Belgeo
Revue belge de géographie

2 | 2016
Mapping, monitoring and modelling of urban areas

An Earth observation based method to assess the influence of seasonal dynamics of canopy interception storage on the urban water balance

Het gebruik van aardobservatie voor de bepaling van de seizoenale invloed van interceptie door landschapselementen op de stedelijke waterbalans

Boud Verbeiren, Ho Khanh Nguyen, Charlotte Wirion and Okke Batelaan

Electronic version
URL: http://journals.openedition.org/belgeo/17806
DOI: 10.4000/belgeo.17806
ISSN: 2294-9135

Publisher:
National Committee of Geography of Belgium, Société Royale Belge de Géographie

Electronic reference
Boud Verbeiren, Ho Khanh Nguyen, Charlotte Wirion and Okke Batelaan, « An Earth observation based method to assess the influence of seasonal dynamics of canopy interception storage on the urban water balance », *Belgeo* [Online], 2 | 2016, Online since 31 March 2016, connection on 19 April 2019. URL : http://journals.openedition.org/belgeo/17806 ; DOI : 10.4000/belgeo.17806

An Earth observation based method to assess the influence of seasonal dynamics of canopy interception storage on the urban water balance

Het gebruik van aardobservatie voor de bepaling van de seizoenale invloed van interceptie door landschapselementen op de stedelijke waterbalans

Boud Verbeiren, Ho Khanh Nguyen, Charlotte Wirion and Okke Batelaan

This research is funded within the frame of the MAMUD project SR/00/105 and the BELAIR 2013 project SR/67/167 (STEREO II programme, BELSPO). Bart Muys, Erik Van Beek en Koen Thijs (Forest Ecology and Management Group, Division Forest, Nature and Landscape, Department Earth and Environmental Sciences) are acknowledged for the field acquisition and processing of hemispherical photos. The authors would like to thank Luca Demarchi from the Cartography and GIS Research Group of the Vrije Universiteit Brussel for providing the EO-derived sealed surface cover fraction map used in this study. Also the anonymous referees are thanked for their useful comments and suggestions.

Introduction

1 Urban areas are typically a conglomerate of different land-cover types, housing a wide range of activities (residential, commercial, industrial, etc.) and forming a patchwork of buildings, streets, parking lots, pavements, gardens, squares, parks, etc. Complexity and heterogeneity are inherent to the urban landscape.

2 Due to these specific characteristics it is not surprising that the urban landscape, compared to rural landscapes, behaves differently with regard to water and energy fluxes, and has a distinct hydrological response. Typically most of the precipitation runs off rapidly at the surface due to the high cover of sealed surfaces in urban areas (Dougherty *et al.*, 2004). Before the precipitation reaches the surface it is however

partially intercepted and evaporated. Interception is the portion of the precipitation that is stored or collected by the surface (mainly vegetal cover) and that subsequently evaporates. In studies of major storm events, the interception loss is generally neglected. However, it can be a considerable influencing factor for small or medium storms and water balance computations would be significantly in error if evaporative losses of intercepted precipitation were not included.

3 Although urban interception remains relatively little studied, there is a growing interest in obtaining urban interception rates (Grimmond and Oke, 1991; Xiao *et al.*, 2000; Ragab *et al.*, 2003; Gash *et al.*, 2007; Asadian and Weiler, 2009). In an urban context interception is mainly caused by urban elements and vegetation. Urban elements such as roofs, pavements or other impervious surfaces account for some interception in the form of temporal storage of water from where it will evaporate shortly after. This type of interception is mostly regarded as depression storage. Also urban vegetation and in particular trees, contribute substantially to urban interception (Grimmond and Oke, 1999; Guevara-Escobar *et al.*, 2007). Interception by vegetation is a complex process, which is affected by the storm characteristics, the species of vegetation, percentage of canopy cover, growth stage, season and wind speed, etc.

4 Interception loss is higher during the initial phase of a storm and approaches zero thereafter (Gerrits, 2010). Vegetation obviously plays an important role in the interception. Asadian and Weiler (2009) state that urban trees are important for reducing storm runoff as a result of higher interception losses. Even twice as much as in natural forest due to urban heat island effects and the isolated position of urban trees, which enables trees to obtain larger structural dimensions. Vegetation characteristics and dynamics determine the spatial and temporal variation of interception rates. Land-use/land-cover changes, e.g. vegetated areas that are turned into urban land-cover types, alter evapotranspiration and interception rates and patterns (Rim, 2009).

5 Since the early days of Earth Observation (EO), monitoring of vegetation has been a key goal. The use of satellite and airborne imagery offers a relatively easy and cost-effective way to monitor and manage vegetated areas. The concept of EO based vegetation indices has become popular due to its area-covering nature and its simplicity to be used in a local as well as regional context at different resolutions (Zheng and Moskal, 2009).

6 Initially EO based approaches for assessing vegetation dynamics were mostly developed for rural/agricultural areas. Andersen *et al.* (2002) and Stisen *et al.* (2008) give examples of how EO can be used to parameterise vegetation and to assess dynamics for hydrological modelling under data sparse non-urban conditions. Andersen *et al.* (2002) derived Leaf Area Index (LAI) from coarse resolution imagery for vegetation parameterisation (root depth, fractional cover, etc.). Stisen *et al.* (2008) integrated EO-derived LAI (to parameterise root depth, crop coefficient) and potential evapotranspiration (PET) into a distributed hydrological model for a large scale basin. Although discharge and actual ET rates were relatively similar for the original and EO based approach, both methods yielded considerable spatial differences. Main disadvantage of the conventional (non-EO) approach was the fact that the limited number of precipitation stations strongly determined the spatial patterns of the model output. Vegas Galdos (2012) presented an approach to obtain spatially distributed estimates for interception storage capacity based on MODIS imagery, which were used as input for an interception model.

7 With respect to urban areas applications on vegetation parameterisation using EO data are more limited. A first topic of interest is vegetation (fraction) mapping. Ridd (1995)

explored the applicability of a vegetation-impervious surface-soil model to describe the urban ecosystem of several cities. A second topic of interest is urban heat island studies (Weng *et al.*, 2004) and the cooling effect of urban vegetation (Loughner *et al.*, 2012). Guevara-Escobar *et al.* (2007) focused on the interception of urban trees. Monitoring a single tree in an urban environment during nineteen storm events showed considerable canopy interception rates (60%) and an influence on the local precipitation distribution. Finally, some studies also aimed at estimating evapotranspiration in an urban context (Boegh *et al.*, 2009; Nouri *et al.*, 2012).

8 As a conclusion one can state that EO has potential and an added value for vegetation monitoring but that its application in urban areas remains relatively under-exploited. In general vegetated surfaces play an important role as areas of recharge, for the redistribution of precipitation and in the regulation of surface runoff, especially for medium storms (Zhang *et al.*, 2011). Therefore detailed and spatially distributed vegetation parameterisation is of great interest for hydrological modelling in urban catchments.

9 This paper addresses the following research questions:

1. To what extent do vegetation dynamics play a role in the hydrological response of an urban river catchment?
2. How can EO contribute to a better hydrological parameterisation of vegetation dynamics at catchment scale?

10 The main objective of our research is to develop an EO based method to assess and to parameterise vegetation dynamics at catchment scale and to integrate these EO based estimates into a distributed hydrological model. This study focuses on EO based estimation of interception storage capacity.

