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A distributed hydrological model for urbanized areas — Model development and application to case studies

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Summary The circulation of rainwater within urban areas has not yet been described in a detailed manner, as studies on this topic often remain limited to the runoff on impervious surfaces. The need for innovative and sustainable methods of water management has incited increased research efforts on the hydrological processes at work in urban areas. A distributed hydrological model based on information supplied by current urban databanks has been developed in this aim. The components of rainwater flux (i.e. surface runoff, soil runoff, drainage flow via the sewer, and evapotranspiration) as well as information on the hydric state of the urban soil (saturation level, storage capacity) are modeled at the parcel scale, and then coupled with a detailed description of the hydrographic network. This model runs continuously and has been intended to reproduce hydrological variables over very long time series. In order to evaluate this model, it has been applied at two different scales, on two urban catchments of various land use, where hydrological data were available. This evaluation is based on the comparison of observed and simulated flowrates and saturation levels, and details the various compartments (soil, impervious or natural areas) to the outflow. This study shows the importance of water fluxes often neglected in urban hydrology, such as the evapotranspiration or the soil infiltration into sewers. This first evaluation has highlighted the capability of mapping most of the hydrological fluxes on urban catchments, such as the capacity of soil to store water.

Introduction

Evolution in the field of urban rainwater management has favored sustainable practices and innovative technologies

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and, in turn, created various research needs. The hydrological behavior of urban areas can no longer be restricted to the runoff of rainwater on impervious surfaces, which constitutes the dominant flow component for design purposes. Experimental data indicate that the flow coefficient for urban catchments varies from one rainfall event to the next (Berthier et al., 1999). Urban surfaces, such as road pavements and parking lots, are not impervious, as shown by Ragab et al. (2003), who observed that 6–9% of total annual rainfall on a paved street infiltrates and that 21–24% evaporates. This result is consistent with the findings of Grimmond and Oke (1991, 2002), confirmed by Berthier et al. (2006) and Dupond et al. (2006), who considered evapotranspiration to be a major component of the water budget within urban areas. Facilitating the infiltration of rainwater results in a higher groundwater level (Göbel et al., 2004). Draining the saturated zone through the sewer system may be considered as a base flow that produces significant runoff volumes (Belhadj et al., 1995). Urban soil can contribute to the flow rate in the form of a subsurface flow component (Berthier et al., 2004). Such studies confirm that the hydrology of urbanized zones is far from being simple: the urban environment is highly heterogenous in terms of land use, subsoil characteristics and other factors, which serve to influence all hydrological processes. This body of literature emphasizes the benefit of an integrated modeling approach to address the entire array of hydrological processes within urban areas. This issue has recently been examined by Jia et al. (2001), who developed a distributed hydrological model that spatially simulates variable water and energy processes in watersheds with complex land use/cover.

Urban areas have been well documented, thanks to the development of urban databanks (UDB). From a hydrological standpoint, UDBs are attractive tools and this for at least two reasons: they readily provide information on the morphology of catchments at a level of detail seldom accessible in hydrological studies; and they retain a record of the evolution in basin morphology thanks to regular updates. In addition, they facilitate the description of local-scale water behavior within the urban area and of its evolution over time. Despite this advantage, use of such information for the hydrological modeling of urban catchments is still not very widespread. The areas drained by sewer system were defined and estimated for each property block connected to the sewer inlets (Djokic and Maidment, 1991; Greene and Cruise, 1995). Water flow paths at the surface were identified from high-resolution digital elevation models, and the drainage pipes were modeled as ''open thalwegs'' (Zech and Escarmelle, 1999; Rodriguez et al., 2000). Sui and Maggio (1999) observed that the conceptualization of space and time embedded in current Geographical Information Systems (GIS) are not always compatible with that in hydrological models. The modeling power of HSPF (Hydrological Simulation Program—Fortran) has been integrated through multipurpose environmental analysis system, like BASINS (Brun and Band, 2000). Moreover, Rodriguez et al. (2003) have demonstrated that representative unit hydrographs can be derived from UDBs.

The objective of this study is to develop a distributed hydrological model (called URBS-MO, for Urban Runoff Branching Structure MOdel) based on the morphological description of the urban environment. This model is intended to: (i) estimate, at different scales (parcel, catchment) and for different land uses, the components of rainwater fluxes (surface runoff, soil runoff, drainage flow through the sewer, evapotranspiration, outflow); and (ii) supply information on the hydric state of the urban soil (saturation level, storage capacity). The model runs continuously and has been designed to reproduce hydrological variables over long time series. This model could potentially make a significant contribution to a new generation of urban hydrological models that address the integrated management of urban rainwater, in promoting best management practices on the basis of rainwater infiltration and storage (Rivard et al., 2005).

This paper is devoted to formulating the URBS-MO model and to assessing the model with respect to its simulation outputs. The validation of a hydrological model is usually based on comparing simulated flow rates at the catchment outlet with observed values at the same location; the data available for calibrating the model is in fact often limited to outlet discharges (Anderton et al., 2002). This type of validation may be applied to URBS-MO but would not be entirely satisfactory given the array of simulated hydrological variables. Moreover, the spatial distribution of hydrological fluxes or outputs could lead to a better understanding of the hydrological behavior of urban catchments. Thanks to the available hydrological data, this paper will focus on validating URBS-MO on the basis of both flow rates and saturation levels. Two case studies will be introduced for this purpose.

This paper has been organized as follows. Urban morphology and hydrological modeling section presents the modeling principles, which are based on the urban morphology as recorded in urban databanks. Modeling of hydrological processes at the UHE scale section lays out the procedure for modeling the urban hydrological element (UHE) and constitutes the paper’s main contribution. Modeling of hydrological processes at the catchment scale section summarizes the mechanism of water transfer from the UHE to the catchment outlet. Presentation of the case studies section presents the main characteristics and experimental devices used in the case studies for evaluating model accuracy. Initial URBS-MO validation on the Rezé catchment: Focus on water budget restitution section is devoted to validating the water budget model on the *Rezé* catchment (5 ha), as regards both flow rates at the outlet and the hydric state of the soil. URBS-MO validation on the Gohards catchment section addresses validation of the complete model on the *Gohards* catchment (180 ha) and illustrates the model capability of simulating the spatial distribution of different hydrological variables. Finally, the last section concludes the paper and draws perspectives.

Urban morphology and hydrological modeling

The role of a catchment’s geometrical features and drainage network on hydrological behavior has been highlighted and discussed by many authors. Thanks to the development of high-resolution digital field models, land use data obtained from remote sensing and GIS applications, river catchments are easier to describe and hydrological modeling has undergone improvements, including the development of