The importance of city trees for reducing net rainfall: comparing measurements and simulations

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Abstract. An in-situ tree interception experiment was conducted to determine the hydrological impact of a solitary standing Norway maple and small leaved lime in an urban environment. During the two-year experiment, rainfall data was collected and divided into interception, throughfall and stemflow. With approximately 38 % of the gross precipitation intercepted by both trees, the interception storage was higher than for similar studies done in Mediterranean regions. The specialized forest interception models by Gash and Rutter, as well as an adapted solitary tree version of the Water and Energy Transfer between Soil, Plants and Atmosphere model (WetSpa), were tested for their accuracy in modelling the measured interception storage. The models in general overestimated interception storage for small interception events (< interception storage) and underestimated interception storage for bigger interception events (> interception storage). The method of Gash slightly overperformed WetSpa and Rutter for all events throughout seasons and trees. However, WetSpa showed a better performance for rainfall events > 10 mm. The similar performance of WetSpa compared with the Gash- and Rutter models is noteworthy because the WetSpa interception model is part of a larger modelling framework that models the whole hydrological balance, while Gash and Rutter are specialized stand-alone interception models. To gain a more complete understanding of the impact of city trees on the full hydrological balance, WetSpa is thus recommended. This study emphasizes the potential of city trees on the whole hydrological balance through a combination of field data and simulation experiments with both specialized interception models (Gash and Rutter) and with a relatively simple interception module of a holistic water balance model (WetSpa).

1.Introduction

1.1 The Context

Currently 54 % of the population is living in an urban environment, with an expected increase to 66 % by 2050 (UN, 2014). The migration of the growing population towards cities gives rise to a whole new set of challenges. An urban environment exhibits built-up areas that significantly alter the natural processes (Grimm et al., 2008). This leads to problems such as the urban heat island effect (UHI) (Lauwaet et al., 2015) and the increased density of particle matter (Zhang et al., 2015). Another prominent problem modern cities face is the increase in runoff during and after rain events (Paul & Meyer, 2001). Due to urban expansion and the use of impervious materials such as concrete and asphalt, the hydrological cycle is altered and natural processes such as infiltration and interception are impeded. This results in an increased runoff that causes significant economic losses, especially during heavy rainfall events. For Western-Europe, the IPCC predicts that the amount and intensity of precipitation will increase considerably in the coming decades, leading to more extreme events, and concludes that an efficient water regulation policy will be the most important challenge of the 21st century (IPCC, 2013).

1.2 The Urban Green

Part of the solution can come from a strategic use of rainwater in urban environments; this approach is known under different names such as 'Water Sensitive Urban Design (WSUD)'(Wong et al., 2013), 'Low Impact Development (LID)' (Dietz, 2007) and 'Sustainable Drainage Systems (SuDS)' (Ciria, 2013). One of their main goals is to try to use rainwater as efficiently as possible in the city itself. Among other measures this approach emphasizes the role of urban trees in the hydrological cycle. Urban trees are known to intercept rainwater, thereby creating a buffer for peak runoff during intense rain events (Livesley et al., 2016; Xiao & McPherson, 2011). Urban built-up areas also benefit from trees during less intense events because of the reduced amount of rainwater that needs to be processed by the sewage system (Szota et al., 2019). Xiao & McPherson (2002) found that the trees in Santa Monica, California intercepted 1.6 % of annual precipitation, thereby saving $110,890 of the costs for flood control, or $3,60/tree. They further advise that planting more large, evergreen trees would increase the long-term benefits in runoff reduction benefit to be $47.3/tree in Lisbon. Most of the rainfall that trees intercept evaporates into the atmosphere, diminishing and redistributing the net rainfall that reaches the ground and is converted to surface runoff. Moreover, green spaces disrupt the impervious cover and allow rain water to infiltrate and contribute to the often depleted ground water tables under cities (Armson et al., 2013; Farrugia et al., 2013; Shields & Tague, 2014) .

Urban trees normally display a different behavior than forest trees due to interactions with anthropogenic structures. Urban built-up affects wind orientation and rainfall, and creates microclimates which influence tree growth and well-being and hence rainfall interception (Pretzsch et al., 2017; Zipperer et al., 1997). Asadian & Weiler (2009) found urban trees intercepting twice as much water as their forest counterparts, possibly due to the UHI effect, to the greater distance between trees (boundary layer effect) and to the open grown canopies. Studies done on natural forest interception thus cannot be easily translated to urban trees.

Several authors have attempted to quantify the contribution of urban trees on the total water balance. Some authors looked at large areas of urban cover and determined the water storage potential of the urban forest based on land cover derived maps (Gill et al., 2007; Haase, 2009; Verbeeck et al., 2013). Thereby they assign empirical storage capacity values to certain vegetation classes based on literature. These studies can give an accurate estimate of the total outflow on a catchment scale, but often fail to account for the smaller scale and the complex heterogeneity specific to an urban environment. Other authors looked at the interception process of a single urban tree (Asadian & Weiler, 2009; Guevara-Escobar et al., 2007; Véliz-chávez et al., 2014; Xiao et al., 2000a, 2000b). While these studies generally succeed in describing the interception process for an isolated urban tree, they usually find it difficult to extrapolate to larger areas and/or other tree species due to the use of complex variables for the prediction of the interception process. To fully understand the potential hydrological impact of urban trees there is a need to integrate a solitary tree interception model in a larger modelling framework, capable of simulating the whole water balance. This solitary tree interception model should be able to accurately model interception on the individual tree level while not being too complex to make extrapolation too complicated.

1.3 The Hydrological Processes

During the initial stage of the rain event, most water is intercepted by the tree canopy. Tree interception is defined as the process of precipitation falling on the tree surface where it is temporally stored. This water then either evaporates into the atmosphere, is absorbed by the leaves, flows down as stemflow or falls through/ drips off to the ground surface (Xiao et al.,2000a). The water that reaches the ground surface is called the net precipitation. A part of this water infiltrates in the ground, the other part runs off. The infiltration/runoff ratio depends on the surface- and soil properties. Part of the infiltrated water is taken up by the tree roots and is transpired back in the atmosphere through the leaves. The other part of infiltrated water replenishes the groundwater table. The total amount of water intercepted during an event and that never reaches the ground is called the interception storage (mm). The main vegetation characteristic influencing the interception storage is the interception storage capacity (mm). This is the maximum amount of water the tree can hold for a given time. There is some confusion in literature regarding the exact definition of the interception storage capacity. This study utilizes the definition used by Xiao & McPherson (2016). They defined two types of interception storage capacity. The first is the surface saturation or minimum storage capacity, which is the amount of intercepted water that is needed on a vegetation unit for flow to begin. This water evaporates back into the atmosphere and does not contribute to throughfall. This type of storage is relatively independent of meteorological characteristics. Vegetation characteristics determining the minimum storage capacity are the canopy architecture, the leaf- and stem surface areas, the seasonal vegetation development and the tree's health condition (Asadian & Weiler, 2009; Véliz-Chávez et al., 2014; Xiao et al., 2000b). The second type of storage is the detention- or maximum storage, this is the maximum amount of water that can temporally be stored on a vegetation unit. The maximum storage can temporarily exceed the minimum storage during very intense rainfall periods when the amount of water that falls through is smaller than the amount of water that is intercepted. However, once a threshold is reached or rain ceases, this extra amount of water quickly drips off until the minimum storage is reached again. This process is clearly observed by Keim et al. (2006) in rainfall simulator experiments on woody vegetation. They defined the two types of storage as the static- and dynamic storage respectively. In our study, we will use the surface saturation or minimum storage. Because this is the volume of water that never reaches the ground and does not contribute to runoff, it is of the most useful to hydrological modelers. The interception storage of an event can be larger than the interception storage capacity when intra-event evaporation or drip-off is present and the interception storage capacity is partially emptied and then filled again with new precipitation.

