Climate, landscape and vegetation controls of behavioral catchments on dominant runoff response and catchment travel time distribution

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Abstract

The three dominant processes contributing to runoff as proposed by the Dunne diagram are Hortonian overland flow (HOF), Dunne overland flow (DOF) and subsurface storm flow (SSF). Using a theoretical perspective, we investigate the impact of climate, soil, topography and vegetation on catchment water balance and the probability distribution of the travel times of each runoff generation component in respect of the connected instantaneous response function (CIRF) including the interaction of a partial contributing area connecting to the outlet. A simple distributed hydrologic model is used to capture the effect of the catchment response and to estimate the CIRFs under different possible integration of combined effect of climate, soil, topography and vegetation. A set of dimensionless similarity parameters represent catchment functions and provide a quantitative explanation of the conceptual Dunne diagram. Behavioral catchments are defined from the empirical range of the Budyko curve and mainly compatible to the physical relationship as illustrated in the Dunne diagram. The results consistent with the Dunne diagram are: (1) DOF and SSF dominates in humid for behavioral sand and silt catchments, (2) HOF dominates in arid for behavioral silt and clay catchments. Inconsistent results are: (1) SSF dominates in arid for behavioral sand, silt and clay catchments, (2) HOF dominates in humid for behavioral clay catchment and (3) no dominant HOF for behavioral sand catchment. For HOF and DOF dominates, the distribution of CIRFs can be grouped into similar shapes, which depend on the relative contribution of hillslope scale and catchment scale. For SSF behavioral catchments, the shape of the CIRFs depends on the dryness index. The combined catchment CIRFs of mean travel time for runoff responses consists with the higher first peak from the HOF and/or DOF and the second peak from the SSF.

Keywords: Water balance, Runoff generation mechanisms, Dunne diagram, Budyko curve, Catchment travel time distribution, Connected instantaneous response function, Distributed hydrologic model, Catchment function.

1. INTRODUCTION

Infiltration excess runoff (or Hortonian overland flow, HOF), saturation excess runoff (or Dunne overland flow, DOF) and subsurface storm flow (SSF) are the three main and well known runoff generation processes occurring in headwater catchments (Horton, 1933). Dunne (1978) explained that the correlative superiority of three runoff generation mechanisms is governed by the combination of climate, soil, topography, and vegetation as presented in the Dunne diagram (Figure 1). However, this illustration of holistic concept of climate and landscape controls on runoff generation processes is still explained in a qualitative way. Freeze (1980) used a distributed model to examine the influences of climate, soil and topography on the process of runoff generations. Simulated numerical results showed that the occurrence of DOF was constrained by a limited integration of soil and topography effects. A quasi-distributed model applied from TOPMODEL approaches (Beven & Kirkby, 1979) was used to investigate the comparative effect of HOF and DOF mechanisms at the event scale (Sivapalan, Beven, & Wood, 1987; Larsen, Sivapalan, Coles, & Linnet, 1994; Robinson & Sivapalan, 1995). The limitation of their work was only two runoff generation mechanisms and conducted at event scales, and neglecting the effect of antecedent condition and SSF. Many studies applied a physically-based model to investigate the influence of climate, landscape and vegetation on runoff generation processes and the co-evolution of catchment properties based on the Budyko curve (Mirus & Loague, 2013; Carrillo et al., 2011; Troch, Carrillo, Sivapalan, Wagener, & Sawicz, 2013).

[Insert Figure 1]

The Budyko curve is an empirical curvilinear relationship between evaporative index (actual annual evapotranspiration / annual precipitation) and the climate aridity (annual potential evapotranspiration / annual precipitation) (Budyko, 1974). Empirical long-term water and energy balance for the co-dependence of climate, soil and topographic properties reflected in the Budyko curve has become clear in recent years. Jothityangkoon and Sivapalan (2009) investigated the role of climate, soil and vegetation factors in controlling both the mean annual water balance and the inter-annual variability of annual water balance. They found that, seasonality is the main influence on annual water yield. However, only DOF and SSF are used for runoff generation processes. Wang and Wu (2013) investigated catchments across USA and expressed the Budyko-type relationship between annual water balance and the patterns of empirical drainage density. Xu, Yang, and Sivapalan (2012) founded a relationship between the proportion of climatic aridity and deep-rooted vegetation to the whole vegetation from over 200 catchments in Australia. Trancoso, Larsen, McAlpine, McVicar, and Phinn (2016) quantified hydrological similarity across 355 tropical and temperate catchments in eastern Australia and demonstrated the linkage between the Budyko framework and the Dunne diagram by using dominant streamflow response spectrum and catchment clusters concept. They confirmed that three runoff generation mechanisms from the Dunne diagram are compatible with the groups of hydrological similarity and biophysical controls. Xing, Wang, Shao, and Yong (2018) identified significant factors affecting the Budyko curve shape parameters incorporate with different characteristics of catchment; climatic seasonality and agricultural activities. Fu and Wang (2019) investigated the control of precipitation seasonality on the lower bond in Budyko space by conducting hydrological simulations for a given basin. Gan, Liu, and Sun (2021) demonstrated that vegetation dynamics and forest cover play important role on the change of annual runoff by using Budyko model.

