Simulating flash floods using remote sensing and GIS-based KW-GIUH hydrological model

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Abstract
Understanding storm flow generation within arid wadis is challenging because of the absence of reliable long-term field measurements. This paper simulates the flash flood runoff within Wadi Billi, Egypt, using remote sensing and GIS-based KW-GIUH model considering the linkage between the watershed’s geomorphological characteristics and its hydrologic response. A morphometric database of 58 parameters for all aspects has been developed using GIS; then, at the sub-basin level, KW-GIUH model has been used to simulate the hydrological response for the storm event of 9th March 2014. The statistical analysis, using Pearson correlation, classified the morphometric parameters according to their hydrological contribution and showed that only 21 parameters are significant. The results lead to isolating the most effective morphometric parameters, and this could be used to optimize the mathematical equations of the hydrological models to be more realistic in representing the physical processes of flash floods. Defining the morphometric parameters at sub-basin level is essential to predict the damages and to forecast the water flow order, which helps in designing a sustainable stormwater system that can protect the downstream areas and use rainwater instead of discharging it to the ocean.

Keywords Flash flood · KW-GIUH model · Remote sensing · Wadi Billi · Egypt

Introduction
The use of water models has been an important tool to optimize and simulate some hydrological process like rainfall and rainfall-runoff process (Price et al. 2011; Abdel-Fattah et al. 2017). Shannon’s entropy models and Machine learning were for flood prediction (Arora et al. 2021). In this regard, the Kinematic Wave Geomorphic Instantaneous Unit Hydrograph (KW-GIUH) model (Lee 1997) has been used in humid zones and in arid zones (Almasalmeh and Eizeldin 2019b; Jarrar et al. 2007; Shadeed et al. 2007; Lee and Yen 1997; Lee et al. 2009).

Natural disasters like flash floods have significant socioeconomic and environmental impacts on the infrastructure and the ecosystem (Abdelkader et al. 2021). The generation and processes of wadi flash floods are very complex and are not well understood (Abdel-Fattah et al. 2017). Flash floods impacts assessment can be made by runoff models like hydrologic model and River Analysis System (HEC-RAS) (Prama et al. 2020) and KW-GIUH (Belyakova et al. 2020) or based on morphometric aspects (Abdelkader et al. 2021). The distributed Hydrological River Basin Environment Assessment Model (Hydro-BEAM) has been used to obtain a good representation of the spatial variability of the rainfall and geomorphology in the basin (Abdel-Fattah et al. 2017).

In this paper, KW-GIUH that has been used in different semiarid areas to simulate flash floods (Shadeed et al. 2007; Shokoohi et al. 2017) was used to simulate the hydrological response for the storm event of 9th March 2014 in Wadi Billi, Egypt. KW-GIUH is a lumped-based hydrological model

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that was developed by Lee (1997) for modelling surface run-off in ungauged catchments (Taiwan Typhoon and Flood Research Institute 2018). The model considering the unit depth of excess rain falls uniformly and instantaneously over a drainage basin, and assuming to be consisted of large number of independent and non-interaction raindrops. Thus, the process of rainfall-runoff can be represented by tracing the excess rainwater, which moves along different paths towards the watershed outlet to produce the outflow hydrograph (Lee and Yen 1997).

This paper simulates the flash flood runoff within ungauged wadis using GIS-based KW-GIUH model considering the linkage between the watershed’s geomorphological characteristics and its hydrologic response. The simulation of flash flood to define the morphometric parameters at sub-basin level is essential to predict the damages and to forecast the water flow order, which helps in designing a sustainable stormwater system that can protect the downstream areas and use rainwater instead of discharging it to the ocean.

**Description of the study area**

The Eastern Desert of Egypt is characterized by drought and rare precipitation. However, events of heavy rain occur increasingly due to climate change (Tügel et al. 2018), which lead to flash floods that extend either to Red Sea coast or to the Nile River. Most of the urban areas that are located in the valley’s delta face floods related risks (Abdalla et al. 2015; Badawy 2008; Elnazer et al. 2017; Hadidi 2016; Moawad et al. 2016). Billi is one of the ungauged arid drainage basins that extends from the Red Sea Hills at the western part to the Red Sea shoreline in the east with an area of 878.7 km² and a maximum elevation of 2126 m. The basin is surrounded by Wadi Umm Masaa, Wadi Umm Diheis, drainage basins of the Nile River, and the Red Sea, Fig. 1.

