand sites where the soil moisture probes were located were characterized by similar stratigraphy and composition (Fig. 2, Table 3). Profiles exhibited only small differences in the depth of the topsoil and A-horizon consisting of, e.g., allochthonous overburden. Heterogenic material, a mixture of debris, artefacts, slag, cinder and soils of different origin, was found beneath the A-horizon. The soils close to the surface could be described as light-to medium in texture, with medium to high porosity and high permeability; the deeper soil was highly skeletal. A rather high physiological depth and heavy rooting indicated good permeability of the soils despite the compactness and stoniness in the deeper parts (Table 3). The soils consist of a relatively "young" body formed by various layers of artificial origin that have been deposited here throughout the history of the city construction. Throughout the whole of both profiles, allochthonous material was present and there was no direct contact with the parent rock material. The hydrophysical values confirm high hydraulic conductivity and fast entrance of water at the surface in both vegetation types (Table 3).

3.2. Gridded climate data

The freely available E-OBS Gridded Climatic data (see acknowledgment) were used in the model. Their accuracy was tested against climatic data obtained from the Czech Hydrometeorological Institute (CHMI) and were deemed as sufficient for the analysis (see Supplementary Figs. 1–3).

3.3. PERSiST soil moisture simulations

Daily changes in soil moisture values based on a water balance (Eq. (1)) were simulated for the park lawn and tree stand land cover types. Based on the results of our soil survey, three soil buckets were used for the description of the soils where the second bucket corresponding to the root zone was of the highest importance as transpiration of plants was modelled from this bucket. Given the expected differences in intensity of transpiration and interception between park lawn, tree stands and impervious surfaces (Konrad and Booth, 2002) the typical sensitive PERSiST parameters were set to values consistent with those obtained during the measurement campaign (Table 2). The fit of the model was then tested by the comparison of the measured and the modelled soil moisture in the second bucket.

Using the aforementioned unorthodox way of model calibration against soil moisture measurements yielded a reasonable fit for temporal patterns observed at both land cover types (Fig. 3a,b). The simple linear regression of modelled soil moisture in the root zone (bucket 2) on mean measured soil moisture (from the three depths) indicated model accuracies of over 66% and 73% for tree stand and park lawn land cover

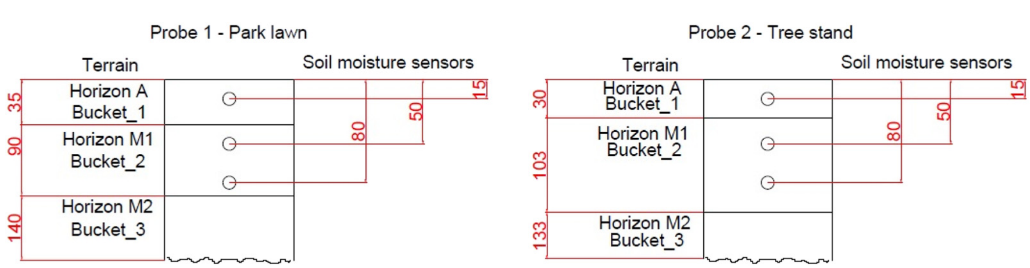

Fig. 2. Soil stratigraphy determined for the two soil moisture probes located under the park lawn and tree stand vegetation cover.