Instantaneous response function (IRF) of a catchment is determined as the probability density function for travel times of generated runoff water from any coordinates or pixel within the catchment area to catchment outlet (Wang, Gupta, & Waymire, 1981; Robinson, Sivapalan, & Snell 1995; Saco & Kumar 2002; 2004). To investigate catchment functioning, catchment travel time distribution can be estimated through detailed field measurement, using environmental tracers (McGlynn, McDonnell, Stewart, & Seibert, 2003; McGuire et al, 2005; Hrachowitz, Savenije, Bogaard, Telzlaff, & Soulsby 2013; Selle, Lange, Lischeid, & Hauhs, 2015), by using river network geomorphology analysis (DiLazzaro & Volpi, 2011), and by using distributed hydrological and transport model (Dunn, Birkel, Telzlaff, & Soulsby, 2010; Remondi, Botter, Burlando, & Fatichi, 2019). Most past studies on the estimation of the IRFs considered geomorphologic configurations with simplify assumption that the contribution area to the outlet is the whole catchment (Yang & Han, 2006; Bhunya, Berndtsson, Singh & Hubert, 2008), exception of Sivapalan, Wood, and Beven (1990) and D'Odorica and Rigon (2003) which included the fraction of saturated areas. Few studies have been concerned with the hydrologic connectivity of spatial pattern of runoff generation to the outlet of catchment (Nippgen, McGlynn, & Emanuel 2015; Li & Sivapalan, 2014). Another past assumption for the estimation of IRFs is that flow pathways and their travel velocities for different runoff generation mechanisms were not considered. Dominated HOF may occur in low-permeability soils with high intensity rainfall, with longer path and time on hillslopes. Dominated DOF occurs in permeable thin soils with long storm durations and wide valley bottoms over a saturated riparian area. Dominated SSF occurs in forest area with steep slopes and duplex soils where clay soil is overlaid by high permeability soil, taking longer flow pathways (Robinson & Sivapalan, 1996). Runoff from all three mechanisms participate common stream network pathways. Therefore, the distribution of travel time for different mechanisms of runoff generation on different pathways can be very different. The definition of IRFs is extended to connected IRFs (CIRF), accounting for flow path connectivity based on the concept of partial contributing area (Nippgen, McGlynn, & Emanuel, 2015; Li & Sivapalan, 2014). Li, Sivapalan, Tian, and Harman (2014) developed a simple distributed hydrologic model to simulate the influences of various combinations of climate, soil, and topography on the mechanisms of runoff generation in a large sample of hypothetical catchments.

The aim of this study is to characterize the difference in travel time distribution or timing response for each of three mechanisms of runoff generation processes, integrating the comparative role of climate, soil, vegetation and topography influences. A distributed hydrological model will be utilized to estimate runoff response, flow velocity, travel time, IRFs and finally CIRFs for a large number of hypothetical catchments with a possible combination of climate, soil, vegetation and topographic properties using a quantitative analysis.

2. METHODS

2.1 Distributed Rainfall-Runoff Model

Figure 2 presents a schematic picture of the distributed rainfall-runoff model. Brief description of the procedure for runoff generation simulation is as follows:

(1) Spatial scale and units of the model is defined as DEM pixels, consequentially grouped into hillslope pixels and channel pixels. Soil depth, soil textures and soil-physical properties are defined to each pixel.

(2) A simple pixel model with two soil layers is applied to simulate interactive soil-water processes both in unsaturated and saturated conditions, including water exchange between these two layers to generate runoff and evapotranspiration.

(3) HOF, DOF and SSF are three main mechanisms of runoff generation processes. HOF occurs in a pixel when rainfall intensity is higher than the infiltration capacity. The dynamics of soil moisture in the unsaturated zone influences infiltration rate. DOF occurs in any pixel when the soil column is completely saturated from the bottom, and forming the variable contributing area from a number of saturated pixels. Subsurface storm flow is generated from

saturated zone where pixels are governed by saturated soil depth and downstream hydraulic gradients. At the same time, if the soil column receives water more than what is lost, the saturated zone in the soil column may increase through the ground surface to generate DOF. In this situation, DOF and SSF are co-existing processes. For every pixel and every time step, HOF is estimated based on the local infiltration capacity provided by the Green-Ampt method (Green & Ampt, 1911). Later, the soil moisture content is changed and the other two runoff rates are generated: DOF and SSF.

(4) Surface overland flow is routed to downstream pixels at open channel velocity estimated using Manning's equation and the subsurface flow is routed downstream with Darcy's velocity.

(5) Apart from river network geometry, soil depth and forest vegetation cover, heterogeneity of other parameters are ignored such as non-homogenous of soil properties and preferential flow pathways on the both surface and in the subsurface.

[Insert Figure 2]

2.2 Design of Virtual Catchments and Experiments

Numerical experiments of hypothetical (virtual) catchments are carried out by using combinations of parameters from climatic regimes, topography, soil properties and vegetation. The model, presented in Section 2.1, is used to receive the combination of below parameters to simulate water balance of the catchment. The selected range of parameters combinations is presented below.

2.2.1 Climate regimes

Nine climate regimes were designed to cover a common range of climatic characteristics from arid to humid, provided by Hawk and Eagleson (1992) and Salvucci and Entekhabi (1994). The details of different climatic regimes are presented in Table 1. The temporal pattern and variability of rainfall and potential evapotranspiration is governed by storm duration, inter-storm period, mean rainfall intensity and potential evaporation rate. In all generated climatic regimes, storm duration and inter-storm period and rainfall intensity are constrained to a constant mean annual rainfall of 1,000 mm. But these input parameters are presumed to be spatially uniform for small catchments. The effects of inter-annual and intra-annual variability, within-storm variability and seasonality are ignored to keep these experiments simple.