1.4 Measurement Methods

Interception storage experiments can be conducted both in ex-situ and in in-situ conditions. Ex-situ experiments usually involve simulating rainfall events in a controlled environment. This allows to accurately determine the amount of rainfall intercepted and which vegetation- and meteorological characteristics are of most influence (Keim et al., 2006; Smets et al., 2018; Xiao & McPherson, 2016). Advantages of this method are that experiments are repeatable, that experiments can be designed to optimally determine the influencing variables and that many individual plants can be used. This method is usually used for smaller green elements like shrubs and grasses. Trees are impractical to transport to laboratories due to their above- and below ground biomass. Laboratory experiments have been done on tree branches (Keim et al., 2006; Xiao and McPherson, 2016), but upscaling to a whole tree level complicates the applicability of the results.

In-situ interception experiments usually involve the collection of rainwater above or besides the canopy and comparing this with rainwater collected under the canopy. The difference is the amount of intercepted water. An often used method is placing tipping buckets under the tree canopy (Asadian & Weiler, 2009; Link et al., 2004). This method only catches part of the throughfall. Throughfall however is usually not equally distributed under the canopy, which makes upscaling results to a whole tree canopy level difficult. Another in-situ measurement method is to collect all throughfall under a tree by constructing a V-catchment construction large enough to cover the canopy area (Véliz-Chávez et al., 2014; Xiao et al., 2000b). Throughfall and stemflow are usually collected in separate containers. A disadvantage of this method is that it is resource intensive and only a few individuals can be measured. Moreover, high wind speeds can cause lateral rain to be intercepted by the V-catchment and can confuse the measurements. However, because upscaling results from individual branches or leaves to the individual tree level remains difficult (Friesen et al., 2015), measurements on the whole tree scale are currently viewed as the most accurate method to quantify rainfall interception by solitary trees and are the preferred method in this research.

1.5 Interception Models

The most commonly used methods to calculate interception storage of a forest canopy are the model of Rutter (Rutter et al., 1971) and the analytical adaptation of his model by Gash (Gash &Morton, 1978). Their conceptual models include gross precipitation, crown storage, throughfall, stemflow and evaporation. These models serve as a starting point for most ulterior interception models (Muzylo et al., 2009). They are most commonly used on weekly/monthly temporal scales and a spatial scale of a forest stand. Rutter calculates the interception storage with a running water balance approach whereas Gash considers a wetting, saturation and drying phase to include the different water balance components. An important difference between the Gash and the Rutter model is that Gash considers rainfall events as discrete events. His model assumes an empty storage compartment at the start of each event and after reaching the saturation phase the amount of water intercepted is held constant and throughfall is assumed to start. Further, Gash & Morton (1978) treat throughfall as a factor in the water balance, while Rutter (1971) uses empirical relationships. Later, Gash refined his model to include open spaces in forests by including a canopy fraction cover (Gash et al., 1995). The canopy fraction cover enables the prediction of interception in open forest structures, and of the amount of interception with a changing leaf cover. Van Dijk and Bruijnzeel (2001) later adapted the refined Gash model to include the leaf area index (LAI). They assumed a linear relationship between the LAI and the interception storage, thereby highlighting the importance of the leaf area in predicting the interception storage capacity. The first model to estimate interception storage on a single tree has been developed by Xiao (Xiao, 2000b). He adapted the Rutter model into a 3-dimensional physically-based stochastic model to gain better understanding of the interception processes from a single leaf to the branch segment and then to the individual tree. He found the interception storage capacity to be the most important factor determining the amount of rain intercepted, followed by the LAI. The most influential meteorological factor for the interception storage was gross precipitation (Xiao, 2000b). The model provides a good tool to better understand the influence of the tree architecture and the detailed meteorological factors on the interception of a single tree in an urban environment. However, the intense model parameterization makes it difficult for application.
Interception storage is the first part within a water balance simulation; estimating net rainfall available for infiltration, evapotranspiration and surface runoff. Therefore it is important to not only focus on interception models but also investigate the capacities of a water balance model to simulate interception storage. The Water and Energy Transfer between Soil Plants and Atmosphere simulator (WetSpa) allows a detailed modeling of the land surface processes (Wang et al., 1996). The flexibility of the model further allows an easy adaptation of the interception module to our purposes. In order to adapt the model to our study of a solitary tree we set-up a V-catchment simulation including LAI for the calculation of interception storage (Salvadore , 2015;Wirion et al., 2017).

1.6 Research Questions

Downscaling current hydrological interception models, which are mainly built for forested areas using a stand scale, to an individual urban tree might not reach satisfactory simulation results. Interception models developed on the individual tree scale are usually complex and require many variables that are difficult to measure in the field. This study tries to bridge this gap by adjusting the interception module of a water balance model (WetSpa) to our solitary tree set-up. The simplicity of the interception calculation of WetSpa is compared to the more specialized forest interception models that have been standard in literature for decades (Gash and Rutter)..

The objectives of this study are:

- to evaluate the interception storage of two urban trees within Belgium.
- to evaluate how the WetSpa model, that is part of a whole water balance framework, compares with the standard stand-alone interception models of Gash and Rutter to estimate the interception of 2 solitary trees.

2. Materials And Methods

2.1 The Study Area

The study area is located in Belgium. The climate of Belgium can be classified as Cfb Climate according to the Köppen climate classification (Kottek et al., 2006): a temperate oceanic climate with the coldest month averaging above 0°C, all months with average temperatures below 22°C and at least four months with average temperatures above 10°C. Rainfall averages to 750 - 850 mm on a yearly basis and is fairly evenly distributed throughout the year. We hypothesize that in temperate climates a larger percentage of rainfall can be intercepted by urban trees than in Mediterranean climates where rainfall is usually restricted to the winter season.

2.2 The Selected Tree Species

Two deciduous trees of similar dimensions were selected for this study: a Norway maple (*Acer platanoides L.*) and a small-leaved lime (*Tilia cordata Mill.*). Both trees are native in extensive parts of West- and East Europe and are introduced in large parts of the European continent. They are popular street trees in urban environments due to their pollution removal abilities (Yang et al., 2015) and due to their growing rate at a young stage (Moser et al., 2015). The Norway maple is located at the VUB Campus Etterbeek (50°52' N, 4°41' E) in the capital region of Brussels. The small-leaved lime is found in 'Kasteelpark Arenberg' (50°52' N, 4°41' E). The Norway maple and small leaved lime were at least 8 m away from obstructions , minimizing possible influences from nearby trees or buildings (Fig. 1). These two trees represent an urban solitary tree. As the urban environment is very heterogeneous, trees are found in widely varying settings such as in parcs, private gardens and on streets. Due to the limitations of an experimental setup (safety, space and logistics) we decide to choose urban solitary trees free from obstructions and with full sun- and wind exposure. The results of our experiment can thus not simply be translated to other solitary urban trees but must undergo some assumptions of the environmental conditions.

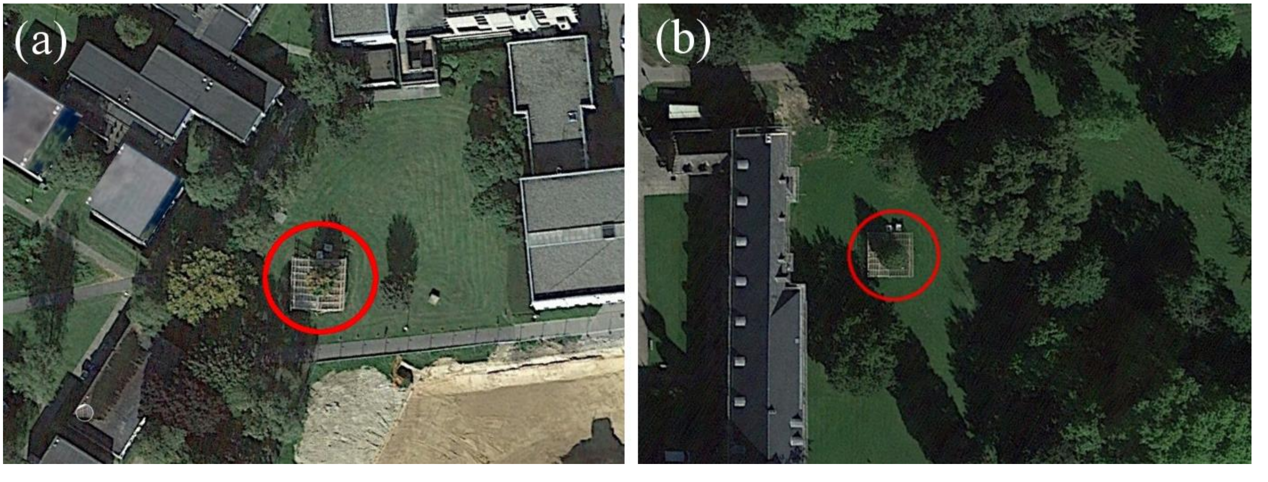


Figure 1: Satellite images of the Norway maple (a) [01/10/2015] and small leaved lime (b) [25/08/2016] [images: Google Earth].