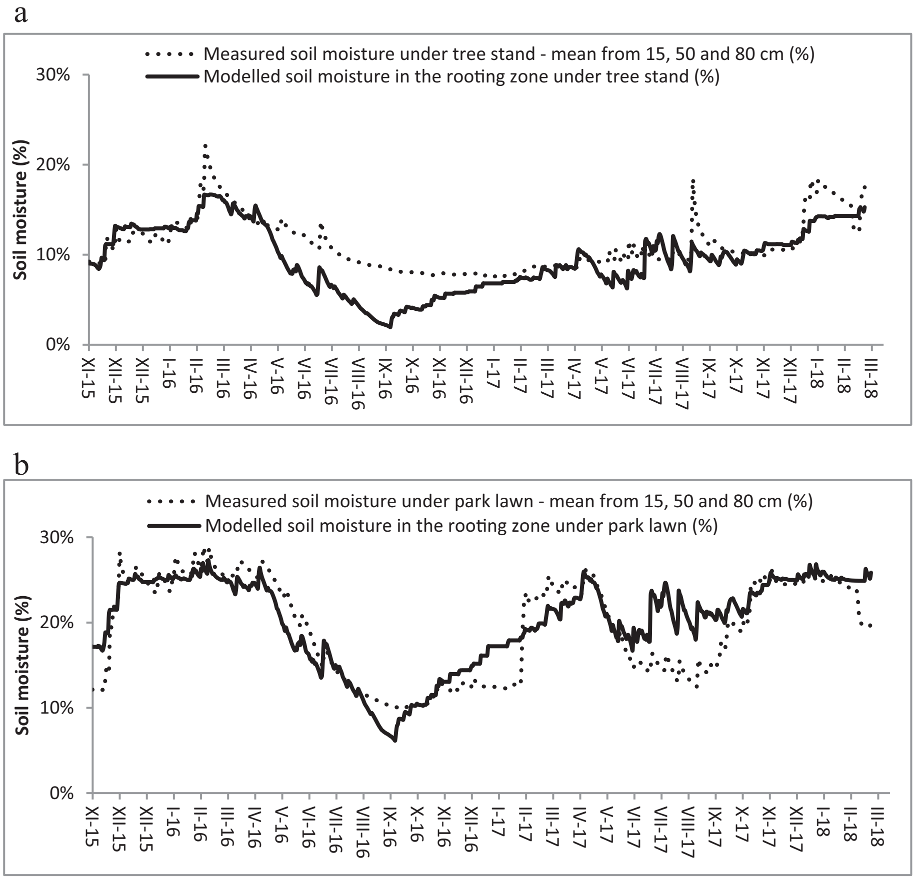

Fig. 3. a Comparison of modelled and mean measured soil moisture under the tree stand land cover type. b Comparison of modelled and mean measured soil moisture under the park lawn land cover type.

types respectively (Fig. 3a, b). When searching for possible sources of error we found differences when comparing observed soil moisture from individual depths to the PERSiST simulations. The measured soil moisture behaved unexpectedly when the air temperature dropped below freezing. Aberrant soil moisture peaks were observed under the tree stand during winters 2016 and 2018 and under the park lawn in winters 2016 and 2017 (Fig. 4a, b).

The results of the hydrological modelling suggested that of the three functional land cover categories present in the locality, tree stand had the highest water loss and the highest runoff mitigation potential. The total modelled water loss (evapotranspiration + interception) reached 81%, 67% and 24% of precipitation for tree stand, park lawn and impervious surface land cover types respectively (Table 4). The runoff over the whole study period reached 138 mm, 265 mm and 872 mm from tree stand, park lawn and impervious surface land cover types respectively, which corresponded to runoff to precipitation ratios of 11%, 22% and 72% respectively (Figs. 5 and 6). The remaining fraction of precipitation (8% for tree stands, 11% for park lawn and 4% for impervious surfaces) contributed to long term changes in soil moisture storage between the beginning and end of the simulation.

The results indicates that the impervious surface was extremely inefficient in containing precipitation when compared to urban green land cover types (both tree stand and park lawn). However, there was also a significant difference between the runoff from tree stand and the park lawn land cover types. Simulated runoff from the tree stand was low due to high interception losses and transpiration demands while runoff from the park lawn (127 mm or 11%) was higher, mostly due to both lower interception and intensity of transpiration.

4. Discussion

We divide the discussion into four sections. First, we discuss the results from our study; second, we review the modelling; third, we reflect on the method used; and finally, we evaluate the broader applicability of our approach.

