Innovative Engineering and Sustainability
Journal Homepage: https://iesj.ft.uns.ac.id
Article ID: 1(2): 50-60

Geomorphological Parameters that Influence the Hydrologic Response of the Watershed

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ABSTRACT

There are many parameters of the watershed that govern the hydrologic responses in the process of rainfall-runoff process. One of the parameters is geomorphological parameters. Some parameters have been well known for their contribution to streamflow discharge, the other parameters do not. We explore some geomorphological parameters that strongly influence the hydrologic response of a watershed, but received inadequate attention to be investigated and discussed. We refer to a rainfall-runoff model in which rainfall is the primary input parameter and runoff in the stream is the output. By identifying a number of rainfall-runoff and other hydrologic models, the data parameters required to run the mode and obtain the output i.e. flood could be identified. We concluded that the watershed parameters of the hypsometric curve, watershed shape, drainage density, channel length, channel slope, channel cross-section, Horton's stream, degree of meandering, are important watershed parameters but lack attention from scholars.

Keywords: Hydrology, hydrometeorology, geomorphology, watershed, parameter, hydrologic response.

ARTICLE HIGHLIGHTS

Received: 28 September 2022

Received in Revised Form: 30 October 2022

Published Online: 31 December 2022

Keywords: Hydrology, hydrometeorology, geomorphology, watershed, parameter.

DOI:

1 Introduction

A watershed or a river basin is a physical and geographical area of land bounded by interconnected highest points along the boundary, in which the precipitations fall within this land drain to the streams and flow to a common outlet such as any point along a larger channel, a reservoir, or a river mouth. A schematic illustration of a watershed is given in Figure 1. A watershed is a unit of hydraulic design, a unit of water resources development, or any other unit associated with hydraulics and hydrology (Singh & Frevert, 2010; Daniel, et al., 2011). It is, therefore, deemed necessary to scrutiny the characteristics of the watershed by exploring the measurable parameters of the watershed.

A watershed stores geographical and geomorphological information that are important and will exhibit the response of the watershed whenever rainfalls are given as inputs of the watershed to produce the response of the watershed.