[Insert Table 1]

2.2.2 Topography

All virtual catchments applied in this study are developed based on the 30 m × 30 m DEM for a realistic catchment with 4,019 pixels, 3.62 km^2, located in LamTaKlong subcatchment of Mun River catchment, Nakhon Ratchasima province, Thailand. Three categories of slope distributions (mild, moderate and steep) are generated by multiplying the initial pixel slopes with a constant factor, details are presented in Table 2. Overall steepness of the hillslope is chosen for this study, which is the most dominant control, compared to the other hillslope distributions including convergence/divergence and convexity/concavity. A topographic map of the catchment is presented in Figure 3.

[Insert Figure 3]
[Insert Table 2]

2.2.3 Soil properties

The required properties of each soil texture for the pixel model included, soil depth saturated hydraulic conductivity, effective porosity, wetting front soil suction head, bubbling pressure and pore-size distribution index. These properties are spatial and scaling variability, and it variability regulates the response. Only the different soil texture is chosen to investigate and leave the other factors to be considered in future research. Hydraulic properties of the soil are varied according to three texture classes: sand, silt loam and clay loam, shown in Table 3. For each class of soil texture, hydraulic conductivity is adopted to vary in three orders of magnitude, 10^{-6}-10^{-4}, 10^{-7}-10^{-5} and 10^{-8}-10^{-6} m/s for sandy soil, silt loam and clay loam, respectively. For the sandy soil, 15 selected hydraulic conductivity values are 1×10^{-6}, 3×10^{-6}, 5×10^{-6}, 7×10^{-6}, 9×10^{-6}, 1×10^{-5}, 3×10^{-5}, 5×10^{-5}, 7×10^{-5}, 9×10^{-5}, 1×10^{-4}, 3×10^{-4}, 5×10^{-4}, 7×10^{-4}, 9×10^{-4} m/s. These chosen values are applied for the other two soil textures. Variation of soil depth (Z_x) is assumed to be a linear function of the topographic wetness index ($\ln(a/\tan\beta)$) (Stieglitz et al., 2003).

$$Z_x = \overline{Z} - (1/f)\left[\ln(a/\tan\beta)_x - \lambda\right] \tag{1}$$

where a is area drained per unit contour length, β is angle of local slope, $\overline{Z}$ is mean water table depth (WTD), λ is mean catchment value of $\ln(a/\tan\beta)$, and f is declining rate with depth of saturated hydraulic conductivity in the soil column. The depth parameter of this function is adjusted to keep the mean soil depth over the entire catchment under three representative cases of soil depth: shallow, moderate and deep with 1.0, 2.5 and 4.0 meters, respectively (Table 4) ($\overline{Z} = 2$ m, $\lambda = 5.18$, $f = 1$).

[Insert Table 3]

[Insert Table 4]

2.2.4 Vegetation

Three types of vegetation cover are varied based on three groups: full (M = 1), partially cleared (M = 0.5) and defoliated (M = 0).

2.3 Analysis of catchment function and response

For a watershed dividing and area, defined as a control volume, partitioning of received precipitation input to a runoff output through a combination of multiple catchment functions. The damping function is defined as soil getting wet from falling precipitation on a land surface and infiltrating into the soil. The storing function is defined as water being stored within the control volume in different pathways of surface and subsurface water, soil moisture, snow and ice. The draining function is defined as water loss from the catchment in two directions: evapotranspiration in the vertical flow, and the gravity flow of drainage water in a horizontal or down slope direction. The drying function is defined as the soil drying by evapotranspiration and a reduction in the amount of drains or runoffs. These functions interact with multiple scales (pixel, hillslope, catchment) potentially lead to new evidence of emergent annual water balance behavior at the watershed scale, respected on the concept of the Budyko curve.

The integration of 9 climate regimes, 3 different soil textures, 3 different slopes, 3 different soil depth distributions, 15 hydraulic conductivity values for each soil texture and 3 different vegetation covers give 10,935 virtual catchments for the simulation cases for the hydrological model.

Annual water balance

The annual water balance is characterized in forms of a two-stage partitioning. For the first stage, the precipitation (P) is partitioned into infiltrated water in the soil (damping W) and the rest of P or excess rainfall flows as a fast runoff of HOF and DOF ($Q_H + Q_D$). It is a competitiveness between damping function and fast surface runoff. For the second stage, the infiltration of water as damping (W) is separated into evapotranspirartion (E) and leaving the catchment in the character of slow runoff i.e. SSF (Q_S). It is a competitiveness between damping function and slow surface runoff. The equation for annual water balance can be formulated as:

$$P = Q_H + Q_D + W \tag{2}$$

$$W = Q_S + E \tag{3}$$

where $Q_H + Q_D$ is the fast runoff and Q_S is the slow runoff.

To investigate the competition between these functions for a catchment, a functional similarity framework is proposed to discover common catchment responses in model prediction of annual water balance. A set of dimensionless parameters for similarity framework composed of relevant climate, soil, vegetation and topographic parameters, are selected and simulation are performed with the results allowing a capture of the competitiveness between the various functions within the catchment (Li, et al., 2014).