On the 9th of March 2014, the basin was exposed to a storm event with an accumulated rainfall depth of 32.8 mm. According to Almasalmeh and Eizeldin (2019b), 2.4 million m³ of water passed through Billi Canyon and continued towards the Red Sea causing damages to the infrastructure of El-Gouna, Fig. 2.

The hydrology, geology, hydrogeology, and geomorphology of Wadi Billi have been studied in detail (Almasalmeh and Eizeldin 2019a; Almasalmeh and Eizeldin 2019b; Hadidi 2016; Tügel et al. 2019). Many practical applications were suggested for risk assessment, protection measures, and harvesting the flooded water (Almasalmeh et al. 2018; Elsisi et al. 2018; Marafini et al. 2018; Tügel et al. 2018). However, the correlation between the morphometric parameters and the hydrological indices under the unpredicted climate change risks has not been addressed (Blöschl et al. 2019; Hettiarachchi et al. 2018) due to the limited reliable long-term field measurements, which usually leads to unreliable results (Wheater et al. 2007).

**Methodology**

**Quantitative analysis of the watershed geomorphology**

A systematically approach has been followed to develop a morphometric database of 58 parameters at the sub-basin level, based on ASTER DEM of 30 m resolution (METI and NASA 2011). The GIS techniques have been applied for geo-processing analysis and to derive the morphometric parameters using Esri ArcMap 10.5 software and parameters equations, Table 1 in the Appendix. Then, rational procedures have been followed to evaluate and assess the results. The derived parameters were classified into four classes: drainage network, basin geometry, relief analysis and texture analysis. Then, the results are presented in maps.

**KW-GIUH model**

**Runoff simulation**

According to Strahler (1952), the drainage basin order Ω can be divided into sub-basins of order i, where i = 1, 2, ..., Ω. Figure 3 shows possible travel paths for excess raindrops over the drainage basin, starting from overland flow to the channel flow of low order then traverse to channel of higher order until they reached to the outlet.

If w denotes a specific path $x_{w} \rightarrow x_{1} \rightarrow x_{2} \rightarrow \ldots \rightarrow x_{Ω}$, the probability of excess raindrop to adopt this path is:

$$
P(w) = P_{OA_{1}} P_{X_{w}X_{1}} \cdots P_{X_{k}X_{Ω}}
$$

where, $x_{w}$ = denote of ith-order overland areas; $x_{i}$ = ith-order channel; $P_{OA_{i}}$ = ratio of ith-order overland area to the total watershed area; $P_{X_{w}X_{i}}$ = transition probability of raindrops moving from ith-order overland area to ith-order channel = unity by definition; and $P_{X_{i}X_{j}}$ = transition probability of raindrops moving from ith-order channel to jth-order channel.

The total travel time for excess raindrops moving along path w:

$$
T_{w} = T_{X_{w}} + T_{X_{1}} + \cdots + T_{X_{Ω}}
$$

The IUH can be represented by the convolution of two groups of probability density functions:

$$
a(t) = \sum_{w \in \mathcal{W}} \left( f_{w_{1}}(t) f_{w_{2}}(t) \cdots f_{w_{Ω}}(t) \right) \left( f_{X_{w_{1}}X_{w_{2}}}(t) \cdots f_{X_{w_{Ω}}}(t) \right) P(w)
$$
The travel time for overland flow area and for storage component of a channel is assumed to follow an exponential distribution, but the translation component of a channel is assumed to follow a uniform distribution. Therefore, the hydrological response of a drainage basin can be considered conceptually as a combination of linear reservoirs and linear channels in series and/or in parallel.

**Travel time estimation**

Lee and Yen (1997) considered a sub-basin as it consists of two identical rectangular overland flow planes (Fig. 4), each of which contributes by lateral discharge into the channel, which has a constant cross-section and slope. By means of the following equations, the travel time for different order

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**Fig. 1** The location of Billi drainage basin

**Fig. 2** Damages associated with the flash flood of March 2014 (Helal 2014)
sub-basins can be estimated from overland and channel hydraulics.

