Sustainable Cities and Society 20 (2016) 210–221

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Exploring the hydrological impact of increasing urbanisation on a tropical river catchment of the metropolitan Jakarta, Indonesia

Federica Remondi[a,b,*], Paolo Burlando[a,b], Derek Vollmer[b,c]

[a] Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland
[b] Future Cities Laboratory, Singapore-ETH Centre (SEC), Singapore
[c] Planning of Landscape and Urban Systems, ETH Zurich, Zurich, Switzerland

ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form
28 September 2015
Accepted 1 October 2015
Available online 22 October 2015

Keywords:
Deforestation
Land use change
Hydrology
Tropical river
Watershed modelling
Urbanization

ABSTRACT

Tropical river catchments face water resource challenges, as populations and urban footprints grow exponentially. It is acknowledged that deforestation of upstream watersheds and urbanisation pressure generally lead to an intensification of extreme flow events, such as floods and droughts, but processes such as groundwater recharge and evapotranspiration are also affected, leading to a broader impact on water balance. In this respect, the Ciliwung River basin – flowing through Jakarta, the capital city of Indonesia – represents an exemplary case of a tropical river catchment experiencing alteration of the hydrological regime as a consequence of highly impacting land use changes following rapid urbanisation. The city of Jakarta situated downstream has experienced catastrophic floods at an increasing frequency (1996, 2002, 2007, 2013), and continued urbanisation in the middle and upper stream may further alter the catchment response, leading to increased flood risk and lower groundwater recharge of the urban aquifer, which is the source of drinking water for a large part of the population. This study explores the effects associated with the rapid and drastic land use changes in the region on the hydrological response of the river, by showing how modern simulations tools can provide insights about the effect of land use policies. To this end, a distributed analysis of the hydrological regime for different scenarios of urbanisation is performed. Watershed response to the realisation of these scenarios is simulated by means of a distributed hydrological model, which allows for a physically and spatially explicit simulation of the major basin processes across the entire basin. Specifically, we used the model to test two hypothetical but plausible future land cover scenarios that correspond to an uncontrolled urban expansion, and to a scenario with strong constraints on urban expansion, combined with afforestation in the upper catchment. Results suggest that the uncontrolled urban expansion leads to a noticeable increase of flood events during the rainy season, and a decrease of base flow in the dry season. The changes in the hydrological budget components are also discussed in view of implications on water resources availability and rehabilitation of the urban river corridor.

1. Introduction

In the past 30 years, land use changes associated with rapid urbanisation and deforestation have greatly altered a large proportion of tropical regions (Drigo, Lasserre, & Marchetti, 2009). Among them, Southeast Asia has the highest deforestation rate with substantial negative consequences for its ecosystems (Sodhi, Koh, Brook, & Ng, 2004; Zhao et al., 2006). Various reviews (Bruijnzeel, 2004; Costa, Botta, & Cardille, 2003; Valentin et al., 2008) present evidence that land use change and soil degradation in the tropics have altered the hydrological response of the catchments. One of the major effects of deforestation and urbanisation is the intensification of basin response and the increase of peak flows enhancing the flood risk during the wet season. On the one hand, following these land cover changes, surface detention and infiltration are reduced thus leading to a greater proportion of overland flow during rainfall events. On the other hand, decrease of flows during the dry season is also experienced (Bruijnzeel, 2004). Land use change can affect not only river flow, but also other compartments of the water cycle, such as groundwater, which can decline during the dry season as a consequence of reduced infiltration volume. This affects groundwater recharge and soil water content more in general, thus contributing to reduce evapotranspiration (ET). ET may also decrease because of higher surface albedo, lower surface

* Corresponding author at: Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland.
E-mail address: remondi@ifu.baug.ethz.ch (F. Remondi).

http://dx.doi.org/10.1016/j.scs.2015.10.001

aerodynamic roughness, lower leaf area and shallower rooting depth caused by changing land use from forest to pasture (Costa et al., 2003). In areas where precipitation recycling is large and strongly depends on ET, this may ultimately affect also microclimate.

This spectrum of hydrological alteration processes are likely to happen in catchments, where land use has been almost exponentially changing from pristine forests to plantations and settlements. The Ciliwung River is a good example and offers an interesting opportunity to analyse more in depth the effects of scenarios that, progressing the urban developments at the present pace, seem to be highly probable in a near future. Evidences of the implications of land cover changes seem to be detected already in the Ciliwung River and especially in the city of Jakarta, through which the river flows before reaching the Java Sea. Floods have historically hit the city on a regular basis during the wet season, due to the combination of seasonal rainfall intensity and naturally flood-prone topography (Steinberg, 2007), but flood impacts and damages have increased in the city with extreme events in January 1996, February 2002, February 2007, January 2013, January and February 2014. The catastrophic flood that affected 60% of the Jakarta region in February 2007 caused 80 casualties, approximately 190,000 people with flood-related illnesses and US$ 453 million in damages (Akmalah & Grigg, 2011; Steinberg, 2007).

