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Research article

Modeling washoff of total suspended solids in the tropics

S.H. Le [a, 1], L.H.C. Chua [b, *], K.N. Irvine [c], H.S. Eikaas [d, 2]

[a] DHI-NTU Water & Environment Research Centre and Education Hub, Nanyang Environment and Water Research Institute, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[b] Division of Environmental and Water Resources, School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[c] National Institute of Education, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[d] Catchment & Waterways Department — Limnology & Water Quality Modeling, Public Utilities Board, 40 Scotts Road, Environment Building, Singapore, 228231, Singapore

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A B S T R A C T

Washoff behavior in the tropics is expected to behave differently from temperate areas due to differences in rainfall characteristics. In this study, rainfall, runoff and total suspended solids (TSS) were monitored from 9 catchments distinguished by different types of land use, in Singapore. The catchments ranged in size from 5.7ha to 85.2ha. Over 120 rain events were studied and more than 1000 storm samples were collected and analyzed. Monte Carlo analysis was applied to obtain the best fit values of the washoff model parameters consisting the washoff coefficient c_3, washoff exponent c_4 and initial mass on surface B_{ini}. The exponent c_4 was found to be approximately unity for all the events monitored, in agreement with other studies. The values of c_3 and B_{ini} were found to vary between events. Among all the rainfall and runoff characteristics studied, rainfall depth of the current event (d) was found to be the single parameter that significantly influenced the values of c_3 and B_{ini}. Contrary to expectations, B_{ini} did not correlate well with antecedent dry period or with rainfall depth of the prior storm event. The results show that the common modeling practice where B_{ini} is assumed to vary with antecedent dry period and previous rainfall depth should be reassessed when applied to catchments in the tropics. ANCOVA analysis showed that land use was not significant, but rather the variation of c_3 and B_{ini} with d was found to correlate well with the catchment area.

1. Introduction

Various models have been developed to assess storm runoff quality and examine its potential impacts on receiving water bodies. Among the models, the empirical washoff model has been widely used to simulate the washoff process (Barbe et al., 1996; Berrentta et al., 2007; Haiping and Yamada, 1996; Park et al., 2008). This model is based on experimental studies by Sartor et al. (1974), which showed a tendency toward an exponential, or first-order decay in total washed-off load. The use of washoff models requires proper calibration of model parameters; however, much uncertainty in predicted results remains even after calibration (Avellaneda et al., 2009; Bertrand-Krajewski, 2007; Gaume et al., 1998; Kanso et al., 2005, 2006; Lindblom et al., 2007; Srianganthakumar and Codner, 1993; Sutherland and Jelen, 2003). One of the major problems is the non-uniqueness of the model parameters which can reduce user confidence in applying a calibrated model for new events. This has highlighted serious limitations of the model's ability to reproduce all aspects of the pollutograph equally well with a single parameter set (Beven, 2009; Gupta et al., 2005). For example, reduction in parameter uncertainty was achieved when calibration of the model was performed using storms with similar characteristics, such as high flow versus low flow events (Avellaneda et al., 2009; Srianganthakumar

* Corresponding author. Current address: School of Engineering, Deakin University, 75 Pigdons Road, Waurn Ponds, VIC, 3220, Australia.
E-mail address: lloyd.chua@deakin.edu.au (L.H.C. Chua).
[1] Current address: Surbana Jurong Pte Ltd, Coastal Engineering, Infrastructure and Land Survey Department, #01-01 Connection One, 168 Jalan Bukit Merah, 150168, Singapore.
[2] Current address: DairyNZ, Canterbury Agriculture & Science Centre, Gerald Street, Lincoln, 7608, New Zealand.

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and Codner, 1993). Gaume et al. (1998) concluded that uncertainty is high especially if rainfall events have different peak intensities or shorter previous dry weather periods than the events used during the calibration phase. This suggests that calibration parameter sets are sensitive to rainfall characteristics such as peak intensity and antecedent dry period in addition to land use. Recently, Gamerith et al. (2013) also showed that parameter sensitivities depend on the chosen rainfall event.

Despite the aforementioned observations, our understanding of how rainfall characteristics can influence model parameters is still limited. Arguably, a proper understanding of these effects is more critical in the tropics, where the frequent and high intensity rainfall often leads to a flashier response and higher runoff volumes. This study investigated the sensitivity of washoff parameters to rainfall and runoff characteristics under tropical rainfall conditions. This study was focused on the washoff of total suspended solids (TSS) since TSS is found in large quantities in stormwater runoff and acts as a vehicle for the transport of other pollutants. The objectives of this study were: (i) investigate the variation of washoff model parameters as a function of rainfall and runoff characteristics for catchments with different types of land use, (ii) identify the significant factors that affect washoff behavior and hence washoff model parameters, and (iii) elucidate the results obtained in this study in the context of runoff behavior in the tropics.