11 The paper is organised as follows: in section 2 the main characteristics of the study area, an urban river catchment, as well as the main EO sources are described. Next, section 3 describes the EO based methodology to retrieve distributed parameter maps, more specifically interception storage capacity. In section 4 a description of the hydrological model for the study area is provided. Section 5 discusses the results of the EO parameterisation and the impact on the hydrological simulation. Finally, the conclusions summarise the main outcomes from a methodological, as well as hydrological impact perspective.

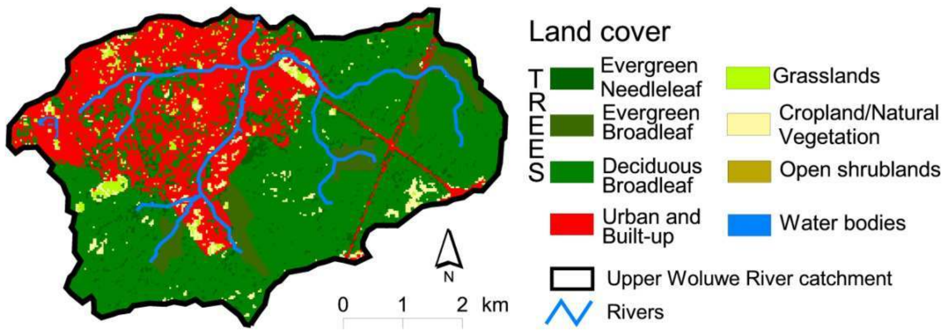
Study area and data

12 The Woluwe River catchment in Brussels (Belgium) is an urban catchment with limited urban dynamics over the last decade, but is characterised by dense vegetation cover (urban green and forest). This makes the Woluwe River catchment interesting for remote sensing based parameterisation regarding vegetation dynamics and to study the impacts on simulated hydrological output.

13 The topography within the Upper Woluwe study area (31.2 km^2) ranges from 49.9 to 128.5 m, with an average of 94.4 m above the sea level. The upper Woluwe has a pronounced topography and is dominated by loamy soil textures. The most important land-cover type in the study area is composed of broadleaf trees (urban green and forest) occupying around 20 km^2 or 65% of the catchment area. The other relevant land-cover class is urban built-up area, covering 9.2 km^2 (29%) of the catchment area and is located in the north-

west. 46% of these urban pixels have extensive vegetation cover. The remaining land-cover classes have a negligible coverage (<5%). Figure 1 shows a land-cover map for the upper Woluwe catchment.

Figure 1. WetSpa land-cover map for the Upper Woluwe River catchment.



ADAPTED FROM: LAND-USE MAP OF FLANDERS AND BRUSSELS, AGIV

14 For the Upper Woluwe catchment a set of medium resolution satellite images was acquired to explore the use of remote sensing derived information, related to vegetation dynamics, for hydrological modelling. Table 1 summarises the used satellite images. The CHRIS/Proba image was used to obtain sealed surface proportion estimates (Demarchi *et al.*, 2012). The ASTER images (09/10/2010 and 02/03/2011) were used to assess seasonality, i.e. to derive vegetation indices for maximum (summer/autumn) and minimum (winter/spring) conditions respectively.

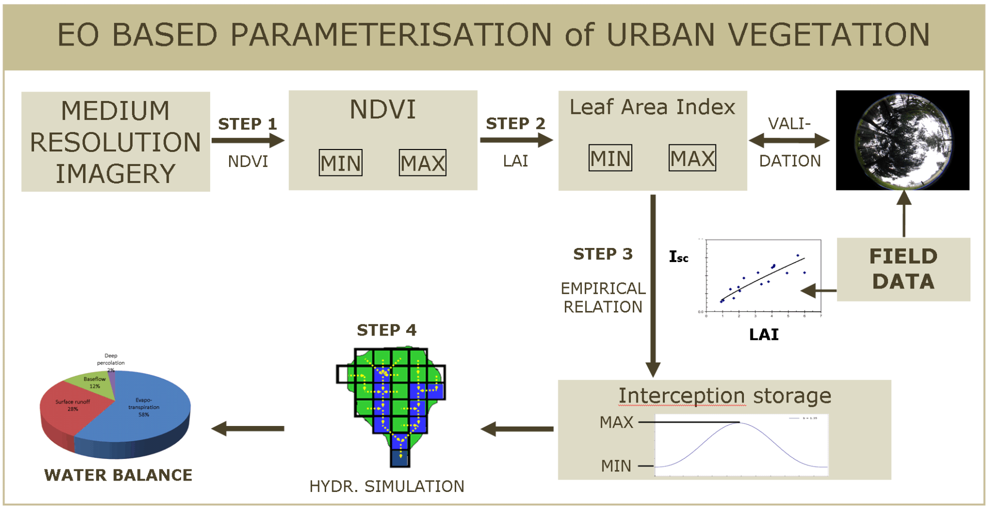
Table 1. Properties of medium resolution imagery used in this study.

Image type	Acquisition date	Resolution VNIR
CHRIS/Proba	2008-05-20 (09:51)	18 m
ASTER Terra Level2b	2010-10-09 (10:45)	15 m
ASTER Terra Level2b	2011-03-02 (10:45)	15 m

Interception storage estimation using Earth observation data

15 This study aims to integrate EO derived interception storage capacity estimates (I_{sc}) of urban green into a distributed physically-based hydrological model (WetSpa). Below follows a step-by-step description of the methodology. Figure 2 summarises the EO based urban vegetation parameterisation approach.

Figure 2. Earth observation based approach for parameterisation of vegetation dynamics related processes.



16 The normalised difference vegetation index NDVI (Step 1) and leaf area index LAI (Step 2) are derived from medium resolution imagery. Both indices have a clear and easily interpretable physical meaning. The LAI maps are validated by field data (collected under seasonal maximum conditions) and are subsequently used in an existing empirical equation (Gomez *et al.*, 2001 - Eq. 5) to obtain distributed I_{sc} estimates for minimum and maximum conditions (Step 3). I_{sc} is regarded as an important parameter for hydrological models (Vegas Galdos *et al.*, 2012). Liu (1998) obtained a medium sensitivity for the maximum interception storage capacity parameter in the WetSpa model. Both the seasonal minimum and maximum interception storage capacity maps form a direct distributed parameter input map for hydrological simulations with the WetSpa model (Step 4). Seasonal variation is simulated at cell level using a sine function.

17 The original version of the WetSpa model uses a land-cover class based approach with a look-up table containing literature based seasonal minimum and maximum interception storage capacity values for each land-cover class (Table 2) and applies a seasonal variation sine-function at class level. This results in interception storage capacity maps with a poor spatial distribution and generic interception estimates. An EO based approach offers the possibility to overcome these limitations by generating spatially distributed and site- and period-specific interception storage estimates.

Table 2. Default literature based interception storage capacity characterising land-cover classes in WetSpa.

