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Development of a modular streamflow model to quantify runoff contributions from different land uses in tropical urban environments using Genetic Programming

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SUMMARY

The decrease of pervious areas during urbanization has severely altered the hydrological cycle, diminishing infiltration and therefore sub-surface flows during rainfall events, and further increasing peak discharges in urban drainage infrastructure. Designing appropriate waster sensitive infrastructure that reduces peak discharges requires a better understanding of land use specific contributions towards surface and sub-surface processes. However, to date, such understanding in tropical urban environments is still limited. On the other hand, the rainfall–runoff process in tropical urban systems experiences a high degree of non-linearity and heterogeneity. Therefore, this study used Genetic Programming to establish a physically interpretable modular model consisting of two sub-models: (i) a baseflow module and (ii) a quick flow module to simulate the two hydrograph flow components. The relationship between the input variables in the model (i.e. meteorological data and catchment initial conditions) and its overall structure can be explained in terms of catchment hydrological processes. Therefore, the model is a partial greying of what is often a black-box approach in catchment modelling. The model was further generalized to the sub-catchments of the main catchment, extending the potential for more widespread applications. Subsequently, this study used the modular model to predict both flow components of events as well as time series, and applied optimization techniques to estimate the contributions of various land uses (i.e. impervious, steep grassland, grassland on mild slope, mixed grasses and trees and relatively natural vegetation) towards baseflow and quickflow in tropical urban systems. The sub-catchment containing the highest portion of impervious surfaces (40% of the area) contributed the least towards the baseflow (6.3%) while the sub-catchment covered with 87% of relatively natural vegetation contributed the most (34.9%). The results from the quickflow module revealed average runoff coefficients between 0.12 and 0.80 for the various land uses and decreased from impervious (0.80), grass on steep slopes (0.56), grass on mild slopes (0.48), mixed grasses and trees (0.42) to relatively natural vegetation (0.12). The established modular model, reflecting the driving hydrological processes, enables the quantification of land use specific contributions towards the baseflow and quickflow components. This quantification facilitates the integration of water sensitive urban infrastructure for the sustainable development of water in tropical megacities.

1. Introduction

Increasing urbanization has severely altered the hydrological cycle in many places worldwide, accelerating runoff due to a decrease of pervious areas and therefore infiltration. In order to efficiently drain the increase in surface runoff, intensive drainage networks are often built to prevent flash floods during heavy storm events (Marshall and Shortle, 2005). However, as cities are dynamically expanding, the continuous increase of impervious surfaces and the accompanied excess runoff often exceeds the present channel capacity resulting in local flash floods. To reduce the impact of surface runoff, water sensitive urban infrastructure (e.g. green roofs, porous pavement, bioretention ponds, swales) retaining rainfall and enhancing infiltration rates in urban cities are being promoted (Burns et al., 2012; Chang, 2010). Water Sensitive Urban Design (WSUD) is an engineering design approach which aims to minimize hydrological and water quality impact of

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urban development by integrating land use planning with urban water management (Singh and Kandasamy, 2009). The implementation of such technologies requires a detailed understanding of runoff contributions from each specific land use in order to plan the location of these local source control measures. Therefore, a better understanding is needed regarding rainfall–runoff processes in urbanized areas, including an accurate assessment of contributions from different land uses towards quickflow as well as baseflow. This understanding would be essential for integrated management and sustainable development of water resources particularly in tropical megacities which are dependent on water sources that are more vulnerable to inter-annual fluctuations in precipitation.

Land use and land cover affect catchment hydrology primarily through changes in hydrological processes such as infiltration, rainfall interception, and evapotranspiration (Calder, 1993, 2005; DeFries and Eshleman, 2004; Potter, 1991; Tran and O'Neill, 2013) which may have significant effects on rainfall–runoff processes and catchment water yields (Roa-García et al., 2011). The various contributions from different land uses towards rainfall–runoff processes have attracted worldwide attention, especially in temperate urban regions (e.g. Burns et al., 2005; Diaz-Palacios-Sisternes et al., 2014; Loperfido et al., 2014; Miller et al., 2014). Comparing runoff generation from different land uses enables us to understand the rainfall–runoff response influenced by particular catchment components and processes and their contribution towards the overall catchment. This understanding contains valuable information with regards to a physical based understanding of rainfall–runoff behaviour when designing appropriate water management infrastructure in tropical megacities. However, it is interesting to note that a review of the literature shows that to date, no detailed investigation has been done to assess the impact of different land uses on rainfall–runoff processes for tropical urban cities.

