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Hydrological model application under data scarcity for multiple watersheds, Java Island, Indonesia

Yanto [a,b,*], Ben Livneh [a,c], Balaji Rajagopalan [a,c], Joseph Kasprzyk [a]

[a] Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO, United States
[b] Civil Engineering Department, Jenderal Soedirman University, Purwokerto, Indonesia
[c] Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado, Boulder, CO, United States

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ABSTRACT

Study region: Java Island, Indonesia.
Study focus: The Indonesian island of Java is home to more than half of Indonesia's population and routinely experiences water related natural disasters. This study represents a first step towards skillful hydrologic prediction and hydrologically-informed mitigation strategies. This is the first study to collate a comprehensive suite of hydrometeorological observations and systematically identify Variable Infiltration Capacity (VIC) Land Surface Model (LSM) parameters on Java to create a set of benchmark simulations.
New hydrological insights for the region: Quality control procedures revealed inconsistencies between precipitation and streamflow with only five watersheds possessing data of suitable quality. Simulations and observations confirmed that both precipitation and streamflow variability increase eastward on the island and that rainfall-runoff response was most frequently dominated by baseflow, rather than surface runoff. The most sensitive VIC parameters were identified and then calibrated with an automatic calibration procedure. In the calibration period, model performance was generally deemed satisfactory with Nash Sutcliffe Efficiency (NSE) between 0.31 to 0.89, whereas the validation period exhibited poorer performance than expected (0.07 < NSE < 0.79). This drop in performance was attributed to a combination of inconsistent data quality, hydrometeorological outliers during the validation period, and over-fitting parameters during the calibration period. The model indicated that direct runoff exhibits more spatial and temporal variability than both rainfall or baseflow, the latter being associated with variability of soil thickness.

1. Background

The Indonesian island of Java, where 160 million of the country's 241 million inhabitants reside, experiences water related natural disasters – i.e., floods, droughts and landslides. In the last decade more than 50% of Indonesian hydro-climatic disasters occurred in Java (BNPB, 2015). Yet, while other main islands (Sumatera, Kalimantan, Sulawesi, West Papua, Nusa Tenggara and Maluku) experience water surplus, annual water demand on Java exceeds supply by an average of ∼69 billion cubic meters (BCM) (Bappenas, 2010). With a large population, these water related hazards have caused severe social and economic impacts.

* Corresponding author at: Civil Engineering Department, Jendearal Soedirman University, Purwokerto, Indonesia.
E-mail address: masyanto79@gmail.com (Yanto).

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Table 1
Hydro-climatic characteristics of Java.

Components	Description
Annual rainfall	Spatial: - 3300 mm in southwest - 2000 mm in northeast Temporal: - 655 mm in dry season - 1800 mm in wet season
Temperature	28 °C coastal plains, 26 °C inland and mountain area, 23 °C higher mountain region
Land cover	61% agricultural area, 25% forest, 10% settlement, 4% water body

Rainfall variability is the primary driver of streamflow in tropical regions and understanding the underlying streamflow generation mechanisms is essential for making predictions. Rainfall-runoff models have been used to model and forecast streamflow (e.g., Wood et al., 2002, 2005; Regonda et al., 2013). Land surface models (LSMs) have been developed to enable coupling with the atmosphere and may also be used to model hydrologic processes. These are typically physically-based models that solve the coupled energy and water balance, more recently focusing on accurate simulation of surface water budget components, particularly streamflow (Linde et al., 2008; Livneh et al., 2011). These have been extensively used to model streamflow in catchments with different hydro-climatic regimes around the world (Arnold et al., 1999; Beck et al., 2013; Livneh and Lettenmaier 2013; Linde et al., 2008). To date, the existing studies of physically-based hydrologic models on Java have only focused on single rivers; these include lumped streamflow and sediment modeling on the Lesti River (381 km^2) in East Java (Apip et al., 2012) and streamflow modeling on the Upper Citarum Basin (~1821 km^2) in West Java (Harlan et al., 2010; Julian et al., 2013).

With the above motivation, we apply the Variable Infiltration Capacity (VIC) LSM (Liang et al., 1994) to simulate watershed hydrology in Java in this paper. The VIC model has been widely applied in numerous hydrological studies across a range of hydro-climatic environments (Nijssen et al., 2001, 2014; Linde et al., 2008; Liang et al., 1994, 1996; Sheffield and Wood, 2007; Sheffield et al., 2006; Shukla et al., 2013; Zhao et al., 2011). The VIC model has also been used to simulate global soil moisture and drought severity (Sheffield and Wood, 2007; Sheffield et al., 2006). The first goal of this study is to collate and describe the available hydrometeorological data and to apply a screening procedure to deal with data scarcity and quality issues. The second goal is to evaluate VIC model simulations of daily and seasonal hydrology and their variability, consisting of model calibration and validation in unique time periods. Overall, this analysis aims to identify key processes and data issues, representing an important first step towards building a sub-seasonal and multi-decadal hydrologic projection system geared towards water resources management and natural disaster mitigation in Java.

The paper is organized as follows. The study region and data sources are first described, with essential data screening steps, resulting in a set of watersheds for analysis in this study. The model is then briefly described together with the sensitive parameters used for calibration. The results section describes model performance in calibration and validation modes; seasonal and temporal performance of the model and insights into the physical processes. The paper concludes with summary and discussion of the results.

2. Study region and data sources

Java is located in the southwestern part of Indonesia. Its mountains have decreasing slope from the center to the south and north coasts (Fig. 1a). The mountain range is made up of a series of quasi-circular volcanoes in the central mountains with the exception of western Java where the mountains are continuously linked (Fig. 1a). Consequently, precipitation over the island is drained to the north and south coastal zones through a series of basins. The spatial and temporal variability of rainfall in Java is influenced by the movement of the Inter Tropical Convergence Zone (ITCZ) across the equator, creating distinct dry (May–Oct) and wet (Nov–Apr) seasons (Qian et al., 2010). In addition, the inter-annual variability of rainfall during the dry season in Java is comparatively larger than during the wet season (Yasunari, 1981). Moreover, the spatiotemporal variability of rainfall in this island is associated with atmospheric circulation patterns driven by the El Niño Southern Oscillation (ENSO). Anomalously low rainfall years correlate well with the warm phase of ENSO while cold phases of ENSO correlate with anomalously high rainfall years (Gutman et al., 2000). The interannual and multidecadal variability of Indonesian rainfall is documented in recent study by Yanto et al. (2016a). The land cover of the island consists mainly of tropical forest, as well as agriculture and urban settlements with significant spatial variability (Fig. 1b). Table 1 summarizes the hydro-climatic environment of Java.

To apply the VIC model for Java we specifically need soil parameters, vegetation, and meteorology inputs, each from disparate sources. Soil parameters were downscaled from Nijssen et al. (2014) from 0.5° × 0.5° to 0.125° × 0.125° resolution using Inverse Distance Weighting (IDW) method, while the vegetation covers were directly derived from the University of Maryland's 1 km Global Land Cover product (Hansen et al., 2000). Four meteorological fields: daily total precipitation,