Damping vs. Surface draining: This similarity variable is indicated as the infiltration index (α), representing the partitioning of rainfall on soil surface to infiltration (damping) and HOF, as follows:

$$\alpha = \frac{K_S}{i} \tag{4}$$

where K_S is the upright hydraulic conductivity in saturation condition, and i is the average rate of rainfall intensity. A large α value means that more rainfall percolated through the soil, resulting in wetter soil. A smaller α means more rainfall becomes HOF.

Damping vs. Drying: the index of climatic aridity (Gamma, γ) is introduced as:

$$\gamma = \frac{E_p}{P} = \frac{N \cdot e_p \cdot (t_r + t_b)}{N \cdot i \cdot t_r} \tag{5}$$

where E_p is the annual potential evaporation, P is the annual precipitation, e_p is the mean potential evaporation rate, t_b is the mean inter-storm period, i is the mean rainfall intensity, t_r is the mean storm duration and N is the number of storms. This dimensionless parameter presents the competitiveness between the cause of drying function E_p and the cause of the damping function P.

Damping vs. Storing: we use a storing index (Sigma, σ) to explain the competitiveness between the storing and damping functions. It is determined as the proportion of the averaged storing capacity (S_b) in the catchment to the annual precipitation (P)

$$\sigma = \frac{S_b}{P} = \frac{d \cdot \phi}{N \cdot i \cdot t_r} \tag{6}$$

where d is the mean soil depth, ϕ is soil porosity.

Damping vs. Subsurface Draining: The dimensionless drainage index (Beta, β) is defined to explain competitiveness between the annual discharge from subsurface drainage and annual rainfall at the catchment scale as follows:

$$\beta = \frac{D_p}{P \cdot A} = \frac{2L \cdot d \cdot K_S \bar{S} N(t_r + t_b)}{N \cdot i \cdot t_r \cdot A} \tag{7}$$

where K_S is the effective lateral hydraulic conductivity in saturation condition, $\bar{S}$ is the mean slope of the catchment bed rock, L is the length of stream channels within the stream network. The subsurface drainage capacity D_p can be defined as the maximum quantity of subsurface water, discharged by both banks for the entire length of the stream network (2 L) from the soil thickness d at the averaged Darcy velocity ($K_S \bar{S}$) over one year, $N(t_r + t_b)$.

2.4 Connected Instantaneous Response Function (CIRF)

The travel time for any runoff is estimated by the accumulation of time runoff spends on the different flow pathways from its original location of runoff generation to the watershed outlet,

$$T = \sum_{i \in L} \frac{\Delta x_s}{V_s} \tag{8}$$

where T is the travel time, V_s is the local constant velocity within a local pixel $i \in L$, L is the total distance comprising the whole flow path and Δx_s is the length of a local pixel.

The instantaneous response function (IRF) is determined as the probability density function of travel time of discharge from original location where it is generated to the outlet of the catchment downstream (Snell & Sivapalan, 1994; Robinson, et al., 1995). The IRF at time τ , $h(t/\tau)$ is defined as follow:

$$h(t|\tau) = \frac{d}{dt} P(T \le t|\tau) \tag{9}$$

where $P(T \le t|\tau)$ is the probability density function for the travel time. The IRF is extended to incorporate for each component of runoff generation, i.e., separated IRFs for HOF, DOF and SSF. The equation (9) is written as:

$$h_\psi(t|\tau) = \frac{d}{dt} P(T \le t|\tau, \psi) \tag{10}$$

where ψ represents various runoff generation processes. Depended on the concept of time varying and contributing (or source) area everywhere within the catchment, the whole catchment contributes to infiltration excess runoff when the rainfall intensity is larger than the particular infiltration capacity or the whole catchment has saturated soil-water storage due to longer rainfall duration. However, these conditions rarely occur, partial contributing area is much more common. Runoff from partial part of the whole catchment is hydraulically linked to the stream network and to the outlets because of the spatial heterogeneity of the runoff generation processes. Some areas are isolated from the stream network by the remaining unsaturated area. Runoff from these unconnected areas may not arrive at stream network as a consequence of re-infiltration over dry periods (Figure 4). Only pixels in blue in Figure 4(b) are defined as the contributing area for the estimation of the IRF. The equation (10) is revised as:

$$h_{\psi}\left(t|\tau,\psi\right) = \frac{d}{dt}\left[P\left(T \le t|\tau,\psi\right)\cdot P\left(\rho = 1|\tau,\psi\right)\right] \qquad (11)$$

where ρ is an indicator state variable, $\rho = 1$ if a pixel is hydraulically linked to the stream network and catchment outlet, $\rho = 0$ if not. The IRF is represented the connected instantaneous response function (CIRF) and it can be estimated for a single mechanism of runoff generation processes at a given time duration, denote h_{Horton}, h_{Dunne} and h_{Sub} matching to HOF, DOF and SSF, respectively.

The CIRFs are calculated based on spatially distributed water sources, runoff pathways, travelling length, and velocities of travelling water provided by a spatially distributed hydrologic model. Two kinds of dispersions from geomorphology and kinematics, are already included in the model for both hillslope and stream pathways (Li, et al., 2014).

[Insert Figure 4]

3. RESULTS

3.1 Controls of climate, soil, topography and vegetation on the annual water balance

For the first step of separation of received rainfall into infiltration (damping) and overland flow (surface draining) through the viewpoint of the functional approach, Figure 5 demonstrates the relationship between the proportion of annual HOF to annual precipitation (Q_H/P) and the infiltration index α .