According to Steinberg (2007), causes of recent floods are only partly related to the topographic configuration of the region. The major factors can be identified as: (i) insufficient flood control infrastructure; (ii) the reduction of structural carrying capacity of waterways and streams, due to poor management, uncontrolled garbage dumping and sedimentation; and (iii) the reduction of rainwater absorption due to urbanization and deforestation.

Land use change can potentially have impacts also on the groundwater compartment. Around 40% of the population in Jakarta relies on groundwater resources, but this percentage is even higher in the upstream cities of Depok and Bogor, where a deficit between abstraction and recharge in the Bogor aquifer is already experienced (BBWSCC, 2012).

These water resource challenges are strictly connected to the strong growth in Jakarta's population and economy that has additionally generated a vast increase in urbanised areas and concomitant land use changes (Poerbandono, Julian, & Ward, 2014; Ward, Pauw, Van Buuren, & Marfai, 2013). From 1972 to 2012, Jakarta's urban footprint increased more than 200 times, and annual urban population growth averaged 2.3%. In the city of Jakarta, population has risen from 2.7 million in 1960 to 9.6 million in 2010 (BPS Jakarta, 2010). The increasing population density together with the urbanization pressure and the high economic value of urbanized land continues to put pressure on remaining green space, affecting also the upstream region that borders a key biodiversity area. The mountainous territory, which is only partly protected by a national park (Nakagoshi, Suheri, & Amelgia, 2014), is experiencing forest loss on its steep slopes, as land is cleared for both drylands agriculture and vacation villas and resorts.

The considerable changes in land use in the Jakartas Ciliwung River basin are assessed in this work to discuss possible drifts of urban river developments, but also with the purpose of critically analysing likely trajectories of future impacts on hydrology and water resources of rapidly changing periurban areas, which are located in regional setups similar to that of Jakarta. To this end, we used an integrated approach, which combines the modelling of land use changes with distributed hydrological models to understand the spatially distributed dynamics of the system, and, ultimately, to show how this can provide suggestions for regional planning. More specifically, the understanding of the interaction between hydrology and land use change is achieved with the implementation of a physically explicit distributed hydrological model fed by past, present and future scenarios of land use change. The selected hydrological model, Topkapi-ETH (Fatichi, Rimkus, Burlando, Bordoy, & Molnar, 2013), simulates the spatial variability of the key hydrological variables accounting for land and climate characteristics, thus being able to simulate the effects of land use changes across space and over time. Land use changes are simulated by means of statistical learning algorithms that predict future changes combining historical evolution with spatial drivers.

Accordingly, this study has two primary objectives: (i) elucidating the hydrological effects of land use change in an exemplary tropical urban catchment of Asia; (ii) providing insights on how alteration of hydrologic dynamics due to land use changes can inspire land development policies in urban and periurban landscape of rapidly expanding cities.

This paper is structured as follows: Section 2 introduces the case study area and the problems the watershed and the city of Jakarta are facing with regards to water resources. This section then illustrates the model we set up to simulate the hydrological processes in the catchment and the land use scenarios taken into consideration. Section 3 presents and discusses the land use scenarios and the hydrologic simulations for the different scenarios, with special focus on the river flow regime as described by the spatially distributed behaviour of surface runoff and groundwater dynamics. Finally, the results are discussed in view of their potential implications on the case study (Section 4) and general urban developments (Section 5) in relation to river rehabilitation and water resources management.

2. Data and methods

2.1. Study area

The Ciliwung is the largest river running through the city of Jakarta. Its basin covers an area of 385 km^2 and is located in the north-west of Java in Indonesia, at approximately 6° S of latitude and 106° E of longitude (see Fig. 1). The river drains south to north, from Mount Gede Pangrango until it reaches the Java Sea. The upper watershed is a mountainous area with elevation from 400 to 3000 m a.s.l. (see Fig. 2) and fairly steep slopes. The downstream region appears as an alluvial plain with relatively flat topography with the river bisecting the cities of Bogor, Depok, and Jakarta.

Around 5 million people live in the entire catchment area, with the highest density of 15,000 people per square kilometre occurring in Jakarta (BPS Jakarta, 2010). Population growth within the city of Jakarta has slowed to less than 1.5% per year, whereas growth in the outlying cities like Depok (pop. 1.8 million, ~8700 people/km^2) and Bogor (pop. 1 million, ~8000 people/km^2) has been closer to 3% per year.

In the period from 1972 to 2012, the extended metropolitan region of Jakarta underwent a massive shift in land cover following a rapid urbanisation. Settlement land increased by more than 2100% during that time, while land devoted to cultivation (primarily rice paddies, mixed gardens, and non-irrigated cash crops like cassava) decreased by 27%. The net loss in agricultural lands was buffered by the dramatic conversion of forests, which were reduced by 71%. During this same time frame, land in the Ciliwung catchment went from 7% to 50% urban, cultivated lands from 45% down to 27%, and forest cover decreased from 46% to 19%. This transition also had a distinct spatial pattern, as agricultural lands and remaining lowland forests in the middle stream were mostly urbanized, and forests in the upper catchment were converted to dryland agriculture or plantations.

The soil composition of the basin is mostly alluvial in the mid- and down- stream region, whereas andosol, volcanic deposit, and rock are prevalent in the upstream region (Delinom et al., 2009;