Estimating flow duration curve in the humid tropics: a disaggregation approach in Hawaiian watersheds

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Abstract:

The authors attempted to develop a simple methodology for estimating daily flow duration curves (FDCs) in island watersheds under humid tropic conditions, to realize better water management in data-limited island watersheds. This study disaggregated a FDC into three parts, namely high, middle and low flow parts and estimated each part independently. Based on Hawaiian watersheds, this study developed a methodology for estimating the high flow part using daily precipitation data and the Curve Number (CN) method, whereas we estimated the middle flow part directly from mean monthly flow (MMF) data. The results for the middle flow part showed the MMF data closely tracking the daily FDCs for nine of the eleven studied watersheds. For the high flow part, the results showed that only after calibration of the CN method, were there significant improvements in estimations. These results suggest it is possible to estimate the middle flow part of the FDC with MMF but the high flow part must use a calibrated CN in the CN method. This study also explored the relationship between calibrated CN and estimated absorption capacity of the studied watersheds to find the possibility of estimating suitable CN of a watershed from its geological characteristics.

KEYWORDS flow duration curve; disaggregation; islands; curve number; mean monthly flow

INTRODUCTION

Have we developed a simple methodology for estimating realistic daily streamflow in less gauged island watersheds? At present the answer is “not yet”. Most developing island countries have ungauged or poorly gauged watersheds which require annual discharge variability for water resources management, flood mitigation and damage reductions. There is limited hydrologic data available and greater efforts are required to better understand the hydrologic response of human influence on fragile water resources, particularly in small islands (Falkland, 1991; Falkland, 2002). Hydrological studies on islands are heavily reliant on methods developed from continental land masses but some areas of research such as small spatial scale of islands can make continental methodology unsuitable (Falkland, 2002). Furthermore, global climate models cannot account for thousands of islands when measuring the effects of climate change specifically to water related issues (Karnauskas et al., 2016). Therefore, the dependence of island hydrological studies on continental methodology restricts progress generated specifically towards development of island hydrological research. To begin with, the flow duration curve (FDC) can be a simple hydrologic tool for exploring island watersheds for the reason that instability of parametrized models often arises from the variability of its components, especially in small catchments which are sensitive to environment alterations (Banasik, 2011).

The FDC is a cumulative frequency curve that sorts streamflow data descendingly from high to low flows without regard for sequence of occurrence (Searcy, 1959; Mohamoud, 2008). Its simplicity and ability to project an image of combined watershed information regarding runoff variability leads to it having many applications (Vogel and Fennessey, 1995). As for such FDCs, Yokoo and Sivapalan (2011) suggested a framework for reconstructing FDCs in a modeling approach. They separated a FDC into fast and slow flow parts and suggested that a strong relationship may exist between fast flows and precipitation for the high flow part and slow flows and the mean monthly flow (MMF) for the other part. The effectiveness of their framework was later confirmed in United States catchments by exploring the physical controls of regional patterns of FDCs (Cheng et al., 2012; Ye et al., 2012). As suggested by Yokoo and Sivapalan (2011), the high flow part of a FDC is highly responsive to precipitation. If so, the Curve Number (CN) method can be used in estimating the high flow part firstly because it is simple and convenient to use (Tedela et al., 2012) and secondly it estimates runoff based on a single CN parameter with an empirical precipitation and runoff relationship. Also, it is suitable to storm loss and its related storm runoff (Boughton, 1989; Ponce and Hawkins, 1996) which is associated with high flows. Researchers have had both support and disapproval of the CN method (Ponce and Hawkins, 1996). Nevertheless, it has the important advantage of being developed directly from small catchment measurements rather than from point scale measurements (Beven, 2001).

Therefore, this study aims to develop a methodology for estimating the shape of a FDC in Hawaii Island watersheds following the framework of Yokoo and Sivapalan (2011). Towards this goal, the present study investigates (1) if we...
can estimate the middle flow part of a FDC from MMF and how can we estimate the high flow part of a FDC from daily precipitation data and the CN method in well-gauged Hawaiian watersheds. The Hawaiian watersheds are used because with rich available data, it has the potential to be a base project for gathering insight into the uniqueness of island hydrologic nature. The method for estimating the low flow part of a FDC will be presented as a separate study.

