Applicability of the Curve Number Method for estimating flow duration curves in the Humid Tropics

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1. Introduction

Most islands are developing countries with poor hydrological data availability which causes stress on hydrological resources due to unmonitored human influence and negligence. There is a need to understand these stresses and influences by building block research specifically targeting islands. Model simplicity must be applied before transitioning to complex ones. The strengths and weaknesses of these simple models have to be identified before full usage.

The flow duration curve (FDC) is one such tool that can be used for estimating runoff in island catchments as it has a simple yet vital role in displaying catchment behavior and overall flow pattern. Its simplicity includes sorting streamflow data in descending order without regard for sequence or occurrence. (Searcy, 1959; Mohamoud, 2008). Another simple model is the curve number (CN) model, developed in agricultural catchments for flood mitigation (Rallison and Miller, 1982). The CN method is convenient and easy to use (Tedela *et al*., 2012), unfortunately its simplicity is also its weakness (Ponce and Hawkins, 1996). Unifying the CN method and the FDC to make estimates will require some alterations. Therefore this study aims to identify an exceedance probability threshold of which the CN method can be used for estimating FDC in the humid tropics.

The first alteration is to consider the FDC as a 2-part system (high and low flows) rather than a single unit. Past researchers have identified the high flows to be generally governed by precipitation which coincides with the reason for development of the CN method to estimate runoff from storm rainfall (Ponce and Hawkins, 1996), this in turn works in favor of the CN method. The low flows of the FDC are controlled by geology, soil and baseflow (Mohamoud, 2008; Yaegar *et al*., 2012) or by evapotranspiration as mentioned by Yokoo and Sivapalan (2011). In the case of evapotranspiration, the CN method does not consider it and therefore may hinder its performance at low end flows.

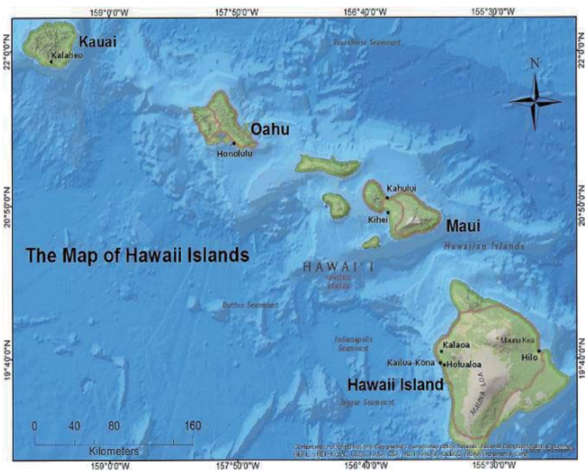

Fig. 1. The Hawaiian Islands

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2. Study area and method

2.1. Study area

This study is based on nine catchments in Hawaiian Islands (Figure 1) because it has sufficient data and can relate to similar natured catchments. The catchments are from different areas on the islands of Kauai, Maui, Oahu and Hawaii. The daily and monthly runoff and rainfall data were downloaded from USGS (USGS, 2012) which contains United States catchments water data. Catchments annual rainfall and area ranges from 1500 to 9000 mm and 1.5 to 569.8 km^2 respectively. To identify a catchments CN a soils map was obtained from ArcGIS SSURGO Downloader 2014 (ESRI, 2014). The CN model was then used to estimate runoff.

2.2. The Curve Number Method

The CN model relates rainfall and runoff with the following equation,

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{1}$$

where Q is runoff, P is precipitation, S is potential retention and I_a is the initial abstraction.

The initial abstraction is defined as,

$$I_a = \lambda S \tag{2}$$

where λ is from 0.00 to 0.3 commonly set at 0.05 (Ponce and Hawkins, 1996; Woodward *et al*., 2010).

The value of S can be defined as,

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where CN ranges from $0 \leq CN \leq 100$ (USDA, 1986).

