Simulating urban interception based on detailed in-situ monitoring and remote sensing data

Simulation des pertes d'eau de pluie liées à l'interception par la végétation urbaine, basée sur l'acquisition de données in situ et de télédétection

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RÉSUMÉ

Cette étude propose une méthode intégrale pour la simulation des pertes d'eau de pluie liées à l'interception par la végétation urbaine. La méthode est basée sur l'acquisition détaillée de données in situ et de télédétection.

Nous nous basons sur une image hyperspectrale APEX pour construire une carte d'occupation du sol à haute résolution spatiale (2m). Nous catégorisons la variation saisonnière de la végétation urbaine avec les nouveaux produits de Proba-V (100m). Les cartes dérivées des données de Proba-V sont validées avec une cartographie détaillée de la couverture végétale pendant toute la saison. A cette fin, nous avons collectionné l'indice foliaire avec le système SS1 Sunscan de tous les arbres et arbustes inclus dans un pixel de Proba-V. Le résultat consiste en une série chronologique de cartes validées qui permettent de caractériser la dynamique de la végétation urbaine en détail.

La carte d'occupation du sol, ainsi que les cartes des indices foliaires sont introduites dans un modèle hydrologique distribué, le 'Wetspa-Python model', pour simuler le bilan hydrologique sur une année dans le bassin de Watermaelbeek à Bruxelles. Les cartes des indices foliaires permettent d'améliorer le paramétrage des pertes d'eau de pluie liées à l'interception par la végétation urbaine et donc les dynamiques spatio-temporelles de la distribution de pluie arrivant sur la surface et de l'évapotranspiration quittant la surface.

ABSTRACT

This study proposes an integrated methodology to simulate urban interception storage using detailed and consistent in-situ measurements along with remote sensing data.

We derive an urban land-cover map at a high spatial resolution (2m) using a hyperspectral APEX image, and we characterize the seasonal variation of urban green with the new daily Proba-V products (100m). We validate distributed LAI maps, derived from Proba-V data, with a detailed mapping of vegetation cover throughout the season. We collected, for this purpose, LAI measurements with the SS1 Sunscan system of all trees and shrubs within a Proba-V pixel. The outcome is a time series of validated LAI maps which enable a detailed characterization of urban vegetation dynamics.

The distributed land-cover map, as well as LAI maps are used as input data for the process-based and spatially-distributed WetSpa-Python model to simulate the urban water balance over one year for the Watermaelbeek catchment in Brussels. The LAI maps allow improving the parameterization of interception storage of urban vegetation and thus the dynamics in spatio-temporal distribution of precipitation reaching and evapotranspiration leaving the urban land surface.

KEYWORDS

Field measurements, interception capacity, remote sensing, urban vegetation

1 INTRODUCTION

Urban interception is defined as the part of rain that is stored on the urban vegetation canopy and subsequently evaporates before reaching the ground. In urban areas, interception plays an important role in controlling the water and energy balance of our cities (Asadian & Weiler 2009). The part of precipitation that is intercepted by urban vegetation is evaporated back to the atmosphere and thus does not contribute to surface runoff.

In hydrological modelling, evaporation from interception storage is often simplified by combining it with the transpiration process or taking a fixed percentage of the rainfall. However, rainfall interception has a strong impact on evaporation, transpiration and surface runoff and should be considered as an important factor in hydrological modelling. The heterogeneity and complexity of the urban landscape makes it difficult to quantitatively assess the spatial and temporal distribution of rainfall interception in urban areas, which therefore is seldom available for modelling purposes (de Jong & Jetten 2007). Conventional mapping implies labour intensive and time consuming field work and thus the mapping of vegetation dynamics and its role in hydrological processes remains a major challenge.

The categorization of surface types in heterogeneous areas can be supported by remote sensing (RS) techniques. Remote sensing measures the radiation that is reflected by the target. The unique spectral response pattern enables the classification of surfaces into land-cover patterns as well as to monitor the changes of land-cover over time. The potential of satellite data for field and regional planning is however limited due to its relatively coarse resolution (30m – km scale) and the challenge of translating images into useful parameters (Carlson and Arthur, 2000). To further improve the parameterization of urban hydrological models, Mass et al. (2002) suggest the use of airborne high-resolution imagery. Advances in high-resolution imaging spectroscopy over the last decade have increased the potential for a thematically detailed mapping of urban areas. Several studies indicate improvements in describing functional vegetation properties (Hermans et al., 2003; Weng et al., 2006). In this study, we characterize the land surface cover at a high spatial resolution (2m) with an airborne hyperspectral APEX (Airborne Prism Experiment) image, while the new daily Proba-V (Project for OnBoard Autonomy – Vegetation) products (100m) are used for a detailed characterization of the seasonal variation of urban green. The Proba-V satellite, which provides daily vegetation data with a 100m resolution as NDVI maps contributes to an improved monitoring of the seasonal variation of vegetation characteristics. The Normalized Difference Vegetation Index (NDVI) is a numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum to identify the amount of living green vegetation.