To evaluate the impact of different land uses on catchment hydrology, rainfall–runoff processes need to be simulated. There are multiple Rainfall–Runoff (R–R) models available that can be applied to simulate rainfall–runoff processes; each one characterized by a different level of complexity, limitations and data requirement (Sorooshian et al., 2008). Physically-based models usually incorporate simplified forms of physical laws and are generally non-linear, time-varying and deterministic, with parameters that are representative of watershed characteristics. Although these models enhance our understanding towards the physics of hydrological processes, they require significant computational time and large amounts of data (Beven, 2012; Dye and Croke, 2003). Over the past decades, machine learning tools such as Artificial Neural Network (ANN) (e.g. Jeong and Kim, 2005; Kisi et al., 2013; Sudheer et al., 2002; Talei and Chua, 2012) and Genetic Programming (GP) (e.g. Babovic, 2005; Babovic and Keijzer, 2002, 2006) have been used to develop rainfall–runoff models. GP offers advantages over other data driven techniques since it is more likely to generate a function with understandable structure. However, most data driven models are one unit models with adequate input variables that cover all system processes in one input/output structure (Abrahart and See, 1999; Bowden et al., 2005). Such models combine all the various flow components losing valuable information on their specific contributions which is needed when designing local mitigation measures (Corzo and Solomatine, 2007). In addition, covering all the rainfall–runoff processes in one unit without taking into account the different physically interpretable sub-processes may lead to low accuracy in extrapolation. Streamflow is commonly conceptualized to include baseflow and quickflow (also called direct runoff) components. The baseflow component represents the relatively steady contribution to streamflow from groundwater flow, while the quickflow represents the additional streamflow contributed by surface flows (i.e. rapid runoff) and shallow subsurface flows (delayed runoff) (Beven, 2012). One way of retaining as much information as possible is to build separate models for each of the different physically interpretable flow components leading to a modular approach. As such, a modular model for the simulation of streamflow time series consisting of separate modular units for baseflow and stormwater runoff would be suitable in quantifying both flow components in a more flexible manner. The concept of a modular model has been used in modelling tools that use a linear reservoir approach (e.g. unit hydrograph methods) by splitting streamflow into baseflow and quickflow components. However, these models may fail to represent the nonlinear dynamics in the rainfall–runoff process (Rajurkar et al., 2002).

Therefore, this paper used GP to develop a physically interpretable modular universally applicable model accounting for baseflow and quickflow. The modular model was applied to address the following research questions in a tropical urbanized system:

- What are the contributions of the various land uses towards quickflow?
- How does the baseflow contribution change among sub-catchments with different land uses?
- How do runoff generation processes vary among the different types of rainfall events?
- What are the effects of antecedent catchment conditions on runoff response?

In this paper, a description of the study site as well as monitoring network is described in Section 2. Section 3 focuses on the methodology used to develop the modular model consisting of baseflow and quickflow components using GP. The methodology with regards to the quantification of land use specific contributions to the quickflow component is presented in Section 4. The results are discussed in Section 5 and lastly, conclusions are summarized in Section 6.

2. Study area and data collection

2.1. Description of the study area

Kent Ridge Catchment, a small catchment (0.085 km^2) within the National University of Singapore (NUS), located in the southern part of Singapore was chosen to setup an intensive monitoring network (Fig. 1). This catchment contains all the main land uses of Singapore and hence is representative from a hydrological point of view. Furthermore, the use of a small catchment reduces data uncertainty and inaccuracy with regards to the spatial distribution of precipitation. The overall topography of the catchment is characterized by steep slopes with elevations ranging between 14.0 m and 75.8 m above sea level.

A land use map of the catchment (Fig. 2) was created combining the information from Google Earth, NUS campus map and field observations. The identified land uses (Table 1), typically for Singapore, included impervious surfaces (i.e. roof top, road, and paved car parks), grasses on mild (Fig. 3a) and steep slopes (Fig. 3b), mixed grasses and trees (Fig. 3c) and relatively natural vegetation (Fig. 3d). Therefore, understanding the behaviour and the mechanism of rainfall–runoff processes at Kent Ridge catchment would yield valuable information for tropical urbanized cities such as Singapore.

Water table in unconfined aquifers is often thought to be a subdued replica of the topography and from the elevation of the water table, flow of groundwater can be approximated (Haitjema and