

Response Reviewer 1

Authors: Thank you for reviewing our paper. We believe that your comments have significantly strengthened the manuscript.

Reviewer main comment 1: The manuscript is, in my opinion, too long and contains details which are not very useful and which don't help the reading. I would recommend a shorter manuscript, written in a more synthetic and efficient way and focusing on the key points of the contribution, and may more rigorous (notation and denomination of variables, model presentation).

Authors response: We agree and shortened the paper from 10340 words to 8006 words (abstract + main text + conclusions). The whole manuscript went from 33 to 24 pages, including references and appendices. Many sections such as the materials and methods, and results section were shortened. The scenario analysis and regression were removed to focus on the key points of the manuscript.

Change in manuscript: See manuscript

Reviewer main comment 2: The manuscript organization could be simplified. Each section is divided into many paragraphs (up to 9 or 10) which don't help the understanding. - The field experiment concerns individual trees. What about the tested models? Do they apply to individual trees or tree covers? Consequences concerning the model evaluation ?

Authors response: We simplified the manuscript, eliminated an merged several paragraphs, removed unnecessary figures, etc. We clarified which models are used for forest cover interception and which models are used for individual trees (Table 4). We discussed the differences between these models more in detail. More elaborated answers are written in response to the line comments.

Change in manuscript: See manuscript and line comments.

Line comments

Reviewer comment: p 1 – line 33-36: if the problem of heavy events should not be forgotten, the growing interest for vegetation in urban areas seems more related to the promotion of sustainable urban development, and more recently to urban climatology.

Authors response: We agree that there are probably other drivers promoting the incorporation of vegetation in urban areas such as for example heat reduction and personal wellbeing.

In case of hydrological ecosystem services, vegetation only functions as a part of the solution and is most functional in the case of less intense and more spread out rainfall events. These events are the most common in our study (average intensity 1.3 mm/h for the Norway maple site and 0.9 mm/h for the small leaved lime site in comparison with an average > 2mm/h in Mediterranean climates (Pereira et al., 2009)).

In the case of heavy rainfall events the storage capacity of trees and smaller vegetation will most likely be exceeded, limiting the influence of the vegetation. However, even in the case of heavy

rainfall events, peak runoff will be delayed and spread out, resulting in less intense pressure on the drainage system (Szota et al., 2019).

Change in manuscript: We decided to not change the text. On p 2 – line 3 we start with ‘part of the solution’, emphasizing that incorporating urban green is not enough and complementary measures are also necessary. Furthermore, on p 1 – line 37-38, we say that an important challenge is an efficient water regulation policy, which includes more than just runoff reduction. We think urban green has an important part in such a policy.

Reviewer comment: p 2 – paragraph 1: I have some agreement to that. The authors may indicate that the role of vegetation in urban areas remains a very open question, largely unstudied so far.

Authors response: We don’t think it is largely unstudied. Actually the influence of vegetation on the urban hydrological cycle has been a booming topic in recent years. For example when looking at google scholar: Inserting the keywords ‘urban’ ‘vegetation’ and ‘hydrology’ results in 17400 results since 2015.

We do think however that there are still some knowledge gaps to address. For example, the most commonly used models that estimate interception storage are stand-alone interception models (Gash, Rutter) that are not incorporated in a complete water balance model. That’s why we compare these specialized models with the interception storage estimates of WetSpa, a model capable of modelling the whole water balance. Another knowledge gap is that most interception studies are done in Mediterranean climates, with different rainfall distribution patterns and vegetation. We want to know if the interception potential of trees in temperate climates is different than in Mediterranean climates.

Change in manuscript: We rewrote the last paragraph of section 1.2 to better emphasize the knowledge gaps we want to address and rewrote the research questions in section 1.6.

Reviewer comment: p 3 – paragraph 1.3: in urban areas, many trees are tree lines, along streets. In that case, the soil around these trees is sealed (impervious). Is the situation studied by the authors really representative of urban trees?

Authors response: in the case of the interception process, our experimental setup is representative, as it is a solitary tree and the ground surface does not influence the interception process. Off course due to the heterogeneous nature of urban environments, trees are found in widely varying settings and cannot all be reproduced in an experimental setup (proximity to buildings and other trees, varying wind directions, sun exposure, etc). We believe it is important to simulate interception storage for such a variety of urban trees and thus propose to use a LAI-based approach to calculate interception storage with a water balance model. The LAI based interception calculation accounts for the tree development/health in the urban environment and the distributed water balance model accounts for further urban constraints in the infiltration, evaporation and runoff calculation (imperviousness, connectivity of water flow, etc.). By placing our experimental setup on a site that is free from obstructions such as buildings and other trees, we believe we represent an ideal case

for urban trees that is adaptable to more specific conditions, providing that some assumptions are made.

Change in manuscript: added the text: ‘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 parks, 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.’ ‘ to section 2.2.

Reviewer comment: p 5-11: The experiment device is interesting and original. Nevertheless, it raises issues. How representative is this experimental setting of urban trees that are subject to very different contexts ?. I would suggest that the authors write in a more synthetic way.

Authors response: See answer above. Our experimental setup represents the ‘ideal’ case of an unobstructed solitary urban tree. This will result in a maximum water storage. A possibility to determine the influence of urban trees in more specific conditions (eg. A tall building 3 m on the south side of a tree in a wide east-west street lane) can be estimated through simulations using our findings as a maximum value. Moreover, because WetSpa takes LAI into account, a much broader variety of urban trees can be modeled. For example, a street tree will probably have a different LAI than a park tree.

Change in manuscript: See previous comment.

Reviewer comment: p 10 – paragraph 2.6: what difference between data processing and modelling (next section ?) It is not clear to me.

Authors response: We merged both sections, eliminated some explanations that are already known for a long time and wrote in a more synthetic way.

Change in manuscript: see manuscript section 2.6 ‘The Data Processing And Model Comparison’

Reviewer comment: p 12 – paragraph 2: If modelling and model comparison is a central part of the manuscript, I would suggest to present the models as part of the manuscript and not in Appendix.

Authors response: We decided to keep the equations in the appendix for multiple reasons: (1) the models are not new but have been developed a long time ago, (2) we don’t change the functionality (equations) of the models , and (3) the readability of the manuscript. We add the equations to the appendix for the reproducibility of our results but believe that the equations have no other added

value to the manuscript as the differences between the models is discussed in the method section (paragraph 2.6).

Change in manuscript: No changes made.

Reviewer comment: p 12 – paragraph 2.8: Do these models apply to individual trees, as the field experiment, or a tree plant cover? I suppose that there is a very important difference between the two. It is a significant point concerning the model relevance.

Authors response: Gash and Rutter developed their models on forest stands whereas WetSpa is not specialized but was built to work at a regional basin scale (therefore the simplifications). However, we adapt the interception module in WetSpa to include LAI and set-up a model representing the V-catchment experimental set-up. We agree that it is important to note that Gash and Rutter were developed on a forest stand and also discuss the possible effects on the outcome in the discussion section.

Change in manuscript: p 12- paragraph 2.6: we added the text ‘The Gash and Rutter model have been developed for a forest stand whereas the WetSpa model is adapted for a solitary tree’ to clarify the differences which are also summarized in table 4.

Reviewer comment: p 13: the scenario analysis appears as important as the modelling and model comparison. Is it really the case, or is it just an illustration example, in which case, I would suggest to reduce its length.

Authors response: The scenario analysis indeed is used as an illustration example to emphasize the potential of urban trees in reducing runoff. To reduce the length of the manuscript we decided to remove the scenario analysis from the paper and instead discuss the potential impact of urban trees in the hydrological cycle in the discussion section (section 4.3 ‘The Potential Benefit Of Trees In An Urban Context’).

Change in manuscript: see section 4.3

Reviewer comment: p 15 – lines 5 to 14: I would suggest to move this lines to Section 2.

Authors response: We agree and moved section 3.1 to Material and Methods (section 2.2).

Change in manuscript: See section 2.2.

Reviewer comment : p 17 – figure 8: I am not convinced that this figure is very useful here, it could eventually be moved in Appendix.

Authors response: We agree that this figure takes up too much space. We removed the figure (it is available upon request) and we now describe the rain event characteristics in section 2.4.

Change in manuscript: See section 2.4.

Reviewer comment: p 19 – paragraph 3.3: is a full page needed to see the weak sensitivity? A few lines would be enough.

Authors response: We agree, we removed the figures and shortened this section substantially. This part is now incorporated in section 2.5.

Change in manuscript: See section 2.5.

Reviewer comment: p 20: line 1-4: small events of 1 mm are not very important from a hydrological point of view

Authors response: We agree, this fact together with the high uncertainty associated with events < 1 mm led us to the decision to remove them from further analyses.

Change in manuscript: See section 2.4.

Reviewer comment: p 20: figure 10: the presence of the inflexion point on the regression lines is not obvious. Is it justified by physical reasons?

Authors response: A disadvantage of the Leyton method is that the inflection point is determined subjectively. We looked at the residual values of the P_g vs T_f plot to determine this point (not shown in manuscript), a sudden change in residual values indicated the inflection point.

We decided however to remove the Leyton analysis for interception storage capacity determination from the manuscript for several reasons:

- 1) The above described inherent subjectivity of the method.
- 2) The Leyton method cannot take into account seasonal changes of leaf cover. As our measurements periods encompass transition periods from leaf off to leaf on, this confuses the Leyton analysis.
- 3) A few large events can significantly alter the analysis.

For these reasons we decided to abandon the Leyton method as a means of comparison with our chosen method to determine interception storage capacity (Equation 5, Gomez et al., 2001). The Leyton method is still used for the free throughfall coefficient calculation, as shown in appendix A.

Change in manuscript: See manuscript section 2.2.

Reviewer comment: p 22: Equation 6. The authors introduce I as interception (in mm). The legend of Table 5 mentions the Interception storage capacity (S in mm), as Equation 5 (p 11) and in Appendix A (Eq. 1) I is the interception storage, and S the crown surface storage capacity, and IS appears in following equations. In equation 6, D is duration and in A-1, it is drip-off A very careful checking of notations is required. What is the difference between interception, interception storage and storage capacity.

Authors response: We carefully checked our notations in the manuscript and made some changes. The definitions of interception, interception storage and interception storage capacity are explained in section 1.3.

In short: interception is a process, interception storage (I) is the total volume of water a tree can hold during an event that does not reach the ground surface and the interception storage capacity (S) is the maximum volume of water a tree can hold for a given time. The interception storage can be greater than the interception storage capacity when there are dry periods during a rainfall event and water can drip off or evaporate.

Change in manuscript: Definitions in section 1.3

Reviewer comment: p 22: Equation 6 – I am sceptical concerning the regression model (eq. 6) which provides better results, but which introduces 9 numbers, that is 9 parameters, which means that this model is strictly limited to the analysed data set, without any generalization. Such a model is of a very limited interest.

Authors response: We decided to remove the regression analysis from the manuscript. One reason for this is the comment mentioned by the reviewer. The other reason is that it allows us to focus more on the comparison between the standard forest canopy interception models (Gash- and Rutter) and the WetSpa, solitary tree model. We think this makes our manuscript more clear.

Change in manuscript: See manuscript

Reviewer comment: p 23: Figure 12 – Interception storage – A new denomination?

Authors response: This is the interception storage as defined in section 1.3, the total volume of water intercepted by the tree for an entire rainfall event.

Change in manuscript: See section 1.3

Reviewer comment: p 25: I would suggest that Figure 13 and Table 6 to be the central points of the model comparison.

Authors response: We agree and structured the text more around this table and figure. These are now Table 7 and Figure 6.

Change in manuscript: See manuscript

Reviewer comment: p 26-27 paragraph 3.7: I wonder about the usefulness of this paragraph “land cover change scenario” in this manuscript. In the light of previous results, it is not surprising that an increase of sealed surfaces generates a runoff increase, and that tree planting generates an increase of water storage.

Authors response: To make the focus of our manuscript clearer and to limit its length, we decided to remove the scenario analyses. We did add a section discussing the relevance of our findings to the urban context (section 4.3).

Change in manuscript: See section 4.3

Reviewer comment: p 27: It seems to me that interesting discussion subject could have been the following: i) validity of this model assessment given the possible differences between individual trees and tree plant cover; ii) application of the models to a more usual urban context: available data, types of trees, ...