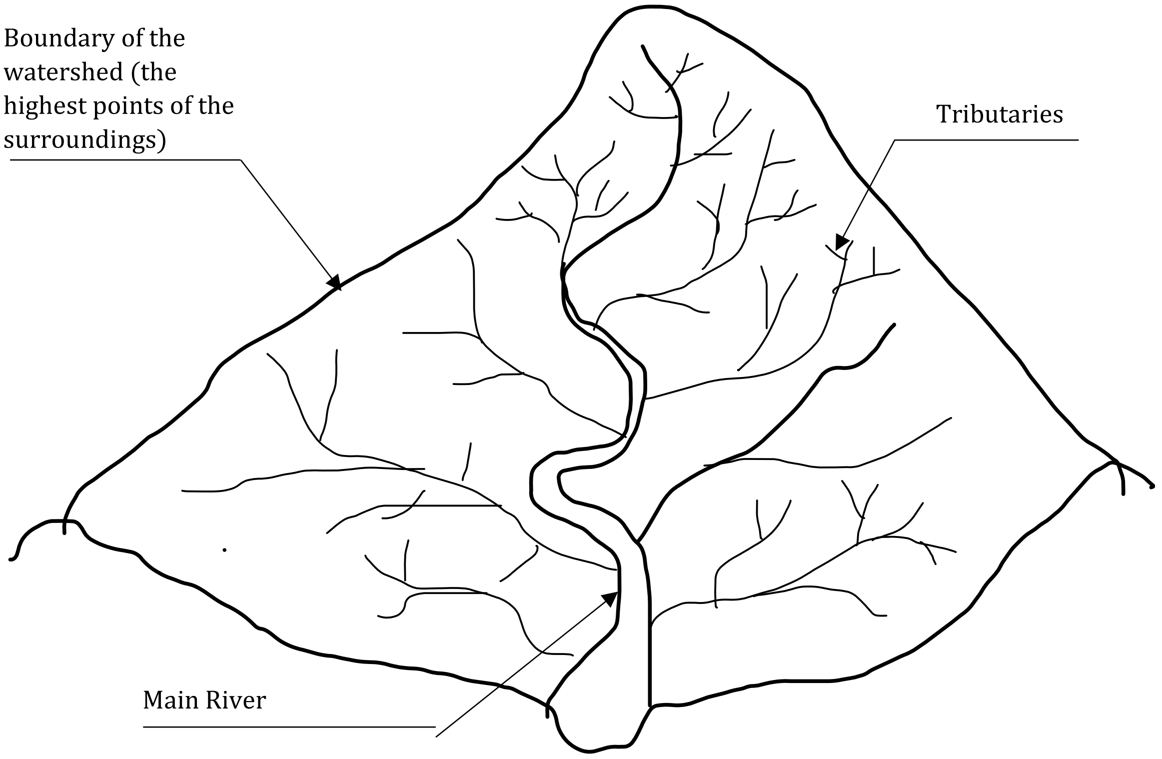


Figure 1 A Watershed

The watershed contains many parameters that determine its characteristics. Thus, to understand the response of the watershed to a particular hydrological event, we need to understand the parameters associated with this event. Some important geomorphological parameters of the watershed are drainage area, length, slope, shape, hypsometric characteristics, main channel length, main channel slope, drainage density, stream density, and Horton's law of stream (Duan, Gupta, Sorooshian, Rosseau, & Turcotte, 2003).

This study aims at accomplishing a philosophical understanding of the correlation between watershed parameters and flood events through reviewing relevant references and secondary data. With this understanding, the planning and design of flood control works could be carried out more optimally, as the planning and design variables are acquired based on the nature of the watershed and the main river.

2. A Random Process for Hydrological Event

There are two primary domains in our study, namely flood events or rainfall events (stochastic process), and watershed characteristics (deterministic qualities). These two domains are strongly connected by rainfall-runoff relationships, for example, through the rational peak discharge formula. We start the discussion by following these two domains. The discussion

A natural process is a random process, and in a hydrological process, this natural process is a stochastic process (Koutsoyiannis, 2006; Koutsoyiannis, 2013). With a precipitation event, this natural process can be mathematically expressed as:

$$P_t = \{P(t)\}_{t \in T} \quad [1]$$

where $T = (0, \infty)$ and $(P_t, t \geq 0)$, and is schematically illustrated in Figure 2.

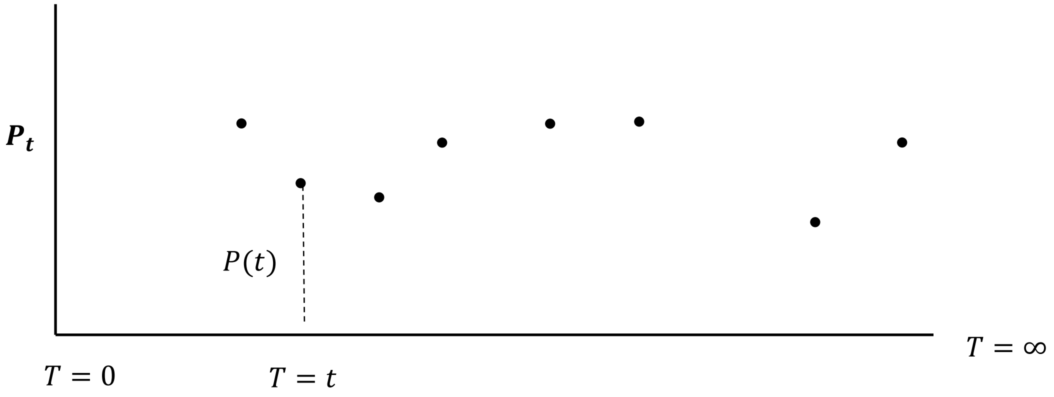


Figure 2 Random Process

This process shows that the quantity of precipitation, P, can be at any positive value along the timeline of 0 to T. Since the runoff stems from the precipitation, and the precipitation is a stochastic process, the runoff is, therefore, the stochastic process as well, even though some deterministic factors have influenced the process. For example, in a process of transforming precipitation into a runoff by employing the rational formula of:

$$Q_p = CIA \quad [2]$$

In which the factors of C and A are deterministic, but result in stochastic Q_p. When a variable is deterministic, then we can theoretically have full control of this variable to modify for accomplishing the planning and design effectiveness. The value of C is controllable and modifiable, even though it may not fully modifiable, as the C depends on the infiltration capacity of the underground soil (Yang, Zhang, & Pan, 2020).