Category	Cover	Interception capacity [mm]	
		Maximum	Minimum
1	**Evergreen Needleleaf Trees/Forest**	**2.0**	**0.5**
2	**Evergreen Broadleaf Trees/Forest**	**3.0**	**0.5**
3	Deciduous Needleleaf Trees/Forest	2.0	0.5
4	**Deciduous Broadleaf Trees/Forest**	**3.0**	**0.5**
5	Mixed Trees/Forest	3.0	0.5
6	Closed Shrublands	2.5	0.5
7	**Open Shrublands**	**2.0**	**0.5**
8	Woody Savannah	3.0	0.5
9	Savannahs	2.0	0.5
10	**Grasslands**	**2.0**	**0.5**
11	Permanent Wetlands	1.0	0.2
12	Croplands	2.0	0.5
13	**Urban and Built-Up**	**0.5**	**0.5**
14	**Cropland / Natural Vegetation**	**1.5**	**0.5**
15	Snow and Ice	0.0	0.0
16	Barren or Sparsely Vegetation	1.0	0.2
17	**Water Bodies**	**0.0**	**0.0**

* **Bold** indicates classes present in the study area

18 For a quantitative assessment of the spatial and temporal distribution of rainfall interception loss at catchment level, use will be made of an EO-based vegetation index approach, inspired by the methodology proposed by De Jong and Jetten (2007). The method of De Jong and Jetten (2007) uses the equation proposed by Aston (1979 - Eq. 1) to calculate:

$$I = C_p I_{sc} \left(1 - e^{-\frac{kP}{I} sc}\right) \qquad \text{(Eq 1)}$$

19 where I is the rainfall interception [mm]; C_p is the fractional vegetation cover [-]; I_{sc} is the maximum interception storage capacity of the canopy at a specific moment [mm]; k is a canopy openness correction factor; and P is the rainfall [mm].

20 Steps 1 to 3 in our approach (Figure 2) are very similar to those in the methodology proposed by De Jong and Jetten (2007). However, an additional LAI equation (Eq. 4) is used and the obtained LAI values are validated with field data.

Step 1: Determination of Normalised Difference Vegetation Index (NDVI)

21 Starting point of the methodology are calibrated and geometrically rectified spectral reflectance data. In this study two medium resolution images (ASTER) are used, corresponding to the minimum (02/03/2011) and maximum conditions (09/10/2010) of the annual vegetation growth cycle.

22 The first step is to calculate the NDVI, which is a generally accepted and widely used vegetation index (Tucker, 1979). It is a measure for the presence of living green

vegetation within an image pixel. The NDVI is calculated using the red and near infrared reflectance bands of an image (Eq. 2). In case of an ASTER image band 2 (*RED*) and band 3 (*NIR*) are used.

$$NVDI = \frac{NIR - VIS}{NIR + VIS} \qquad \text{(Eq 2)}$$

23 NDVI values range from -1 to 1. A value of 1 indicates full vegetation cover, while a value close to 0 indicates bare soil conditions. Negative values mainly indicate clouds, snow or water.

Step 2: Determination of Leaf Area Index (LAI)

24 The LAI is also a commonly used vegetation index, but contrary to the NDVI it is not as straightforward in its use as there is no universal way for the calculation of the LAI. In this study LAI is related to the NDVI. NDVI shows an asymptotical behaviour in relation to LAI (Carlson and Ripley, 1997), resulting in poor estimates for high LAI values.

25 In this study two different equations for the calculation of LAI are used. Firstly, the equation of Tabarant (2000) (Eq. 3) used by De Jong and Jetten (2007), which is an empirical linear relation for oak forest in southern France that is assumed to be representative for broadleaf trees:

$$LAI = 8.238\ NDVI - 2.93 \qquad \text{(Eq 3)}$$

26 Secondly, the equation of Su (1996) (Eq. 4) is used, which has the advantage of yielding positive LAI values only. However, it has the tendency to underestimate LAI for dense vegetation:

$$LAI = \sqrt{NVDI \frac{1 + NDVI}{1 - NDVI}} \qquad \text{(Eq 4)}$$

27 Using different equations will of course yield different LAI maps. The main objective of the LAI mapping was to get an idea of the LAI ranges for broadleaf trees dominating the study area. LAI results (for maximum conditions) were validated using field LAI measurements, which can be measured using either direct or indirect methods (Gower *et al.*, 1999; Kussner and Mosandl, 2000). In this study, (hemispherical) photos of tree plots were processed using the gap fraction theory (Norman and Campbell, 1989; Pearcy, 1989) to obtain a LAI value for each tree plot.

28 On 14 October 2010 a hemispherical camera (Digital HR reflex camera Canon 5D with a Sigma 8 mm f/4 circular Fisheye lens, equi-angular projection) was used to obtain field data (Jonckheere *et al.*, 2004) for maximum conditions. Ten broadleaf tree plots (owned and monitored by the Environmental Service BIM/IGBE of Brussels and UCL) were selected for gathering field LAI data (Remark: three plots are located just outside the model area and are not plotted on Figure 4). The number of trees per plot was varying from one plot to another. A 16-point grid covers a plot of 30 by 30 m. At every point a hemispherical photo was taken.

29 The hemispherical photos (blue band) were processed using the Hemisphere 1.5.2 software. The gap fraction theory uses the amount of light that comes through the gaps in the foliage to estimate LAI. Both the method of Lang and Xiang (1986) and the method of Norman and Campbell (1989) were used to compute the LAI values. For each plot the obtained LAI values (2 x 16) were averaged.

Step 3: Determination of Storage Interception Capacity (I_{sc})

Tree canopy interception

30 Next, the LAI maps are used to calculate the interception storage capacity (I_{sc}) of mainly tree canopies in the urban catchment. The I_{sc} value refers to the amount of water that can be stored in the canopy and litter. As can be expected this storage depends on the vegetation type.

31 De Jong and Jetten (2007) analyzed a large number of publications on the estimation of interception storage capacity, resulting in a number of I_{sc} equations to be used for specific vegetation types.

32 For broadleaf trees De Jong and Jetten (2007) use the following equation (Eq. 5) from Gomez *et al.* (2001):

$$I_{sc} = 1.184 + 0.490\ LAI\ (\text{Sample size n} = 5, R^2 = 0.76) \qquad (\text{Eq 5})$$

33 Recently, also Vegas Galdos *et al.* (2012) made an attempt to develop a universally applicable equation for different vegetation types linking I_{sc} to LAI, using a vegetation-dependent factor. Despite these efforts to establish generally applicable equations, it is advisable to check the applicability for local conditions (site, species) using field data. For 30 locations on the VUB university campus in Brussels interception storage for broadleaf canopy was estimated by throughfall water collection during a 4-hour rainfall event under full-leaf (maximum) conditions (Khanh, 2014). Unfortunately this validation set just falls outside the study basin. The measured interception storage estimates could however be compared with corresponding estimates obtained by applying Eq. 5 using the measured LAI. A reasonable linear fit was obtained (R^2 = 0.60). Due to the lack of a better alternative the above mentioned equation 5 (Gomez *et al.*, 2001) was used.

Urban interception

34 Next to (broadleaf) tree coverage also urban land cover is abundantly present in the Upper Woluwe River catchment. Due to the strong heterogeneity in the urban zone image pixels often constitute of a mixture of impervious surface cover and urban green. Following the standard assumption that urban pixels are fully impervious would cause a considerable underestimation of interception, as such an approach would not account for the urban green present in those pixels. Therefore sealed surface proportion maps (Demarchi *et al.*, 2012) were used to obtain a better estimation of urban interception, assuming that I_{sc} in every urban pixel is the combination of interception on an impervious fraction (low interception) and on a vegetated fraction, i.e. grass (high interception). This is mainly important for estimations under maximum conditions (Eq. 6) where a large difference occurs between I_{sc} for urban (0.5 mm) and grass (2.0 mm), while there is no difference under minimum conditions (Eq. 7) (see Table 2).

$$I_{sc,urban}(max) = 0.5\,S + 2.0(1 - S) \qquad (\text{Eq 6})$$

$$I_{sc,urban}(min) = 0.5 \qquad (\text{Eq 7})$$

35 where *S* is the sealed surface proportion (%) in a pixel.

Step 4: Integration of I_{sc} into hydrological simulations

36 The hydrological model WetSpa uses the yearly minimum and maximum interception storage capacity (I_{sc}) as a direct input, where seasonal variation is simulated assuming a sine-shaped function.