Authors response: We restructured the discussion in a way that it better reflects and emphasizes our research questions. It is now structured as follows:

- 1) Comparison of our gathered dataset with datasets from other studies.
- 2) Comparison of model performance between the standard forest interception models and the individual tree WetSpa model.
- 3) Relevance of our experimental setup and model results to an heterogeneous urban environment.

Change in manuscript: See discussion section

Reviewer comment: p 32: Table to remove, it is unreadable (the data set can be provided on request).

Authors response: We removed the table for the manuscript.

Response Reviewer 2

Authors: We would like to thank reviewer 2 for his time to review our paper, we think his constructive comments have significantly improved the quality of our manuscript.

Reviewer main comment 1: The manuscript is, however, unusually long, and contains extended reviews of basic and standard canopy interception concepts that are not necessary and make the original contributions of the work difficult to extract. For example, Figures 1 and 5 are unnecessary: these have been standard for 50 years, and also the same analysis as Figure 5 was done for this research and presented as Figure 10. Sections 1.2, 1.3, and 2.6 could all be reduced substantially.

Authors response: We restructured the paper and shortened the manuscript. The main focus is now on the original contributions of the work: 1) The experimental setup and gathered dataset 2) Comparison of the performance of on one hand, the standard specialized forest interception models (Gash and Rutter) and on the other hand an adapted water balance model (WetSpa).

Change in manuscript: The regression analysis was removed because of its narrow application. The scenario analysis was also removed and instead a section (4.3) was added to discuss the relevance of our research to an urban context. Several paragraphs and subsections were removed or merged (e.g. section 3.3 ‘The sensitivity analysis’ was substantially reduced and incorporated in sections 2.3 ‘The V-catchment Design’ and 2.5 ‘The Meteorological Stations’). Figures 1, 5, 6, 8, 9, 10, 11, 14 and 15 were removed.

Reviewer main comment 2: The choice of and behavior of WetSpa for interception modeling is difficult to evaluate. The WetSpa equations in Appendix A contain symbols that are not defined and the cited source for these is a white paper not contained in the References. As far as I can determine the simple assumptions it makes have never been tested in the refereed literature, despite the citations to support use of the WetSpa interception formulation (e.g., P5L15) that do establish that it has been used. There appears to be no scientific reason to include this model in a comparison, and it seems likely that it was chosen because of its familiarity to the authors.

Authors response: We want to test the performance of a water balance model to simulate interception storage of a solitary tree in order to be able to use the model in an urban context. WetSpa has been chosen due to the flexibility of the model which makes it easy to adapt it to our purposes (including LAI and setting up a V-catchment). The model flexibility and V-catchment set-up is well described in the PhD thesis of Elga Salvadore (Salvadore, 2015). The inclusion of LAI in the interception calculation is described in Wirion et al., 2016.

Change in manuscript: To better describe why we include WetSpa in the analysis we changed Paragraph 1.5 ‘Interception Models’ and paragraph 1.6 ‘Research Questions’.

Reviewer main comment 3: The simplicity of the WetSpa formulation as an ultra-simple bucket model with, e.g., no provision for drip when storage is less than capacity or reduced evaporation rates from partially wetted canopy, is an interesting test against the more sophisticated Gash and Rutter models. That it appears to give empirically similar or superior results is a very useful finding for canopy interception science. However, the discussion makes essentially no attempt to explore the ramifications of this finding, either from a utilitarian (e.g., “should we be using simpler models”) or physical (e.g., “what does it mean that only the coarsest components of the water budget need modeling?” Or “Is the superior performance of the super-simple model a fluke of this environment or should we be applying it more generally?”) perspective. Re-stating and discussing the “WetSpa” formulation in terms of other, similar models in the older literature would help it to make the biggest contribution to the canopy interception literature.

Authors response: We agree that the good performance of WetSpa is surprising and important to notice. Further, we believe that different models serve different purposes. The disadvantage of Gash and Rutter in this case is that they were developed on forest stands and we believe this might affect their performance for bigger rainfall event as the evaporative potential differs in an urban context. We elaborate on this in the discussion of the results. We still promote the use of more specialized interception models for a more detailed understanding of interception on solitary trees. In the context of urban management, however, WetSpa seems a good alternative to quantify the interceptive potential of urban trees as a starting point to further analysis of other water balance components such as infiltration and runoff. When it comes to hydrological modelling the potential of interception storage is usually underestimated, simplified or even disregarded as its potential for flood mitigation is low. However, our study shows that most rainfall events in our climate are moderate and that 38% of the rainfall water during rain events is intercepted. It is thus important to consider interception in hydrological simulations and therefore we propose a simpler approach such as the one WetSpa uses.

Change in manuscript: Paragraph 4.2: Discussion on the model comparison.

Reviewer main comment 4: I think the urban hydrology modeling is a separate topic that is best left for another paper. Removing it would help shorten the paper to a more manageable size and also allow the strengths of the interception data to be better emphasized. Perhaps it is only a matter of taste, but I think the style in which the urban hydrological modeling text is written suggests bias on the part of the authors about the importance of urban trees, when a dispassionate evaluation would be more effective

Authors response: We agree with the reviewer’s comments and removed the scenario analysis from the manuscript to focus more on the gathered dataset and the model comparisons.

Change in manuscript: Removal of the scenario analysis and addition of section 4.3 ‘The Potential Benefit Of Trees In An Urban Context’ in the discussion, where the relevance of our findings in an urban context are discussed.

Reviewer main comment 5: The canopy interception conclusions mostly consist either of simple data or bland inferences based more on previous understanding of urban hydrology than on the results of this work. Adding theoretical discussion and making theoretical inferences from the data would help readers understand the scope of the work beyond the immediate context of this experiment.

Authors response: We have rewritten the conclusions with the aim to better emphasize our contributions to the urban hydrology literature. Furthermore, we elaborated on the model comparisons in the discussion section.

Change in manuscript: 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.

Line comments

Reviewer comment: P12L15 Salvadore et al. 2015 published a general review of models of urban hydrology, and it is not clear how that review supports this work.

Authors response: We agree, her PhD is a better reference on why we use the WetSpa model.

Change in manuscript: The sentence has been deleted as the information is redundant (cf: introduction).

Reviewer comment: Figure 2 is not needed; its function is duplicated by Figure 3.

Authors response: We decided to keep Figure 2 as it gives a good overview of the environment and near surroundings of the trees. Figure 3-4 are presenting a clear image of the schematic- and actual experimental construction.

Change in manuscript: None

Reviewer comment: Section 3.1 should be Methods

Authors response: We agree and moved this section to Methods. It is incorporated in section 2.2 and 2.4.

Change in manuscript: See section 2.2 and 2.4

Reviewer comment: Sections 2.5.2 and 3.3 the sensitivity analysis is difficult to understand. It seems like the data in the two panels of Figure 9 probably came from the same assumptions, but I cannot follow the text P9L34-37

Authors response: We removed Figure 9 because it took up too much space and wrote the sensitivity analysis more concisely. This part was added to section 2.3 and 2.5..

Change in manuscript: See section 2.3 and 2.5.

Reviewer comment: Figure 10 the inflection point is plotted at ~2.5 but listed as 4.72.

Authors response: Because we decided to remove the Leyton analysis to estimate interception storage capacity from the manuscript, Figure 10 was also removed. A modified version of this figure, used to determine the free throughfall coefficient, can be consulted in Appendix A.

Change in manuscript: See manuscript

Reviewer comment: Figure 13e is unnecessary. The same information is in a-d. The equations for the regressions should be presented

Authors response: We added the regression equations and R^2 on the plot area and removed Figure 13d (the regression) and Figure 13e from the manuscript.

Change in manuscript: See figure 13 in the manuscript

Reviewer comment: Table 2 I disagree that regression does not account for evaporation during the event. It simply does so implicitly.

Authors response: We agree with this comment but decided to remove the regression from the manuscript because of its limited applicability.

Change in manuscript: See manuscript

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

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10 **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. ~~A regression analyses for the Norway maple found rainfall duration, rainfall amount and the tree's leaf area index to be the most important variables influencing interception storage. The regression analysis and the~~ The specialized tree-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 regression analysis wasn't stable throughout seasons, event sizes and trees, making it unsuitable for generic use.~~ 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. A scenario analysis, featuring the construction of student houses on a university campus, demonstrated the potential of urban trees to retain rainfall water. Even though trees alone could not restore the natural hydrological balance, they could partly mitigate the increased runoff volume and peak discharge caused by sealing of the natural surface through decreasing the net rainfall that reaches the ground. This study emphasizes the potential of city trees on the whole hydrological balance -through a combination of gathered field data and simulation experiments with both specialized interception models (Gash and Rutter) and with a relatively simple interception module of a wholeholistic water balance model (WetSpa). highlights the role of solitary trees in an urban environment where natural hydrological processes are severely altered.

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1. Introduction

1.1 ~~The context~~ Context

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Currently 54 % of the population is living in an urban environment, with an expected increase to 66 % by 2050 (United Nations, Departement of Economic and Social Affairs, 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. ~~Flood frequency in Western Europe has increased six fold since 1970 (Barredo, 2006) and affected over 3 million people between 1998 and 2009, resulting in an economic loss of 60 billion euro (EAA, 2016).~~ 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~~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 ~~very~~ 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 ~~behaviour~~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.

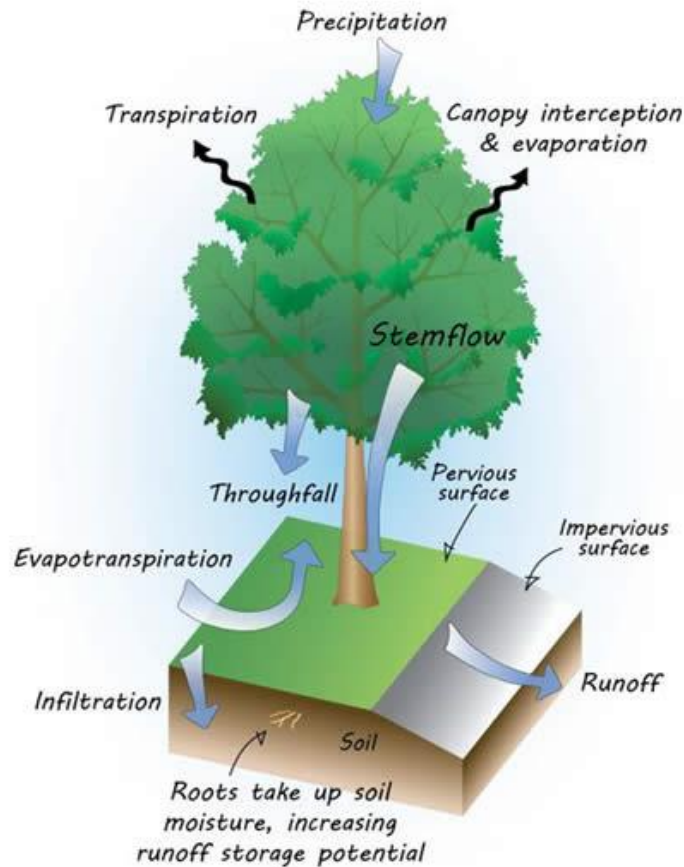
Several authors have attempted to quantify the contribution of urban trees on the total water balance. Some authors looked at large areas of urban cover and determined the water storage potential of the urban forest based on land cover derived maps (Gill et al., 2007; Haase, 2009; Verbeeck et al., 2013). 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 ~~influence~~interception process of a single urban tree ~~on the water balance~~ (Asadian & Weiler, 2009; Guevara-Escobar et al., 2007; Véliz-chávez et al., 2014; Xiao et al., 2000a, 2000b). ~~These~~ While these studies generally accurately succeed in described~~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.

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However, due to the use of complex variables for the prediction of the interception process, the results are often difficult to extrapolate to larger areas and/or other tree species. Moreover, these 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. Extrapolating results from previous studies is thus not straightforward.

1.3 The hydrological processes

Several hydrological processes interact with each other when gross precipitation falls on a tree (Fig. 1):



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Figure 1: Hydrological processes at work on the individual tree level (Image from: (EPA, 2015)).

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 most convenient way of expressing this term is on the basis of the vertical projection area (VPA) in mm~~ 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~~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~~Models

5 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.

25 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. For this study, the focus is on WetSpa's capacity for simulating the interception storage for a V-catchment set-up (Salvadore et al., 2015; Verbeiren et al., 2016; Wirion et al., 2017).