[Insert Figure 5]

Figure 6 shows a family of curves, Q_S/W is plotted against the dimensionless drainage index β, having a typical shape of characteristic curve. For each curve, obtains that Q_S/W is zero when β is below a critical value. Above this critical β, Q_S/W increases rapidly with an increasing β and asymptotically approaches a maximum value due to no more increases in the subsurface flow (Q_S).

[Insert Figure 6]

Figure 7 presents the proportion of volumes between DOF and SSF (Q_D/Q_S), as a function of the drainage index (β). As the drainage capacity or drainage index (β) increases, the saturated soil-water discharges rapidly as SSF, resulting in lower saturated soil-water storing, a lower fraction of saturated area contribution, thus giving a smaller volume of DOF and lower values for Q_D/Q_S with all climate regimes.

[Insert Figure 7]

3.2 Behavioral constraints on the annual runoff for behavioral catchment

All possible combinations of parameters from climatic regimes, topography, soil properties and vegetation do not exist in nature with equal probabilities and frequencies. Some parameters are more likely to occur than the others. At specific spatial and temporal scales, mean annual water balance of feasible catchments are more likely to follow empirical relationship of the Budyko curve (Budyko, 1974). These parameter combinations of the virtual catchments are called “behavioral” and are analyzed and compared with the Budyko curve with a certain allowance.

The calculated results are presented in Figure 8, where the solid line represents the empirical Budyko curve and all points are predicted E/P by the water balance model for virtual catchments. To include the allowance for uncertainty in the Budyko curve, the allowance band $[(E/P)_{Budyko}-e_1, (E/P)_{Budyko}+e_2]$ for the lower and upper bounds of the mean Budyko curve are drawn. There is some empirical evidence that most of the observed E/P fall within the 10% range of the Budyko curve (Gentine, D’Odorico, Lintner, Sivandran, & Salvucci, 2012). The parameter e_1 is selected as 10% of the disparity between $(E/P)_{Budyko}$ and zero, which is the lowest value for E/P, The parameter e_2 is selected as 10% of the disparity between E/P and $(E/P)_{Budyko}$ (when $E_p/P < 1$) or 1.0, which is the highest value for E/P.

[Insert Figure 8]

The plot of the drainage index β, versus the aridity index, γ or E_p/P, for the behavioral catchments are presented. These results are grouped in terms of three different soil types and the three dominant runoff mechanisms in Figure 9. Both axes in these Figures are reversed from high to low values to keep the trend in agreement with the Dunne diagram (Figure 1). These results in Figure 9(a) for the behavioral sand revealed that DOF dominates in humid climates (low E_p/P) when the damping function of the catchment dominates the subsurface drainage by more than a factor of ten ($\beta < 0.1$), and the subsurface discharge dominates when the subsurface drainage value is higher than the value of damping function ($\beta > 0.1$).

[Insert Figure 9]

For behavioral silt in Figure 9(b), DOF dominance is similar to behavioral sand, but HOF dominance occurs in arid climates when $\beta < 0.2$ ($E_p/P = 2$), as well as in semi-humid climates ($Ep/P \approx 0.875$ to 1.00) when $\beta < 0.07$.

For behavioral clay as seen in Figure 9(c), DOF dominance is similar to that with silt in a humid climate. HOF dominance occurs not only in an arid climate but also in humid and semi-humid climates. In humid climates ($Ep/P \approx 0.5$ to 0.625), the dominance of runoff generation can vary between HOF, DOF and SSF as the drainage index varies from very low ($\beta < 0.001$) to moderate and high values ($\beta > 0.1$).

3.3 Examples of component CIRFs

By using the distributed hydrological model for certain virtual catchments, CIRFs are constructed at the end of the duration of rainfall input. Figure 10 demonstrates examples of dimensionless CIRFs of the three components: h_{Horton} for HOF, h_{Dunne} for DOF and h_{Sub} for SSF, which area under each curve is in unity. The travel time distribution corresponding to the various mechanisms of runoff generation processes. The CIRF of DOF (h_{Dunne}) has a larger peak, lower time-to-peak and a shorter base time compared with the CIRF of HOF (h_{Horton}) and the CIRF of SSF (h_{Sub}) (Figure 10).

[Insert Figure 10]

Figure 11 presents the development of the saturated area during a storm event from model results, in which the hydrologic responses on the catchment scale have been reasonably captured. Table 5 shows the mean travel times for each mechanism of runoff generation process averaged over the behavioral catchment with the same climatic, topographic soil and vegetation conditions which were used to generate Figures 12 to 14.

[Insert Figure 11]

[Insert Table 5]

3.4 Dimensionless CIRFs

To gain an understanding of different mechanisms of runoff generation processes and the impacts of climate, soil, vegetation and topography, we generated a simulation and analyses for behavioral catchments that comply with the Budyko curve, within a 10% band nearby the curve. This included a combination of climate, soil, vegetation and topography used to produce the mean annual water balance with the number of behavioral catchments being 2,286 out of 10,935 virtual basins (Table 6). A non-dimensionalisation of the CIRFs is estimated by normalizing the travel time distribution by mean travel time for each mechanism, to exhibit the dispersion effects.

[Insert Table 6]

Figure 12 (a) presents the dimensionless CIRFs for HOF from over 467 combinations (Silt = 120 and Clay = 347) at the hillslope scale. These mixtures are chosen respected on two criteria: (1) behavioral, and (2) a HOF dominant runoff process. For HOF dominant, the shapes of the dimensionless CIRFs at the catchment outlet are similar and the contributing area is relatively stationary under uniform soils and rainfall intensities, shown in Figure 12(b). The relative involvement of hillslope and channel travel time substantially affected the shape of the dimensionless CIRF. From the hillslope scale to the catchment scale, the shape of CIRFs for HOF are changed from high peaks with strongly positive skewed curves to lower peaks with weakly positive skewed curves, which are governed by channel responses.