The flow process in the watershed is initiated by the precipitation, which at that moment accumulates and transfers it being the overland flow on the way to the stream flow, and part of the precipitation infiltrates. During this event, the governing factors of the overland flow are land surface states and soil types, existing conditions, as asserted mathematically by equation [2] and according to the following Horton's equation (Beven, 2004):

$$f = f_c + (f_0 - f_c)e^{-kt} \quad [3]$$

In which f_c and f_0 are infiltration capacity of the soil. Infiltration capacity cannot be modified, since the soil is to some extent modifiable but a modification of the soil is not that efficient economically as it involves vast areas of the watershed. The infiltration capacity of the watershed determines the runoff coefficient of the watershed along with the ground surface of the watershed itself. The ϕ index could also be employed to simplify the non-linearity of the f. The ϕ index simplifies the infiltration by assuming that f is constant for the whole period of the rainfall. The ϕ index separates the direct run-off and infiltration. Therefore, the part of rainfall that contributes to run-off and eventually to the discharge in the river is known. Both f and ϕ are deterministic variables resulting from the stochastic variable of rainfall.

3. The Watershed Parameters and Their Contribution to Streamflow

The geomorphological parameters of a watershed that are known to determine its characteristics are (Jena, S K; Tiwari, K N;, 2006; Chen, et al., 2004; McCuen, 1998) (a) hypsometric curve, which shows the correlation between elevation and the area of the watershed, (b) watershed shape factors, which consisted of length to the center of the watershed, L_{ca}, shape factor, L_s, (c) PA ratio, R_{PA}, which is the ratio between the watershed perimeter and the area of watershed (d) circularity ratio, R_C, which exhibits the ratio between the area of the watershed and the area of a circle in which its perimeter is equal to the perimeter of the watershed, (e) elongation ratio, R_E, (f) channel slope, S, and (g) drainage density, D_D. These geomorphological parameters would either significantly or trivially contribute to the streamflow in the river, and therefore there is a necessity to clearly understand these parameters. The parameters are subject to alteration because of the development of the watershed. This development could be considered a disturbance to the geomorphological watershed parameters (Prepas, E E; Burke, J M; Whitson, I R; Putz, G; Smith, D W, 2006; Bedan, E S; Clausen, J C;, 2009). The disturbances that lead to the alteration of the geomorphological parameters of the watershed may be caused by an extensive natural disaster e.g. earthquake that generates massive landslides or development e.g. reservoir, irrigation, and urban development, or any extensive development of the built environment.

3.1 The Hypsometric Curve

The hypsometric curve shows the relationship between elevation and the area of the watershed. The hypsometric curve determines the time of concentration of the rainfall in the watershed. Some authors, as shown in Table 1, provide correlations that prove the hypsometric parameter contributes to the time of concentration in the watershed and therefore determines the flood discharge.

Table1 Time of Concentration according to Some Authors

Author (Year)	Equation	Notes
Kirpich (1940)	$T_c = 0.066\left(\frac{L_c}{\sqrt{S_c}}\right)^{0.77}$	All elements in the equations are in British Unit T_c: time of concentration in minutes L_c: length of the flow path in feet S_c: the longitudinal slope is dimensionless
Chow (1962)	$T_c = 0.000003035\left(\frac{L_c}{\sqrt{S_c}}\right)^{0.64}$	
Watt and Chow (1985)	$T_c = 0.0014\left(\frac{L_c}{\sqrt{S_c}}\right)^{0.79}$	
Haktanir and Sezen (1990)	$T_c = 0.734{L_c}^{0.841}$	

The hypsometric curve measures the relative area, which is the comparison between the area at a particular point in the watershed and the total area of the watershed, and also relative elevation, which is the comparison between the elevation at a particular point (same point as the relative area) in the watershed and the total elevation difference of the watershed. The hypsometric curve is associated with the area and elevation of the watershed, and the longitudinal slope can also be expressed by the comparison between the elevation and L_c or $S_c = elev/L_c$. In line with this association, the time of concentration is a function of L_c and S_c. This fact shows that the hypsometric factor contributes to the hydrologic response of the watershed.

