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Hydrologic response of a tropical watershed to urbanization

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SUMMARY

Urbanization has profound influence on the hydrologic response of landscapes. Urban transformation affects the storages and processes that determine the generation of hydrologic fluxes. It also changes the time-scales associated with hydrologic processes. Shifts in hydrologic response of the watershed unit due to urban transformation may be more complex than the simple linear mixing (weighted sum) of responses from the urbanized and non-urbanized fractions of the landscape. This may especially be the case for tropical watersheds where the precipitation forcing of the watershed is frequent and intense – interacting with the shifting time-scales and changing storages with increasing urbanization. In this study, a fully distributed hydrological model (MOBIDIC) that captures hydrologic dynamics during storms and interstorms is applied in order to characterize the potentially nonlinear response of a tropical watershed to urban transformation. Indices that quantify the departures from linear response are introduced and used to test the effects of urbanization on different hydrologic processes and fluxes in a mixed (urban and non-urban) watershed. The tropical Kranji watershed in Singapore is used in this study. Fortunately two sub-watersheds within Kranji that have streamflow gaging stations are well-suited for the calibration of the model. One sub-watershed is nearly fully urbanized and another is pristine (non-urban). As a result the contrasting components (urban and non-urban) can be calibrated in the model. The simulation system is then used to assess the hydrologic response due to changing levels of urbanization. For some fluxes and storages, the hydrologic response due to changing urban fraction cannot be simply predicted from a linear mixing model.

1. Introduction

Many cities worldwide, especially in Asia, are undergoing rapid urban expansion. This transformation of the landscape is so pervasive that in aggregate it represents a major component of global environmental change. Urban land use is characterized by a mix of impervious and vegetated (lawns, parks, etc.) surfaces. The degree of landscape perturbation when compared to a primary or secondary forest depends on the pattern and type of urban settlement. In general and in the context of this study urbanization is taken to be landscape change where the dominant features are introduction of impervious surfaces and efficient engineered drainage system. This transformation affects the available storage volume for water in the landscape. It also affects the time-scales associated with hydrologic response. The interaction of these factors with intermittent precipitation in mixed land use watersheds can be complex so that it cannot be characterized by a simple linear mixing model of urbanized and non-urbanized hydrologic response. Linear mixing predicts the response by weighting the response of urbanized and non-urbanized hydrologic responses by their relative area fractions.

The effects of urban expansion on watershed hydrologic response – especially on streamflow – have been investigated in many studies owing to the prevalence of the issue. The literature on shifts in hydrologic response due to urbanization can be generally categorized into following three approaches: Watershed analysis, companion-watershed comparison, and process-based modeling. The first one relies on observational analysis of streamflow records (e.g., Yang et al., 2010). Long records of stream stage and flow estimates are required for this approach. The flow has to be unimpeded by man-made hydraulic structure. Such studies are most reliable if the quality-control of the observational record can be established. The second approach is also called in-pair comparison (e.g., Chang, 2007). The hydrologic characteristics of

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an urban watershed are compared with those of a less urbanized watershed. This method requires the companion watersheds have similar climatic and geological characteristics. The third and last classified approach uses hydrologic models to simulate the effects of different scenarios of land use changes. The requirement is that hydrologic model should be well calibrated especially in terms of the hydrologic response of the two principal constitutive landscapes (urban and nonurban). Given the strict requirements of the first two approaches, this third approach has gained significant attention (e.g., Bhaduri et al., 2000; 2001; Chen et al., 2009; Hundecha and Bardossy, 2004; Im et al., 2009 among others).

Given the diversity of hydrologic models (lumped versus distributed, event-based versus continuous, etc.), sensitivity results even for the same watershed may vary from study to study (model to model). In addition the climate and hydrometeorological setting can potentially have significant impacts on the sign and magnitude of the hydrologic response change due to urbanization.

In this study we approach the general problem starting with a typical example of rapidly urbanizing watershed with unique water resource issues. The example is situated in tropical Singapore. Singapore is a densely populated country (7022 persons/km^2). The nation-state population is projected to increase in the coming decades. Singapore is considered to be a water-scarce country not because of lack of rainfall (2400 mm/year), but because of the limited amount of land area where rainfall can be stored (Tortajada, 2006). Currently, the water supply comprises (1) local catchment water; (2) imported water from Malaysia; (3) highly-purified reclaimed water known as NEWater; and (4) desalinated water. In order to reduce its dependence on imported water, the Singapore has been developing major hydraulic systems alongside its urbanizing centers (MOEWR, 2006). However, there are few studies on the impact of urbanization on the hydrologic system in Singapore. There is also a distinct lack of long term observational flow records that limit the applicability of the first two approaches listed above. This study relies on the process-based modeling approach but make effective use of the limited but opportune hydrographic observations.