35 1.6 Research ~~questions~~Questions

40 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 using a relatively simple our solitary tree set-up. solitary tree interception model (WetSpa) that is part of a whole water balance modelling framework. The simplicity of the interception calculation of WetSpa is compared to the more~~The accuracy of WetSpa is compared with specialized forest interception models that have been standard in literature for decades (Gash and Rutter). This study evaluates different models~~

for the simulation of the interception storage on urban trees while keeping model input limited to a few variables that are easy to measure.

The objectives of this study are:

- to evaluate the interception storage of two urban trees within Belgium, ~~(Western European temperate climate).~~
- 5 • to evaluate how ~~accurate different modeling frameworks describe the interception process on an individual tree level.~~ estimates of the solitary tree interception 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.
- ~~to illustrate the importance of trees for the urban surface water balance, by simulating the changes due to the removal of trees on a university campus site.~~

2. ~~Materials~~ and methods ~~Methods~~

2.1 The ~~S~~study Aarea

15 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.

20 2.2 The ~~selected~~ Selected Ttree Sspecies

25 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. 21). These two trees represent an urban solitary tree free from obstructions and with full sun and wind exposure. As the urban environment is very heterogeneous, trees are found in widely varying settings such as in parks, 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. in urban environments that are impossible to all reproduce in an experimental setup.



Figure 21: Satellite images of the Norway maple (a) [01/10/2015] and small leaved lime (b) [25/08/2016] [images: Google Earth].

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

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

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

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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 leaf 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 leaf 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.

5

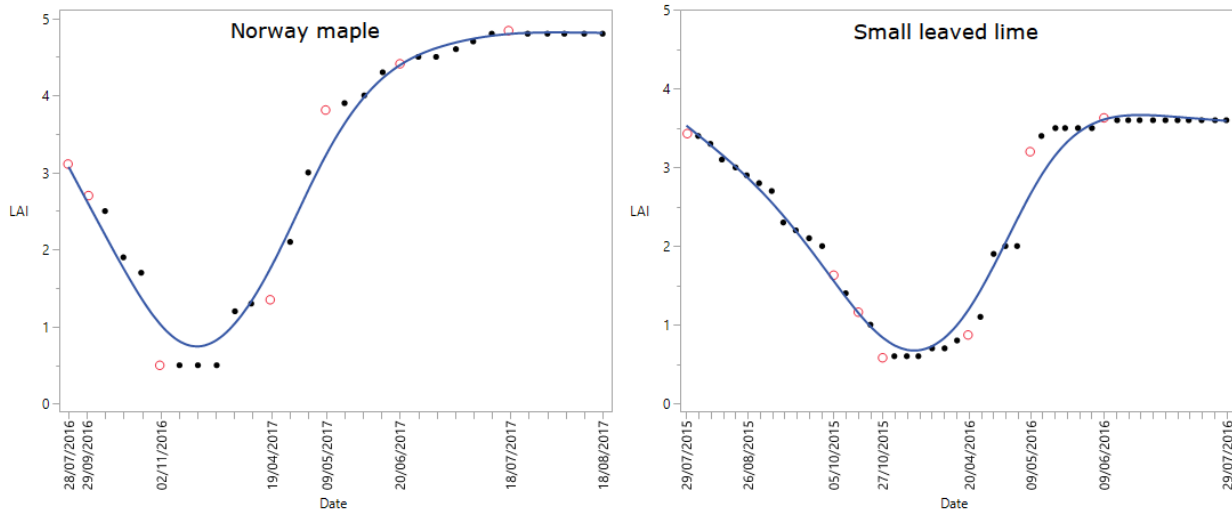


Figure 2: The variation of the LAI of the Norway maple (left) and the small leaved lime (right). Hollow red dots indicate the dates of the measurements.

The free throughfall coefficient was calculated with 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.

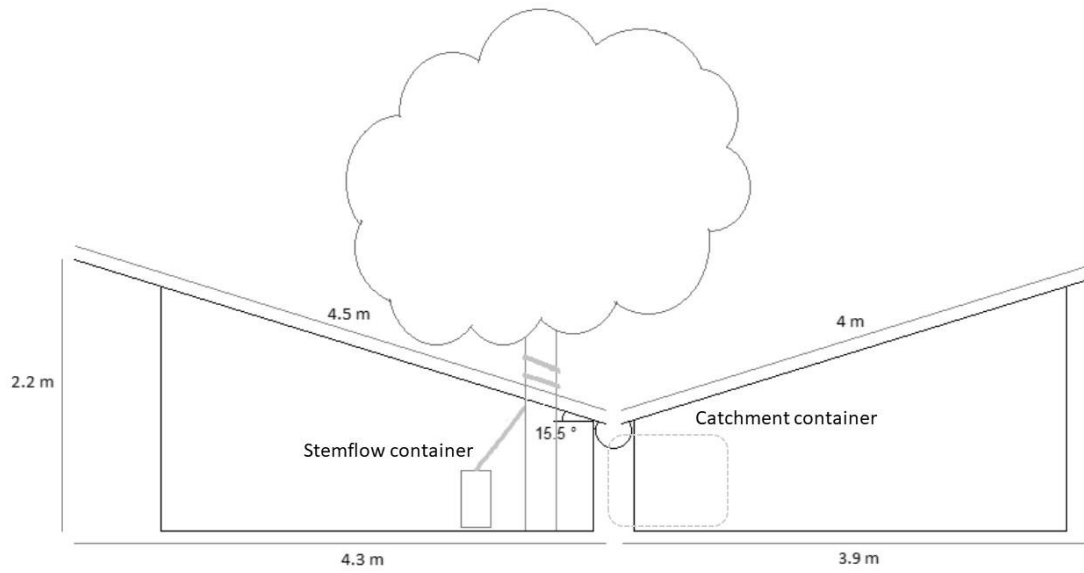
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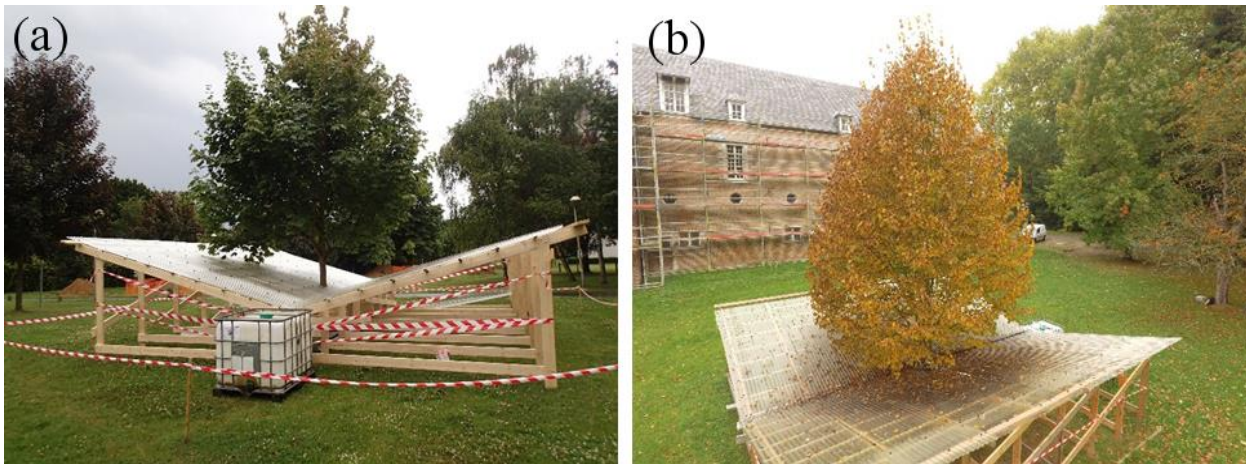
2.3 The V-catchment **design**Design

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).

20



Figure_33: Schematic representation of the V-catchment construction.



Figure_44: 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 July-October 2015 until 23 March 2016 for the Norway maple and from 13 November 2016 until 14 April 2017 for the small leaved lime. ~~Both trees were of similar dimensions and 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.

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, intensity and intra-event rainfall intermittency (IERI) were determined (Dunkerley, 2015).

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 1). 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 1: 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	15/04/2017–					
-	(n=17)	18/08/2017	3	1.8 km	0.01 mm	15 min	Yes

2.4.4 ~~The Sensors-Sensors~~

5 The water level in both the catchment- and stemflow container was monitored by pressure sensors (Mini Diver D1501, 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 (cmH₂O).

10 ~~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).~~

~~2.5 The accuracy of the measurements of the water balance components~~

~~2.5.1 The accuracy of the volumes stored in the containers~~

20 ~~The pressure divers had an accuracy of 5 mm H₂O.~~ 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.

2.5.2 The detention storage of the V-catchment

5 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.

10 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. 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):

25 **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 (%).**

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

(1)
(2)

30 These two sources of inaccuracy, the sensor inaccuracy and detention storage, had 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. Results are slightly different for both trees because the vertical projection area of the trees differ slightly. A sensitivity analysis of the detention storage was done by simulating 1 liter of variation in the detention storage (corrugated sheet and gutter detention) for rain events of different sizes. No sensitivity analysis of the stemflow was done because very few events displayed significant stemflow.

35 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.

5

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.

10

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.

15

20

Table 3: The meteorological stations.

	Period	Ref station	Distance to tree	Rainfall resolution	Time resolution	Other measurements
Norway maple						
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

25

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

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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~~-Data processing-Processing Aand Mmodel Ceomparison

The following paragraph describes how to calculate throughfall, interception storage and stemflow data from the raw data received by the pressure sensors and tipping buckets:

The water balance for a rainfall event states:

$$P_g = I + T_f + S_t \quad (1)$$

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 ($P_{g \text{ free}}$). Another part of P_g falls on the tree ($P_{g \text{ tree}}$), of which a small part of this water 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:

$$P_g = P_{g \text{ free}} + P_{g \text{ tree}} \quad (2)$$

$$P_g = P_{g \text{ free}} + I + T_f + S_t \quad (3)$$

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

$$I = (P_g * VPA_{\text{constr}}) - ((P_{g \text{ free}} * VPA_{\text{free}}) + (\Delta H_{\text{cont}} * VPA_{\text{cont}}) + (\Delta H_{\text{St}} * VPA_{\text{St}})) \quad (4)$$

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)

$$S = 1.184 + 0.490 \text{ LAI} - R^2 = 0.76$$

~~For comparison, we also used the method developed by Leyton et al. (1967) to calculate the interception storage capacity. A line of unit slope, minus the stemflow percentage, is drawn on a gross precipitation vs throughfall plot through those rain events where evaporation is assumed minimal. Only events where P_g is large enough to fill the storage capacity are used. The determination of the amount of precipitation to reach canopy saturation is subjective and based on the recognition of an inflection point on the graph. To make recognition of this inflection point easier, the residuals of the P_g vs T_f regression were plotted against the P_g . The inflection point is recognized by a sudden change in the variability of residual values. The interception storage capacity is then found by the negative intercept of this upper envelope line with the y axis. The upper envelope represents events with minimal evaporation. The points left of the inflection point represent events where rainfall was insufficient to fill the canopy storage completely. The parameter of the gross precipitation of a regression through the lower envelope of these points represents the free throughfall coefficient. An example of this method from (Sadeghi et al., 2015) is shown in Fig. 5. 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 his method over above 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. because equation 5 takes into account seasonal changes by using LAI as independent variable. Both our measurement periods (Table 1) span transition periods between leaf on and leaf off, which makes the use of the Leyton method to calculate interception storage capacity less preferable. Other downsides of the Leyton method are its inherent subjectivity and possible skewing of results through one or two very large rain events.~~

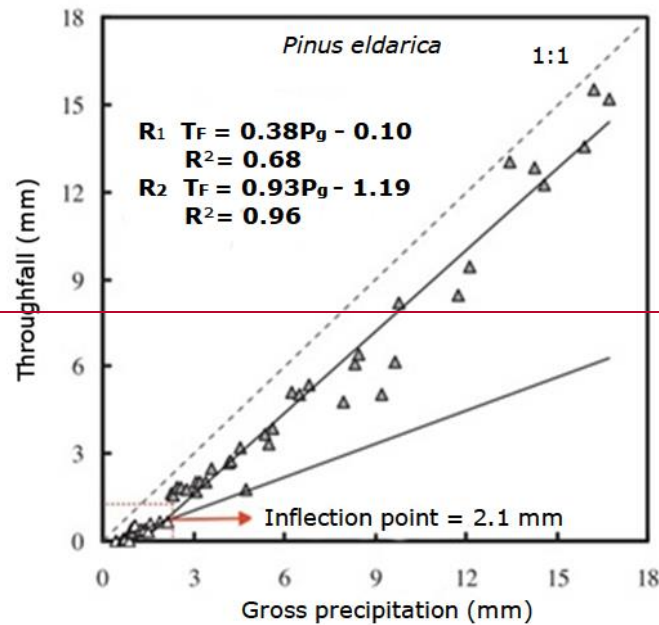


Figure 5: Example of the Leyton method from (Sadeghi, 2015). The lower and upper envelopes are represented by equations R1 and R2 respectively. In this example the interception storage capacity of a Pinus Eldarica is 1.19 mm and the free throughfall coefficient is 0.38. With T_f being the Throughfall and P_g the Gross precipitation.