2.3. Hydrologic Soil Group (HSG) and Weighted CN

Where catchments have multiple HSG, the average weighted CN (WCN) was calculated by the following equation,

$$WCN = \frac{\sum_{i=1}^{n} CN_i \times A_i}{A_T} \tag{4}$$

where CNi is a CN for a type of soil group in the catchment, Ai is the soil area of CNi that intersects within the catchments area and A_T is the total catchment area. (Detailed information on HSG can be found in USDA-NRCS Technical Report (USDA, 1986).

2.4. Calibration of CN model

Initially, WCN and λ are set as 0.2 and 0.05 but after analysis of the Q_{est}, the WCN and λ parameters are calibrated with the least squares method (LSM, Equation 5) and the solver function in Microsoft Excel software to improve estimated runoff. In Equation 5, Q_m is the measured streamflow and Q_{est} is the estimated streamflow. The ability to achieve stable parameter estimations is one reason this formula is often used (Huang *et al*., 2006).

$$\mathrm{LSM} = \min \sum_{i=1}^{n} (Q_m - Q_{est})^2 \tag{5}$$

3. Results

Figure 2 shows a comparison of measured runoff (Alakahi Qm), calibrated estimated runoff (Alakahi LSM) and uncalibrated estimated runoff (Alakahi WCN-Lamba 0.05 and 0.2) for Alakahi catchment. The uncalibrated runoff are seen to overestimate runoff, therefore the Q_m is calibrated to improve estimations. Majority of the catchments had inconsistencies at the low end where at times the estimated curves bend up implying an error in estimations. After the calibration of the CN model to achieve better runoff estimates, the accuracy of the estimates were measured by setting the error bound of ± 30% of Q_m. If the Q_{est} values were within this range then it was considered accurate and assigned a value of 1 (true), otherwise it was given a zero value (false). Figure 3 confirms the Q_{est} accuracy. The estimated values are sorted in descending order on the vertical axis. If a value is within ± 30% then it is automatically placed at 1 on the horizontal axis and if out of range it is placed at zero on the same axis. In the figure, the poor runoff estimates (out of range) are concentrated at the low end. Figure 4 shows a transformation of figure 3 as a complete FDC. The low end is observed to have values out of range thus inaccurate estimates. Two high end data points also are out of range but this was not consistent for all catchments. Furthermore the calibrated values of WCN and λ were less than the ones initially used.

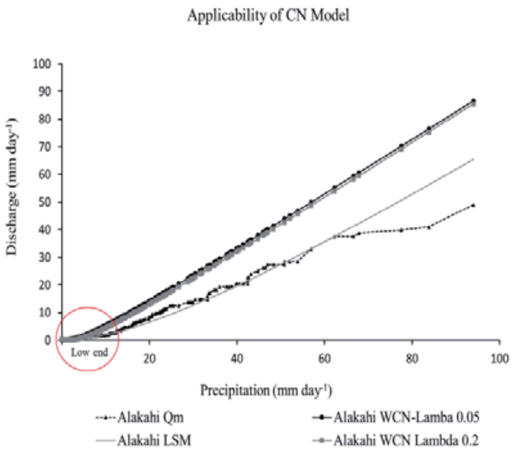

Fig. 2. Applying the CN method to Alakahi catchment. Alakahi WCN-Lamba 0.02 and 0.05 are the estimated runoff at λ = 0.2 and 0.05 respectively. Qm is the measured runoff and LSM is the calibrated estimated runoff

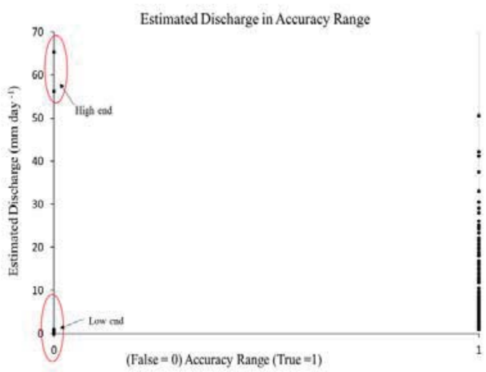

Fig. 3. The point on the 1 value represent the data within the ± 30% range. Those on the 0 value represent out of range values