4.1. Study results - soil structure and hydrologic regime

The results of the soil survey indicated that the soil in the locality consists mostly of anthroposols that did not originate by natural paedogenesis but rather were transported to the location. The soils in this locality are probably younger than 600 years. As such, the soil can be characterized as low cohesive and highly permeable. In areas of tree cover, the soil was more compacted due to their weight. Furthermore, reinforcement of the soil by the root systems also creates a significant armature for the low cohesive anthroposols and functions as a ground anchor. Trees have a significant positive effect on the hydrological regime of the locality. Their retention potential, which is mainly due to their high interception and transpiration relative to other land cover types in this study returns a significant fraction of precipitation to the atmosphere.

Trees in the Northern Terraces park in Hradec Králové city play an irreplaceable role in providing ecohydrological services and other functions including cultural and aesthetic ecosystem services. The trees mainly affect soil structure by their weight, and soil water content which is controlled by high rates of evapotranspiration and interception (Perry et al., 2003). The structural roots of the trees reached up to

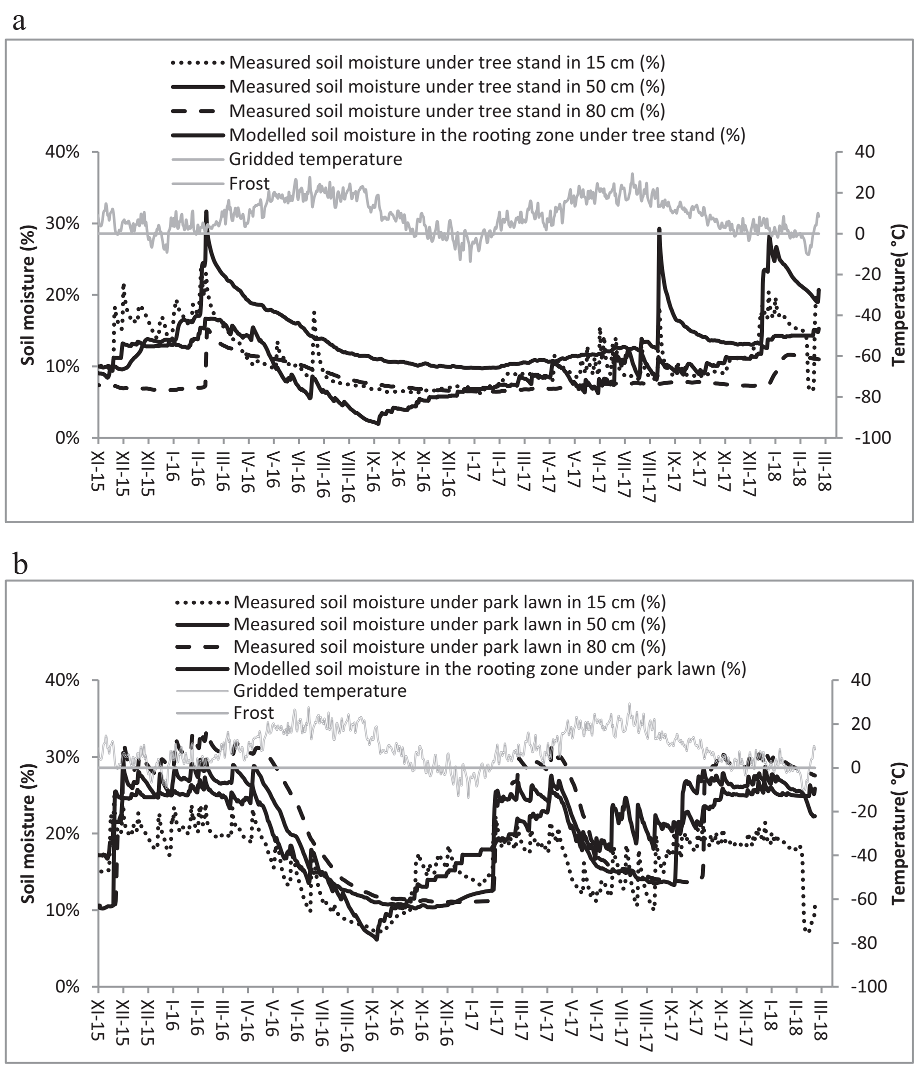

Fig. 4. a Comparison of modelled and measured soil moisture in all depths under the tree stand land cover type. b Comparison of modelled and measured soil moisture in all depths under the park lawn land cover type.