Based on the high spatial resolution of the airborne image and the high temporal resolution of Proba-V we can create distributed leaf area index (LAI) maps to simulate interception storage in urban areas with the process-based and spatially distributed WetSpa-Python model. The Water and Energy Transfer between Soil Plants and Atmosphere tool (WetSpa) (Wang et al., 1997; Liu and De Smedt, 2004) allows for a detailed simulation of the hydrological processes at the surface in a continuous and distributed manner. Its recent Python version (WetSpa-Python) was developed in view of application in urban areas (Salvadore et al., 2012, 2015). The WetSpa-Python model has increased flexibility as the different model components represent physical processes and every component can have a different spatial and temporal resolution. This allows to account for the heterogeneous distribution of urban green and the seasonal effects of the vegetation.

2 METHODS

2.1 Ground-truth validation for RS data

The generation of the urban land-cover map is based on the airborne hyperspectral APEX image with a 2m resolution. There are two methods of image classification: supervised and unsupervised. With supervised classification, the user develops the spectral signatures of known categories and then the software assigns each pixel in the image to the cover type to which its signature is most similar. With unsupervised classification, the software groups pixels into categories of similar signatures, and then the user interprets what cover types those categories represent. Based on 200 known pixels, so-called training pixels, per class a supervised classifier, the Support Vector Machine (SVM) classifier, was applied to the APEX image to generate the high-resolution land-cover map of the Watermaelbeek catchment using 31 sub-classes such as impervious roofing and pavements (tiles, asphalt, concrete) or pervious vegetated (trees, shrubs, grasses) and non-vegetated surfaces (water, bare soil). The ground-truthing of RS data includes a detailed mapping of land-cover characteristics and more specifically vegetation cover throughout the seasons. Two Proba-V pixels on the VUB and ULB campus in Brussels, Belgium are selected to monitor the dynamics of the tree canopies from April to October 2015. Within the 100 x 100m Proba-V pixels, all 2x2 m pixels of the land-cover map without trees are assumed to be stable throughout the season. The seasonal variation of LAI within the Proba-V pixel is thus only influenced by the dynamics of the tree canopies within that pixel. For assessing the leaf area index (LAI), we use the Sunscan system (Type SS1-COM-R4) to measure incident and transmitted photosynthetically active radiation. The SS1 Sunscan system is used to measure LAI of all trees within the pixel. To validate the Proba-V data we calculate the LAI based on the provided NDVI maps and using the method of Su (Su, 1996).

Once the Proba-V pixels are validated, distributed LAI maps can be created and used as an input to the hydrological model to improve the calculation of interception storage.

2.2 Calculating interception storage based on RS data

To determine interception storage with optical imagery, the LAI and the fractional vegetation parameter V% are derived using spectral mixture analysis and spectral vegetation indices (de Jong & Jetten, 2007). Interception is calculated by the following equation (Aston, 1979):

$$I = V\% * I_{max} * \left(1 - \left(e^{-\frac{k_c * P}{I_{max}}}\right)\right) \qquad \textit{Equation 1}$$

where I is the cumulative interception loss [mm], I_{max} is the canopy interception storage capacity [mm], P is the cumulative rainfall for one rainfall event [mm], and k_c is the correction factor of canopy openness. Different values for the correction factor k_c for most common urban trees, shrubs and lawns are found in literature (e.g.: Aston, 1979; Gomez et al., 2001).

The canopy interception storage capacity I_{max} in urban areas is related to LAI using linear regression (de Jong & Jetten, 2007).

$$I_{max}^{trees} = 1.184 + 0.490\ LAI\ (n = 5; R^2 = 0.76) \qquad \textit{Equation 2}$$

2.3 Simulation with the WetSpa model

The Wetspa-Python model has an adaptable structure as every hydrological process is implemented in a separate, generic module. This allows introducing equations 1 and 2 into a new interception module of the Wetspa-Python model. Further, modules are interchangeable and can have different spatial and temporal resolution according to the data availability. Therefore, we can use both the land-cover fraction map at a 2m resolution derived from the APEX image and the LAI maps derived from Proba-V data (100m resolution) as inputs to the Wetspa-Python model. Based on the distributed land-cover fraction map each 2m pixel is divided into different land cover types. For the vegetated land-cover types, the seasonal LAI maps are used to calculate the interception storage capacity based on equation 2. The interception loss per pixel is derived from equation 1. However, this equation does not account for the fact that interception loss is higher during the initial phase of a storm and approaches zero thereafter. If the total rainfall during the first time increment is greater than the interception storage capacity, the rainfall rate is reduced by the same capacity. Otherwise, all rainfall is intercepted in the canopy and the remainder of the interception capacity is removed from the rainfall in the following time increments.

$$I_i(t) = \begin{cases} I_{i,0} - SI_i(t-1) & for\ P_i(t) > I_{i,0} - SI_i(t-1) \\ P_i(t) & for\ P_i(t) \leq I_{i,0} - SI_i(t-1) \end{cases} \qquad \textit{Equation 3}$$

where $I_i(t)$ is the interception loss at cell i over the time interval (mm), $I_{i,0}$ is the cell interception storage capacity (mm), $SI_i(t-1)$ is the cell interception storage at time step t-1 (mm), and $P_i(t)$ is the cell precipitation amount (mm).The interception storage capacity is a function of the LAI and plant species as described above.