Figure 13 (a) (b) present the dimensionless CIRFs of DOF from behavioral catchments for the hillslope and catchment scales. For the catchment scale, two CIRF shape patterns are exhibited. The first pattern is similar to HOF with high peaks and a positively skewed curve. The second pattern, opposite to the HOF, is solely affected by the contribution of the hillslope response.

Figure 14 (a) to (d) presents CIRFs for SSF. The shapes of CIRFs for the different climatic regimes are not too different with high spike peaks with positive skewed curves. For humid and semi-humid climates, a more flat distribution of CIRFs with a broad distribution of dimensionless travel time presents itself.

[Insert Figure 12]

[Insert Figure 13]

[Insert Figure 14]

3.5 Controls on Mean Times Spent Travelling

Figure 12 (c) and (d) present mean travel times for HOF from hillslope scale and mean travel times to catchment outlets, graphed as a function of a dimensionless parameter (Zeta, ζ) (Li & Sivapalan, 2014):

$$\zeta = \frac{(t_r + t_b)}{\alpha \cdot t_r} S_{surf} \qquad (12)$$

where t_r is the mean storm duration, t_b is the mean inter-storm period, S_{Surf} is the averaged slope of land surface of the watershed, and α is an infiltration index (Equation 4). Hillslope travel distance, from a hillslope pixel generating runoff to the nearest channel pixel, is normally much shorter than the travel distance in a channel (from a channel pixel to the watershed outlet), and the channel velocity is much higher than the hillslope velocity. These travel times counterbalance for each other.

The travel times of DOF is calculated by the flow velocity of excess runoff on the saturated area, and the travel distance was measured using the size of the linked saturation area. Figure 13(c) presents the distribution of DOF travel times as a function of saturated area to total area, A_{sat}/A_{Total}. Figure 13(d) shows that the draining function is influenced by the damping function when β is very small. Higher β indicated that the drainage capacity influences over the damping function, and soil-water discharges are increased with the SSF, while the area of saturated soil is decreased. The effect of γ on the proportion of saturated area is that, a higher γ implied a drier climate providing a smaller saturated area.

Figure 14 (e) presents the mean travel times of the SSF as a function of the multiple of $K_s S_{sub}$, where K_s is the saturated hydraulic conductivity of the soil and S_{sub} is the average bedrock slope.

3.6 Controls of Climate and Landscape on CIRFs

The mean travel times for the three mechanisms of runoff generation processes are different as presented in Figure 10. The assumption of their interaction is simplified so that they are considered independent. The combined CIRF ($h(t)$) can be estimated by a linear superposition of the various components CIRFs, as fallow:

$$h(t) = \frac{Q_H}{Q_H + Q_D + Q_S}\overline{h_H}(t) + \frac{Q_D}{Q_H + Q_D + Q_S}\overline{h_D}(t) + \frac{Q_S}{Q_H + Q_D + Q_S}\overline{h_S}(t) \qquad (13)$$

where Q_H Q_D and Q_S are the quantity of generated runoff from the HOF, DOF and SSF, respectively. These quantity proportions have an influence on the formation shape of the combined CIRFs, particularly, the magnitude and duration of the multi peaks of CIRF.

For the catchment scale, the combined CIRFs are demonstrated in Figure 15 for different specific cases to investigate how the contribution of different runoff mechanisms affect the resulting CIRFs. The list of all main parameters, which are averaged values of the catchment and relative volume proportion of the various runoff mechanisms, is presented in Table 7. Figure 15 presents the shape of CIRFs with two peaks, a quicker shape with spike peak caused by overland flow, and a platykurtic (flat) distribution with slower peak due to SSF. For some combination of climate, soil, topography and vegetation, the first peak is high if surface overland flow (HOF and /or DOF) is the dominant volume, and the second peak is high if SSF is the dominant volume.

[Insert Figure 15]

[Insert Table 7]

Figure 15(a) presents the effect of climate (humid, semi-arid and arid) on a selected behavioral catchment with similar soil type, mean surface slope, soil depth and a chosen effective mean hydraulic conductivity. There is no HOF in any of the three cases. This means that the infiltration capacity of the sand soil is always larger than the rainfall intensity.

For a humid climate, the DOF appears in the first peak (the thin blue line), relating to the surface runoff of DOF from the saturated hillslope area and SSF appears in the second peak (thin red line).

Figure 15(b) presents the impact results of different slopes of topography on CIRF. Only DOF and SSF are feasible in this condition. With increasing slope, more water moves downhill direction with a higher velocity and less water ex-filtration, inducing in lesser saturated area and lower proportion of DOF. For mild slope, combined CIRF (thick purple line) is almost identical to CIRF of DOF (thin blue line) due to a high proportion of DOF compare to SSF.

The effect of saturated hydraulic conductivity (K_s) are presented in Figure 15(c). For the low K_s equated to the rainfall intensity, a low ratio of the rainfall percolates allowing the HOF to completely dominate compared to the DOF and SSF, resulting in the clear appearance of the first peak due to the HOF.