5

2.8 Modeling and model comparisons

The measured interception storage ~~will be is~~ compared to different simulation approaches: the Gash, Rutter ~~and~~ WetSpa ~~models and classical regression analysis~~ (Table 42). The equations for the different simulations of the interception storage can be found in appendix AB. ~~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 ~~— as well as the regression method~~ 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 §2.34). This approach enables an emptying of the storage by evaporation during the event. ~~The equations of Gash and Rutter have been developed for a forest stand, whereas the WetSpa model is adapted to a single tree/ V catchment (Salvadore et al., 2015).~~ 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).

20

25

~~As an addition to the simulations we also use a linear regression analysis. For urban planners or policy makers such a method can be more straightforward and thus more appealing to use. To select the most significant predictor variables for the regression, a PCA analysis was performed, resulting in 3-5 principal components. Based on this PCA analysis, a clustering of the variables was made. A clustering algorithm was used that iteratively splits the variables in smaller clusters according to the principal components of the clusters. Splitting occurs on the cluster with the largest second eigenvalue. Once split, a~~

5

correlation analysis is performed and the variables are reassigned to the cluster they are most correlated with. The algorithm stops when the second eigenvalue of all the clusters is smaller than one. Initially, 5 clusters were found. All the variables in each cluster were then fitted to the interception storage (mm). The two clusters with the lowest predictive performance were eliminated. The variables inside the 3 remaining clusters were examined separately. Based on their individual predictive performance and expert knowledge, one variable was selected from each cluster and used as an independent variable in a multiple linear regression of the Norway maple dataset. Before fitting, variables were normalized in the range $[-1,1]$ to make the parameter estimates more meaningful. The dataset of the small leaved lime was used to validate the regression equation.

Table 24: 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, ...
Regression	Discrete	Single tree	∅	No	No	Interception

10

2.9 The scenario analysis

5 To illustrate the effects of the interception storage in an urban environment, we simulated the surface water balance of the university campus of the Vrije Universiteit Brussel (VUB) before and after the construction of new student houses. The construction area covers 16692 m². Before the construction started in July 2015, trees covered 15 % of the area, grass 45 %, bare soil 3% and urban materials 37 % (Fig. 6c). After the construction works, trees only cover 2 %, grass 4 %, bare soil 33 % and urban materials 61 % (Fig. 6d).

10 To analyze the effects of land cover change on the net rainfall and thus on the surface water balance we use a calibrated WetSpa model (Wirion et al., 2017). Wirion et al., 2017 calibrated the WetSpa model for the Watermaelbeek catchment for the year 2015. We use the same meteorological input (709 mm of rain in 2015).

15 The LAI of trees before the construction started has been measured in 2015. On average the trees had a LAI of 0.52 in low leaf conditions (measured April 10, 2015) and a LAI of 2.95 in maximum leaf conditions (measured June 4, 16 and July 6, 2015). The measured LAI values are used to estimate the interception storage of the trees before the construction starts. For the interception occurring on grass and bare soil constant values, retrieved from remote sensing data, are used (Wirion et al., 2017). We assume that urban surfaces do not intercept rainfall.

20 We analyze two scenarios to evaluate the effect of different landscape design scenarios on the university campus site: (1) an urban scenario, where all bare soil land cover is sealed/turned impervious once the construction works are finished and (2) a natural scenario, where all bare soil land cover after construction is covered by urban trees. For the second scenario we attribute the characteristics of the Norway maple tree to the newly covered tree areas. Further, we assume soil characteristics to be similar to clay as it has become highly compacted due to anthropogenic activities.

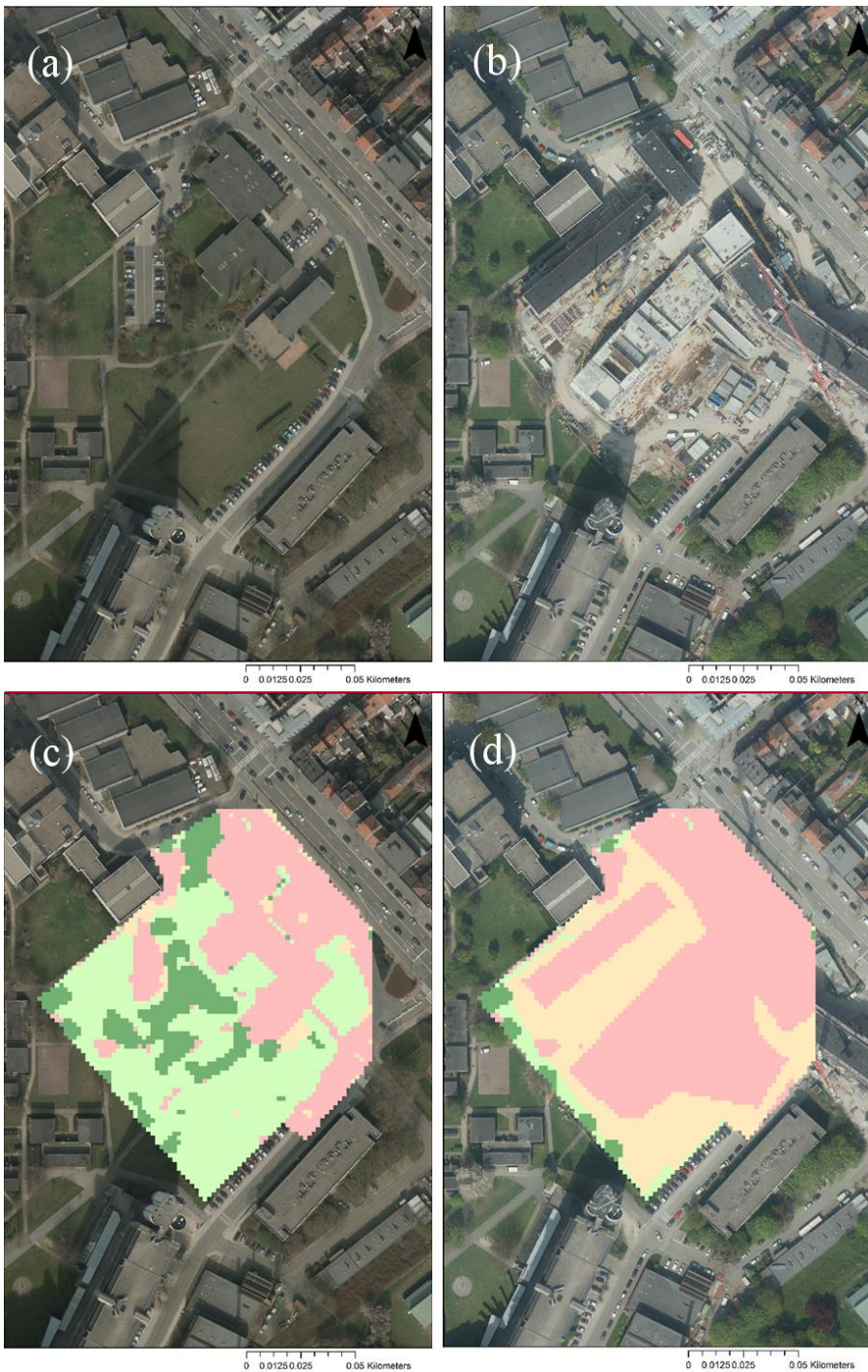


Figure 6: The university campus before and after the construction of new student houses. 1) Orthophotos before [2012] (a) and after [2017] (b) the construction works. 2) land cover map before (c) and after (d) construction works; dark green: trees, green: grass, rose: urban, beige: bare soil.

3. Results3. Results

3.1 Descriptive statistics

The vegetative characteristics of both trees are described in Table 3

5 *Table 3: 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 (m ²)	27.83	32.30
Leaf area (cm ²)	90.36 ± 43.76	41.41 ± 17.63
Average branch angle (°)	38.15 ± 17.54	41.29 ± 17.83

Both trees are similar in dimensions and characteristics. A noticeable difference is the average leaf area of the Norway maple, being twice as large as the leaf area of the small leaved lime. The change in LAI of both trees can be seen in Fig. 7. Both trees are deciduous. For both trees we measured the LAI on 7 moments during the season, to cover low, medium and full leaf conditions. We then use a linear interpolation between each measurement to assign an LAI value for each rain event (Fig. 7). The LAI of the small leaved lime (LAI = 4.8) in full leaf 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.

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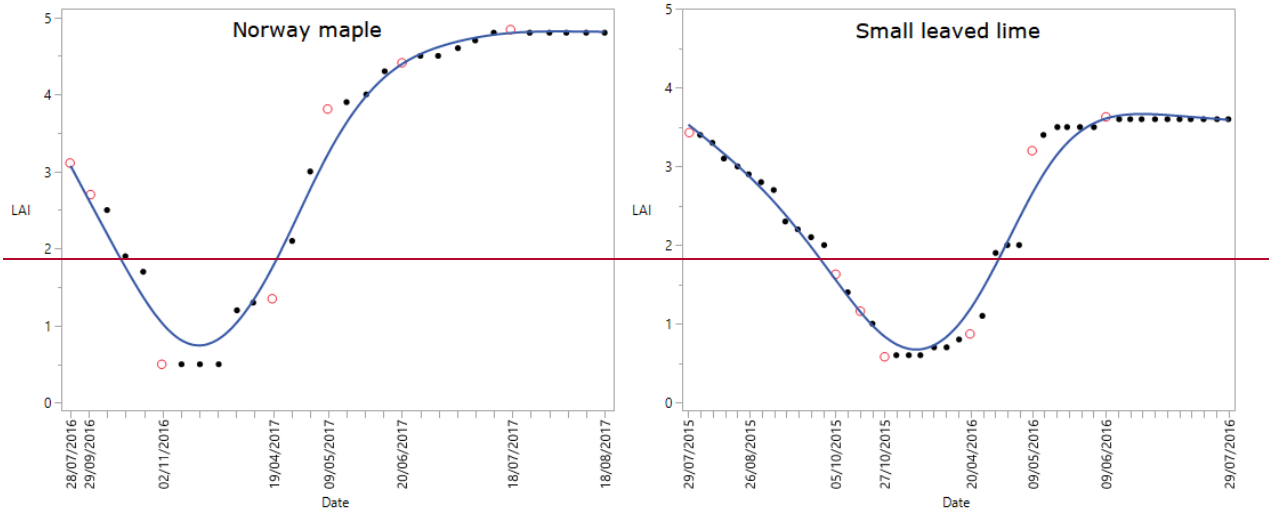


Figure 7: The variation of the LAI of the Norway maple (left) and the small leaved lime (right). Hollow red dots indicate the dates of the measurements.

5

Histograms of the precipitation, the event duration, the intensity, the intra rain event intermittency (IERI) (—) and the wind speed (m/s) are shown in Fig. 8. IERI is calculated by dividing the time it didn't rain during an event by the total event time. An IERI value close to zero means that it rained almost continuously during an event.