The vegetative characteristics of both trees are described in Table 1:

Table 1: Vegetation characteristics of the Norway maple and small leaved lime.

	Norway maple	Small leaved lime
Diameter (m)	8.92	8.79
Diameter at breast height (cm)	47	46
Crown diameter (m)	5.95	6.35
Crown height (m)	7.39	7.09
Crown shape	Oval	Oval
Vertical projection area (m²)	27.83	32.30
Leaf area (cm²)	90.36 +- 43.76	41.41 +- 17.63
Average branch angle (°)	38.15 +-17.54	41.29 +- 17.83

The LAI was measured periodically with the SunScan system (Type SS1-COM-R4). This system uses photodiodes to measure global and diffuse radiation either as photosynthetically active radiation (PAR) (mmol m^{-2} s^{-1}) or energy (W m^{-2}). By measuring the incoming radiation in eight compass directions under the tree, an approximation of the energy received by the ground surface under the tree can be made. By comparing these values with a reference sensor that is placed outside the tree canopy, an estimation of the energy absorbed and reflected by the tree is made. A conversion to LAI is done using an equation based on the Beer-Lambert Law. For a full description of the methodology and validation of this procedure we refer to Wirion et al. (2017).

The change in LAI of both trees can be seen in Fig. 2. For both trees we measured the LAI on 7 moments during the season, to cover low, medium and full leave conditions. We then use a linear interpolation between each measurement to assign an LAI value for each rain event . The LAI of the small leaved lime (LAI = 4.8) in full leave conditions is higher than the LAI of the Norway maple (LAI = 3.6). In minimum leaf conditions the LAI is lower for the small leaved lime (LAI = 0.5) than for the Norway maple (LAI = 0.58). The changes in LAI throughout the season are thus more important for the small leaved lime.

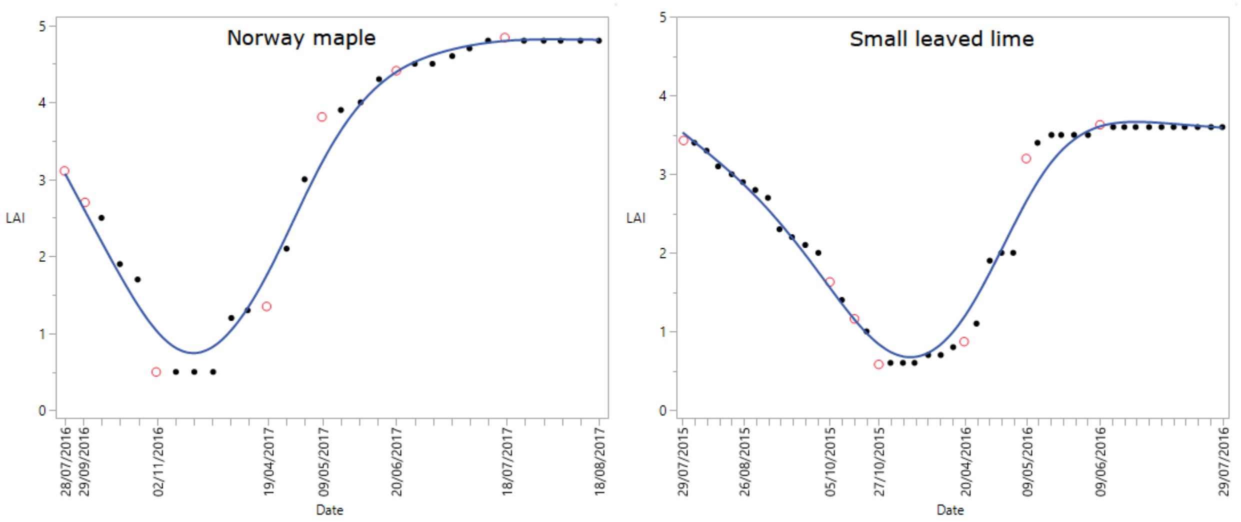


Figure 2: The variation of the LAI of the Norway maple (left) and the small leaved lime (right). Hollow red dots indicate the dates of the measurements.

The free throughfall coefficient was calculated witht the method of Leyton et al. (1967). This method plots the gross precipitation (P_g) vs the Throughfall (T_f) of all rainfall events. The method is dependent on identifying an inflection point that represents the amount of rainfall necessary to saturate the canopy. By drawing a line through the points with the least amount of throughfall left of this point, the free throughfall coefficient is found as the parameter of P_g. The P_g vs T_F graphs of both trees, with their equations and free throughfall coefficients can be consulted in the appendix A.

2.3 The V-catchment Design

A rainfall catchment was constructed under both trees to make throughfall measurements. The design of the construction was inspired by Xiao et al., 2000a. The skeleton was made out of *Pinus sylvestris* and covered with corrugated sheets (Super-Kristal, 450 g/m²) that intercepted rainfall and guided the water in a gutter that fed into a catchment container with a volume of 1 m³. The corrugated sheet was attached to the wooden skeleton with screws on the high sides of the waves. These screws were then topped with a rubber sealing to avoid water leaking. Stemflow was collected by spiraling a half-open garden hose (Ø 2.5 cm) around the tree stem. This hose led to a separate stemflow container with a storage capacity of 26.75 L (Fig. 3).

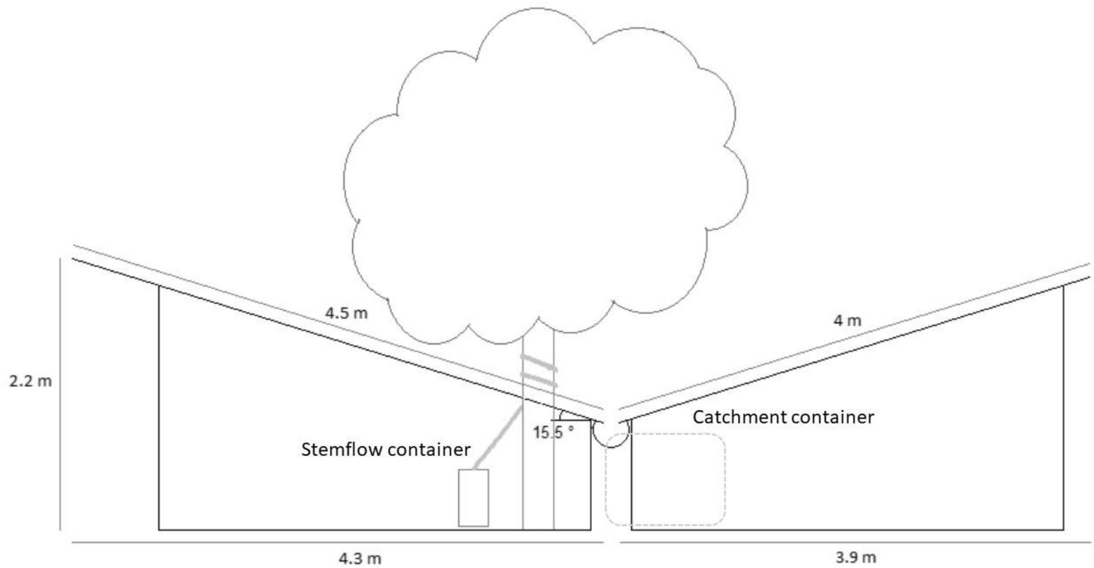


Figure 3: Schematic representation of the V-catchment construction.