37 The impact of using an EO based estimate following the approach described above instead of a literature based estimate was assessed by evaluating the water balance for different simulations.

Distributed hydrological modelling

38 Hydrological models are indispensable tools to describe, understand and simulate hydrological conditions and processes in (urban) river catchments. Both lumped or (semi-) distributed approaches are used to simulate hydrological processes in river catchments. Jacobson (2011) notes that in complex urban environments, spatially detailed data is important for proper model calibration. Therefore a thorough characterisation of urban land cover and estimation of related hydrological parameters for hydrological modelling is of utmost importance.

39 In this research the focus lies on the spatiotemporal simulation of urban interception. Therefore the preference is given to fully-distributed hydrological modelling, which allows spatial and temporal analysis of various water balance components. A drawback is the demanding needs for spatially distributed input data, which are often difficult and/or expensive to collect. Earth observation is put forward as an important source for providing detailed spatiotemporal information on the characteristics of the Earth surface, useful for hydrological parameterisation and modelling.

40 The physically-based, distributed rainfall-runoff model WetSpa (Liu and De Smedt, 2004) is used in this study. Based on a number of base maps (land cover, digital elevation model and soil texture) the necessary physically-based parameter maps for WetSpa are derived to simulate the hydrological response of the Upper Woluwe River catchment.

41 In WetSpa, the rainfall is reduced until the interception storage capacity is filled. If the total rainfall during the first time increment is greater than the interception storage capacity, the rainfall is reduced by the capacity. Otherwise, all rainfall is intercepted in the canopy or the urban element, and the remainder of interception is removed from the rainfall in the following time increments.

42 By integrating the spatially distributed EO based interception storage capacity maps into the WetSpa model, hydrological simulation of interception storage for the dominating urban tree and urban class can be done on a pixel by pixel basis, instead of on a class by class basis like in the original WetSpa approach.

43 A set of meteorological time series (precipitation P, potential evapotranspiration PET) forms the input to the model. The hourly simulation results are evaluated based on a comparison with an observed discharge time series. For the Upper Woluwe River catchment an hourly discharge time series (2010-2011) for the Goubert station (www.flowbru.be) is available.

44 Calibration of the model on the Upper Woluwe catchment was carried out for an 8 month period (Jul. 2010 - Feb. 2011). Validation also covered an 8 month period (May 2011 - Dec.

2011). Calibration was initiated by an extensive manual trial-and-error calibration, which increases understanding on model behaviour as a result of parameter changes. The manual calibration enabled us to obtain a realistic value for the initial groundwater storage, while ensuring a satisfactory volumetric efficiency. The manual calibration was followed by automated parameter estimation (PEST) for the rest of the global WetSpa parameters.

45 Though the Nash-Sutcliffe efficiencies are on the low side (0.47 for calibration and 0.40 for validation, with higher NSE values for high flows, 0.64 and 0.51 respectively) the model performs well regarding the water balance simulation, with a volumetric efficiency between 0.75 and 0.80. The volumetric efficiency ranges from 0 to 1 and represents the fraction of water delivered at the proper time. Also the near-to-zero value for model bias (0.09 for calibration and -0.03 for the validation period) gives an indication of a satisfying goodness-of-fit. The relatively poor model performance for some criteria can most probably be attributed to some limitations of the WetSpa model, which does not consider the presence and explicit influence of the sewer system.

46 A more extensive description of the WetSpa model for the Upper Woluwe River is provided in Verbeiren *et al.* (2013).

47 Using the calibrated WetSpa model for the Upper Woluwe catchment, in this study simulations with an hourly resolution were run for the period 1 January 2010 till 31 December 2011. A first scenario used the literature based look-up table of interception storage capacity for different land-cover classes (reference), while a second scenario used the EO based I_{sc} maps. In order to assess the sensitivity of the model output to the I_{sc} map input the literature values were arbitrarily increased/decreased with 25% and these sensitivity I_{sc} maps were subsequently used in WetSpa simulations (sens+ and sens-).

Results and discussion

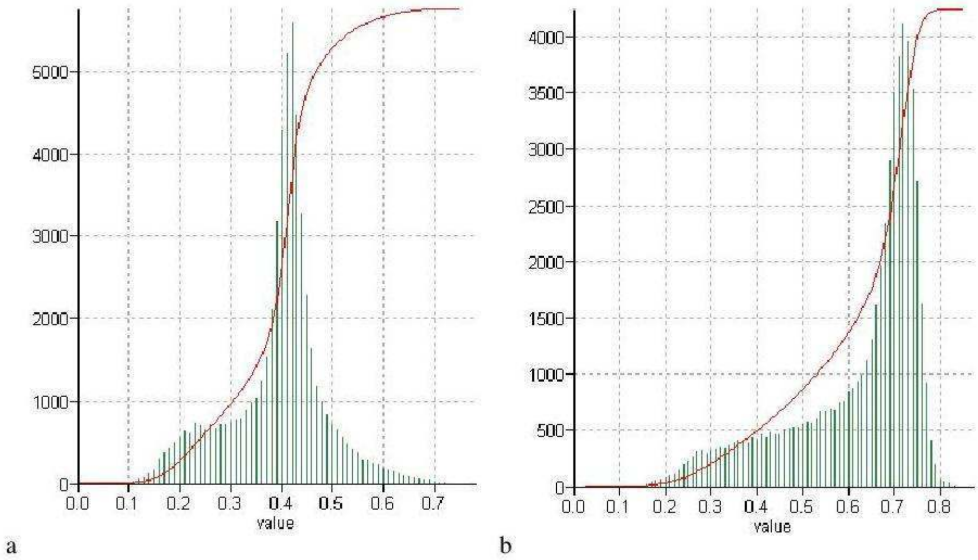
NDVI mapping

48 As explained above, in this study two ASTER images (level2B) for the Upper Woluwe River catchment were used, one from 9 October 2010 and one from 2 March 2011, corresponding respectively with maximum and minimum conditions in the annual vegetation growth cycle.

49 The obtained NDVI maps (15 m resolution) for minimum and maximum conditions were resampled (bilinear method) to 30 m corresponding to the spatial resolution of the WetSpa model.

50 Figure 3 shows the histogram of NDVI values for both minimum (winter/spring) and maximum (summer/autumn) conditions. NDVI values range from 0.15 to 0.8. As expected, the average NDVI value for maximum conditions (0.62) is considerably higher than the average NDVI value for minimum conditions (0.39).

Figure 3. Histogram of NDVI values for minimum (a – 2nd of March) and maximum (b – 9th of October) conditions.

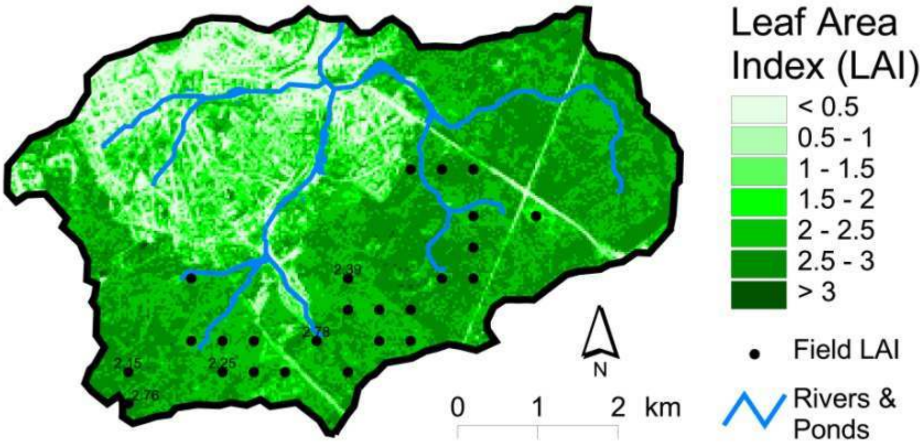


Leaf area index mapping and validation

51 Applying the EO based equations of Tabarant (2000) and Su (1996) four LAI maps were obtained: two under minimum (March 2011) and two under maximum (October 2010) vegetation conditions. Based on field data the maximum LAI maps were validated (see below). Finally a combined LAI map was generated. Figure 4 shows this map for the Upper Woluwe River catchment under maximum vegetation conditions.