The hypsometric curve might have a different shape, as a watershed is a random process in nature. However, as shown in Figure 1, the hypsometric curve has three common stages in the geological scale, which are (1) the initial stage, where the upstream and the middle stream parts of the watershed are relatively stable with a small amount of erosion. The erosion at this stage commences from the downstream part of the watershed and slowly propagates upstream (2) the final stage, where the erosion at the middle part of the watershed is almost negligible and the river is in an equilibrium state, that is to say, the river regime is accomplished. At this stage, the river experiences no significant change in its length, cross-section, longitudinal section, sediment transport, and other parameters. It is reflected in the hypsometric curve, that the relative elevation of the downstream part of the watershed is stable (3) The middle stage is in between of initial stage and the final stage. The state cannot be exactly determined, as the time scale is the geological scale, which can be million years.

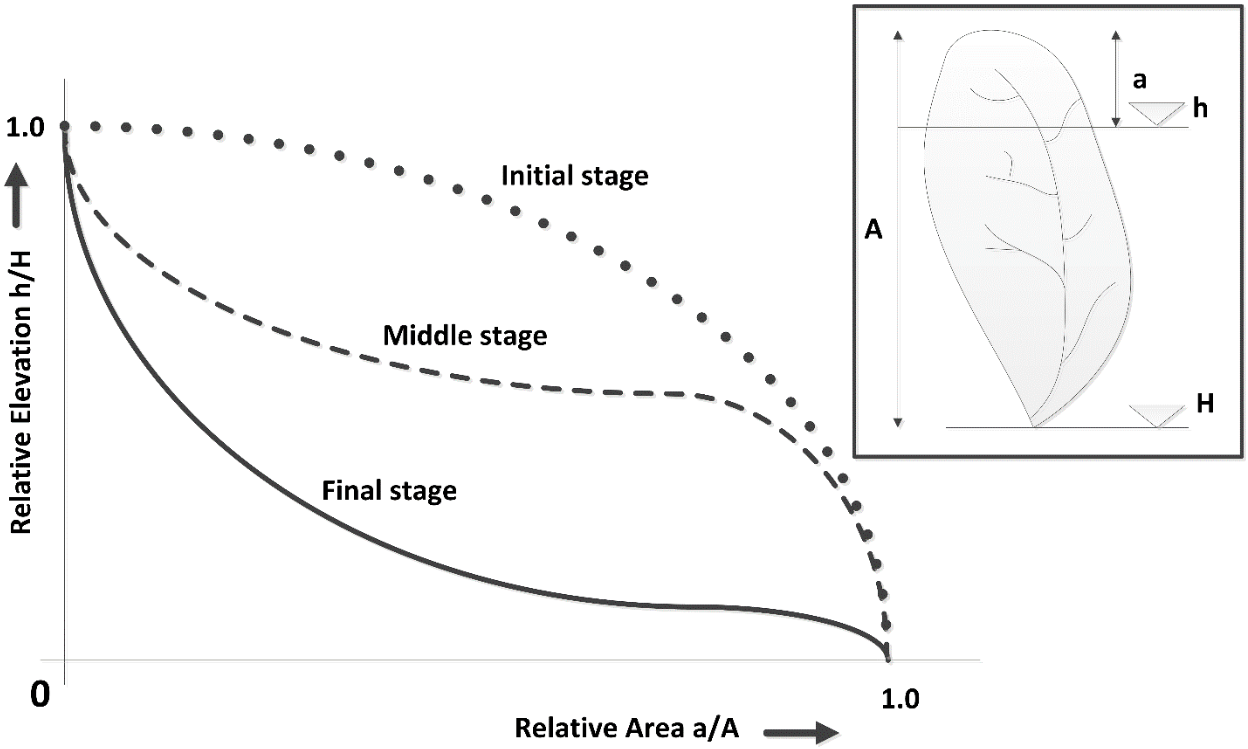


Figure 3 The Hypsometric Curve of a Watershed

3.2 The Watershed Shape

The watershed shape has an infinite number, as it is random. However, there is an obvious watershed parameter that determines the time of concentration as discussed in subsection 3.1. The watershed shape is determined by the following parameters:

Shape factor:

$$S_w = (LL_c)^{0.3} \qquad [4]$$

Where L is the length of the watershed.

L_c will govern the time of concentration where all the runoff reaches a common point and accumulates to contribute to the flood. By this notion, the shape factor plays in part in the flood discharge at the outlet of the watershed.

Another important watershed shape parameter is the circularity ratio, which is expressed by:

$$R_c = \frac{A_w}{A_o} \qquad [5]$$

In this case, A_w is the area of the watershed, and A_o is the area of a circle having the same perimeter as the basin perimeter.