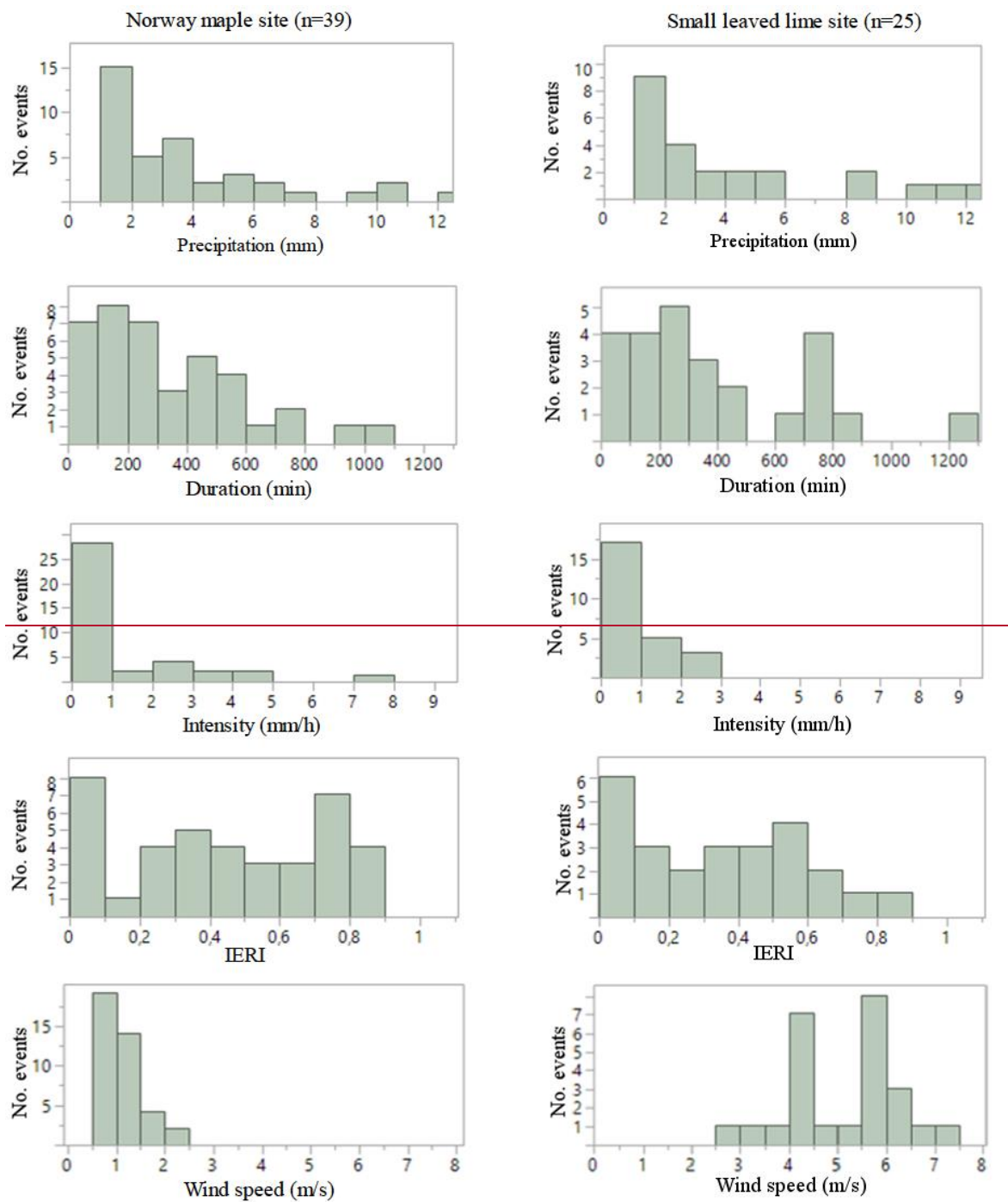


Figure 8: Histograms with precipitation event characteristics for the Norway maple (left) and small leaved lime (right).

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). The intra rain event intermittency (IERI) shows more equally distributed values across its spectrum, meaning rain events exhibit different lengths of intra event dry periods. Average wind speeds are low for the Norway maple site but high for the small leaved lime site. 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. The values of these rain event characteristics are typical for temperate climates.

3.2-1 Event Summary

The gross precipitation of each event was divided in throughfall, interception storage and stemflow (Table 45).

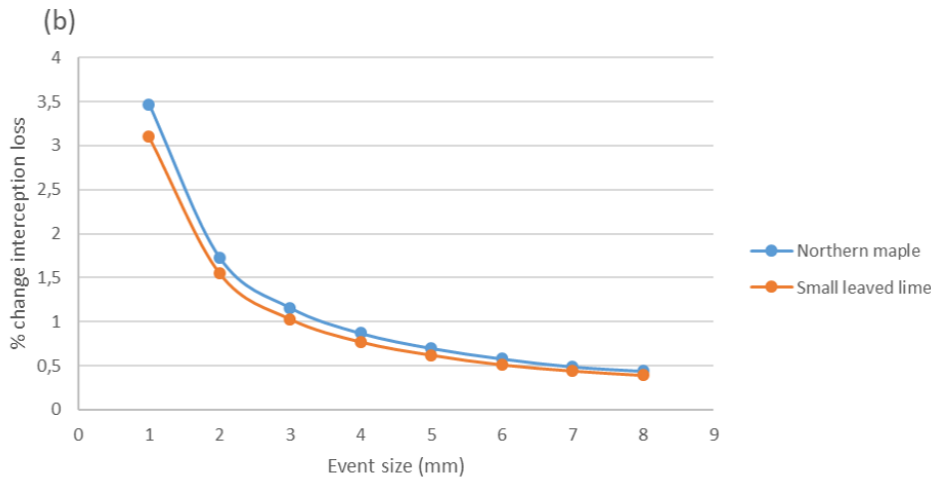
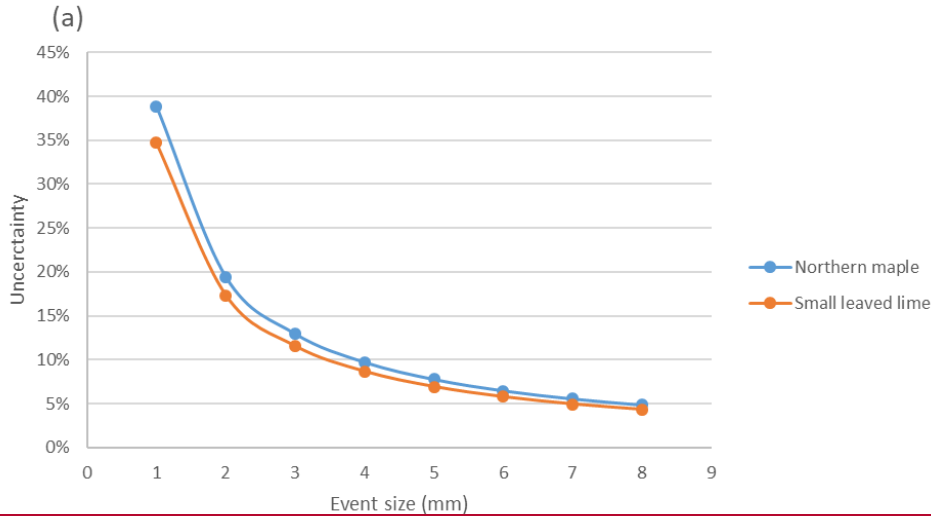
Table 504: Event summary of the precipitation events of both trees.

		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.

3.3 The sensitivity analysis

5 *Figure 9a shows the uncertainty of the interception estimates associated with rain event size while Fig. 9b shows the influence of the detention storage on event size with a one liter variation in detention storage. The equations can be found in appendix B.*



10 *Figure 9: Analysis of (a) the uncertainty in interception storage estimates with increasing event size and (b) Influence of the detention storage on interception storage estimates with increasing event size with a one liter variation in detention storage.*

As can be seen from Fig. 9a, for small events of 1 mm, uncertainty is quite high, being 38.8 % for the Norway maple and 34.7 % 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 %.

The sensitivity analysis of the detention storage yields far smaller values. For events of size 1 mm, a change of one liter in detention storage only changes the interception storage around 3 %. For events larger than 3 mm, this change in interception storage drops below 1 %. It is clear that the dominant error is the error associated with the pressure divers. Due to the high uncertainties associated with small events we decided to exclude events < 1 mm from the analysis.

3.4.2 The Interception Storage Capacity and Simulations and free throughfall coefficient estimation

The most influential parameter for estimating interception storage with simulations is the interception storage capacity (Xiao et al., 2000b). Figure 10a and 10b show the determination of the canopy storage capacity for the Norway maple and small leaved lime for the whole measurement period with the method of Leyton et al. (1967). For the small leaved lime, two points right of the inflection point were chosen to be included in the lower envelope. The Leyton method allows for this to a certain degree due to the inherent subjectivity in the determination of the inflection point.

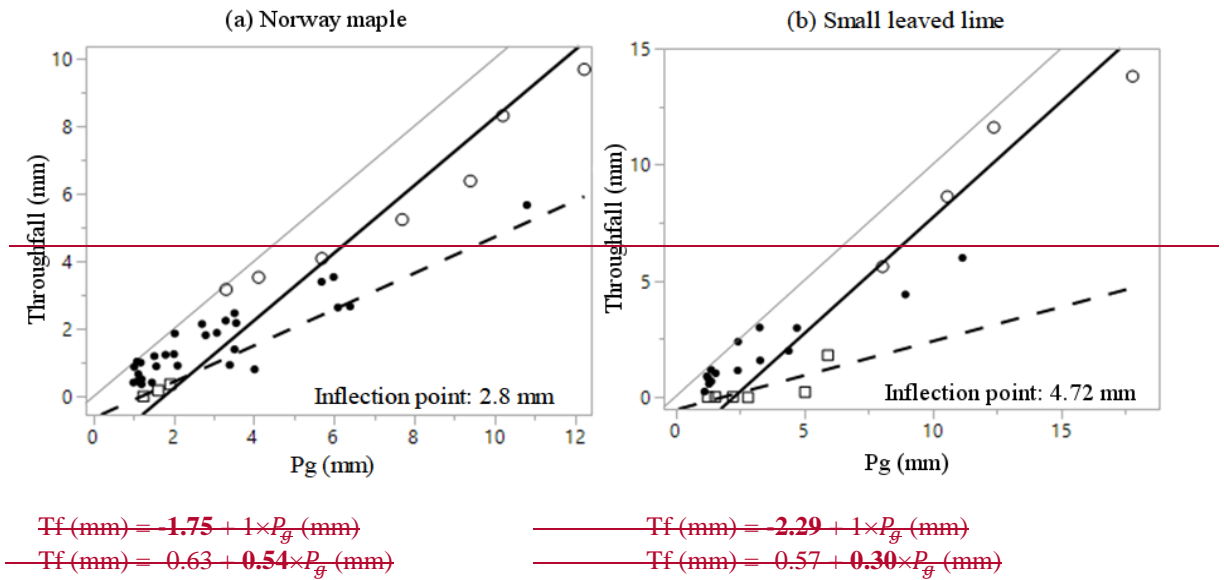


Figure 10: Leyton regression analysis of (a) the Norway maple (n=39) and (b) the small leaved lime (n=25). Hollow dots are the points used to draw the upper envelope line; hollow squares are the points used to draw the lower envelope line. The points not used to draw the envelopes are depicted in black.

Table 56: Interception storage capacity (S; mm) and free throughfall coefficient (p; dimensionless) as calculated by the Leyton method and the method of Gómez for all datasets.