The results of soil depth are illustrated in Figure 15(d) and Table 7. Soil depth is increased from shallow sand to deep sand, dominant runoff is still DOF with higher proportion of SSF. For shallow soil, combined CIRF (thick purple line) is similar to CIRF of DOF alone (thin blue line) because of low proportion of CIRF of SSF (thin red line). The effect on runoff composition causes the smaller of the first peak and higher of the second peaks. HOF does not occur due to chosen K is large, all of water is infiltrated.

The effect of vegetation cover is presented in Figure 15(e). For the defoliated condition, a high ratio of DOF cause combined CIRF (thick purple line) is identical with CIRF for DOF (thin blue line) compared with the CIRF for SSF (thin red line).

4. DISCUSSION

4.1 Controls of behavioral catchments

On the annual water balance, a large α means that more rainfall has infiltrated into the soil and less rainfall is partitioned as HOF. With an assumption of constant rainfall intensity, uniformity of soil properties and anisotropic hydraulic properties of the soil, the value of HOF can be underestimated value (Figure 5). The maximum value of Q_S/W is a function of the climate and soil properties, if a catchment is more arid and the soil textures is more silt and clay, the maximum value of Q_S/W is smaller (Figure 6). Results from the catchment with sand, silt and clay soil also provides a similar pattern and variation between (Q_D/Q_S), as a function of the drainage index (β)(Figure 7).

Only virtual catchments that provide E/P values inner these allowances are classified behavioral (Figure 8). Due to the inclusion of vegetation parameters, the number and distribution of the points of this study are higher than the results from Li and Sivapalan (2014). The cross symbols between the lower and upper bounds in Figure 8 represent behavioral catchments. The number of behavioral catchments is about one in five for the entire set of virtual catchments.

Results on reversed scale plot of the drainage index (β) versus aridity index (γ) are compatible with the Dunne diagram. For behavioral sand, Figure 9(a) also presents that dominant process under arid climates could be SSF (high E_p/P) different from the expectation of the Dunne diagram and the dominance of HOF is not feasible in all climatic regimes, which is inconsistent with the Dunne diagram. Sand soil with a high infiltration capacity under arid climates may reduce the dominance of HOF and enhance the dominance of SSF. However, if sand soil is disturbed by human activities such as agricultural processes resulting from increased soil compaction, the dominant runoff can shift from SSF to HOF, consistent with the Dunne diagram. Results of behavioral silt are corresponding with the Dunne diagram. Some inconsistencies include the occurrence of dominant SSF in an arid climate, which can be explained by the same reasoning as with the case of sand soil (Figure 9(b)). For behavioral clay, the presence of dense vegetation on clay soils in humid and semi-humid climates may decrease the existence of HOF and enlarge the dominance of DOF and SSF through the role of preferential flow such as with macro-pores and cracked soil, which is are excluded in this study (Figure 9(c)).

4.2 Flow paths and travel time

The travel pathway and travel velocity govern the travel time of each runoff component. The travel pathway of both HOF and DOF comprises of two components: a hillslope component and a channel component which has a higher velocity than the hillslope component. The saturated area is in a small proportion of the whole watershed area. This causes the travel time of DOF across the hillslope component to be less than the travel time for HOF (Figure 10).

The SSF flow paths comprises of four portions: vertical unsaturated infiltration from the ground surface to the saturated soil layer, the horizontal saturated subsurface flow to the location of seepage (exfiltrates cross the saturated area), the overland flow portion across the saturated area, and the flow through the stream network to the watershed outlet. For simplicity, vertical flow is assumed arriving at the saturated zone instantly after vertical infiltration, followed by lateral movement. Therefore, the flow paths of SSF comprise of a hillslope portion (lateral subsurface), a saturated zone portion, and a channel portion. The velocity of the subsurface flow is much less than the velocity of overland flow. Consequently, the travel time of subsurface flow is much longer than that of the overland flow and the channel part. CIRF of h_{Sub}, depicted in Figure 10(b), is governed by the hillslope subsurface flow on the hillslope. The anisotropy of saturated hydraulic conductivities and macro pore effects are ignored in this study. This is persuaded by the truth that there is no generally accepted upon approach to include their effects in a valid manner.

4.3 Controls of CIRFs

The mean travel time and the non-dimensionless CIRFs can be controlled by various mechanisms of runoff generation processes, the distribution of flow pathways is separated to hillslope pathways (surface and subsurface) and stream pathways that relate to channel flow velocities. For the condition of HOF, the effective area contributing to the HOF is an unsaturated hillslope area where rainfall intensity is higher than a local infiltration capacity and is linked to the outlet. The travel time is estimated from a summation of the travel time on hillslope and in the channel.

For controls on the mean travel times of DOF, the enlargement of the linked saturation area contributes to the increase of hillslope travel times due to the longer travelling distance (Figure 13(c)). Accumulated surface water and its depth at the lower part of a hillslope cause the increase in velocity of overland flow. Inversely, the travel times is decreased at the lower portion of the hillslope. This compensation effect provides to retarding of the increase in the travel times on the hillslope over the size of the saturated area of the catchment. The variation of A_{sat}/A_{Total} is found engaged by two dimensionless parameters, the catchment drainage index (β), and the dryness index (γ) introduced by Li and Sivapalan (2014).

The SSF travel times are estimated using Darcy 's law with simplifying assumptions: neglecting anisotropy, macro pore effects and ignoring the travel time in the unsaturated zone. The variation in simulated travel time may come from connected pixels in a series of subsurface runoff routing (Figure 14(e)). The sizes of the SSF travel time estimated in this study are not reasonable equated to the tracer-based estimation of the SSF residence time (McGuire et al., 2005).