Similar to other parameters of watershed shape, circularity dictates the time of concentration in the watershed. The less eccentricity of the circular shape, the less time of concentration will be, and therefore contributes to the accumulation of the basin rainfall, and eventually flood. With the circularity with higher eccentricity, the travel time of the runoff will be different for different parts of the watershed, and therefore the peak discharge will be smaller in comparison to the watershed with an almost circular shape.

3.3 Drainage Density

The drainage density (D_d) is the ratio between the total stream length (L_s) in the watershed and the area of the watershed (A_w). It is expressed by:

$$D_d = \frac{L_s}{A_w} \qquad [6]$$

The drainage density governs the susceptibility of the flood plain in the watershed from the runoff. We can observe that the higher drainage density, the vulnerability of a plain to flood inundation due to lack of drainage network is less. One of the efforts to reduce the flood vulnerability of land is by increasing the length of the drainage channel on that land.

3.4 The Channel Length

The channel length governs the time of concentration, the time to peak discharge, and the hydrograph base time. These parameters are important in hydrologic design.

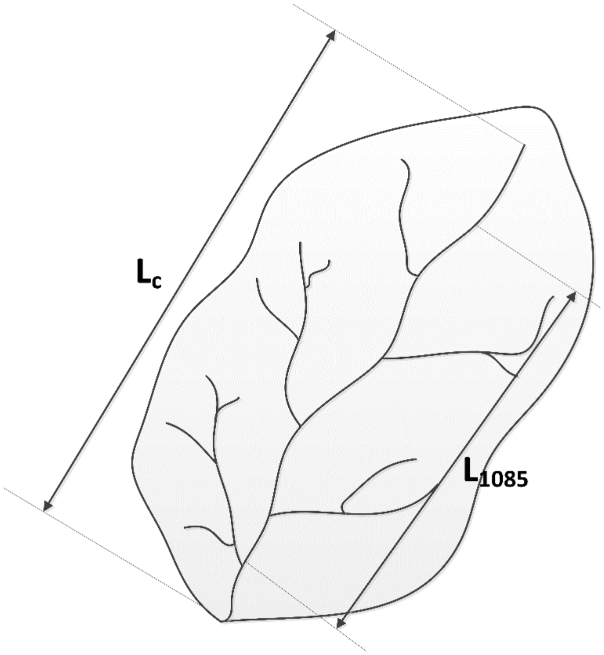


Figure 4 Channel Length

There are two definitions of the channel length in hydrologic computations (1) the length of the main river from the watershed outlet (river mouth) to the upper-end of the main river (channel) or L_c (2) the same measure but from a point located at 10% (lower part) to another point located at 85% of the length(upper part) of the river. It is measured from the river mouth going upstream or L_{1085}(Figure 4). The measure of the 10% (lower part) and 85% (upper part) was based on the empirical fact that the most important part of the river is common between these two points. However, observing the river works in many river basin development projects, the flood control projects are usually located at the downstream-end part of the river. Therefore the 10% of the downstream of the river cannot be ignored.

3.5 Channel Slope

Similar to the channel length, for hydrological design, the channel slope is also computed based on two conditions as expressed in two equations below:

$$S_c = \frac{\Delta E_c}{L_c} \quad [7]$$

$$S_{1085} = \frac{\Delta E_{1085}}{L_{1085}} \quad [8]$$

ΔE refers to the vertical displacement of the river i.e. the different elevations between two points where subscript c refers to the total length of the river, and subscript 1085 refers to points of 10% downstream and 85% upstream.

