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Review Paper

Hydrological modelling of urbanized catchments: A review and future directions

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SUMMARY

In recent years, the conceptual detail of hydrological models has dramatically increased as a result of improved computational techniques and the availability of spatially-distributed digital data. Nevertheless modelling spatially-distributed hydrological processes can be challenging, particularly in strongly heterogeneous urbanized areas. Multiple interactions occur between urban structures and the water system at various temporal and spatial scales. So far, no universal methodology exists for simulating the urban water system at catchment scale. This paper reviews the state of the art on the scientific knowledge and practice of modelling the urban hydrological system at the catchment scale, with the purpose of identifying current limitations and defining a blueprint for future modelling advances.

We compare conceptual descriptions of urban physical hydrological processes on basis of a selection of 43 modelling approaches. The complexity of the urban water system at the catchment scale results in an incomplete understanding of the interaction between urban and natural hydrological systems, and in a high degree of uncertainty. Data availability is still a strong limitation since current modelling practice recognizes the need for high spatial and temporal resolution. Spatio-temporal gaps exist between the physical scales of hydrological processes and the resolution of applied models. Therefore urban hydrology is often simplified either as a study of surface runoff over impervious surfaces or hydraulics of piped systems. Many approaches target very specific objectives and the level of detail in representing physical processes is not consistent. Based on our analysis, we propose a blueprint for a highly complex integrated urban hydrological model. We regard flexibility, in terms of model structure and data assimilation, as the key characteristic for overcoming these limitations. We advocate the use of modular, process-based approaches, which are flexible and adaptable to research needs. Higher complexity is inevitable, and higher uncertainty is a major consequence. Remote sensing data, measurable model parameters and new spatially-distributed calibration techniques might help to reduce uncertainties.

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1. Introduction

This paper aims to review the state of the art on the scientific knowledge and practice of modelling hydrological processes in urban environments at the scale of a catchment. Urban catchment hydro(geo)logy, or the study of water fluxes in urbanized catchments, is among the different sub-disciplines of the hydrological sciences, clearly gaining in importance during the past few decades (Niemczynowicz, 1999; Price and Vojinović, 2011; Schirmer et al., 2012; Braud et al., 2013; Fletcher et al., 2013). A major driver for this trend is the growing concern about urban water sustainability and human health protection. In fact, for the first time in human history since 2009, more than half of the world population is living in urban and semi-urban zones (United Nations, 2010). Moreover, population projections show that by the year 2030 urban population will exceed 80% of the total population, with growth/migration particularly concentrated in megacities and developing countries. Growing population and urbanization augment the pressure on the environment and often challenge water resources sustainability (Lee and Heaney, 2003; Carle et al., 2005). Land use modifications, such as an increase in urbanization, can have a significant impact on hydrological processes (DeFries and Eshleman, 2004). Governments are aware of these threats and demand solutions in terms of environmental monitoring and water-resources protection (European Parliament, Water Framework Directive 2000/60/EC), (CWA/Clean Water Act, P.L. 92-500, 1972 and amendments).

Urban development and urban water systems interact mutually: (1) on one hand urbanization is considered to be the major cause of pollution/depletion of water resources; while (2) on the other hand increased urban flooding threaten human security and infrastructure integrity. Many researchers have investigated the link between (ground)water pollution and urban growth (Cronin et al., 2003; Carle et al., 2005; Rueedi et al., 2009; Vizintin et al., 2009; Carey et al., 2013) and identified urbanization as a major cause of contamination of groundwater and surface water resources. This contamination is the consequence of accidental releases of toxic substances or more often by leakage of sewers. The type of pollutants as well as their load can greatly vary according to location and urbanization density (Beck, 2005; Eiswirth et al., 2003). Urban areas have shown to be among the most vulnerable systems to the adverse impact of heavy rainfalls. Floods are becoming more frequent and more devastating than ever before as urban areas are enlarging and becoming denser (Kang et al., 1998; Mark et al., 2004; Schmitt et al., 2004; Chen et al., 2009). Society suffers yearly from the consequences of (flash) floods, with mortality nearly homogeneous over different continents (Jonkman and Vrijling, 2008). Economic losses are large, overall losses in Europe due to weather disasters in the period 1980–2010 accounted for about 5–35 billion US$ per year (Kron et al., 2012). The Floods Directive (2007/60/EC) was therefore defined to mitigate the effects of floods by demanding floods risk assessment and mapping (CEC, 2007). Reliable assessment of water fluxes is crucial for human lives, environmental protection and infrastructures/goods safety. Water movement in urban areas is however not well understood, and so are the physical principles that regulate this movement as well as the interactions occurring between the hydrological processes. Scientific understanding can be supported by detailed and consistent measurements and by hydrological modelling, therefore urban hydrology will be a major issue in the decades ahead (Delleur, 2003; DeFries and Eshleman, 2004; Praskievicz and Chang, 2009; Fletcher et al., 2013).

Driven by developments in computer capability and the availability of remote sensing data, the use of distributed hydrological models is becoming more and more a common practice. Hydrological modelling of urban catchments is highly challenging as urban catchments are strongly heterogeneous and have very specific hydrological processes. "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" (Rodriguez et al., 2008). Developments in this direction generally focus either on very specialized tools for a particular aspect of the urban hydrological cycle, or on generic software that combines and/or integrates several semi-specialized components to describe the total water cycle in urban areas. Bach et al. (2014) recognized the importance of integration in modelling the urban water system and proposed to classify models based on their 'degree of integration'. However there is little agreement so far on a universal concept or methodology for simulating the urban water cycle at the catchment scale.

This review is articulated in four sequential sections with the aim of answering 11 questions regarding urban hydrological modelling practice (Fig. 1). In this first section we provided the motivations that make urban hydrological modelling a globally-relevant subject. The second section gives a definition of 'urbanized catchment' and discusses the main hydrological processes of the urban water cycle. These processes are compared to natural hydrological systems, while we highlight their characteristic spatial and temporal scales. As this topic was also addressed by the recent review of Fletcher et al. (2013), the second section of this manuscripts therefore takes their work as a starting point for an extended discussion on the spatial and temporal scales of the hydrological processes. The purpose of the second section is to provide a basis for comparison for the following evaluation of modelling practice, and to assess how consistent hydrological tools are with respect to the complex interactions of physical processes in the urban environment. We particularly focus on the quantitative assessment of the changes induced by urbanization on the water system with brief references to the relevant qualitative aspects. It is however not within the scope of this paper to review the chemical processes of urban-water pollution. In the third section we describe the current practice in urban hydrological modelling, highlighting the most important developments and the characteristics of such modelling approaches. To this end we compare and describe 43