The mean travel times are widely different for three mechanisms of runoff generation processes. Hillslope travel times for HOF is in the same order of magnitude as the channel travel times in all cases, which is proved by the similar shape for the dimensionless CIRF. For DOF, travel time is smaller unless the whole area is saturated and the channel travel times are still dominant. Subsurface travel time in the hillslope is much longer than the travel time in the stream network. Therefore, the total travel time for SSF is dominated by the travel time on the hillslope.

Combined CIRFs of humid climate (thick purple line) present second peak with high amplitude because the dominant runoff type is SSF. For an arid climate, the surface runoff DOF disappears and the subsurface runoff portion has a retarded peak relative to more humid climates. This means that the climate has an impact on the runoff composition between the DOF and SSF, and for the subsurface component of the CIRF (Figure 15(a)). Under steeper topography, the amplitude of the first peak (from DOF) is lower and times-to-peak is faster, together with the second peak (complementary to SSF), the amplitude is larger and time before the peak is faster (Figure 15(b). The distribution shape of the combined CIRF for the low K_s (thick purple line) is similar to the individual CIRF of HOF (thin green line) due to a higher proportion of the HOF over the DOF (thin blue line) and SSF (thin red line). For moderate K_s, HOF disappears and the dominant runoff shifts to DOF over SSF, providing a larger spike peak and shorter times-to-peak. For a high K_s, the subsurface flow is the most contribution, directing to a co-existent second peak with a low amplitude and a long time-to-peak (Figure 15(c). Shallow soil has low soil-water storage capacity, and the storage is easily filling up, generating more dominant DOF and the first peak of CIRF. The smaller first peak and the higher second peak are found with increasing soil depth. (Figure 15(d)). Different vegetation cover does not give significant changes to CIRF shapes. (Figure 15(e)).

5. CONCLUSIONS

Inspired by the Dunne (1978) diagram, this study has investigated the climate, soil, topography and vegetation controls on the annual water balance and on the temporal runoff responses, in the configurations of the IRF at a pixel scale and a catchment scale. The total runoff responses are qualitatively divided into three groups of runoff generation mechanisms: HOF, DOF and SSF. By using a simple distributed hydrologic model, adopted for the purpose of a functional model, the model incorporates the damping, storing, draining and drying functions at the pixel scale represented soil column. The role of climate, soil, topography and vegetation on these functions are parameterized and applied at the watershed scale from upstream to downstream connection between all three mechanisms of runoff generation processes. A large set of hypothetical catchments from a possible range of climate, soil, topography and vegetation parameters is used to produce catchment responses that represent the real world complexity of natural conditions.

For each runoff generation mechanisms, IRFs are estimated in the format of a CIRF including the dynamics and connectivity of contributing area of runoff generation to the watershed outlet. In this manner, the derived CIRFs are similar to what exhibits in a real catchment. The controls of climate, soil, topography and vegetation on the temporal responses are investigated separately for each component of the CIRFs and combined catchment CIRF. The finding from detailed analyses of the simulations using the distributed model can be separated into three parts, make a summary below:

Firstly, from wide range of parameter, the runoff response at the spatial scale (catchment) and temporal scale (annual) can be explained in the form of concise functional relationship. These relationships are represented by a small number of dimensionless similarity parameters including the aridity index, infiltration index, storing index and draining index. These indices provide qualitatively view of the climatic and landscape controls on dominance mechanisms of runoff generation processes, presented in the Dunne diagram.

Secondly, simulation results representing the combined effect of climate, soil, topography and vegetation parameters were carried out in the setting of the physical characteristics of the Dunne diagram and the setting of physically based hydrological models. The results of the simulated mean annual runoff from the combination of full set of parameters were constrained by the empirical Budyko curve, distinguished feasible results in nature or “behavioral” catchments. The full set of parameter combination is integrated, which may be expected in real catchment. The results from our model indicated that the absence of dominant HOF or HOF never coexist with DOF and SSF for behavioral sands. For behavioral clay, the results showed that dominant HOF, DOF and SSF exist in humid climates and dominant DOF disappeared when moving to an arid climate. For behavioral silt, only dominant DOF and SSF are presented in a humid climate.

Thirdly, mean travel time for each runoff mechanisms are distinctly different from each other, due to the variation between the pathways of each mechanism (travelling lengths, velocities, and its variation). From the large number of virtual numerical experiments, the CIRFs for each of three mechanisms of runoff generation processes, are non-dimensionalised and plotted versus non-dimensional mean travel time. These relationships can be compacted into similar characteristic shapes. The results of the combined catchment CIRFs are conforming to results achieved by Li and Sivapalan (2011, 2014).

To keep the model simple, many assumptions were made: (1) not including anisotropic soil properties, e.g. lateral hydraulic conductivity is constant in all directions, (2) ignoring preferential flow in soil: macro-pores flow, finger flow and funnel flow, (3) ignoring the time spent travelling in the vertical unsaturated zone, (4) ignoring the structure heterogeneity of bed rock topography. Despite these limitations, this study gives a greater understanding about the characteristics of the runoff timing (routing) response. These study results provide a theoretical framework for the analysis of the results from field studies for the estimation of travel time distribution in a catchment, with points of view reflecting the underlining climate, soil topography and vegetation controls.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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