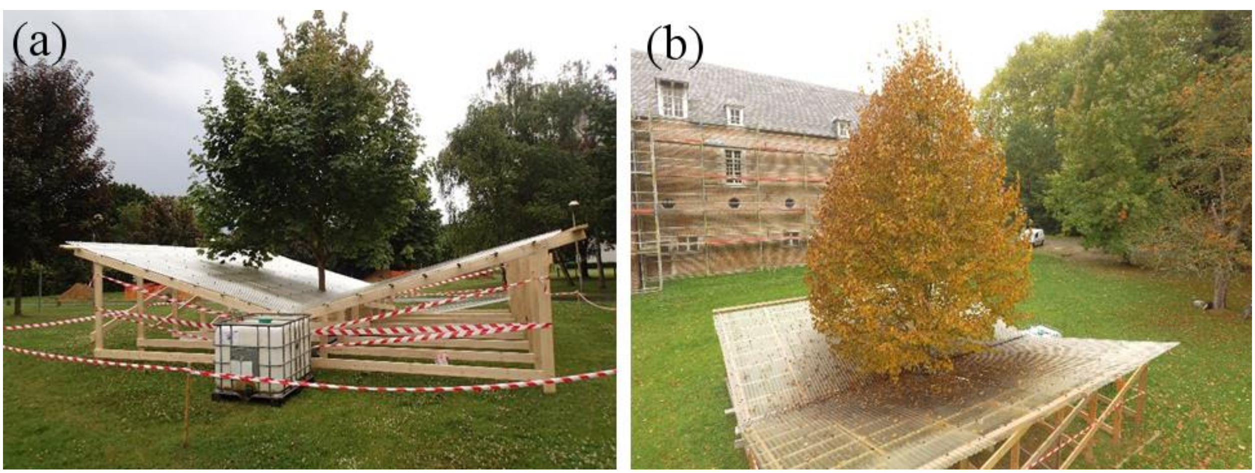


Figure 4: Images of the V-catchment under the Norway maple (a) [picture: 30 July 2015] and small leaved lime (b) [picture: 21 October 2016] .

The catchment measured throughfall under the Norway maple from August 2015 until August 2016. Under the small-leaved lime, it was operational from September 2016 until August 2017. During winter, when no leaves were present on the trees and throughfall registration could be affected by frost and snow, no measurements were performed. Measurements reinitiated when the trees started to grow leaves again. Measurements were paused from 15 October 2015 until 23 March 2016 for the Norway maple and from 13 November 2016 until 14 Abril 2017 for the small leaved lime. No substantial adaptation to the catchment had to be made because of the similar size of both trees. The V-catchment under the Norway maple had a total surface area of 66.4 m² and a vertical projection area of 65.04 m². The V-catchment under the small-leaved lime had a total surface area of 68.9 m² and a vertical projection area of 66.4 m².

After a rainfall event, a certain amount of water is retained on the corrugated sheets of the V-catchment and evaporates into the atmosphere again. To quantify this amount, a detention storage measurement was performed. A corrugated sheet of 0.209 m² was positioned at the same angle as the construction (15.5°) and sprayed with water until droplets started flowing of the bottom edge. The remaining water was then collected after one minute with highly absorbing tissues. The difference in tissue weight before and after absorbing water delivered the amount of water retained on the corrugated sheet. The balance had a precision of 1 g. This process was repeated 10 times, which led to an average water retention on the corrugated sheet of 16 g, equivalent to 0.077 mm/m².

To calculate the detention storage of the rain gutter, a spare piece of gutter measuring 3.27 m was hanged on the same angle as the rain gutter on the construction (1cm descend/m = 0.57°/m). A known volume of water (2000 mL) was poured into the gutter and was collected again on the lower end. Three repetitions were made and an average of 1974 mL was collected again. This means that per meter of rain gutter, 8 mL of water is retained. For the whole construction the gutter measured 8.25 m, which accumulates to a total of 66 mL of water retained. The detention storage of the corrugated sheet and rain gutter were taken into account while analyzing the data.

2.4 The Sensors

The water level in both the catchment- and stemflow container was monitored by pressure sensors (Mini Diver Dl501, Schlumberger Water Services). The sensors are calibrated by the manufacturer and have an accuracy of 5 mm. They store up to 24 000 measurements and are programmed to measure in specific time intervals. For this study, the sensors were set to measure every 30 seconds. Using this time interval, the sensors register data for 8.33 days before the memory is full. An identical sensor was installed on the same height under the tree to act as a barometer. This way the measurements in the containers are compensated for atmospheric pressure before translating them to water column height (cmH20).

To calculate the water stored in the container after a rainfall event, two diver readings had to be made (initial- and end value). The resulting accuracy will thus be the sum of the two reading accuracies (10 mm). As the vertical projection area of the container was 1.12 m², 10 mm of water level rise translates to a volume difference of 11.2 liter. Because the catchment container had rounded corners, the water level was always kept between 200 and 700 liters, meaning that no correction factor was needed to calculate throughfall. This meant that the maximum capacity of the storage container was reached after an event of approximately 7.5 mm (493 liter) , without taking the storage of the tree into account. Because of the storage capacity of the tree, the actual rain event size needed to fill the storage container was slightly higher. The stemflow container was cylindrical shaped with a vertical projection area of 0.0625 m². One cm rise in water level equals a volume difference of 0.3125 liters. The total volume of the stemflow container was 26.75 liters, which was large enough to capture stemflow of a rain event of any realistic size.

Because the sensor inaccuracy is a constant (11.2 l or 10 mm water level rise in the storage container), it will have a smaller effect for larger rainfall events. To quantify this effect, a sensitivity analysis was done. For both the Norway maple and the small leaved lime, rain events of several sizes were analyzed. For every rain event size, the decrease in percentage interception storage with 10 mm water level rise of the container was analyzed. This percentage reflects the uncertainty in interception storage estimates. Results are slightly different for both trees because the vertical projection area of the trees differ slightly. The following equations were obtained (Table 2):

Table 2: Uncertainty estimates Norway maple and small leaved lime. x is the rain event size (mm) and y is the uncertainty of interception storage (%).

Tree	Uncertainty estimate
Norway maple	$y = 0.39 \times x^{-1}$
Small leaved lime	$y = 0.35 \times x^{-1}$

For small events of 1 mm, uncertainty is quite high, being 39 % for the Norway maple and 35 % for the small leaved lime. This uncertainty drops fast however and for events with 2 mm size, uncertainty for both trees is beneath 20 %. For events larger than 4 mm, uncertainty drops below 10 % and for events larger than 7 mm, uncertainty is around 5 % . Because of their negligible importance from a hydrological perspective and the high uncertainties associated with them, we decided to exclude events < 1 mm from the analysis. No uncertainty analysis of the stemflow was done because very few events displayed significant stemflow.

2.5 The Meteorological Stations

Reference data from a meteorological station was used for the measurement of the gross precipitation. A rain event was defined as a rain volume record of minimum 0.1 mm, registered by the tipping bucket. In accordance with authors such as Asadian & Weiler (2009) and Staelens et al. (2006), rain events were separated by a dry gap of minimum four hours. For each rain event, characteristics such as duration and intensity were determined.

For the period August 2015 until November 2015, a tipping bucket was installed on the top of a flat roof, approximately 20 m from the Norway maple. Additional meteorological data for the period August 2015 - November 2015 was gathered from a nearby weather station (RMI, Uccle). For the period March 2016 until August 2016, a meteo station was installed approximately 100 m from the Norway maple. Besides a tipping bucket (0.02 mm/ tip), this meteo station also included measurements of temperature, humidity, wind speed, wind orientation and solar radiation. These data had a temporal resolution of 5 minutes. For the period September 2016 until August 2017, a commercially operated meteo station was used located approximately 1.8 km from the small-leaved lime. The precipitation data from the tipping bucket had a resolution of 0.01 mm and a time resolution of 15 min. This station also provided several other meteorological measurements such as temperature, humidity and wind speed (Table 3). The difference in time resolution between the reference stations did not affect measurement results in a significant way because of the above-mentioned definition of a rain event.