3 RESULTS

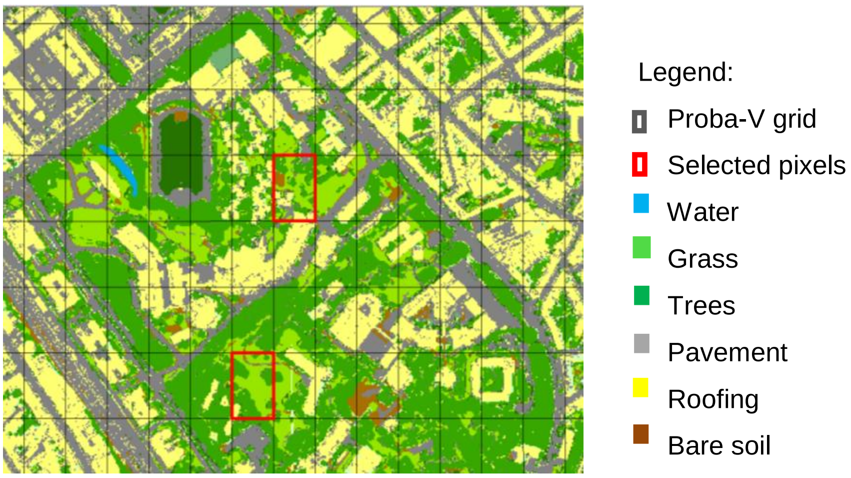

Figure 1: simplified land-cover map for VUB campus with the selected Proba-V pixels.

The detailed land-cover map (Fig. 1) allows to define the area within the Proba-V pixel that is covered with trees versus the area covered with grass or urban materials which are assumed constant over the season. Results of seasonal LAI measurements indicate that different tree species have different seasonal canopy growth (Fig. 2) but also that LAI varies within tree species as canopy growth also depends on the amount of water and the hours of sun (shadow of buildings is important) reaching the tree. This motivates the development of seasonal LAI maps based on Proba-V data, where the LAI can be based on the spectral response of the vegetation within a Proba-V pixel.

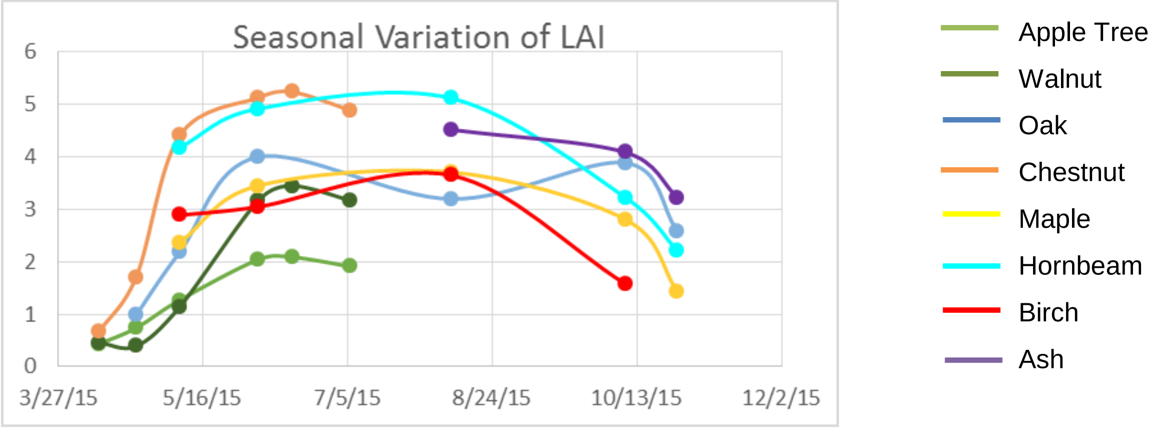

Figure 2: Seasonal dynamics of LAI for different tree species.

Further we expect that by including the spatially distributed land-cover and the seasonal LAI maps into the WetSpa-Python model we will improve the spatio-temporal distribution of the precipitation reaching and evapotranspiration leaving the urban land surface and thus get a more realistic simulation of surface runoff in urban areas.

4 CONCLUSIONS

As interception by urban trees plays an important role to control the water balance in urban areas, it is important to characterize urban vegetation in detail. This study uses RS data validated with ground-truth measurements to characterize urban green in a spatially distributed way throughout the season. The WetSpa-Python model allows to input spatially distributed land-cover and seasonal LAI maps in order to simulate the urban water balance in the Watermaelbeek catchment. We expect that the LAI maps will improve the parameterization of interception storage of urban vegetation and thus improve the simulation of net precipitation and surface runoff.

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