130 cm deep, which is slightly deeper than expected (Schenk and Jackson, 2002) and is probably a consequence of the low cohesive anthroposols (Stokes et al., 1996) in which they are growing. The hydraulic conductivity measurements indicated that the weight of the tree biomass together with its root system functioned to reinforce the deeper parts of the soil below 30 cm (Table 3). This more compact soil structure slows the speed of subsurface runoff that in return becomes limited, which reduces its erosive potential (Pretti, 2013; Gray, 2009;

Table 4
Components of the water balance simulated for tree cover, park lawn and impervious surface land cover types for the whole simulation period and expressed as annual means.

Total ammount during the whole study period (875 days)	mm (liter/m^2)	Total from given area (m^3)	Total from given area per year (m^3/year)	%
Precipitation	1218	75415	31423	100%
Evapotranspiration tree stand	559	16810	7004	46%
Evapotranspiration park lawn	638	4783	1993	52%
Evapotranspiration impervious surface	294	7169	2987	24%
Interception tree stand	429	12906	5377	35%
Interception park lawn	177	1327	553	15%
Interception impervious surface	0	0	0	0%
Water loss tree stand	988	29716	12382	81%
Water loss park lawn	815	6110	2546	67%
Water loss impervious surface	294	7169	2987	24%
Runoff tree stand	138	4147	1728	11%
Runoff park lawn	265	1986	828	22%
Runoff impervious surface	872	21225	8844	72%
Total runoff		27359	11399	
Tree stand vs. park lawn runoff difference	127	3824	1593	14%
Tree stand vs. Impervious surface runoff difference	734	22068	9195	81%

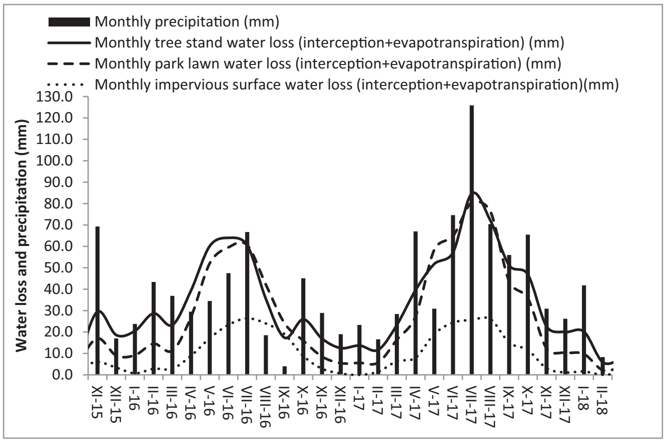

Fig. 5. Monthly modelled water loss (interception + evapotranspiration).

Ali et al., 2012). Such a compact soil structure, however, was not observed under the intensively managed park lawns (Table 3), since no reduction in hydraulic conductivity was observed in those areas (Gray and Sotir, 1996; Lammeranner and Meixner, 2008).

The comparison of simulated runoff from different land cover types indicated relevant differences between tree stand and park lawn land cover types. The runoff from tree stand was minimal (11%), while the runoff from park lawn reached up to 22% of total precipitation. This would indicate a lower ecohydrological effect of intensively managed park lawns on mitigating runoff as opposed to tree stands. This, together with the anchoring effect of roots, could explain why tree stands can increase slope stability up to ten times more than grass cover (Gray and Sotir, 1996; Gray, 2009).