52 LAI values roughly range from 0.25 to 3. Close-to-zero values are obtained for the urban pixels with low vegetation cover in the north-western part of the catchment. The abundant broadleaf tree class (urban green and forest) clearly yields high LAI values, mainly between 2 and 3, corresponding to the field measured LAI estimates (black dots).

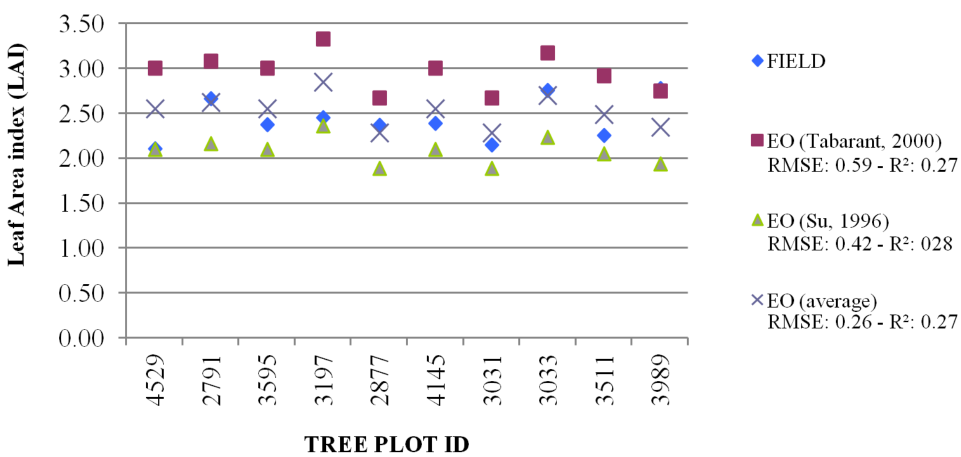
Figure 4. LAI map under maximum vegetation conditions.



BLACK DOTS INDICATE MONITORED BROADLEAF TREE PLOTS, THE VALUES INDICATE FIELD MEASURED LAI ESTIMATES.

53 Figure 5 clearly indicates that the LAI equations of Tabarant (2000) and Su (1996) respectively over- and underestimate LAI values measured in the field (maximum conditions). Overall Su (1996) yields slightly better results (RMSE: 0.42). However, averaging both LAI maps yields a RMSE of 0.26. Therefore it was decided to use the averaged LAI maps for further processing.

Figure 5. Field and EO based LAI estimates [-] for ten broadleaf tree plots in the Upper Woluwe River catchment.



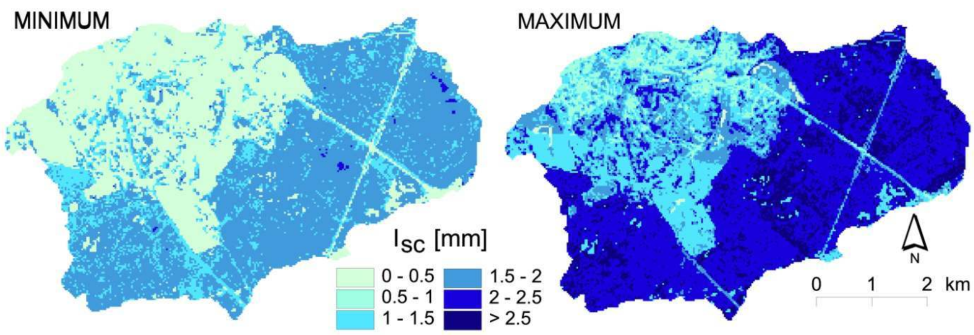
FIELD DATA WAS COLLECTED ON 14.10.2010; THE IMAGE DATES FROM 09.10.2010.

Distributed interception storage capacity maps

54 EO based interception storage capacity estimates for both tree canopy and urban pixels were combined into one map under minimum and maximum vegetation conditions. For the other classes, with a limited coverage in the study area, the literature based values

from the WetSpa look-up table (Table 2) were used. Figure 6 shows the minimum and maximum interception storage capacity maps for the Upper Woluwe River catchment. The majority (90%) of interception storage capacity values (I_{sc}) range from 0.5 to 1.8 mm (mean: 1.2 mm) and from 1.2 to 2.6 mm (mean: 2.0 mm) under minimum and maximum conditions respectively. These values correspond very well to the ranges (0.6 - 2.6 mm) presented by Breuer *et al.* (2003) for I_{sc} of *Fagus sylvatica* (beech), the dominating species in the upper Woluwe area. Aussenac and Boulangeat (1980) report interception storage capacity values ranging between 1.7 and 1.9 mm for similar beech tree stands (*Fagus sylvatica*). More recently André *et al.* (2008) performed local field experiments for a beech tree stand (*Fagus sylvatica*) in Belgium yielding somewhat lower I_{sc} values (0.53 - 1.17 mm).

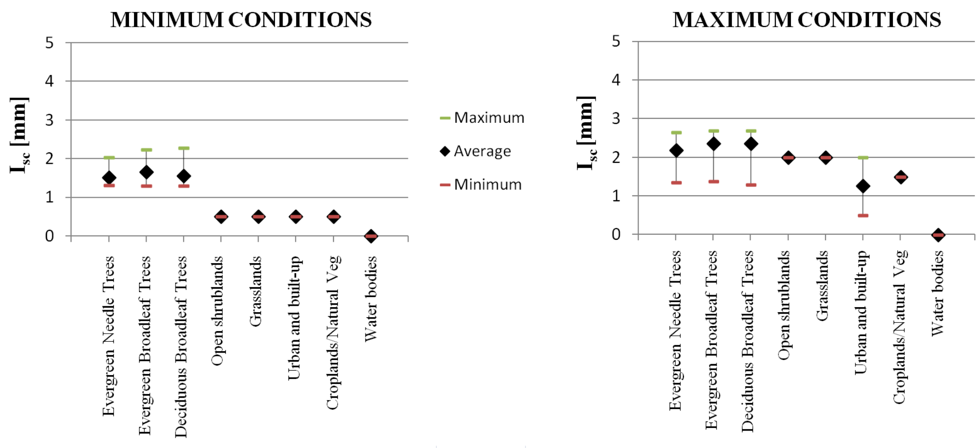
Figure 6. Earth observation based interception storage capacity maps under minimum and maximum vegetation conditions.



55 Under minimum conditions one can note that I_{sc} values are not only considerably lower for the broadleaf tree class, but also for the urban zone. The latter is a direct result of the very low interception capacity of urban vegetation during winter/spring.