Table 3: The meteorological stations.

Norway maple	Period	Ref station	Distance to tree	Rainfall resolution	Time resolution	Other measurements
1st measurement period (n=13)	14/08/2015 - 14/10/2015	1	20 m	0.1 mm	1 sec	No
2nd measurement period (n=26)	24/03/2016 - 29/07/2016	2	100 m	0.02 mm	5 min	Yes
Small leaved lime						

1st measurement period (n=8)	29/09/2016 - 12/11/2016	3	1.8 km	0.01 mm	15 min	Yes
2nd measurement period (n=17)	15/04/2017 - 18/08/2017	3	1.8 km	0.01 mm	15 min	Yes

Rain events on both sites are predominantly low in precipitation amount, duration and intensity. For the Norway maple site, an average event contained 3.7 mm of rain and lasted 325 min with an intensity of 1.3 mm/h. An average event on the small leaved lime site contained 4.7 mm of rain and lasted 392 min with an intensity of 0.9 mm/h. These intensities are lower in comparison to Mediterranean climates where average intensity > 2 mm/h is common (Pereira et al., 2009). Average wind speeds are low for the Norway maple site with 1.1 m/s compared to the small-leaved lime site where an average wind speed of 5.2 m/s was measured during rain events. This is probably due to the complex wind patterns typically present in urban environments and to the more exposed location of the weather station of the small leaved lime.

2.6 The Data Processing And Model Comparison

The water balance for a rainfall event states:

(1)

$$P_g = I + T_f + S_t$$

where P_g is the gross precipitation, I is the interception storage of the tree, T_f is the throughfall under the tree and S_t is the stemflow of the tree.

P_g (mm) is recorded by a pluviometer close to the V-catchment and extrapolated to the vertical projection area of the construction to calculate the total water volume that falls on catchment surface. Part of the P_g falls directly on the catchment and is guided to the catchment container ($P_{g\ \mathrm{free}}$). Another part of P_g falls on the tree ($P_{g\ \mathrm{tree}}$), of which a small part is free throughfall that never comes in contact with the tree. The majority of water however is intercepted by the tree's leaf- and stem surfaces. Once the interception storage capacity of the tree is filled, throughfall will occur. Water that flows downwards from the stem gets collected in a separate stemflow container. The interception storage of the tree is then the difference between on the one hand the gross precipitation fallen on the whole construction during the event and on the other hand the sum of the precipitation fallen on the free construction, the throughfall and stemflow readings. For the V-catchment the water balance reads:

(2)

$$P_g = P_{g\ \mathrm{free}} + P_{g\ \mathrm{tree}}$$

(3)

$$P_g = P_{g\ \mathrm{free}} + I + T_f + S_t$$

After including the vertical projection areas, the water level readings of the pressure sensors and rearranging Eq. 3 becomes:

(4)

$$I = \left(P_g * \mathrm{VPA}_{\mathrm{constr}}\right) - \left(\left(P_{g\ \mathrm{free}} * \mathrm{VPA}_{\mathrm{free}}\right) + (\Delta\mathrm{H}_{\mathrm{cont}} * \mathrm{VPA}_{\mathrm{cont}}) + (\Delta\mathrm{H}_{\mathrm{St}} * \mathrm{VPA}_{\mathrm{St}})\right)$$

VPA_{constr}, VPA_{free}, VPA_{cont}, VPA_{st} are the vertical projection areas of the whole V-catchment construction, the part of the construction not covered by the tree, the catchment container and the stemflow container respectively. ΔH_{cont} and ΔH_{St} are the height differences recorded after a rain event in the catchment- and in the stemflow container.

Not taking the tree interception into account, the catchment container reached its maximum capacity (493 L) when a rain event of 7.5 mm occurred. To take into account larger rainfall events, we followed the procedure explained below:

Each rain event that filled the catchment container was divided in two parts: the first part lasts until the container is filled and the second part starts when the container is full and all additional rain overflows to the ground. If the amount of rain fallen until the moment the container filled was larger than the interception storage capacity of the tree, it was assumed that the interception storage capacity was reached and all additional water would be converted to throughfall. Otherwise the event was discarded. The throughfall values of the first and second part of the event are then summed and compared to the interception storage values of the first part of the event. The stemflow container never filled completely and was analyzed on a whole event basis.

The interception storage capacity (S; mm) was calculated with an empirical equation based on LAI (-) (Gómez et al., 2001):

(5)

$$S = 1.184 + 0.490\, LAI \quad R^2 = 0.76$$

Due to the empirical background of the equation, it might not be fully applicable to our case. However, we prefer to use the equation of Gómez over the more widely known method of Leyton et al. (1967) for 3 reasons: (1) equation 5 has no subjective interpretation, (2) equation 5 is based on LAI which can be easily measured or retrieved from optical imagery and (3) because seasonal changes in interception storage can be taken into account. The latter is crucial for deciduous trees in temperate climates.

The measured interception storage is compared to different simulation approaches: the Gash, Rutter and WetSpa models (Table 4). The equations for the different simulations of the interception storage can be found in appendix B. The Gash and Rutter model have been developed for a forest stand whereas the WetSpa model is adapted for a solitary tree. The Gash model considers separate rainfall events and the interception storage capacity is assumed to be completely emptied before each event. The continuous simulations with Rutter and WetSpa are performed at the same timestep as the rainfall measurements (see §2.4). This approach enables an emptying of the storage by evaporation during the event. For all models we estimate the interception storage capacity with the measured LAI (Eq. 5, Gómez et al., 2001). Gash, Rutter and WetSpa empty the storage via evaporation from the leaves based on the potential evapotranspiration estimated with the Penman-Monteith equation (Monteith, 1965). Gash estimates free throughfall with the gap fraction (Gash and Morton, 1978; Leyton et al., 1967; Rutter et al., 1971; Xiao et al., 1998). Further drip-off from leaves is estimated using the simplification of Gash et al. (1999), in order to avoid empirical parameterization (Rutter et al., 1971).

Table 4: Characteristics of the different simulation approaches.

	Time step	Spatial extent	Interception storage capacity	Drip-off	Evaporation during event	Hydrological processes simulated
Gash	Discrete	Forest stand	LAI (eq. 5)	Yes	Yes	Interception, throughfall
Rutter	Continuous	Forest stand	LAI (eq. 5)	Yes	Yes	Interception, throughfall, evaporation

WetSpa	Continuous	Single tree	LAI (eq. 5)	No	Yes	Interception, throughfall, evapotranspiration, infiltration, depression loss, runoff, …

3. Results

3.1 Event Summary

The gross precipitation of each event was divided in throughfall, interception storage and stemflow (Table 5).

Table 5: Event summary of the precipitation events of both trees.

			Throughfall		**Interception storage**		**Stemflow**	
Northern maple	Events (#)	P_g (mm)	Total (mm)	Percent (%)	Total (mm)	Percent (%)	Total (mm)	Percent (%)
Total	39	143.71	88.03	61.26%	55.61	38.70%	0.19	0.13%
Events < 5 mm	29	63.47	36.41	57.37%	27.04	42.60%	0.01	0.02%
Events 5-10	7	46.98	27.96	59.51%	19	40.44%	0.12	0.26%
Events 10-20	3	33.26	23.66	71.14%	9.57	28.77%	0.06	0.18%
M. period 1 (mm)	13	41.1	21.41	52.09%	19.69	47.91%	0.07	0.17%
M. period 2 (mm)	26	102.61	66.62	64.93%	35.92	35.01%	0.12	0.12%
Small leaved lime	Events (#)	P_g (mm)	Total (mm)	Percent (%)	Total (mm)	Percent (%)	Total (mm)	Percent (%)
Total	25	117.31	70.35	59.97%	44.12	37.61%	0.11	0.09%
Events < 5 mm	17	37.52	18.3	48.77%	16.43	43.79%	0	0.00%
Events 5-10	4	27.9	12.05	43.19%	15.81	56.67%	0.03	0.11%
Events 10-20	4	51.89	40	77.09%	11.88	22.89%	0.08	0.15%
M. period 1 (mm)	8	26.89	21.52	80.03%	5.35	19.90%	0	0.00%
M. period 2 (mm)	17	90.42	48.83	54.00%	38.77	42.88%	0.11	0.12%

Taking all events into consideration, both trees are very similar in behavior. Both trees intercept 38 % of the rain and stemflow is negligible for both trees. The largest difference is found in the events between 5 and 10 mm, where the Norway maple intercepts 40% of the rainfall while the small leaved lime intercepts 57 %. Another noticeable difference is seen when we compare the measurement periods. In the first measurement period the Norway maple intercepts significantly more (47.9%) than the small leaved lime (19.9%). Interception storage in the second measurement period is more similar between both trees with 35 % of rain intercepted by the Norway maple and 42.9 % by the small leaved lime.