Over the study period, the total volume of runoff reached 4,147 m^3, 1,986 m^3 and 21,225 m^3 as opposed to the total volume of water loss caused by evapotranspiration and interception 29,716 m^3, 6,110 m^3 and 7,169 m^3 from tree stand, park lawn and impervious surface respectively (Table 4). The total simulated volume of runoff from the whole Northern Terraces area reached 27,359 m^3 which corresponds to a mean annual runoff of 11,399 m^3. Were the trees removed and the area of tree stand changed in favour of park lawn, it would cause a 14% increase in runoff equal to 3,824 m^3 corresponding to a mean increase in runoff equal to 1,593 m^3 per year. If the area of tree stand was changed in favour of impervious surface, the increase in runoff would reach 81%, equal to 22,068 m^3 corresponding to a mean annual increase in runoff of 9,195 m^3. This indicates that potential tree removal on the slopes of the Northern Terraces locality could lead to dramatic changes in the local rainfall-runoff processes. The water currently used by tree vegetation would drain from the locality in the form of surface and subsurface runoff, which could lead to overfilling of local canalization and increase the risk of a local flood. At the same time, more intense erosion would be expected in the form of slope failure and landslides due to the excessive moisture in the low cohesive soils and the loss of anchoring roots. This is even more alarming in the case of extreme years/events that are expected to occur in association with global climate change (Trenberth et al., 2003; IPCC, 2007; Bates et al., 2008).

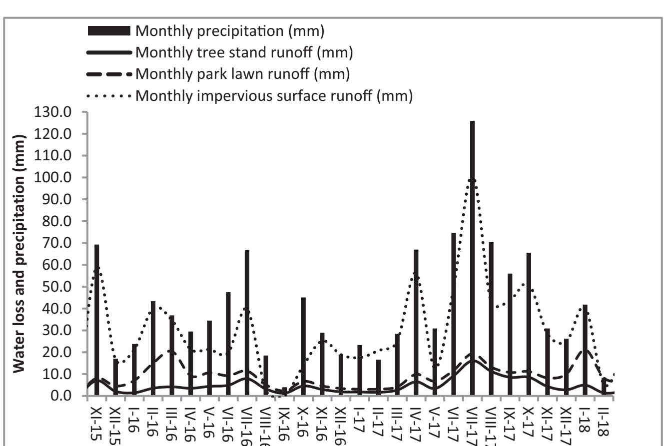

Fig. 6. Monthly modelled runoff.

4.2. PERSiST soil moisture simulations

To obtain the presented results, the PERSiST model was used in an unorthodox way. This conceptual model is typically applied to an individual catchment and is then tuned through a process of parameter value adjustment until an acceptable fit is achieved between modelled and observed streamflow values (Futter et al., 2014). In this case, no observed values of streamflow were used as there was no surface stream present in the locality. The model calibration was instead driven by soil moisture observations in a "bottom up" manner (Konrad and Booth, 2002) and the fit of the model was tested against continuous soil moisture measurements. Basic soil survey data in combination with actual results published in the literature were used as references for setting realistic parameter values. One of the goals of this paper was to find out whether such a minimalist approach can be used to obtain a reasonable fit of the model and most importantly whether a realistic description of the hydrological behaviour of such a locality can be reached. A good fit between soil moisture probe measurements and modelled soil moisture was obtained, supporting this hypothesis (Figs. 3a,b, 4a,b).

It is most likely that the lack of PERSiST model ability to capture the aberrant soil moisture peaks can be explained by the soil moisture measurement device being frozen and giving erroneous results (so-called "disinformative observations", Beven and Westerberg, 2011). When we tracked back temperature during these events, most peaks occurred during periods of thaw. Nonetheless, this could be the most important limiting factor of possible better model accuracy as it can be argued that during the winter periods the modelled data were actually better at capturing the natural soil moisture behaviour than the measured ones and therefore the overall accuracy of the model was probably higher than what the results of the linear regression suggest.