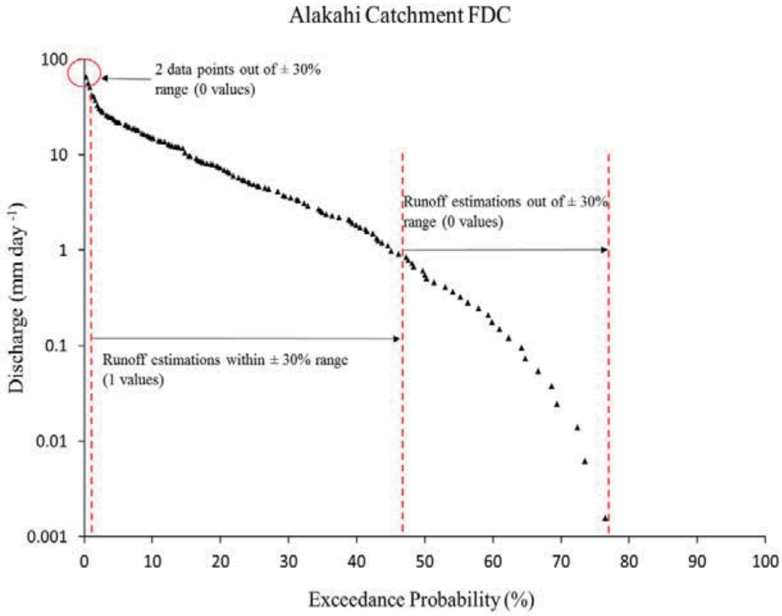

Fig. 4. The transformation of figure 3 as a FDC

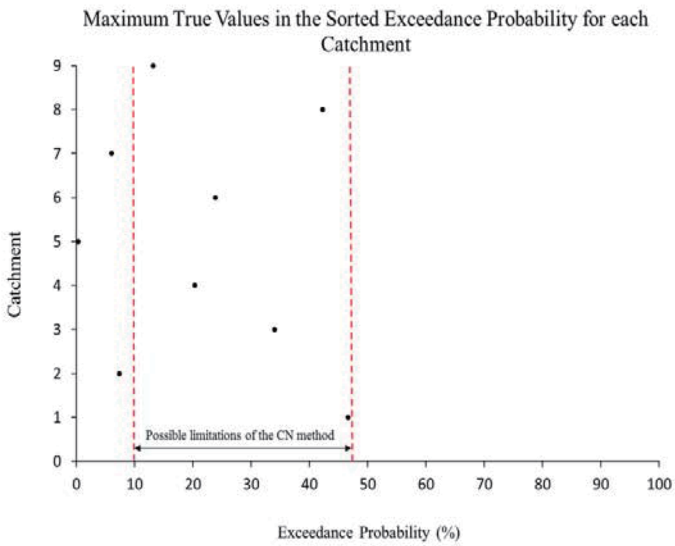

Fig. 5. Each catchment showing the maximum percentage that the CN method can estimate runoff within the ± 30% range from its FDC

4. Concluding Discussion

Past researchers have identified possible dominant controls of the FDC shape and based on these we can identify the applicability of the CN method to the FDC. The CN method was developed to estimate runoff from storm rainfall (Ponce and Hawkins, 1996) thus it may function well in the top end of the FDC where precipitation is dominant. At the low end, geology, soil and base flow control the low tail of the FDC (Mohamoud, 2008; Yaegar *et al*., 2012). Furthermore the CN method does not consider evapotranspiration which is a dominant control in the low flows (Yokoo and Sivapalan, 2011). Figure 5 shows each catchments maximum exceedance probability for accurate estimates when using the CN method. Based on this, the calibrated CN method can possibly only make stable estimations in FDCs up to approximately 50% exceedance probability. The accuracy of the estimations was set at ± 30% of Q_m. The need to calibrate runoff in forested mountainous catchments is almost certain based on studies done by Tedela *et al*. (2012) and Ajmal *et al*. (2016) in US and Korean forested mountainous catchments respectively. The former suggested to calibrate the CN to reduce uncertainty and the latter showed that when λ = 0.2 or 0.05 the results were poor, however when λ = 0.01 or 0.0, it showed improved results which was consistent with his study.

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