Norway Maple	Period	S (Gómez)
All year (n=39)	14/08/2015 - 29/07/2016	2.47
1 st measurement period (n=13)	14/08/2015 - 14/10/2015	2.40
2 nd 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
1 st measurement period (n=8)	29/09/2016 - 12/11/2016	1.90
2 nd 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 56. In general measurement period 1 and 2 cover both low- and high leaf 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. There is quite a discrepancy between the Leyton method and the method of Gómez (Eq. 5). The trends are similar, however the absolute values differ significantly. Both methods are~~ 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). ~~In their paper, Gómez et al. (2001) acknowledge a slight overestimation of the interception storage capacity whereas Gash and Morton, 1978 recognize a slight underestimation using the method of Leyton. For the small leaved lime tree, measurements in autumn are limited and thus the estimated interception storage capacity is unrealistically low. Further the values are in general a bit lower than the values estimated based on LAI. The Leyton method is a subjective method that also depends on the quality of the measurements (Gash & Morton, 1978). This makes the method of Leyton more difficult to apply than the method of Gómez which we therefore decided to use throughout this paper. The free throughfall coefficients for both trees are higher in the 1st measurement period (loosing leaves) than in the datasets of the second measurement period (gaining leaves). Further the gap fraction for the small leaved lime is smaller than for the Norway maple which corresponds to the LAI measurements. The values are comparable to literature where values are found between 0.1–0.86 for the gap fraction (Aston, 1979; Gash & Morton, 1978; Valente et al., 1997; Véliz-chávez et al., 2014; Xiao et al., 2000a).~~

3.5 The regression analysis

The three variables selected based on the clustering algorithm and expert knowledge are the gross precipitation (mm), the duration of the event (min) and the LAI (-). The results of the clustering algorithm can be consulted in appendix C. The resulting regression equation reads:

(6)

$$I(\text{mm}) = 3.12 + 1.37 \left(\frac{D(\text{min}) - 620}{610} \right) + 1.47 \left(\frac{P_g(\text{mm}) - 9.39}{8.39} \right) + 0.62 \left(\frac{LAI - 2.65}{2.15} \right)$$

Where D stands for the rain event duration in minutes. All three independent variables significantly contribute to the model (P value < 0.01). By normalizing the variables to fall in to a range of [-1,1], their relative contributions to the interception storage become apparent when looking at their regression coefficients. The gross precipitation has the largest influence on the interception storage, closely followed by the duration of the event. LAI also significantly influences the amount of water intercepted but its contribution is less important than the two above mentioned variables.

The R² and R²_{adj} of the regression are 0.81 and 0.80 respectively with a root mean square error (E_{RMS}) of 0.52 mm. Only the events of the Norway maple (N=39) were used (Fig. 11).

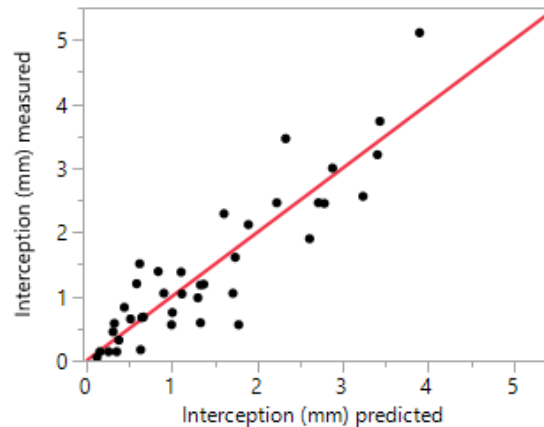


Figure 11: Measured vs predicted interception using the regression analysis.

3.6.3 The simulations

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. 125). For bigger rainfall events ($P_g > 10\text{mm}$) the measurements indicate an average interception of 25% of rainfall whereas for smaller rainfall events ($P_g < 10\text{mm}$) we measure an average interception rate of 47 % of rainfall.

Table 7 Table 6 7 shows that the method of Gash is most stable throughout the 2 trees and seasons ($R^2 = 60\% \pm 2\%$, $E_{RMS} = 0.85 \pm 0.2 \text{ mm}$). The other methods show more variation. The regression method for instance performs very well for the calibration tree (Norway maple, $R^2 = 81\%$, $E_{RMS} = 0.52\text{mm}$) whereas an important reduction in performance can be seen for

the validation tree (small leaved lime, $R^2 = 53\%$, $E_{RMS} = 1.08\text{mm}$). It is thus difficult to use the linear regression equation of the Norway maple tree for other trees even with similar characteristics. It is also unclear if it should be used for different climate conditions as the performance varies a lot between the losing leaves period (August—November) and the gaining leaves period (March—August).

5 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 ($P_g > 10\text{ mm}$) with the method of Rutter (Fig. 125). WetSpa performs best for rainfall events $P_g > 10\text{ mm}$ and Gash performs worst. This might be related to its discrete behavior versus the continuous simulations of Rutter and WetSpa, and the regression method performs worst (Table 7 Table 6 7, Fig. 125, Fig. 136). For small events ($P_g < 10\text{ mm}$) all simulations overestimate the interception storage with Gash showing the best performance. The regression method followed by Gash perform best for events $P_g < 10\text{ mm}$.

10 In Fig. 13-6 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 use the higher estimate for calculate the storage capacity with Gomez et al., 2001 (Scf paragraph 3.42), 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.

15 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 $P_g > 10\text{ mm}$, WetSpa shows the best performance. This makes us confident to use WetSpa for estimating the net rainfall in urban environments.

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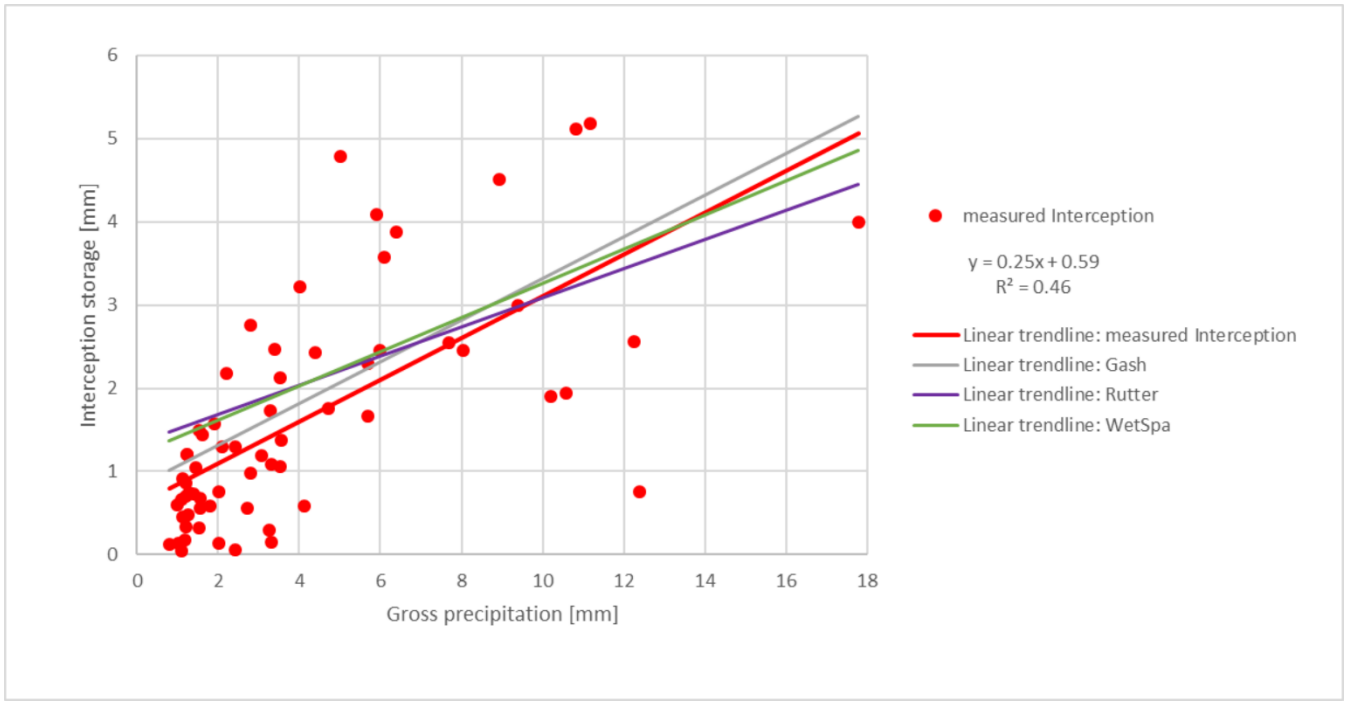
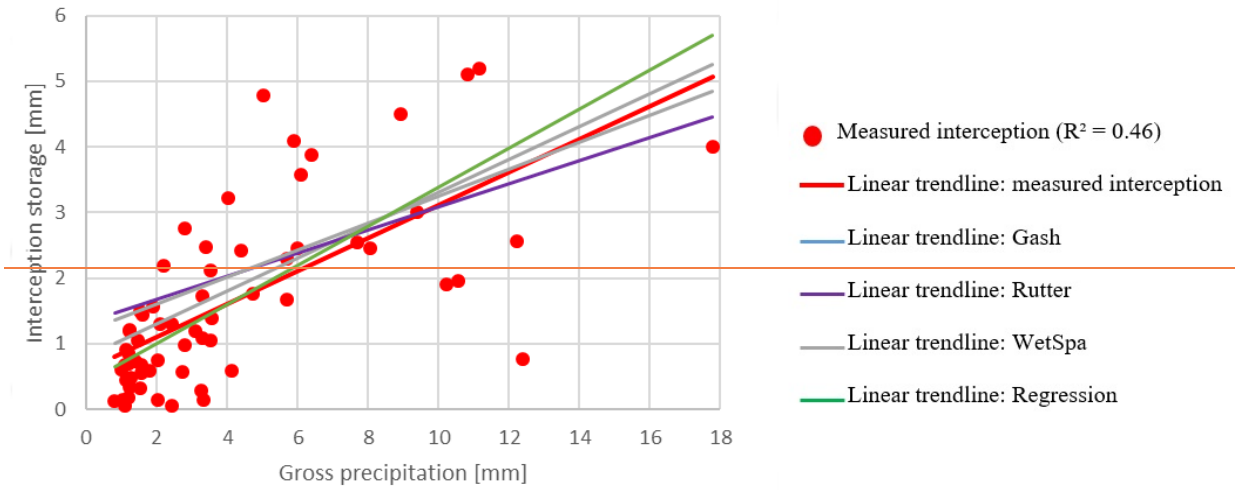
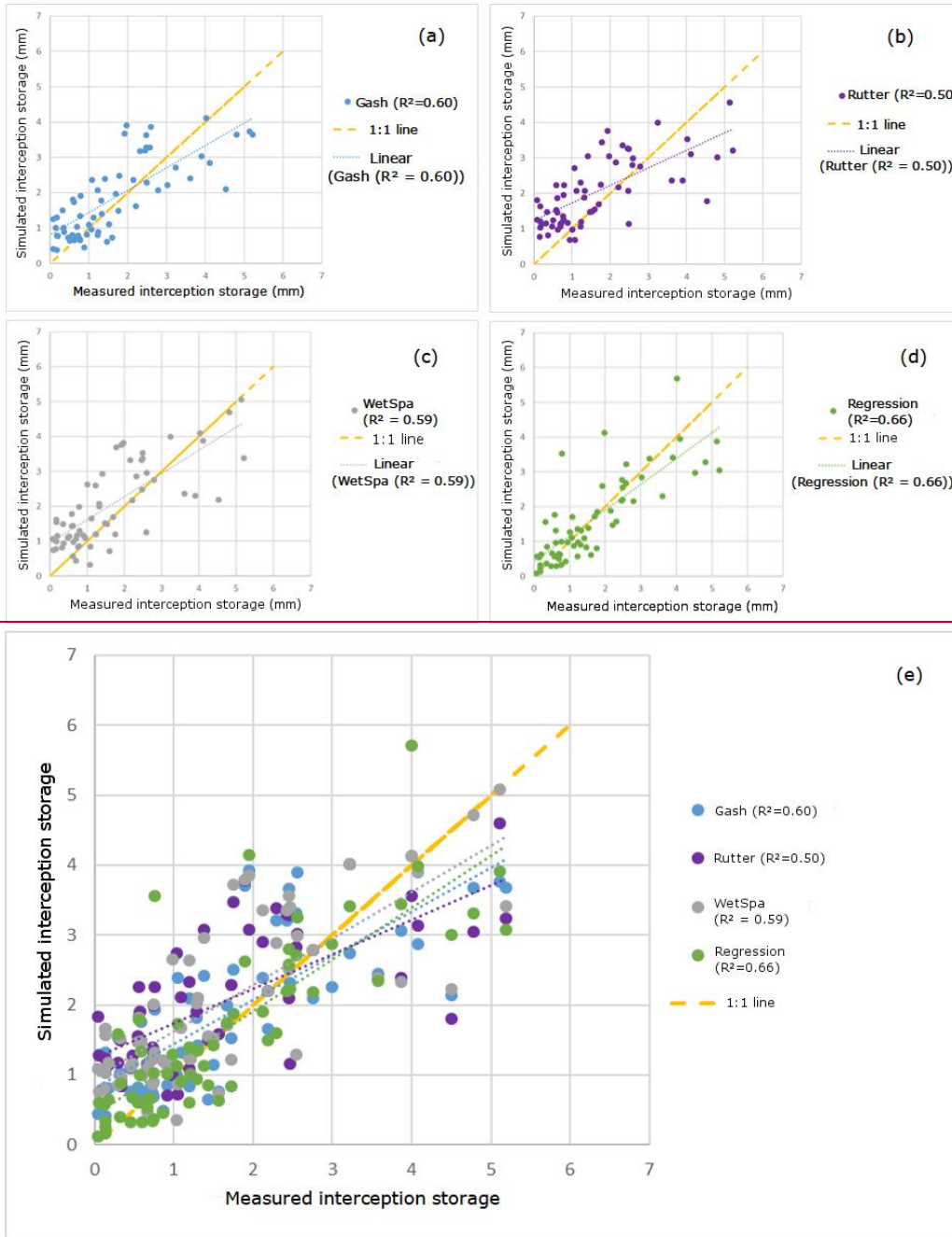