The travel time for ith-order overland plane can be obtained using the Kinematic-Wave approximation as:

\[
T_{x_i} = \frac{B_i}{2q_i L_{oi}} (h_{oi} - h_{col}) = \frac{B_i}{2q_i L_{oi}} \left( \frac{\bar{S}_{oi}^{0.5}}{n_i} \right)^{-\frac{3}{m}} h_{col} - h_{col}
\]  

(5)

where \(\bar{S}_{oi}\) the mean slope of ith-order overland region; \(n_i\) the effective roughness coefficient for the overland planes; \(m\) = constant and recognized as 5/3 from Manning’s equation.

The travel time for an ith-order channel:

\[
T_{xoi} = \frac{h_{osi}}{q_i} = \left( \frac{n_o L_{oi}}{\bar{S}_{oi}^{0.5} q_i^{m-1}} \right)^{\frac{1}{m}}
\]  

(4)

where \(\bar{S}_{oi}\) the mean ith-order overland slope; \(n_o\) the effective roughness coefficient for the overland planes; \(m\) = constant and recognized as 5/3 from Manning’s equation.

The travel time for an ith-order channel:

Input parameters

Morphological parameters of Billi drainage basin The values of drainage basin area \(A\), the stream order numbers \(N_i\), average length of stream order \(L_{ci}\), the mean channel gradient \(\bar{S}_{ci}\), and the gradient of overland regions \(\bar{S}_{oi}\) were derived using GIS techniques. Other parameters are calculated using the following equations that developed by (Lee and Yen 1997):

The transition probability of raindrops moving from channel of ith-order to jth-order is computed as:

\[
P_{x_i x_j} = \frac{N_{ij}}{N_i}
\]  

(6)

where, \(N_i\) = number of ith-order channels; and \(N_{ij}\) = number of ith-order channels that contribute to jth-order channel.

The mean of drainage area of order i is calculated as:

\[
\overline{A}_i = \frac{1}{N_i} \sum_{j=1}^{N_i} A_{ji}
\]  

(7)

where, \(A_{ji}\) denotes the area of overland flow regions that drain directly into jth channel of order i, and overland areas drained into the lower order channels tributary to this jth channel of order i.

The ratio of ith-order overland areas to the total drainage basin area can obtained as:

\[
P_{OA_i} = \frac{1}{A} \left( N_i \overline{A}_i - \sum_{j=1}^{i-1} N_j \overline{A}_j P_{x_i x_j} \right)
\]  

(8)
where, $A$ = total area of the watershed.

The mean length of $i$th-order V-shape overland flow planes:

$$L_{oi} = \frac{AP_{OAi}}{2N_i L_{ci}}$$  \hspace{1cm} (9)

To simplify the field investigation work, Lee and Yen (1997) assumed a linear variation for main channel widths at the outlet point for each sub-basin, and suggested the following equation:

$$B_i = \frac{B_{i\Omega} \sum_{i=1}^{\Omega} L_{ci}}{\sum_{i=1}^{\Omega} L_{ci}}$$  \hspace{1cm} (10)

where, $B_{i\Omega} = \text{denotes the channel width at the watershed outlet.}$

The element-based method cited by (Arcement and Schneider 1989) has been followed to estimate the channel roughness coefficient, and the adjusted equation used to derive the overland roughness value:

$$n = \left( n_0 + n_1 + n_2 + n_3 + n_4 \right) m_s$$  \hspace{1cm} (11)

where $n_0$ is relating a straight, uniform or smooth channel; $n_1$ is a value added to correct the effect of surface irregularities; $n_2$ is a value added to correct the effect of the shape and size of the channel cross section; $n_3$ a value for obstructions; $n_4$ a value for vegetation and flow conditions; and $m_s$ is a correction factor for meandering the channel.