3.2 The Interception Storage Capacity And Simulations

Table 6: Interception storage capacity (S; mm)

Norway Maple	**Period**	**S (Gómez)**
All year (n=39)	14/08/2015 - 29/07/2016	2.47
1st measurement period (n=13)	14/08/2015 - 14/10/2015	2.40
2nd measurement period (n=26)	24/03/2016 - 29/07/2016	2.50
Small leaved lime		**S (Gómez)**
All year (n=25)	29/09/2016 - 18/08/2017	2.62
1st measurement period (n=8)	29/09/2016 - 12/11/2016	1.90
2nd measurement period (n=17)	15/04/2017 - 18/08/2017	3.14

Considering the whole year, interception storage capacities (S) for the small leaved lime are higher than for the Norway maple as expected when we consider the LAI measurements. Further we separate the measurements into measurement period 1 and 2, based on our measurement campaign. The timespan these periods cover are shown in Table 6. In general measurement period 1 and 2 cover both low- and high leave coverage. Therefore differences in S are not so outstanding. However in the period where trees lose their leaves S seems to be a bit lower than in the period where trees gain new leaves. The differences are higher for the small leaved lime which is also what we expect from LAI measurements. In their paper, Gómez et al. (2001) acknowledge a slight overestimation of the interception storage capacity. We find the interception storage capacity values are within the range of expected interception storage capacity values found in literature and ranging between 0.2 and– 3.58 mm (André et al., 2008; Aston, 1979; Breuer et al., 2003; Gash & Morton, 1978; Gómez et al., 2001; Liu & Smedt, 2004; Valente et al., 1997; Xiao et al., 2000a).

The V-catchment measurements include free throughfall, drip-off and stemflow. As our stemflow measurements are very low (< 0.2 %) we exclude stemflow from our simulations. In general all simulation methods perform similarly and predict an interception storage close to the measurements (I = +- 40 % of rainfall) (Fig. 5). For bigger rainfall events (Pg > 10mm) the measurements indicate an average interception of 25% of rainfall whereas for smaller rainfall events (Pg < 10mm) we measure an average interception rate of 47 % of rainfall.

Table **7** 7 shows that the method of Gash is most stable throughout the 2 trees and seasons (R^2 = 60% +- 2%, E_{RMS} = 0.85 +- 0.2 mm), the other methods show more variation. As in the paper of Véliz-Chávez et al. (2014) the performance of the Rutter model is below the performance of Gash. Similarly, we also observe an underestimation of the interception storage for higher rainfall events (P_g> 10 mm) with the method of Rutter (Fig. 5). WetSpa performs best for rainfall events P_g > 10 mm and Gash performs worst. This might be related to its discrete behavior versus the continuous simulations of Rutter and WetSpa.(Table **7** 7, Fig. 5, Fig. 6). For small events (P_g < 10 mm) all simulations overestimate the interception storage with Gash showing the best performance.

In Fig. 6 we can observe that all models simulate lower interception storage than measured for the bigger interception events (> tree storage capacity) and higher interception storage than measured for smaller interception events (< tree storage capacity). For small interception events the storage capacity is not filled in our simulations, and trees intercept all rainfall water. However, due to wind speed and direction, rain inclination angle, leaf zenith angle and other meteorological and tree architectural parameters not all rainfall water is intercepted even for small events. Even though we calculate the storage capacity with

Gomez et al., 2001(§cf paragraph 3.2), our models still underestimate the interception storage for bigger interception events. We assume that the emptying of the storage via evaporation from leaves during the event is underestimated in our simulations.

With regards to the correlation values, WetSpa performs better than Rutter but worse than Gash. For the small leaved lime tree, for the gaining leaves period and for rainfall events where $P_g > 10$ mm , WetSpa shows the best performance.

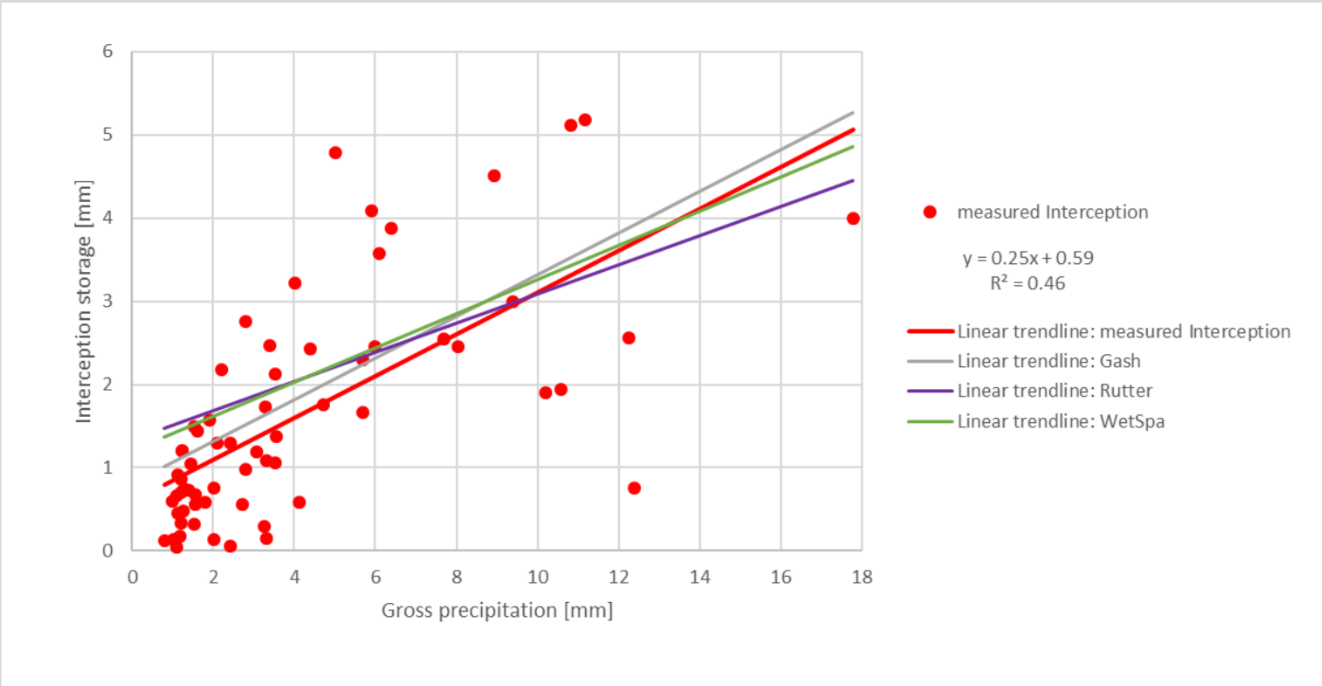


Figure 5: Interception storage vs gross precipitation for all events for both trees.

Table 7: Correlation between measured and simulated interception storage (R^2/RMSE).