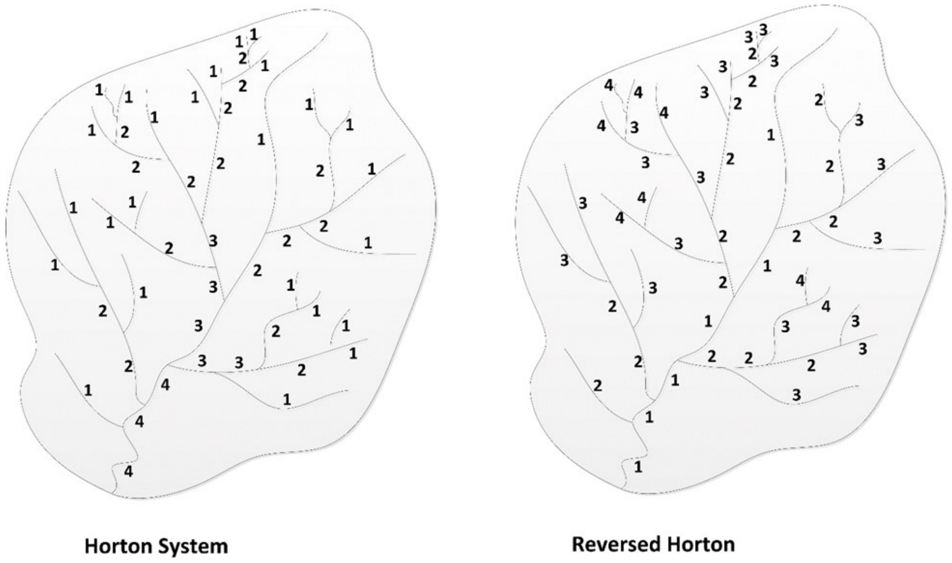
The channel slope determines the average velocity of the flow as shown by following Manning's formula, and the average velocity governs the magnitude of the river discharge.

$$v = \frac{1}{n} R^{0.67} S^{0.5} \quad [9]$$

Where R is the hydraulic radius, and S is the longitudinal channel slope.

3.6 The Horton's Law

There are other geomorphological parameters of the watershed such as Horton's Law of Stream (length and number) but does not strongly correlate to the hydrological design. The law shows the level of the order of the river in the watershed, and also the extent of the watershed. The higher order of the stream, we can expect the larger extent of the watershed. For example, a watershed with the highest stream order (the principal stream) of 6 would have a larger watershed area compared to a watershed with the highest order of 4. From the order of the stream, we can expect the magnitude of the flood and the time concentration of the rainfall that contributes to the peak discharge.



Horton System **Reversed Horton**

Figure 5 Horton System and Reversed Horton

Despite no correlation to the hydrological design, the stream order designated by Horton's Law is an important parameter for the stream inventory in a watershed. However, the current system of stream order cannot be used smoothly as the same stream order does not necessarily have the same level of the stream, as the order starts from the highest and smallest stream. To avoid this issue, the order of the stream is to be reversed from what Horton's Law defined. This is shown in Figure 5.

In Horton's Law stream order, the lowest order starts from the upstream part of the stream in the watershed and ends at the primary stream. Thus, the primary stream will always be the highest order in number e.g. 4. In the reversed Horton stream order, the primary stream will always be number 1, and the numbering continues to the most upstream part of the stream with the following rules: at a junction, the two streams are compared to one another and be determined which one among two is more predominant for the discharge, and a stream with larger discharge or the sub-watershed area will keep the order of the stream, and the other will be considered as a tributary. If the two streams have comparable discharge or the sub-watershed area, these two streams share the same order i.e. if the order of the downstream stream is 2, then the order of the two streams is 3, etc.

3.7 The Cross Section

The cross-section of the channel is one of the variables that determines the discharge carrying capacity of the river along with the longitudinal slope, hydraulic radius, and the roughness of the channel. This variable governs the vulnerability of the floodplains in this spot to flood events. The channel improvements to avoid the flood i.e. increasing the carrying capacity of the river commence from this point, as the longitudinal slope of the channel is naturally given and cannot be modified, or modifiable only in a very limited condition. The same situation with the channel roughness. This variable, to some extent, can be modified by introducing the lined channel.

3.8 Degree of Meandering

River meandering is part of the river dynamics when all hydraulic variables of the river seek a dynamic equilibrium condition. The equilibrium condition according to Lacey (1958) is achieved when the following conditions are met.

$$v = 0.794Q^{1/6}f^{1/3} \tag{10}$$

$$R_h = 0.47Q^{1/3}f^{-1/3} \tag{11}$$

$$A = 1.26Q^{5/6}f^{-1/3} \tag{12}$$

$$P = 2.66Q^{1/2} \tag{13}$$

$$S = 0.00053f^{5/3}Q^{-1/6} \tag{14}$$

$$f \cong 1.59d^{1/2} \tag{15}$$

In this case [all parameters are in British Unit ft, ft/s, ft^2, except d in mm]:

v	average flow velocity
R_h	hydraulic radius
A	flow area
P	wet perimeter of the flow
S	longitudinal slope