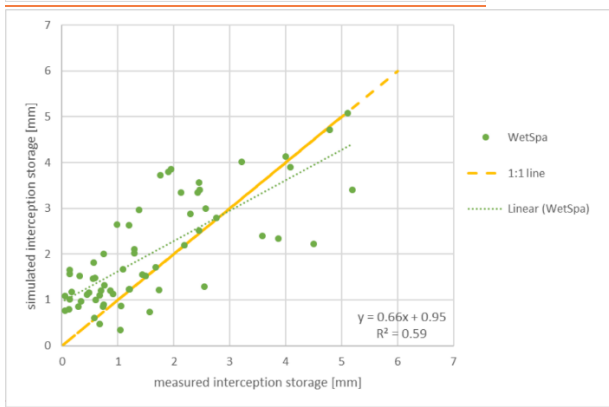
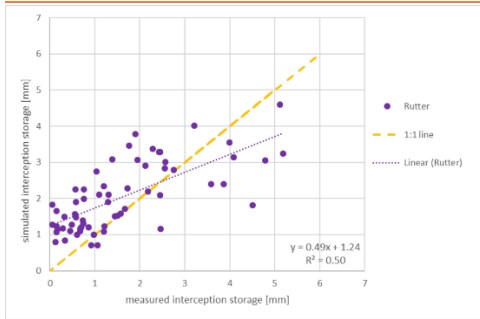
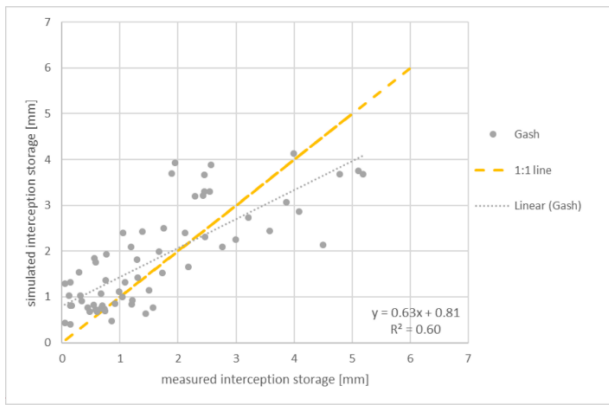
Figure-512: Interception storage vs gross precipitation for all events, for both trees.

5 Table-76: Correlation between measured and simulated interception storage (R^2 /RMSE).

R^2 [%] / E_{RMS} [mm]	Gash	Rutter	WetSpa	Regression
----------------------------	------	--------	--------	------------

All events (64 events)	60/ 0.87	50/ 1.10	59/ 1.02	66/0.78
Norway maple (39 events)	62/ 0.78	49/ 1.10	52/ 1.06	81/0.52
Small leaved lime (25 events)	59/ 0.99	53/ 1.10	65/ 0.96	53/1.08
Loosing leaves period (21 events)	58/ 0.65	53/ 0.84	55/ 0.71	41/0.83
Gaining leaves period (43 events)	59/ 0.96	48/ 1.20	63/ 1.15	72/0.76
Big events (Pg > 10mm) (7 events)	30/ 1.44	44/ 1.28	46/ 1.25	5/1.79
Small events (Pg < 10mm) (57 events)	60/ 0.78	41/ 1.02	53/ 0.93	80/0.55





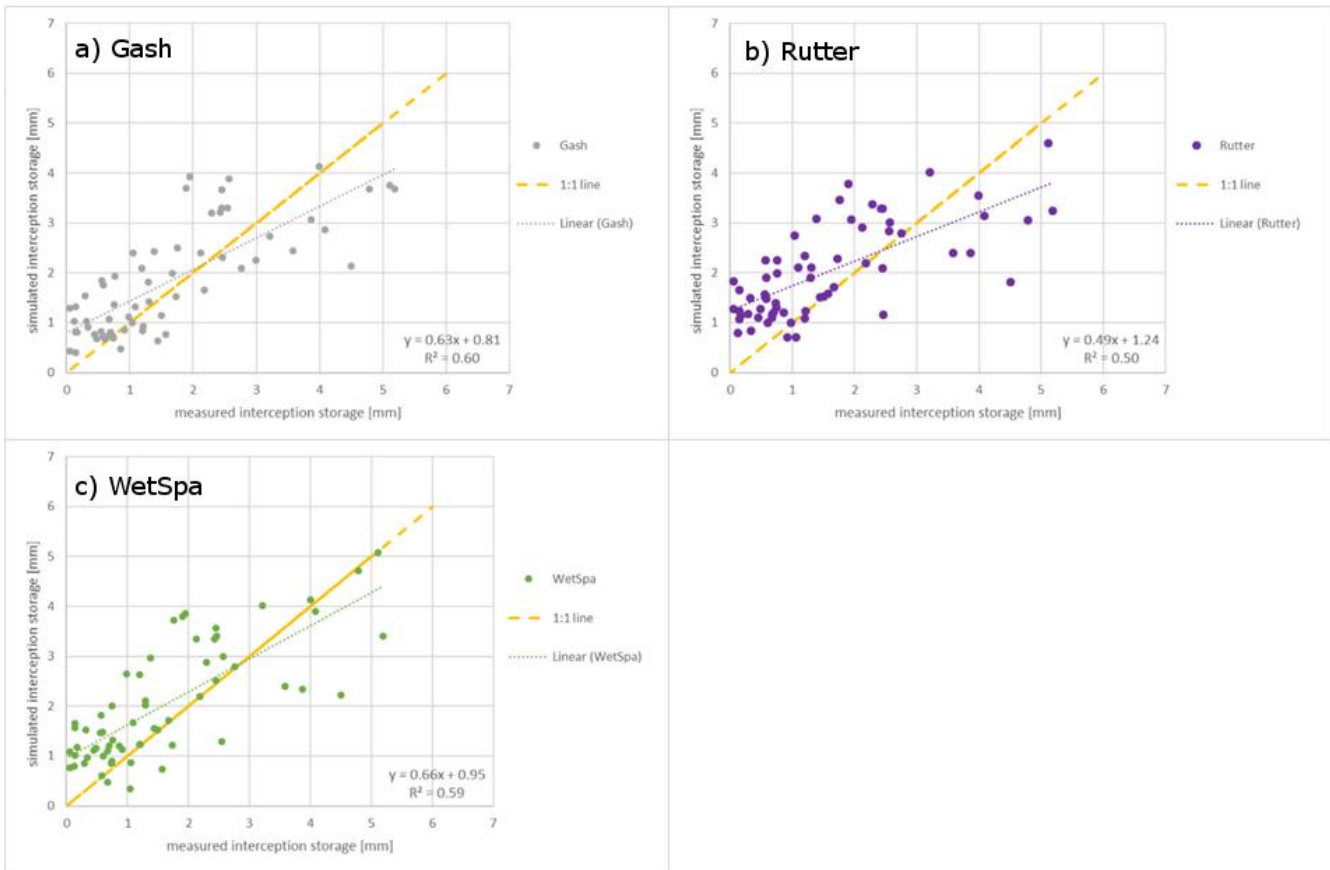


Figure 6-143: Measured vs simulated interception storage of the Gash- (a), Rutter- (b) and WetSpa (c) model

and the regression (d). (e) superimposes all four methods.

3.7 The land cover change scenario

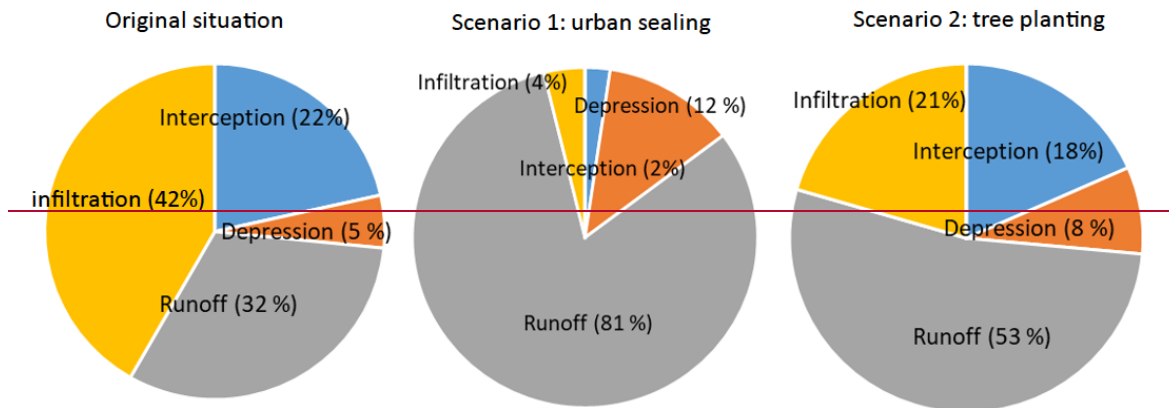
5 3.7.1 Scenario 1

10 In scenario 1 we assume that all the surfaces around the new student houses of the VUB Campus are sealed, resulting in an increase of the sealed surface by 54 % and a reduction of the tree area by 13 %. The simulation shows that this leads to an increase of the yearly net rainfall by 19 % (136 mm for 2015). The increased amount of rainfall reaching the ground surface is, in our simulations, distributed to depression storage and surface runoff (Fig. 14). The important increase in surface runoff volume (49 %, 352 mm) is due to the reduction of trees impeding interception and the sealing of pervious soil obstructing infiltration. Further the increase in depression storage might be higher than expected as we keep the original elevation map where due to the more natural landscape depressions are more common. If we consider the runoff flux an increase of 147 % (+ 0.128 m³/s) is reached in scenario 1 (Fig. 15). Due to the small catchment area no redistribution in time of the peak runoff can be illustrated.

3.7.2 Scenario 2

5

In scenario 2 we assume that all the surfaces around the new student houses of the VUB Campus are replanted with trees (Norway maple). This leads to a tree cover of 35 % and an impervious cover of 61 %. This scenario shows that the high tree coverage restores interception storage to 18.4 % (130.31 mm) versus 21.5 % (152.53mm) before construction works started. The 24 % increase of sealed surfaces compared to the original situation results in an increase of 21 % of surface runoff, mostly related to the obstruction of infiltration. The hydrograph in Fig. 15 of Scenario 2 shows an 64 % increase (+0.05 m³/s) of peak flow for the June event in 2015. The rainfall stored by tree interception is thus able to limit the increase in peak discharge to less than half of scenario 1.



10

Figure 14: Yearly (2015) surface water balance [% rainfall] for the different scenario's.

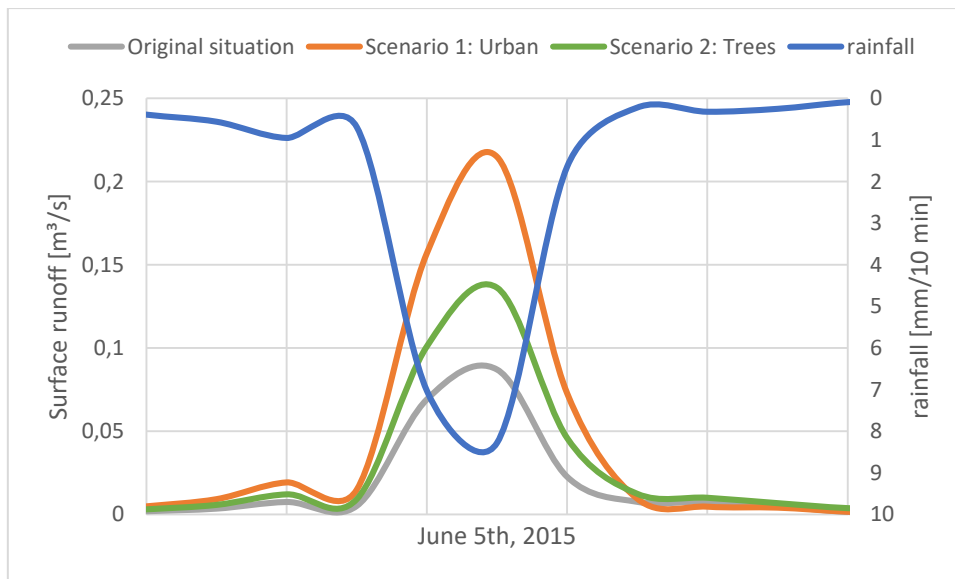


Figure 15: hydrographs for 2015 event (return period 2 years Ucele).