The PERSiST simulations presented here used a delineation of landscape elements based on land cover and soil hydrologic group. No attempt was made to incorporate slope class as slopes were uniform between land cover types. Incorporating slope class into the delineations would have increased the numbers of free parameters without offering any real gain in predictability. Thus, the delineations used here are not strictly comparable to HRUs (Flügel, 1995), which incorporate the effects of land cover, parent soil type and slope. If the approach presented here was to be applied in a catchment with heterogeous slopes, it would of course be appropriate to incorporate slope class into the delineation of landscape elements.

4.3. Minimalistic field campaigns and open data

Here, we have presented an innovative approach for assessing some of the ecohydrological services provided by urban trees using a combination of minimalistic field sampling, freely available software and open access data. While the approach we present is scientifically rigorous, it is not sufficiently detailed for use in research catchments. However, because of its low demand for human and financial resources, it has the potential to be implemented by park managers, consultants, municipal staff, E-NGOs and even concerned citizens.

The purpose of the study which initiated this project was to provide credible estimates as to what might happen if trees were removed from the steep slopes of the Northern Terraces park in Hradec Králové city. "One off" field campaigns and simple laboratory analyses were needed to characterize the stability of soils underlaying treed and park lawn areas. Long term monitoring was needed to constrain temporal patterns in soil moisture under the treed and non-treed land cover types. Having two full hydrological years of soil moisture measurements for the two land cover types of interest strengthens the credibility of the conclusions of the modelling exercise.

It was not the purpose of this study to determine whether one of the many currently available rainfall runoff models is better than another. In the modelling exercise, we used PERSiST because our group is familiar with its use. However, any openly available and easy to use hydrological model which can simulate the effects of change in land cover and generate time series of soil moisture such as, e.g. HBV-Light (Seibert and Vis, 2012) could have been used. At our study site, we had access to long-term instrumental observations of temperature and precipitation which could have been used for hydrological modelling. However, there are many locations where such data either have not been collected or languish behind a pay wall. Gridded meteorological data have been shown to give comparable or better results to instrumental data when used as input in rainfall-runoff modelling (Ledesma and Futter, 2017) and are freely available for sites across Europe and much of the rest of the world.

4.4. Broader applicability - potential for use at other sites

The approach we present here has the potential to be applied to other sites where there is a need to quantify the value of ecohydrological services provided by trees in urban parks. If soil data are not available, a minimal sampling campaign and subsequent soil characterisation would be needed to apply the approach presented here to a new site. While soil moisture data would be desirable, they are not essential as literature values could be used for components of the water balance under different vegetation types. The availability of open access, user-friendly modelling software and open data mean that this approach could have widespread applicability as there are relatively low barriers to its use.

5. Conclusion

When comparing treed to park lawn land cover types, a number of conclusions can be drawn. Tree covered soil is more stable, in part due to greater soil compaction and deeper, thicker roots which contribute to structural reinforcement of the deeper layers. Tree covered soils are also drier than soils underlaying park/lawn land cover types. All other things being equal, drier, more stable soils are less likely to be subject to erosion, landslide or other catastrophic slope failure. Simulated runoff also differed between the three land cover types. Treed landcover had significantly less surface runoff than park lawn, which in turn had much less runoff than impervious surfaces. Such findings are important to keep in mind in any discussions about urban flooding and about whether trees need to be retained in urban areas.

Given the good fit of modelled and observed soil moisture data, it seems that the minimalist approach described in this paper has the potential to be a very useful tool for local policy makers as it offers a cheap, freely available and relatively easy alternative for the support of the decision-making process regarding urban greenery.

Acknowledgements and software availability

The PERSiST software and supporting documentation is available on request from M. Futter (martyn.futter@slu.se). The temperature and precipitation data used here were obtained from the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu). Instrumental measurements of temperature and precipitation were provided by the Czech Hydrometeorological Institute (CHMI).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.11.277.

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