56 Figure 7 shows the statistics (average, minimum and maximum) of I_{sc} values per land-cover class in the Upper Woluwe River catchment, both under minimum as well as maximum conditions. One can note the permanently high values for forested and urban green areas, varying between 1.5 and 2.5 mm. Nevertheless the ranges under minimum and maximum conditions indicate a relatively high within-class variation for broadleaf tree pixels. In between the different tree types (3) very little differences are seen. All tree types show similar ranges, indicating a similar variation in foliage coverage. Nevertheless evergreen tree types show a somewhat lower difference between minimum and maximum conditions compared to deciduous trees, but the contrast is less than expected. The variation within the urban and built-up class (under maximum conditions) can be entirely explained by the variation in urban vegetation cover (fraction of vegetation in mixed urban pixels).

Figure 7. Earth observation based interception storage capacity estimates per land-cover class in the Upper Woluwe River catchment, under minimum and maximum vegetation conditions.



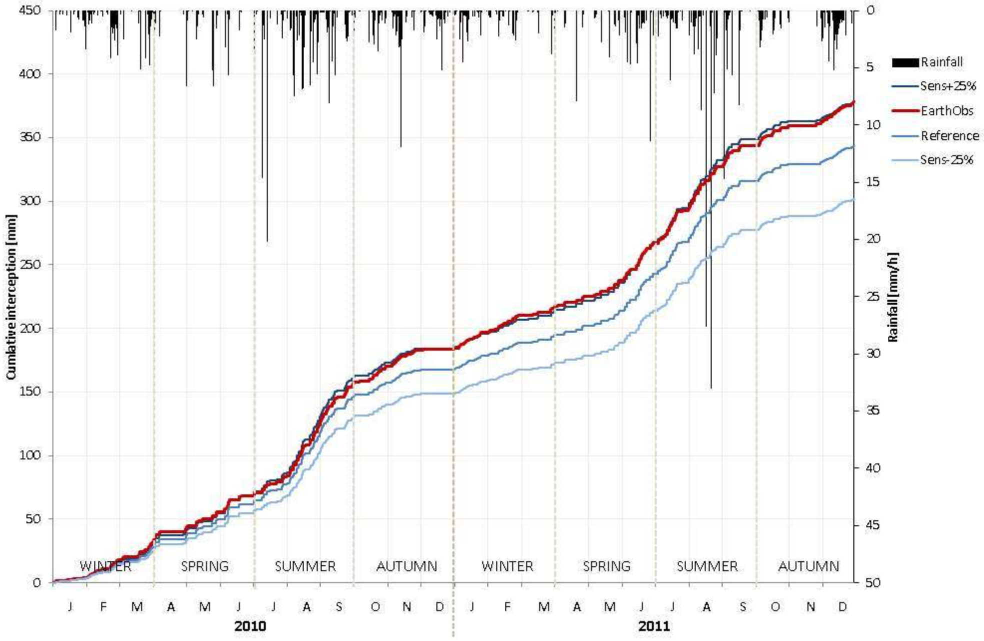
57 The literature based approach considerably underestimates interception storage capacity for broadleaf trees under minimum vegetation conditions (winter/spring) in comparison to EO-based estimates. Under maximum conditions there is a slight overestimation of I_{sc} for the literature based approach compared to the EO based estimation of I_{sc} for trees. For urban areas the values are clearly lower, suggesting an underestimation and confirming the importance of taking into account the pervious/vegetated fraction of urban pixels.

58 It is also worth mentioning that the EO based method, which aims at being generally applicable, enables to obtain site- and time-specific I_{sc} estimates for entire river catchments.

Hydrological simulation: look-up versus Earth observation approach

59 Figure 8 shows the simulated cumulative interception for the Upper Woluwe catchment for 2010-2011. Using the EO estimates for I_{sc} yields a higher total interception (+10.1%) compared to the literature based look-up table approach. The EO based cumulative curve yields a very similar result to the sens+ simulation, indicating that the EO based I_{sc} estimates are in the order of 25% higher than the original literature based I_{sc}. One can also note that the difference between the EO and look-up table based approach is not constant throughout the year. During autumn and winter the EO based curve tends to divert from the reference curve, indicating that EO estimates for I_{sc} are considerably higher. While in spring and summer the EO curve gets closer to the reference cumulative curve, indicating a smaller difference in I_{sc} values. This seasonal variation is a result of a seemingly slight overestimation of I_{sc} values by the look-up based approach when trees have dense foliage and an underestimation in case of sparse tree canopy foliage.

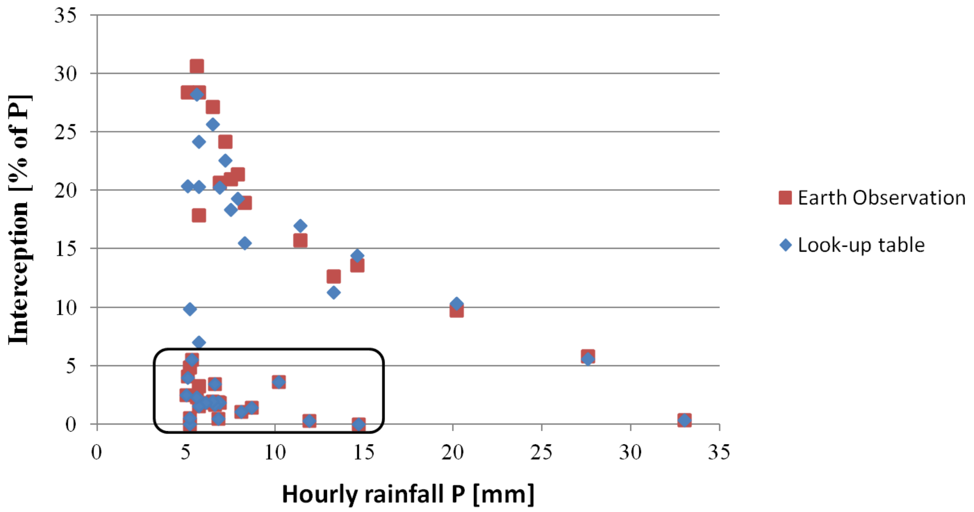
Figure 8. Simulated cumulative interception (2010-2011) in the Upper Woluwe River catchment: a comparison of the original literature based and the Earth observation based approach. Also the +/- 25% sensitivity ranges are indicated.



60 In the Upper Woluwe catchment interception amounts to 21.5% of the precipitation (2010-2011) according to the reference run using literature values from the WetSpa look-up table. The increase of 10.1% for the EO based WetSpa interception simulation corresponds to an increase of 2.2% of interception in the water balance. This increase goes mainly at the expense of infiltration. The other components of the water balance seem to be little affected. It is important to note though that these results and the conclusions drawn from it are for this specific study area and for the overall water balance for the two simulated years.

61 In order to assess temporal differences, rainfall events of varying magnitude were studied.

Figure 9. Simulated interception (2010-2011) for rainfall events with hourly P > 5 mm (T = 1 month) using the look-up table based and the Earth observation based approach.



62 Figure 9 ranks all hourly rainfall events with a return period of 1 month (P = 5 mm) or longer and plots the interception rates for both approaches (look-up and EO) as a percentage of the precipitation. The results indicate a clear difference between heavy rainfall events and smaller rainfall events. For the hourly rainfall events with a return period of 10 years (P > 23 mm) or longer, interception is low (on average 3% of P), while for hourly rainfall events with a return period of 1 year or more (P >12 mm) interception amounts to around 13% of precipitation. For the hourly rainfall events with return periods less than a year (P < 12 mm) it is worth mentioning that there are a large number of events with little or no interception (marked in the box in Figure 9), deviating from the overall trend. These low interception values are a result of a succession of events. Due to the short return period it is more likely that the interception storage is still filled, so that no or little interception can take place. When ignoring these events (box) the average interception rates amount to 21% of the precipitation with maximum interception values around 30%.