R^2 [%]/ E_{RMS} [mm]	Gash	Rutter	WetSpa
All events (64 events)	**60/ 0.87**	50/ 1.10	59/ 1.02
Norway maple (39 events)	**62/ 0.78**	49/ 1.10	52/ 1.06
Small leaved lime (25 events)	59/ 0.99	53/ 1.10	**65/ 0.96**
Loosing leaves period (21 events)	**58/ 0.65**	53/ 0.84	55/ 0.71
Gaining leaves period (43 events)	59/ 0.96	48/ 1.20	**63/ 1.15**
Big events (Pg > 10mm) (7 events)	30/ 1.44	44/ 1.28	**46/ 1.25**
Small events (Pg < 10mm) (57 events)	**60/ 0.78**	41/ 1.02	53/ 0.93

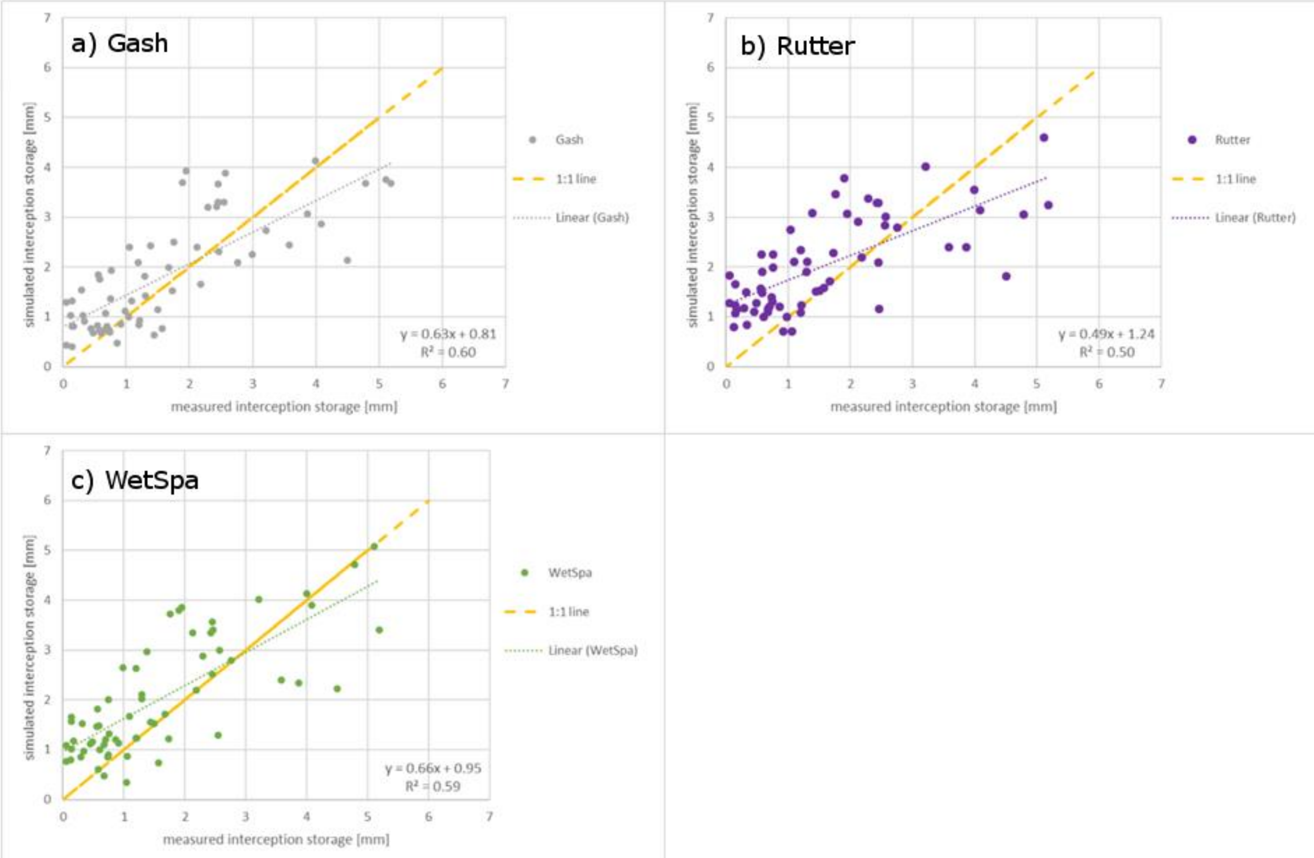


Figure 61: Measured vs simulated interception storage of the Gash- (a), Rutter- (b) and WetSpa (c) model

4.Discussion

4.1 The Tree Interception Storage

Average interception storages during the measurement periods for both trees are, with 38.70 % for the Norway maple and 37.60 % for the small leaved lime, very similar. In general, the interception storage we measured is relatively high in comparison with other studies (Gómez et al., 2001; Staelens, 2010; Pereira et al., 2009; Xiao et al., 2000b; Xiao & McPherson, 2011). However, caution should be taken to directly compare interception storage as measurement conditions are different. Our measurement periods only covered full leaf area- and transition periods. Defoliated trees were not monitored and, if included, these would lower the average amount of rain intercepted. Moreover, to our knowledge most studies are usually done in Mediterranean climates which have a distinct precipitation pattern with dry summers and wet winters. In comparison, temperate climates have a more evenly distributed rainfall pattern. There are however meaningful comparisons to be made. For example an evergreen *Gingko biloba* in the study of Xiao & McPherson (2011) and an evergreen *Quercus ilex* in the study of Pereira et al. (2009) were found to intercept 25 % and 23 % of the gross precipitation respectively. Even though no defoliation occurred and leaf coverage was high, these interception storage values are still far below the values measured in this study. In another study, Xiao et al. (2000a) derived interception storage values of a *Pyrus calleryana* 'Bradford' and a

Quercus suber with constant LAI in a Mediterranean climate and found they intercepted 15 % and 27 % of the gross precipitation. The higher interception storage values we find indicate the suitability for tree interception in our temperate climate in comparison to the Mediterranean climate. Measured rain intensities in our study are low in comparison with those mentioned in studies performed in the Mediterranean area, where average intensities larger than 2 mm/h are common (Pereira et al., 2009). Xiao et al. (2000a) found that when small rain events of low duration follow up on each other with a high frequency, the amount of intercepted water increases due to the consecutive wetting and drying of the crown surface.

4.2 The Model Comparisons

The Gash, Rutter and WetSpa models show similar performances. For bigger interception events (> interception storage capacity) we simulate lower interception storage than we measure. We assume that the emptying of the storage by evaporation is higher than we simulate with our models especially for Gash who doesn't account for a continuous evapotranspiration during the event. The lower performance of Gash and Rutter compared to WetSpa for big interception events might be related to their origins based on forest stands and not on solitary trees. Evaporative behavior in forest stands differs from solitary urban trees due to differences in canopy architecture, tree physiology, and their response to the urban climate (Grygoruk et al., 2014; Zipperer et al., 1997)). To gain deeper understanding at a single tree level, more specialized interception models such as the method of Xiao et al. (2000b) might be more recommendable. Unfortunately we could not measure all the parameters needed for this method and were not able to evaluate its performance for our trees. This indicates the operational limitations of such a model. Due to the LAI based calculations, the biophysical characteristics of solitary trees in an urban environment are represented (Wirion et al., 2016; Degerickx et al., 2018) and the need of measuring physical parameters for the simulations is avoided. This is of interest especially if we want to evaluate the net rainfall potential and further water balance components (infiltration, runoff and evaporation) in an urban context. The simplicity of the WetSpa model and its water balance framework, as well as the high similarity in performance of the specialized interception models (Gash and Rutter) and its relatively good performance for big interception events make it a competitive tool to evaluate the retention of rainfall water on city trees.

4.3 The Potential Benefit Of Trees In An Urban Context

In our V-catchment experiment, 38% of gross precipitation was intercepted. This amount is very significant and proves that trees can be an important addition to an integral water management plan. The temperate climate where the experiments were conducted in is beneficial for tree interception due to the relatively even rainfall distribution throughout the year and its characteristic long, low-intensive rain events. In the case of heavy rainfall events the interception storage capacity of the trees is quickly reached and thus most rainfall contributes to surface runoff. Even though urban trees alone cannot be a flood control measure, they help to delay and spread out peak runoff and to reduce pollutant wash-off, thereby limiting the pressure on the drainage system (Szota et al., 2019; Wang et al., 2008). Another hydrological benefit of urban trees, not covered in this research, is that they make openings in the impervious surface, thereby giving runoff water the opportunity to infiltrate (Armson et al., 2013). Our experimental setup reflects an ideal case of a solitary city tree, unobstructed by buildings with full sun and wind exposure. In reality urban trees are found in a wide variety of conditions and interception will diverge from our experiments (Xiao et al., 2016; Asadian and Weiler, 2009; Xiao et al., 1998; Zipperer et al., 1997). To represent the diversity of urban trees, an LAI based simulation is proposed. The experimental results and our simulations show that city trees should be considered for urban water management And the WetSpa tool can be a good alternative to do so.