4. Discussion

4.1 The Tree Interception Storage

5 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 ~~with studies in Mediterranean climates.~~ 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 (~~Fig. 8~~) 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.

25 ~~We hence conclude that our initial hypothesis was correct and that trees in temperate climates are able to intercept a higher percentage of rainfall due to their more favorable rain event's characteristics (Cfr. Section 3.1).~~

4.2 The Model Comparisons

30 The Gash, Rutter and WetSpa models show similar performances. ~~The regression equation performs best overall. However the difference in performance between the Norway maple and the small leaved lime indicates a strong tree dependency. Further, the difference between the seasons and the low performance for bigger rainfall events ($P_g > 10$ mm) also indicate that the regression method is not robust and therefore unsuitable to be used on a wider scale.~~

35 ~~The model outputs are strongly depending on the interception storage capacity. Two methods to determine this variable have been investigated: the Leyton method (Leyton et al., 1967) and This variable is calculated using an LAI based equation (Gómez et al., 2001). The equation of Gómez is preferred over the Leyton method chosen for 3 reasons: (1) the equation has no subjective interpretation, (2) the equation 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.~~

40 ~~found that the simulations overestimate the interception measurements for small rainfall events ($P_g < 10$ mm) and small interception events ($<$ interception storage capacity). This overestimation is occurring as some factors such as wind speed and~~

orientation, rain intensity and inclination angle, leaf zenith angle and other meteorological and tree architectural parameters are not taken into account (Xiao et al., 2000b). 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. Again a limitation of accounting for detailed meteorological and tree architectural parameters in our simulations might be the cause. Even though big interception events are most important for the retention of rainfall water on city trees, we still believe that

this limitation is acceptable to limit the need of physical parameters in our simulations, as measuring all this parameters needs a lot of resources. The high similarity in performance of the specialized interception models (Gash and Rutter) and the regression and the water balance model (WetSpa) let us conclude that WetSpa can be used for studies on interception storage. 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. However, as we could not measure all the parameters needed for this method, we were not able to evaluate its performance for our trees, which indicates the operational limitations of this model.

4.3 The Potential Benefit Of Trees In An Urban Context

In our Vv-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 will be reached quickly and thus most rainfall contributes to surface runoff. Even though urban trees alone can not be a flood control measure, they however even in this case trees are valuable because they help to delay and spread out peak runoff and to reduce pollutant wash-off, thereby reducing 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 and replenish the groundwater table (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 likely be less than in 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 however that city trees should be considered for in every urban water management policy. And the WetSpa tool can be a good alternative to do so.

4.3 The land cover change scenario's

Our scenario analysis of a small construction site on the VUB-campus ($< 0.02 \text{ km}^2$) shows that by replacing this small green area with new buildings the water balance is highly disturbed (scenario 1). As net rainfall increases and the infiltration capacity is limited, due to the sealing of surfaces, a high amount of surface runoff is produced. For a rainfall event with a return period of 2 years the increase in surface runoff is of 147 % of the initial runoff flux. Such an increase of surface runoff on a small scale accumulates over an urban catchment through the connectivity of imperviousness (Verbeiren et al., 2013) and challenges the capacities of installed drainage systems and retention reservoirs. To avoid such scenarios it is important to mitigate the effects of new constructions. Therefore we considered a second scenario where surroundings of buildings are kept permeable and are covered with trees. This scenario almost restores the interception capacity of the area. The retention of net rainfall due to tree interception limits the effect the increased sealed surfaces (+24 %) have on the surface runoff. The increase of the peak discharge for the event with return period 2 years is limited by tree interception to less than half of scenario 1. However, even this unrealistic scenario of planting trees all around the buildings doesn't allow to re-establish the water balance and additional compensation measures would be needed (green roofs, compensation off site, etc.).

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. ~~Further we performed a scenario analysis to evaluate the effect land cover changes on the water balance of a small scale pilot case.~~

Our main conclusions are:

1) Both trees intercepted around 38% of gross precipitation, emphasizing making them a very effective tool in reducing net rainfall the importance of (1) interception storage for reducing net rainfall and (2) accounting for interception storage in an urban water balance model.

~~(1) With 38 % of the gross precipitation, the intercepted rainfall was higher than observed for solitary trees in Mediterranean climates. Trees in temperate climates are believed to be more capable of intercepting rain water due to the more favorable rain event characteristics such as a longer event duration and a lower rain intensity.~~

~~(2) The water balance model (WetSpa) performed similarly to 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. Because the WetSpa interception model is part of an integrated water balance framework, the influence of individual city trees on the whole urban balance can be accurately simulated. The Gash model performs better than the Rutter model on the individual tree level in temperate climates. The performance of WetSpa is in between both interception models and best for bigger rainfall events ($P_g > 10 \text{ mm}$).~~

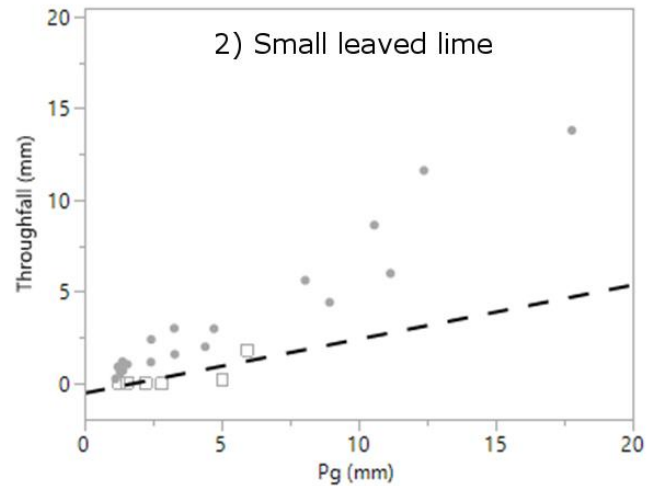
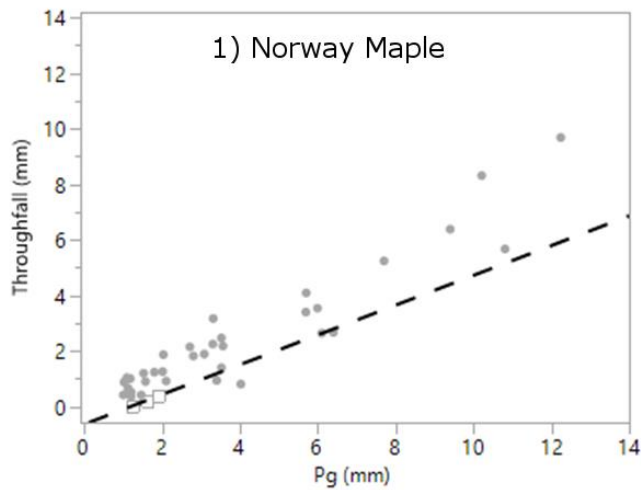
~~(3) The regression equation we developed for the interception storage in temperate climates was found to be tree- and season-specific. We therefore don't recommend its use for a wider application as its performance is limited by the amount of meteorological data and by the tree architectural characteristics.~~

~~(4) The scenario analysis shows that even small scale construction sites can have an impact on the water management in cities. In our scenario a green space is replaced by new student houses on the VUB campus in Brussels, Belgium. This change increases net rainfall by 20 % and surface runoff by 49 %. A more sustainable scenario where all areas around buildings are covered by trees re-establishes the interception storage and thus limits net rainfall. However, due to less pervious surfaces, infiltration is still limited and surface runoff increased. This scenario analysis gives an indication of how city trees retain rainfall water and limit surface runoff production.~~

2)

Appendix A: Free throughfall coefficient estimation:

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



$$T_f (\text{mm}) = -0.63 + 0.54 \times P_g (\text{mm})$$

$$T_f (\text{mm}) = -0.57 + 0.30 \times P_g (\text{mm})$$

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

Appendix AB: Model equations:

$$I = S + E = P_g - (T_f + D + S_f)$$

equation 1 (Xiao, 1998)

I : interception storage [mm]

S : crown surface storage capacity = interception storage capacity [mm]

E : evaporation [mm]

10 P_g : gross rainfall [mm]

T_f : free trough-fall [mm]

D : drip-off [mm]

S_f : stemflow [mm]

$$15 \quad T_f = P \times P_g \quad \text{-----} \quad \text{-----} \quad \text{equation 2 (Xiao, 1998)}$$

P_- = gap fraction [-]

20

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

5 Gash

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

$\mathbf{E}a$: mean evaporation / canopy cover [-]

10 \mathbf{R} : mean rainfall/ saturated canopy cover [-]

\mathbf{P}' : precipitation reaching canopy saturation [mm]

$$\mathbf{P}' = -\frac{\mathbf{R}}{\mathbf{E}a} \times \mathbf{S} \times \ln\left(1 - \frac{\mathbf{E}a}{\mathbf{R} \times (\mathbf{1}-\mathbf{p})}\right) \text{---equation 6}$$

(Gash, 1979)

15

Rutter

$$\mathbf{P}_{\text{soil}} = \mathbf{T}_f + \mathbf{D}_- + \mathbf{S}_f$$

20

and

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

25

\mathbf{P}_{soil} : precipitation reaching the ground (net precipitation) [mm]

\mathbf{IS}_- : interception storage at timestep before actual rainfall [mm]

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

30

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

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

WetSpa

35

$$\begin{cases} \mathbf{I} = \mathbf{S} - \mathbf{IS} & \text{for } \mathbf{P} > \mathbf{C} - \mathbf{IS} \\ \mathbf{I} = \mathbf{P}_g & \text{for } \mathbf{P} \leq \mathbf{C} - \mathbf{IS} \end{cases} \text{---equation 10 (WetSpa manual, 2009; Liu et al., 2004)}$$

and

40

$$\mathbf{IS}(\mathbf{t}) = \mathbf{IS}(\mathbf{t}-1) + \mathbf{I}(\mathbf{t}) - \mathbf{E}(\mathbf{t}) \text{---equation 11 (Liu et al., 2004; WetSpa manual, 2009)}$$

and

$$\mathbf{E}(\mathbf{t}) = \mathbf{IS}(\mathbf{t}-1) \text{ for } \mathbf{PET} > \mathbf{IS}(\mathbf{t}-1) \text{---equation 12 (Liu et al., 2004; WetSpa manual, 2009)}$$

$$E(t) = PET \quad \text{for } PET < IS(t-1)$$

Appendix B: equations Figure 9.

Figure 9a: Uncertainty equation Norway maple: $y = 0.3884 \times x^{-1}$

Uncertainty equation small leaved lime: $y = 0.3468 \times x^{-1}$

Figure 9b: Sensivity equation Norway Maple: $y = 3.4658 \times x^{-1}$

Sensivity equation small leaved lime: $y = 3.097 \times x^{-1}$

Appendix C: Clustering variables regression equation

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
P_g	LAI	PET	Duration	Max. wind speed
Min. wind speed	Min. T	Min. Humidity	P_w	Av. wind speed
Rel. wind speed	Max. T	Max Humidity	Intensity	-
W	Av. T	Av. Humidity	IERI	-

P_g = Gross precipitation; W = Relative windspeed/ P_g ; PET = Potential evapotranspiration; P_w = P_g /intensity; Relative windspeed = av. windspeed/max. windspeed

Cluster 3 and 5 were eliminated from the regression. The variables chosen for the regression in Cluster 1,2 and 4 are highlighted in bold.

Appendix D: Individual rain events

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.

Conflicts of Interest: The authors declare no conflict of interest.

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