METHOD

Study Catchments

This study uses eleven catchments from the islands of Oahu, Hawaii, Maui and Kauai in the Hawaiian Islands (Figure 1-Panel a). Figure 1 (Panel b) shows the selected watersheds from Kauai Island, the other islands are in Figure S1. The catchments have minimal urban development and no intensified agricultural practice as identified by land maps from Hawaii Agricultural Land Use (ESRI, 2014a) and soils map from ArcGIS SSURGO Downloader 2014 (ESRI, 2014b). The catchment boundaries were accessed from USGS Streamstats (US Geological Survey, USGS, 2012b) and precipitation and streamflow data (daily and monthly) from 2007 to 2012 were downloaded from USGS (US Geological Survey, USGS, 2012a) which contains water data from catchments across the United States. The catchment drainage areas ranges from 1.5 to 569.8 km$^2$ and annual precipitation from 1500 to 9000 mm. Finally, the annual FDCs for each catchment were plotted, analyzed and disaggregated into three parts, high, middle and low parts.

Estimating the middle component

Based on the proposed framework by Yokoo and Sivapalan (2011), the MMF was used in estimating flows in the FDC middle component. Therefore, the FDCs of daily measured discharge ($Q_m$) and MMF were plotted and the two quantities were analyzed at the middle part.

Estimating the top component: CN Method, Hydrologic Soil Group and Weighted CN

The CN method described in Text S1 was used for estimating streamflow in the high flows. The calculation of Weighted CN is explained in Text S2 and hydrologic soil group is explained in Text S2, Table SI and Table SII. Application of CN model to the top section

For each watershed, the top 40% exceedance probability (EP) of streamflow and precipitation was used to compute the estimated streamflow ($Q_{est}$). The coefficient of initial abstraction, Lambda ($\lambda$), was set as 0.05 and 0.2, but after analyzing $Q_{est}$, the weighted Curve Number (WCN) and $\lambda$ parameters were calibrated to better estimate streamflow by using the least mean squares method in Equation (S3-1) in Text S3 and Microsoft Excel solver function. This equation is used for its ability to generate stable parameter estimations (Huang et al., 2006).

RESULTS

The disaggregated components of the FDC were determined by graphically compiling and analyzing the FDCs for all watersheds. Figure 2 shows the possible disaggregated sections of a FDC in Hawaii. The graph shows the top section (high flows) partitioned at 0–40%, the middle section from 20–80% and the low end from 60–100%. The disaggregated sections have 20% overlapping sections to account for watershed variability.

The middle component of the FDC

The results show that MMF was observed to mimic $Q_m$ for nine of the eleven studied watersheds and two other watersheds showed a slight deviation of MMF from $Q_m$. Figure 3a shows estimations in the middle section for Hanalei watershed. The “mean monthly flow” mimics the “daily discharge measured” curve ($Q_m$) from approximately 40–80%. Hence, it is possible to use MMF for estimating streamflow in the middle section of the FDC.

The top component of the FDC

Using the uncalibrated CN method, there was an overestimation of streamflow. After calibration of WCN and $\lambda$, estimations were improved in the watersheds. For most watersheds, the calibrated $\lambda$ was zero and the calibrated WCN (CWCN) was less than the original WCN. Some watershed characteristics and calibration results are in
Table SIII. Figure 3b shows the high flow section of Hanalei catchment, where “Hanalei WCN-Lambda 0.05” and “Hanalei WCN-Lambda 0.2” are uncalibrated $Q_{\text{est}}$ which both overestimate streamflow, but after calibration, the “Hanalei CN estimation” (or calibrated $Q_{\text{est}}$) improved estimations.