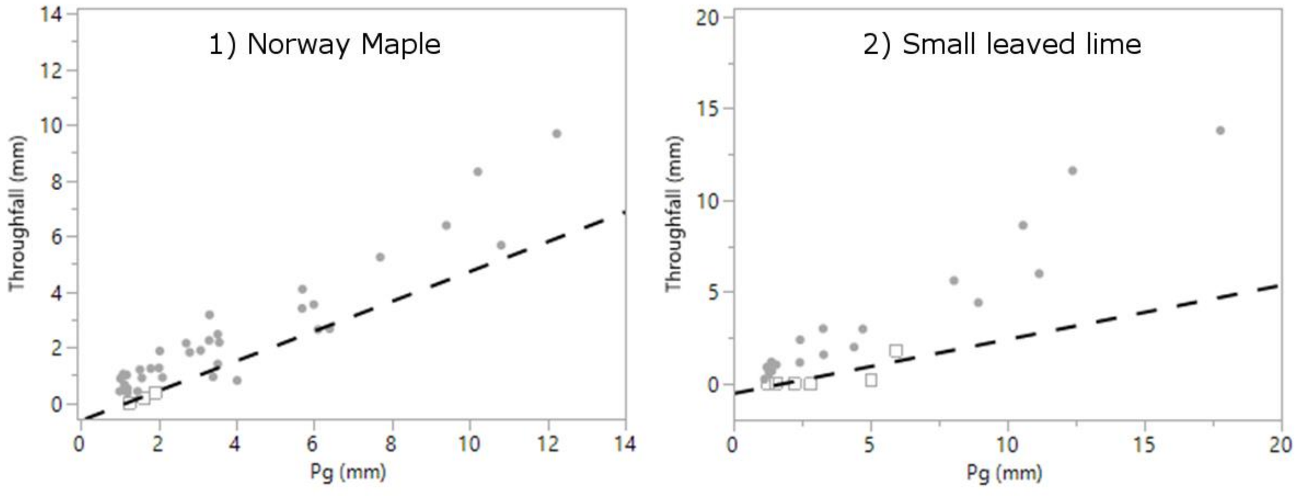
5. Conclusions

To evaluate the importance of city trees for reducing the net rainfall in a temperate climate we evaluated (1) in-situ interception experiments and (2) different interception simulation tools on two solitary trees. Our main conclusions are:

1) Both trees intercepted around 38% of gross precipitation, emphasizing the importance of (1) interception storage for reducing net rainfall and (2) accounting for interception storage in an urban water balance model.
2) The water balance model (WetSpa) and the specialized interception models of Gash and Rutter showed a similar performance when compared to the measurements. The three models underestimate interception storage for bigger rainfall events which we relate to a poor understanding of the evaporative behavior of intercepted rainwater during rain events in an urban environment. However, the relatively good performance of WetSpa for bigger rainfall events, its simplicity and its water balance framework promote it as a tool for assessing the interceptive potential of urban trees.

Appendix A: Free throughfall coefficient estimation:

Leyton graphs for the Norway Maple (all year n= 39) and small leaved lime (all year n=25):



$\text{Tf (mm)} = -0.63 + \mathbf{0.54} \text{ X Pg (mm)}$ $\text{Tf (mm)} = -0.57 + \mathbf{0.30} \text{ X Pg (mm)}$

Norway Maple	**Free throughfall coefficient (p)**
All year (n=39)	0.54
1st measurement period (n=13)	0.6
2nd measurement period (n=26)	0.32
Small leaved lime	
All year (n=25)	0.3
1st measurement period (n=8)	0.47
2nd measurement period (n=17)	0.25

Appendix B: Model equations:

$$\boldsymbol{I = S + E = P_g - (T_f + D + S_f)}$$ equation 1 (Xiao, 1998)

$\boldsymbol{I}$: interception storage [mm]
$\boldsymbol{S}$: crown surface storage capacity = interception storage capacity [mm]
$\boldsymbol{E}$: evaporation [mm]
$\boldsymbol{P_g}$: gross rainfall [mm]
$\boldsymbol{T_f}$: free trough-fall [mm]
$\boldsymbol{D}$: drip-off [mm]
$\boldsymbol{S_f}$: stemflow [mm]

$$\boldsymbol{T_f = P \times P_g}$$ equation 2 (Xiao, 1998)

$\boldsymbol{P}$ = gap fraction [-]

$$\begin{cases} \mathbf{D = 0} & \mathbf{for\ I < S} \\ \mathbf{D = I - S} & \mathbf{for\ I \geq S} \end{cases}$$ equation 3 (Valente et al., 1995)

Gash

$$\begin{cases} \mathbf{I = (1\text{-}p) \times} \boldsymbol{P_g} & \mathbf{for\ P< P'} \\ \mathbf{I = (1\text{-}p) \times P' +} \frac{\boldsymbol{Ea}}{\boldsymbol{R}} \times (\boldsymbol{P_g}\text{-}\mathbf{P'}) & \mathbf{for\ P> P'} \end{cases}$$ equation 5 (Gash, 1979)

$\boldsymbol{Ea}$: mean evaporation / canopy cover [-]
R: mean rainfall/ saturated canopy cover [-]
P': precipitation reaching canopy saturation [mm]

$$\mathbf{P' = -\frac{R}{Ea} \times S \times} \boldsymbol{ln}\left(\mathbf{1 - \frac{Ea}{R \times (1-p)}}\right)$$ equation 6 (Gash, 1979)

Rutter

$$\mathbf{P_{soil} = T_f + D + S_f}$$

and

$$\begin{cases} \mathbf{P_{soil} = P_g - E\text{-} (S\text{-}IS)} & \mathbf{for\ P - E > C - IS} \\ \mathbf{P_{soil} = 0} & \mathbf{for\ P - E <= C - IS} \end{cases}$$ equation 7 (Vegas et al., 2012)

$\mathbf{P_{soil}}$ **:** precipitation reaching the ground (net precipitation) [mm]
IS: interception storage at timestep before actual rainfall [mm]

$$\mathbf{E = \frac{IS}{S} \times PET}$$ equation 8 (Vegas et al., 2012)

PET: Potential evapotranspiration estimated with the Penman-Monteith equation (Monteith, 1965).

$$\mathbf{I = E + (S\text{-}\ IS)}$$ equation 9 (Vegas et al., 2012)

WetSpa

$$\begin{cases} \mathbf{I = S - IS} & \mathbf{for\ P > C - IS} \\ \mathbf{I = P_g} & \mathbf{for\ P <= C\text{-}\ IS} \end{cases}$$ equation 10 (Liu et al., 2004)

and

$$\mathbf{IS\ (t) = IS\ (t\text{-}1) + I\ (t) - E\ (t)}$$ equation 11 (Liu et al., 2004)

and

$$\begin{cases} \mathbf{E(t) = IS(t\text{-}1)} & \mathbf{for\ PET > IS(t\text{-}1)} \\ \mathbf{E\ (t) = PET} & \mathbf{for\ PET < IS(t\text{-}1)} \end{cases}$$ equation 12 (Liu et al., 2004)

Author Contributions: V.S., C.W., B.S. and B.V. conceived and designed the ground-truthing experiments and the simulation strategy. V.S. and C.W. set-up the V-catchment and performed the ground-truthing measurements. V.S. took the lead in the analysis of the measurement results and C.W. fulfilled the simulations and scenario analysis. V.S., C.W., B.S. and B.V analyzed the results, and prepared the structure of the manuscript. V.S. and C.W. wrote the initial draft of the paper. W.B., M.H., B.S. and B.V supervised the research and contributed to improving the manuscript prior to submission.

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