63 Regarding the difference between the EO and look-up table based approach, differences seem small for rainfall events with longer return periods. The main differences occur for events ranging between 5 and 10 mm. Also, for events with return periods shorter than a month (P < 5 mm) large relative differences (up to 60-70%) are observed, however, due to the low precipitation values the effect is limited.

Conclusions

64 This study focused on the added value of EO to monitor and assess the influence of seasonal dynamics of canopy interception storage on the urban water balance of the Upper Woluwe catchment, using the WetSpa model. To obtain spatially distributed and location-specific values for interception storage capacity use was made of the leaf area index (LAI) as an indicator for vegetation status.

65 With respect to the parameterisation of interception storage capacity for broadleaf tree vegetation, the proposed EO based approach yields considerable differences in canopy interception rates compared to the original WetSpa look-up table based method. For

minimum conditions (winter/spring) EO canopy interception estimates for broadleaf trees are considerably higher. For maximum conditions (summer/autumn) both methods yield similar estimates. Analysis of the use of sealed surface proportions for the estimation of interception storage for mixed urban pixels reveals considerably lower interception under maximum conditions when using the original look-up table based approach. This suggests an underestimation of interception storage when these sealed surface proportions are not considered. Comparison of the EO based method and the original look-up table based approach also reveals important spatial differences. Due to a lack of proper field data though, validation is difficult to accomplish. Spatially explicit field validation forms a major challenge for future research.

66 With regard to the hydrological impacts in the Upper Woluwe River catchment, the sensitivity analysis shows that EO based estimates of interception storage capacity are around 25% higher than the original look-up table based estimates, resulting in an increase of 10% of the simulated cumulative interception (over a 2-year period). Analysis of interception rates linked to rainfall events with varying intensity shows that on average interception rates are decreasing with rainfall intensity. Rainfall events ranging between 5 and 10 mm (T < 1 year) show the biggest difference in EO and look-up table based interception rates.

67 To conclude it is important to state that, despite the fact that the EO-based methodology presented aims at offering an alternative for site- and period-specific quantification of interception storage, the findings in this paper are primarily valid for the catchment and the time period studied. Results need to be confirmed by extending the approach to a multi-year analysis using more imagery and a longer time series, preferably accompanied by (extensive) ground truthing.

BIBLIOGRAPHY

ANDERSEN J., DYBKJAER G., JENSEN K.H., REFSGAARD J.C. & RASMUSSEN K. (2002), “Use of remotely sensed precipitation and leaf area index in a distributed hydrological model”, *Journal of Hydrology*, *264*, 1-4, pp. 34-50.

ANDRÉ F., JONARD M. & PONETTE, Q. (2008), “Effects of biological and meteorological factors on stemflow chemistry within a temperate mixed oak-beech stand”, *Science of The Total Environment*, *393*, pp. 72-83.

ASADIAN Y., WEILER M. (2009), “New Approach in Measuring Rainfall Interception by Urban Trees in Coastal British Columbia”, *Water Quality Research Journal of Canada*, *44*, 1, pp. 16-25.

ASTON A.R. (1979), “Rainfall interception by eight small trees”, *Journal of Hydrology*, *42*, pp. 383-396.

AUSSENAC G., BOULANGEAT C. (1980), “Interception des précipitations et évapotranspiration réelle dans des peuplements de feuillus (Fagus sylvatica L.) et de résineux (Pseudotsuga menziesii (Mirb) Franco)”, *Annals of Forest Science*, *37*, 2, pp. 91-107.

BOEGH E., POULSEN R.N., BUTTS M., ABRAHAMSEN P., DELLWIK E., HANSEN S., HASAGER C.B., IBROM A., LOERUP J.K., PILEGAARD K. & SOEGAARD H. (2009), "Remote sensing based evapotranspiration and runoff modelling of agricultural, forest and urban flux sites in Denmark: From field to macro-scale", *Journal of Hydrology*, *377*, 3-4, pp. 300-316.

BREUER L., ECKHARDT K. & FREDE H.-G. (2003), "Plant parameter values for models in temperate climates", *Ecological Modelling*, *169*, 2-3, pp. 237-293.

CARLSON T.N., RIPLEY D.A. (1997), "On the relation between NDVI, fractional vegetation cover, and leaf area index", *Remote Sensing of Environment*, 62, 3, pp. 241-252.

de JONG S.M., JETTEN V.G. (2007), "Estimating spatial patterns of rainfall interception from remotely sensed vegetation indices and spectral mixture analysis", *International Journal of Geographical Information Science*, *21*, 5, pp. 529-545.

DEMARCHI L., CANTERS F., CHAN J.C.-W. & VAN DE VOORDE T. (2012), "Multiple endmember unmixing of CHRIS/Proba imagery for mapping impervious surfaces in urban and suburban environments", *IEEE Transactions on Geoscience and Remote Sensing*, *50*, 9, pp. 3409-3424.

DOUGHERTY M., DYMOND R.L., GOETZ S., JANTZ C.A. & GOULET N. (2004), "Evaluation of impervious surface estimates in a rapidly urbanizing watershed", *Photogrammetric Engineering and Remote Sensing*, *70*, 11, pp. 1275-1284.

GASH J.H.C., ROSIER P.T.W. & RAGAB R. (2007), "A note on estimating urban roof runoff with a forest evaporation model", *Hydrological Processes*, *22*, pp. 1230-1233.

GERRITS A.M. (2010), *The role of interception in the hydrological cycle*, PhD thesis, Delft University, 146 p.

GOMEZ J.A., GIRALDEZ J.V. & FERERES E. (2001), "Rainfall interception by Olive trees in relation to leaf area", *Applied Water Management*, *49*, pp. 65-76.

GOWER S.T., KUCHARIK C.J. & NORMAN J.M., (1999), "Direct and indirect estimation of leaf area index, fAPAR, and net primary production of terrestrial ecosystems", *Remote Sensing of the Environment*, *70*, pp. 29-51.

GRIMMOND C.S.B., OKE T.R. (1991), "An evapotranspiration-interception model for urban areas", *Water Resources Research*, *27*, 7, pp. 1739-1755.

GUEVARA-ESCOBAR A., GONZÁLEZ-SOSA E., VÁLIZ-CHÁVEZ C., VENTURA-RAMOS E. & RAMOS-SALINAS M. (2007), "Rainfall interception and distribution patterns of gross precipitation around an isolated Ficus benjamina tree in an urban area", *Journal of Hydrology*, *333*, 2-4, pp. 532-541.

JACOBSON C.R. (2011), "Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review", *Journal of Environmental Management*, *92*, 6, pp. 1438-1448.

JONCKHEERE I., FLECK S., NACKAERTS K., MUYS B., COPPIN P., WEISS M. & BARET F. (2004), "Review of methods for in situ leaf area index determination: Part I. Theories, sensors and hemispherical photography", *Agricultural and Forest Meteorology*, *121*, 1-2, pp. 19-35.

KUSSNER R., MOSANDL R. (2000), "Comparison of direct and indirect estimation of leaf area index in mature Norway spruce stands of eastern Germany", *Canadian Journal of Forest Research*, *30*, pp. 440-447.

LANG A.R.G., XIANG Y.Q. (1986), "Estimation of leaf-area index from transmission of direct sunlight in discontinuous canopies", *Agricultural and Forest Meteorology*, *37*, pp. 229-243.

LIU S. (1998), "Estimation of rainfall storage capacity in the canopies of cypress wetlands and slash pine uplands in North-Central Florida", *Journal of Hydrology*, *207*, 1-2, pp. 32-41.