Reconstruction of FDC

Figure 4 shows the FDC reconstruction for Hanalei watershed by combining the disaggregated sections with their respective methods of estimations, except for the low flow part. For high flows, we estimated daily FDC from 0 to 40% EP using daily precipitation and CN model where the parameter CN was calibrated against daily flow data. The calibrated CN method works well for the high flow range but gradually offsets when approaching the overlapping range (20–40% EP). Hence, we estimated daily FDC by plotting the average values of the calibrated CN model daily flow curve and MMF at certain points in the high flow range. Beyond 40% we just plotted MMF until 80% EP. Although the reconstructed FDC is partly departed in some parts from observed FDC, it is considerably close to the observed FDC. Hence, it is possible to estimate daily FDC with daily precipitation, calibrated CN and MMF.

Quantifying CN as potential maximum absorption capacity

In estimating daily FDC in ungauged island watersheds, we cannot calibrate CN with the lack of daily flow data. As an alternative, we graphically illustrate and demonstrate an approach to estimate the value of CN from the potential maximum absorption capacity ($\Delta P$), which is potentially estimated by watershed geology. Figure 5a shows a result where “Hanalei $Q_m$” represents the measured discharge, “Hanalei CN estimation” is the estimated discharge, “Hanalei CN = 100” is the estimated discharge when CN = 100 and “Hanalei Parallel at CN = 100” is the parallel line to “Hanalei CN = 100” drawn from the maximum estimated discharge ($Q_{\text{maxest}}$) point and extended through the horizontal-axis. When CN = 100, precipitation equals discharge ($P = Q$) and by projecting a parallel line to this from the $Q_{\text{maxest}}$ point, it intercepts the horizontal axis thus discharge is zero (vertical axis = 0) but precipitation is a non-zero value $\Delta P$.

The significance of $\Delta P$ is in Figure S2 where $\Delta P$ for three watersheds on Kauai Island are combined. In the figure, it shows that as $Q_{\text{maxest}}$ decreased for individual watersheds, the $\Delta P$ increased (or vice versa). Therefore $\Delta P$ is assumed to be a form of maximum retention since it has a negative relationship to maximum discharge. Furthermore, the CN method indicates that $Q$ and CN have a positive relationship. Therefore, we can assume that “$\Delta P$ and $Q$” or “$\Delta P$ and CN” have a negative relationship.

Figure 5b shows a negative relationship between $\Delta P$ and calibrated CN showing that $\Delta P$ is a form of retention. This relationship was consistent for all watersheds separated to
their individual islands, further indicating that this concept is possibly only applicable to watersheds based on individual islands and not in a combination of islands. \( \Delta P \) is a physical quantity unique to each watershed, possibly providing information on potential retention for island research. However, this study only offers a guide for future development by mentioning dependency and deductive reasoning rather than mathematical interpretations. Furthermore, the magnitudes of \( \Delta P \) explored in this study are obtained only from a geological perspective. Therefore, its potential is yet to be tested and proven as a hydrological tool. The possible future application is mentioned in Text S4 as possible future directions.

CONCLUDING DISCUSSION

This study outlines the possibility of disaggregating the FDC into high, middle and low flow parts shown in Figure 2. Each component has a flexible range rather than a fixed range to account for watershed uniqueness and variability. In the figure, A is the high section from 0–40%, B shows the mid-section from 20–80% and C shows the low flow section from 60–100% EP. The decision for disaggregation points should depend on the user and the studied watershed. Except for Yokoo and Sivapalan (2011) and its related research works, the sectioning of FDCs was not widely tested in literatures and it could be a powerful approach to estimate daily FDC in ungauged watersheds.

Figure 6 shows the methodology used in this study. The MMF was used to estimate flows in the middle section of the FDC where nine of the 11 watersheds showed good estimates. Cheng et al. (2012) and Ye et al. (2012) have found this method to function well in humid catchments that exhibit strong seasonality and in dominant forested catchments but not in agricultural intensified areas where irrigation cannot be ignored. In addition to their work, we could demonstrate that the Yokoo and Sivapalan (2011) framework can be applied in island watersheds in humid tropics.

