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Coupling of a distributed hydrological model with an urban storm water model for impact analysis of forced infiltration

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SUMMARY

Only few studies have attempted to couple a storm water runoff model with a distributed hydrological model even though infiltration or exfiltration processes between pipes and canals of urban runoff systems and groundwater are widely recognised. We present a fully coupled model that allows simulation of the complete urban freshwater cycle including: runoff from paved and impervious areas, flow through the runoff network, overland flow, infiltration through the unsaturated zone, evapotranspiration (at green areas), and groundwater flow in complex, urban geology. For example, at the investigated urban area at the City of Silkeborg, Western Denmark, the coupled model show that one fourth (24%) of water input to the storm water runoff systems arrives from groundwater sources. The study furthermore quantifies groundwater feedback mechanisms of forced infiltration to surface water systems by the fully coupled hydrological and urban runoff model. Three local area recharge scenarios with forced infiltration are compared with the present situation without forced infiltration. The forced infiltration impacts the local groundwater table with an average rise of up to 69 cm resulting in significant feedback from the groundwater to the runoff system via drains, overland flow and leakage of groundwater to the pipes and canals of the urban runoff network.

1. Introduction

The interaction between surface waters and groundwater beneath urban areas are complicated by the many anthropogenic designs to manage waterways through the city with zones of high economic and social value (Schirmer et al., 2013). Overland flow is different from rural areas with introduction of new impervious and pervious surfaces as roofs, pavements and green gardens. Routing of water away from the different surfaces via drainage systems to streams is also different from the natural condition. The influence of urbanisation on streams reaches beyond geomorphologic changes to affect runoff timing and volume. This is well-known and documented in several studies during the last decades (e.g. Ando et al., 1984; Ng and Marsalek, 1989; Cheng and Wang, 2002). Groundwater recharge is influenced by the urbanised surface with both less recharge under paved areas and more in areas with artificial recharge of storm runoff. A septic tank system is a possible source for groundwater recharge (Lerner, 1990) but according to several studies, leakages from water supply and sewer systems contribute most significantly to groundwater recharge. For example, Yang et al. (1999) found that 138 mm/year of the present groundwater recharge of 211 mm/year at Nottingham, UK can be attributed to leaking water mains and 10 mm/year to leaking sewers. Vazquez-Sune et al. (2010) estimated groundwater recharge at the city of Barcelona with the use of several chemical tracers and found 30% to originate from sewer leakage, 22% from water supply leakage, 20% from runoff infiltration, 17% from rainfall and 11% from the Besos River. Kim et al. (2001) provides an extreme example of groundwater recharge from a leaking water supply system at the city of Seoul with a 93% contribution to the total groundwater recharge. In a review by Lerner (2002) it is concluded that groundwater recharge in most cities are higher than a rural equivalent because of leakage from water supply and from storm drainage systems. This is supported by Barron et al. (2013a,b) in a study of the Southern River catchment in Western Australia where groundwater recharge was shown to increase due to less evapotranspiration and storm runoff infiltration in an urbanised zone. Opposite to this, Erickson and Stefan (2009) found a decrease in groundwater recharge of 20–40% of present recharge was caused by an increasing of the urbanised area with 18% (Vermillion River Catchment, Minnesota). Jeppesen et al. (2011) also showed that a rising groundwater table in the Copenhagen area, Denmark, only could be explained by an increase in precipitation

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in historical time (1850–2003). Without the increase in precipitation, groundwater levels would have been decreasing during urbanisation.