LIU Y., DE SMEDT F. (2004), *WetSpa Extension, A GIS-based Hydrologic Model for Flood Prediction and Watershed Management,* WetSpa Manual, latest update (February 2009), Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel.

LOUGHNER C.P., ALLEN D. J., ZHANG D. L., PICKERING K. E., DICKERSON R. R. & LANDRY L. (2012), "Roles of Urban Tree Canopy and Buildings in Urban Heat Island Effects: Parameterisation and Preliminary Results", *Journal of Applied Meteorology and Climatology*, *51*, 10, pp. 1775-1793.

NORMAN J.M., CAMPBELL G.S. (1989), "Canopy structure", *in* PEARCY R.W., EHLERINGER J.R., MOONEY H.A. & RUNDEL P. (eds.), *Plant Physiological Ecology. Field Methods and Instrumentation,* New York, USA, Chapman and Hall, pp. 301-325.

NOURI H., BEECHAM S., KAZEMI F. & HASSANLI A.M. (2012), "A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation", *Urban Water Journal*, pp. 1-13.

PEARCY R.W. (1989), *Plant physiological ecology: field methods and instrumentation*, New York, USA, Chapman and Hall.

RAGAB R., BROMLEY J., ROSIER P., COOPER J.D. & GASH, J.H.C. (2003), "Experimental study of water fluxes in a residential area: 1. rainfall, roof runoff and evaporation: the effect of slope and aspect", *Hydrological Processes*, *17*, 12, pp. 2409-2422.

RIDD M.K. (1995), "Exploring a V–I–S (Vegetation–Impervious Surface–Soil) model for urban ecosystem analysis through remote sensing: Comparative anatomy for cities", *International Journal of Remote Sensing*, *16*, 12, pp. 2165-2185.

STISEN S., JENSEN, K., SANDHOLT I. & GRIMES D. (2008), "A remote sensing driven distributed hydrological model of the Senegal River basin", *Journal of Hydrology*, *354*, pp. 131-148.

SU Z. (1996), *Remote sensing applied to hydrology: The Sauer river basin study*, Ph.D. Thesis, Bochum, Germany, Faculty of Civil Engineering, Ruhr University Bochum.

TABARANT F. (2000), *Apport de la télédetection et de la modélisation à l'étude de la dynamique de production d'un écosystème méditerranéen de Chênes verts dans le Sud de La France*, Report SPI 00.124, Ispra, Italy, JRC Space Applications Institute.

TUCKER C.J. (1979), "Red and Photographic Infrared Linear Combinations for Monitoring Vegetation", *Remote Sensing of Environment*, *8*, 2, pp. 127-150.

VEGAS GALDOS, F., ÁLVAREZ C., GARCÍA A. & REVILLA J.A. (2012), "Estimated distributed rainfall interception using a simple conceptual model and Moderate Resolution Imaging Spectroradiometer (MODIS)", *Journal of Hydrology*, *468-469,* pp. 213-228.

VERBEIREN B., VAN DE VOORDE T., CANTERS F., BINARD M., CORNET Y. & BATELAAN O. (2013), "Assessing urbanisation effects on rainfall-runoff using a remote sensing supported modelling strategy", *International Journal of Applied Earth Observation and Geoinformation*, *21*, pp. 92-102.

WENG Q., LU D. & SCHUBRING J. (2004), "Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies", *Remote Sensing of Environment*, *89*, 4, pp. 467-483.

XIAO Q., MCPHERSON E., USTIN L., GRISMER M. & SIMPSON J. (2000), "Winter rainfall interception by two mature open-grown trees in Davis, California", *Hydrological Processes*, *14*, pp. 763-784.

ZHANG W., AN S., XU Z., CUI J. & XU Q. (2011), "The impact of vegetation and soil on runoff regulation in headwater streams on the east Qinghai-Tibet Plateau, China", *CATENA*, *87*, 2, pp. 182-189.

ZHENG G., MOSKAL L.M. (2009), "Retrieving Leaf Area Index (LAI) using remote sensing: theories, methods and sensors", *Sensors, 9,* 4, pp. 2719-2745.

ABSTRACTS

Vegetation is often represented in an oversimplified way in hydrological models for urbanised catchments, resulting in a generalised parameterisation of urban green. This is common practice, despite the fact that some studies clearly indicate that both the coverage and influence of urban green is often underestimated. In general vegetated surfaces play an important role as areas of recharge, for the redistribution of precipitation and in the regulation of surface runoff, especially for medium intensity storms. Hence, a more realistic and spatially distributed vegetation parameterisation would be of high value for hydrological modelling in urban catchments. In this paper an Earth observation based methodology is presented as an alternative to quantify the influence of canopy interception storage as well as the influence of seasonal dynamics on the urban water balance. Results indicate that Earth observation based interception storage capacities for the Upper Woluwe catchment (Brussels) are up to 25% higher than values obtained from literature, resulting in an increase of cumulative interception rates with 10% over a two year period. The results seem to vary with the rainfall intensity as well as with seasonal dynamics. In order to prove the general applicability of the proposed approach, these results need further confirmation using multi-year analyses and preferably a validation with ground truthing, which is a challenging future task.

In een stedelijke context wordt vegetatie vaak op een overmatig eenvoudige manier voorgesteld in hydrologische modellen. Dit resulteert meestal in een zeer ruwe parameterisering van urbaan groen. Deze benadering is wijd verspreid, ondanks het feit dat studies aantonen dat zowel de dekking, als de invloed van stedelijk groen vaak onderschat wordt. Begroeide oppervlakken spelen een belangrijke rol inzake infiltratie in de bodem en de aanvulling van grondwater, de herverdeling van neerslag en de regulering van oppervlakkige afvoer, in het bijzonder voor middelgrote stormen. Dit maakt dat een meer realistische en ruimtelijk verdeelde parameterisering van urbane vegetatie van grote waarde kan zijn voor de modellering van stedelijke waterbekkens. In deze paper wordt een aardobservatie gebaseerde methode voorgesteld voor de kwantificering van interceptie door het stedelijk landschap (vnl. vegetatieve landschapselementen zoals bomen, struiken, etc.), alsook de seizoenale dynamiek en de invloed op de stedelijke waterbalans. De resultaten tonen dat de aardobservatie gebaseerde interceptie in het bovenstrooms gedeelte van het Woluwe-bekken (Brussel) tot 25% hoger liggen dan de waarden gebaseerd op literatuur. Over een periode van 2 jaar betekent dit een toename met 10% van de cumulatieve interceptie. De interceptiewaarden blijken ook te variëren in functie van de neerslagintensiteit en vertonen een seizoenale dynamiek. Een meerjarige analyse, bij voorkeur met grondmetingen, is noodzakelijk om de bekomen resultaten te bevestigen, wat een uitdaging vormt voor de toekomst.

INDEX

Keywords: urban green, ASTER Terra, interception storage, urban water balance, seasonality, Upper Woluwe (Brussels)

Trefwoorden stedelijk groen, ASTER Terra, interceptive, stedelijke waterbalans, seizoenaliteit, Woluwe bekken (Brussel)

AUTHORS

BOUD VERBEIREN

Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, boud.verbeiren@vub.ac.be

HO KHANH NGUYEN

Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, Vietnam Institute of Geosciences and Mineral Resources, Department of Remote sensing and Geomatics, hokhanh.hk@gmail.com

CHARLOTTE WIRION

Vrije Universiteit Brussel, Department of Hydrology and Hydraulic Engineering, charlotte.wirion@vub.ac.be

OKKE BATELAAN

Flinders University, School of the Environment, okke.batelaan@flinders.edu.au