The CN method was used to estimate streamflow in the high flow part. Tedela et al. (2012) reviewed that the CN method was widely used to estimate runoff from precipitation because it is simple, convenient and the equation uses only one parameter (the CN). Furthermore, Tedela et al. (2012) suggested to calibrate the CN in forested watershed studies to reduce uncertainty. This was consistent with this study in that before calibration, streamflow was poorly estimated for the majority of the watersheds but after calibration estimations were improved. The results also showed that the CWCN was less than the original WCN used, and in most watersheds, the CWCN was less than 30 in contrast to the original CN table (US Department of Agriculture, USDA, 1986) which takes the lowest CN values at CN = 30. The original information used to develop the CN is unavailable, consequently so is the original material used to estimate the tabulated CN for woods (Hawkins et al., 2009;
Fennessey and Hawkins, 2001). This may contribute to the reason CN values are lowest at 30 even if actual values are less. A separate study in Hawaii by Cooley and Lane (1982) concurs that actual CN values are lower than CN table values. The CN method was developed empirically based on studies in agricultural catchments across the United States of America, particularly the Midwest region with continental characteristics, and therefore the CN values for continental US may not be representative of oceanic islands such as Hawaiian Islands. In addition to this, the accuracy of estimations in forested catchments by the CN method is not yet determined (McCutcheon et al., 2006). These reasons including increasing evidence of geological age influencing watershed response (Musiake et al., 1981; Yokoo and Oki, 2009; Yoshida and Troch, 2016) suggest the need for the development of new CN values for Hawaiian Islands. The CN is dependent on HSG which is based on the infiltration rates and these rates differ based on development period or geological age as verified in Hawaii by Lohse and Dietrich (2005). The altitude and the size of island terrain which are dominant hydrological control factors, vary accordingly to the age of the island (Finucane et al., 2012). The Hawaiian Islands are young oceanic islands, possibly having lower CN values than those developed in continental watersheds.

The coefficient of initial abstraction equals zero when calibrated for ten watersheds and is in the expected range 0.00 ≤ λ ≤ 0.3 (Ponce and Hawkins, 1996; Woodward et al., 2010). A study by Ajmal et al. (2016) using the CN method in forested mountainous watersheds in South Korea showed that when λ = 0.2 or 0.05 the results were poor, while when λ = 0.01 or 0.0, it exhibited improved results. Furthermore, the founder of the CN method, Victor Mockus, mentioned that λ could be any value as long as the data warranted it (Ponce, 1996). The CN method is inapplicable for modeling long term hydrologic response of watersheds because it does not include evapotranspiration and evaporation which are effective in non-storm events. It is suitable only to storm loss and its related storm runoff (Boughton, 1989; Ponce and Hawkins, 1996) and is quite evident in this study where the calibrated CN method works well for high flows but gradually offsets when approaching the overlapping range to the middle section. To improve streamflow estimations in the overlapping range, the average values of MMF and calibrated CN values were calculated. For this study, the CN method is used for estimations only in the high flows of the FDC where precipitation and storm runoff are prevalent and this may reduce the effect of ω in the high flow section.

This study glimpses into hydrological studies in islands by using simple tools such as the FDC, MMF and the CN method to make streamflow estimates in island watersheds. The MMF is seen to make proper estimates in the middle section of the FDC and this method has the potential to be used in islands of similar nature as Hawaiian Islands. However, it is yet to be tested. An arctic study by McNamara et al. (1997) signified the importance of geology and soil influencing different responses in different hydrological regions, hence in this study we also discuss the effect of geology in estimating streamflow in the high flow section of the FDC. The CN method is used to make estimates in the high flow section of the FDC, and although it needed further calibration to make better estimations, the study identifies its applicability and weaknesses and in future can be used as a guide to build new CN values for Hawaiian watersheds. The use of simple methods is important in initial stages of studying islands as it builds ideas and opens doors into new methods to be developed specifically for islands in the humid tropics.

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SUPPLEMENTS

Text S1. The Curve Number method
Text S2. Hydrologic soil group and weighted CN
Text S3. Least Mean Square (LSM) method
Text S4. Possible future directions
Figure S1. Selected watersheds from Oahu, Maui and Hawaii Island
Figure S2. Combination of potential maximum absorption capacity for catchments on Kauai Island
Table S1. The classification of hydrological soil group
Table SII. The curve number for woods with different hydrological soil conditions and soil groups
Table SIII. Hawaiian catchment characteristics with calibrated parameters CN and λ based on the year 2009–2010

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