Due to the complexity in the surface water – groundwater interaction and the dominating influence of anthropogenic elements, detailed studies on understanding the flow system and to support urban infrastructure designs often require sophisticated integrated hydrological modelling. Integrated modelling of urban networks (storm runoff, sewer, and water supply systems) and groundwater systems has been conducted with simplified groundwater formulations with the focus on infiltration/exfiltration between urban networks and groundwater (e.g. Karpf and Krebs, 2011 or De Silva et al., 2006). The term distributed hydrological models is hereafter used for a model with a physically based distributed 2D or 3D parameterisation and simulation of surface and subsurface compartments as overland flow, river flow, evapotranspiration, unsaturated zone fluxes and groundwater flow. Some simulate one or two of these compartments (e.g. MODFLOW; McDonald and Harbaugh, 1988) while others integrate the complete surface–subsurface water cycle (e.g. HydroGeoSphere (Therrien et al., 2004), ParFlow (Maxwell et al., 2010), MIKE SHE (Abbott et al., 1986a,b), MODHMS (Panday and Huyakorn, 2004)). A number of studies have applied these distributed hydrological models to assess urban impacts on groundwater resources. This is often done in a two-step sequential coupling procedure where an unsaturated zone model, or root zone model is given urban conditions (parameters) and simulated groundwater recharge is hereafter applied in a groundwater model (e.g. Gobel et al., 2004; Im et al., 2009; Dimitriou and Moussoulis, 2011; Barron et al., 2013a,b). Only two studies introduce modelling systems with full couplings with full feedback within each computational time step between a distributed hydrological model and a detailed urban storm water drainage model (full coupling). Delfs et al. (2012) performed a coupling between SWMM and OpenGeoSys models and applied it on the Poltva Catchment, Western Ukraine. According to the authors, the coupling of the urban runoff model (SWMM (Rossman, 2004)) and the OpenGeoSys groundwater model is able to show responsiveness of catchments to urbanisation. As noted by the authors, results should, however, be used with caution, because the modelling system is without a physical and mathematical description of the unsaturated water fluxes and the evapotranspirative fluxes. The coupling of the urban runoff model, with all its specific urban elements and the catchment scale groundwater model is nevertheless a significant step forward to an understanding of the complex interplay between artificial and natural hydrological urban conditions. Domingo et al. (2010) present another attempt to simulate the interplay, applying the fully distributed MIKE SHE model with simulation of unsaturated zone, evapotranspiration, groundwater flow and overland flow. The MIKE SHE is coupled to the MIKE URBAN (MOUSE (Mark et al., 1998)), an urban runoff model simulating runoff from individual catchments and flow through pipes and canals in the urban drainage system. The coupled model is used to predict surface flooding and results are compared with a state-of-the-art 1D–2D hydraulic flooding model, MIKE FLOOD at the city of Greve, Denmark. Only few details of the two models are given by Domingo et al. (2010) and results are therefore difficult to evaluate. Nevertheless, Domingo et al. (2010) illustrate one of the potentials of coupled distributed hydrological models and urban runoff models for catchments with interacting groundwater – surface water and urban arrangements. The almost absence of fully coupled distributed hydrological models with urban runoff models can probably be accredited to the two very different modelling approaches. For example, the temporal scale for urban runoff behaviour is 1–10 min, event based and with model time steps of seconds, whereas distributed hydrological models operate on daily to yearly temporal scales and hourly time-steps, if not steady-state simulations are applied to estimate average hydrological conditions. The spatial scales and conceptualisation of catchments also differ between the models. A distributed hydrological model is often defined around one larger catchment following a groundwater divide. Urban runoff models normally consist of several smaller and discretely defined urban catchments (e.g. parking lots or housing parcels) which generate runoff to exact manholes on a drainage or sewer network. Areas not defined as urban catchments and therefore not connected to the urban drainage network, e.g. green areas, are typically not simulated in the urban runoff model.

1.1. Problem identification

A remaining challenge with urbanisation is to divert rainwater from impervious surfaces. One of the new management instruments is to infiltrate to the subsurface instead of increasing the flow capacity of runoff systems. Forced infiltration will increase groundwater tables (Endreny and Collins, 2009; Thompson et al., 2010; Carleton, 2010; Maimone et al., 2011; Roldin et al., 2013) and can therefore be critical with a small unsaturated zone and if hydraulic conductivity of the subsoil is relatively low (Gobel et al., 2004). The local effect of forced infiltration depends on hydrogeology, climate, and type of infiltration (e.g. local infiltration systems at the parcel level or larger infiltration ponds). Since base flow to surfaces waters from groundwater changes with a changing groundwater table, several of the hydrological compartments are affected by forced infiltration. In a recent review, Hamel et al. (2013) identify a scientific gap between studies analysing the effect on groundwater table from storm water infiltration and the responding change on the base flow component of an urban stream. A suitable model for analysing the different effects of forced infiltration is therefore a fully coupled model including both the natural hydrological system and the urban runoff system.

At the City of Silkeborg, Denmark, integrated management of urban drainage systems together with groundwater is highly relevant because adaptation strategies for climate change have the potential to alter the surface water – groundwater balance. One component in the local adaptation strategy is to reduce peak flows in the urban runoff system with forced infiltration. Forced infiltration will likely impact an already high groundwater table and this will result in a potentially higher leakage of groundwater into the urban drainage system.

1.2. Objective and scope

The study provides a first attempt to evaluate dynamic urban hydrology simulated by a distributed hydrological catchment scale model fully coupled with an urban runoff model. The objective of the study is to evaluate the water fluxes between the different compartments of the urban water cycle which is an issue that is relevant at cities around the world. Furthermore, the objective is to analyse and test the developed coupled model setup with a forced infiltration scenario, where water fluxes between urban hydrological compartments are likely to be different from the present day condition.

2. Study area

The city of Silkeborg is located in the central part of Jutland, Denmark, Fig. 1. The northern part of the city, north of the Gudenå River and Lake Langsø, had a severe incident of urban flooding during a 100 year rain event, 9th of September 2000 (Orbicon, 2010). After this event a storm water runoff system was constructed and a MIKE URBAN model was setup for the