The aim of this study is to apply a type of simulation model that is relatively least constrained by spatial and temporal aggregation. Distributed models provide the capability to investigate the impacts of spatiotemporal dynamics of urbanization on distributed hydrologic response. The MOBIDIC distributed hydrologic model is selected owing to its structure (distributed and continuous) and to its parsimony that allows effective calibration (Castelli et al., 2009). The Kranji basin in Singapore is the context for the modeling study. Two sub-watersheds in the Kranji basin have reliable stream gauge records. In addition, the two basins have contrasting landuse that allow calibration of the two main mixing landscapes: one sub-watershed is mostly urban and the second sub-watershed is mostly pristine tropical landscape. The observational record at these two gauges allows effective calibration of the two landscape types. The urban fraction in the larger embedding basin is then varied based on the calibrated parameters and the distributed hydrologic response is characterized. Metrics are introduced in order to assess the degree to which the basin hydrologic response can or cannot be predicted by the simple linear mixing of the two landscape hydrologic responses. Since urbanization affects the storages and time-scales of hydrologic processes, intermittent storms may result in hydrologic responses that are more complex than linear mixing.

Section 2 of this study introduces the hydrologic model and provides description of its features that are more relevant for this application. In this section the case study area – the Kranji Reservoir watershed is also introduced. Scenarios for urbanization are described. Section 3 includes the simulation results with a focus on the metric capturing the degree to which the basin response is nonlinear with respect to change in urban area fraction. The study Section 4 includes conclusions and identifies areas for further research.

2. Approach

2.1. The MOBIDIC distributed and continuous hydrologic model

MOBIDIC (MOdello di Bilancio Idrologico DIstribuito e Continuo) is a distributed and raster-based hydrological model (Campo et al., 2006; Castelli et al., 2009) that simulates energy and water balances on a cell basis. The energy balance component solves the heat diffusion equations in multiple vertical layers in the soil-vegetation continuum (Castelli et al., 2009). This approach yields estimates of ground heat flux that are phased properly with respect to surface energy balance that include turbulent heat fluxes (latent and sensible) as well as shortwave and thermal radiative fluxes. The water balance is also solved for each cell. However in contrast with the traditional approach of soil moisture profile characterization in order to account for available soil water storage dynamics, MOBIDIC soil water balance uses the physical types of soil water storage as basic states for water balance. The approach is parsimonious and it allows effective characterization of water balance with contrasting time scales (more details below).

In the energy balance calculations for updating land surface temperature state, latent heat (LE) and sensible heat (H) fluxes from the land surface (soil and vegetation) are computed following a bulk heat transfer formulation across humidity and temperature gradients between the land surface and the atmosphere (Castelli et al., 2009):

$$LE = \rho \cdot L \cdot C_H \cdot U \cdot (q_s - q_a) \tag{1}$$

$$\mathrm{H} = \rho \cdot C_p \cdot C_H \cdot U \cdot (T_s - T_a) \tag{2}$$

where U is the wind speed (m s^{-1}), C_p air specific heat (J kg^{-1} K^{-1}), L latent heat of vaporization (J kg^{-1}), q_s surface specific humidity (kg kg^{-1}), q_a atmospheric specific humidity (kg kg^{-1}), T_s land surface temperature (K), T_a atmospheric temperature (K), and C_H is the bulk transfer coefficient for heat and includes roughness length scale for heat flux as well as static stability effects (following the characterizations in Van Den Hurk and Holstlag, 1997). The windspeed, air temperature and air humidity are measured at the standard screen height of 2 (m). Air density ρ is taken to be equal to a nominal value 1.2 (kg m^{-2}).

The water balance across each computation cell is characterized in terms of fluxes in and out of physical reservoirs. In the soil matrix there is capillary storage (W_c (m)) and gravity (W_g (m)) storage. Above the soil matrix there may be surface storage in ponds and rivers. Below the soil matrix a groundwater storage is also defined. Groundwater is allowed to have lateral redistribution and hence links water balance for cells across the landscape. The soil matrix storages are linked through exchange terms among each other as well as fluxes across medium boundaries:

$$\frac{dW_g}{dt} = I_{nf} - S_{per} - Q_d - S_{as} \tag{3}$$

$$\frac{dW_c}{dt} = S_{as} - E_T \tag{4}$$

where I_{nf} (m s^{-1}), S_{per} (m s^{-1}), Q_d (m s^{-1}), E_T (m s^{-1}), and S_{as} (m s^{-1}) are infiltration, percolation, interflow, evaporation, and adsorption from gravitational storage to capillary storage. They are represented and parameterized as:

$$S_{per} = \gamma \cdot W_g \tag{5}$$