2. Site description and methodology

2.1. Site description

Singapore is a small island nation (area ≈700 km^2), located at the southern end of the Malaysian peninsula in Southeast Asia. The climate of Singapore is classified under the Koppen system as a tropical rainforest (Af) with no true dry season. Annual mean rainfall is approximately 2300 mm and annual mean temperature is 27 °C. The annual maximum 60 min rainfall intensity, 1980–2010, ranged between 70 mm/h and 130 mm/h. The mean number of days per month with rain ranges between 11 and 19 and the minimum number of rain days per month is in the range of 1–3 (Chang and Irvine, 2014); in essence, it rains every other day on average. Water in Singapore is a matter of national security and currently the runoff from two-thirds of the island's surface drains to 17 reservoirs to help service the country's water demand. As such, Singapore has developed a sophisticated, closed-loop approach to water management (Irvine et al., 2014; Ong, 2010; Tortajada, 2006).

Fieldwork for this study was conducted in the Kranji Reservoir catchment (1°25′N, 103°43′E), located in the north-western part of Singapore. The catchment is approximately 5700 ha (Fig. 1). An earlier monitoring and sampling program was conducted in 2006 and further information on the Kranji Reservoir catchment and results of the 2006 monitoring program can be found in Chua et al. (2009). In the present study, additional data from 9 smaller, land use-specific sites were collected in 2011–2012. The selection of the 9 sub-catchments targeted three types of land use that are dominant in the Kranji Reservoir catchment: (1) Residential, (2) Agricultural, and (3) Forest. Among these 9 monitoring stations, Verde is a low-density residential catchment, CCK Ave; CCK Cres and CCK North are high-density residential catchments; Sg Tengah, Sg Tengah 2, Sg Tengah 3 and Neo Tiew are agricultural catchments; and Forest KJE is a secondary forest area. Further details on the nine gauging stations are provided in Table S1. Agricultural practices in Singapore are different from large scale activities practiced elsewhere. The term “agriculture” used here includes soil-based vegetable farming, nurseries, ornamental fish and poultry farms, all carried out in small (less than 5 ha) plots of land. The “other urban” land use in this study includes military training areas, parks and grassed areas reserved for future development. Runoff in the studied catchments is conveyed by a channelized drainage system which is separate from the sanitary sewer system. The storm drains typically consists of surface drains that are usually concrete-lined, and are designed to convey the high peak discharges typical of drainage systems in the tropics (Fig. S1). At the monitoring sites

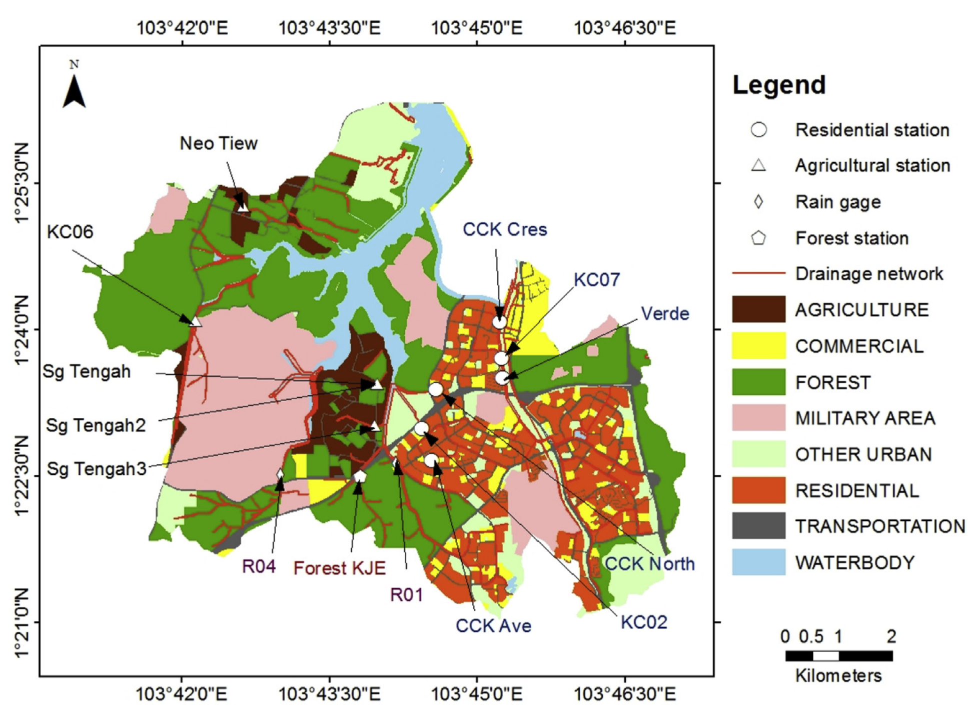

Fig. 1. Locations of all monitoring stations and rain gages in the Kranji Reservoir catchment. Agricultural, forest and residential catchments are presented in black, red and blue, respectively. (Land use map provided by the Urban Redevelopment Authority (URA), Singapore).