Theoretically, when a straight river does not meet the hydraulic equilibrium condition as expressed by the equations [10] through [15], the river will try to accomplish an equilibrium state by changing dynamically its parameters. The meandering process is a changing of the longitudinal slope of the river by expanding the length of the river stretch while keeping the vertical displacement at that stretch unchanged, and thus the longitudinal slope of the river is gradually reduced. Understanding the meandering process concerning the dynamic equilibrium of the river is important in structural measures of flood control since a river must be considered as an integral part from downstream to upstream. It means the change in the downstream will affect the condition in the upstream. A study by CIDA revealed that the most efficient flood control work, which is the minimum cost per unit hectare of secured previously flood-vulnerable area, was optimum when the flood control works approach was following the equilibrium state. As such, the construction works were carried out where no other equilibrium approach options were available, e.g. avoiding an extensive channel straightening which will change the longitudinal slope extensively and therefore change the river equilibrium as a whole.

4 The Significant Importance of Watershed Parameters in Hydrologic Modelling

Hydrology is largely about nature, random processes, and a large number of natural i.e. hydrological variables. Because of this character, we cannot perfectly represent the myriad natural variables in a few equations. Therefore, we need hydrological models that can characterize meticulously the natural feature into a mathematical equation. By this simplification, we can predict a hydrological phenomenon with accuracy. Hydrological modeling can therefore be considered one of the techniques to predict the hydrological process (Hingray et al., 2015).

Table 2 shows some hydrologic or rainfall-runoff models, the type, the basis, the data input required, and the output produced.

Table 2 Selected Hydrologic or Rainfall-runoff Models

Model Name/ Developer	Type	Basis	Input required	Output
NAM, DHI	Conceptual	Lumped module	Geographical and geomorphological data of watershed; rainfall, Hydrograph	Runoff Q, erosion
HEC-RAS, USCE	Physical	Semi-distributed	Ditto	Runoff, Sediment discharge
SWM, Stanford University	Conceptual	Continuous	Ditto	Runoff Q, erosion, water quality
SHE	Physical	Distributed	Ditto	Q, Sediment discharge, water quality
Kineros, University of Arizona	Physical	Semi-distributed	Ditto	Q, erosion,
SWAT, TAMU	Physical	Distributed	Ditto	Groundwater, Land Use Impacts

Source: Danish Hydraulics Institute, US Corps of Engineers, Systeme Hydraulique Europe, University of Arizona, Texas A&M University.

Hydrological modeling represents a naturally given hydro system and hydrological phenomena to emulate and simulate in whole or in part this hydro system to produce another hydrological event. For example, from the input-process-output model, with the input of rainfall hydrograph, and with a hydrological model as a processor, the output of discharges can be expected. The watershed has tens of thousands of natural variables which are hard to manage, but with the help of a model, the watershed could be simplified, and the model produced outputs.

The rainfall is usually the primary variable and the discharge is the primary output. For this fact, the model is usually called the rainfall-runoff model.

There are two types of data required in the model:

a. Meteorological data that represent the meteorological condition of the watershed, for example, precipitation, temperature, evaporation, wind, etc. These data are expected available in time series with a long record;
b. Geographical data that characterize the physical appearance of the watershed such as watershed parameters that include the shape of the watershed, soil types, drainage density, channel length, meandering, channel cross sections, hydraulic structure, and other variables.

Without the presence of those two types of data, the model would not produce the required outputs. It is, therefore, safe to say that the watershed parameters discussed earlier are paramount to the output of the model i.e. runoff in the river. The watershed parameters dictate not only the accuracy of the predictive output but also the warranty that the system will run and produce the expected output.

5 The Way Forward

Due to the essential function of the hydrological and meteorological data, as well as geographical data including watershed parameters in predictive hydrology, the data must be systematically stored. The data for each watershed must be continuously measured, collected, recorded, and placed in a secure database system along with a geographic information system that stores and manages geographical data. The system should be maintained by an agency in which its authoritative power covers the hydrological boundary instead of the administrative boundary. This is to avoid the overlapping function with the other agency whose authoritative power works under administrative boundaries. The

Acknowledgment

The authors acknowledge the support of the Faculty of Engineering, UNS, Indonesia, and the Department of Civil Engineering, School of Engineering, KMITL.

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