**Hydrological parameters of the 9th of March 2014 storm event** The weather parameters of the 9th of March 2014 storm events have been recorded using Vaisala® Weather Transmitter WXT520 sensor and published by Hadidi (2016). The accumulated rainfall depth reached 32.82 mm. Due to the small-time scale of the heavy precipitation in combination with the cloudiness, decreasing of temperature, and less of vegetation, the losses of water due to the evapotranspiration process during the storm event assumed to be insignificant, while the infiltration process has a strong effect on the surface runoff behaviour. The infiltration losses determined empirically using the Soil Conservation Service Curve Number (SCS-CN) method after Mishra and Singh (2003).

**Model calibration**

The field measurements of Hadidi (2016) were considered unreliable, as the measurements’ number is limited and non-uniform temporally with only 6 values over 18 h and done in one point of shallow water due to the hard accessibility. So, the resulted IUH of KW-GIUH model cannot be calibrated, and the field measurements of Hadidi (2016) were used only as an indication. The resulted hydrograph, Fig. 5 shows the peak value of 65.33 m$^3$/s at 07 PM, and the water volume is 2,405,700 m$^3$ (Almasalmeh and Eizeldin 2019b).

**Statistical analysis**

Statistical analysis was performed using Pearson correlation between the morphometric parameters of the sub-basins and the hydrological indices of the flash flood of 9th March 2014, to investigate the relationship between the morphometric characteristics and its hydrological implications. The analysis was performed using SPSS 25 software to determine the linear correlations, to isolate the most effective parameters, to classify the morphometric parameters into groups according to their hydrological contribution, and to reduce of the number of considered parameters for flash flood studies.

**Results**

**Morphometric parameters**

The landform characteristics are discussed at the sub-basin level, and the derived parameters were classified into four classes the drainage network, basin geometry, relief analysis, and texture analysis, Fig. 6. The results refer to the monadnock stage of the development cycle indicating the attainment of a
stable state in the processes of erosion and transportation within the drainage network and its contributing slopes, and a system of channel slopes and valley wall slopes has been developed. The range of values of the sub-basins shows moderate to high drainage density indicating gullied slopes and surface of low permeability (Almasalmeh and Eizeldin 2019a).

Hydrological modelling of flash flood event of 9th March 2014

Five sub-basins (SB2, SB5-6, SB9, and SB13) have been selected to simulate the hydrological response as they include the most extreme values for different morphometric parameters, Fig 7. The runoff hydrographs have been estimated using the KW-GIUH model for the same storm event of 9th March 2014. Significant variations can be noticed in the shape of hydrographs and the hydrological indices (Fig. 8) due to the spatial variability of the morphometric characteristics. A sudden rising limb attained the peak discharge directly after the storm peak, and the lag time estimated by 1 h, then followed by a gradual recession until reach zero flow. The maximum peak value is 8.7 m$^3$/s for SB2, and the minimum value is for SB13 with 3.67 m$^3$/s.

Sensitivity analysis

The sensitivity analysis has been performed for all input parameters and the applied range of values determined according to the possible range of mistake for each parameter (Fig. 8).

The results show significant inverse relation for channel and overland roughness with peak value and insignificant effect over time to peak. The morphometric parameters that derived using GIS techniques showed limited change in peak value for all parameters, except for the sub catchment contributing area ($A_i$) that showed significant correlation, while they showed no observed effect on time to peak. For the only parameter measured in the field, a minor effect of the channel width on the discharge peak with no observed effect on time to peak (Almasalmeh and Eizeldin 2019b).

Statistical analysis

The resulted runoff hydrographs for all sub-basins are derived based on the same hydrological input data. Therefore, the differing in their hydrological indices (discharge peak, time to peak, and water volume) is attributed to the variation of the morphometric parameter that controls the hydrological response of each sub-basin. The correlation matrix of the hydrological-morphometric parameters is classified according to $R^2$ as the following: very strong $[0.9–1]$, strong $[0.65–0.9]$, good $[0.35–0.65]$, weak $[0.1–0.35]$, and very weak $[0–0.1]$. Generally, there is a significant correlation between the drainage basin parameters related to scale and relief characteristics, in addition to drainage network parameters that showed relevant relation with basin-scale network parameters, while basin texture parameters showing an insignificant relationship.

Basin geometry parameters

Many morphometric parameters and the way in which floods are formed and move depend on the geometry characteristics of the basin. The results show geometry parameters, such as basin area, length area relation, basin perimeter, basin length, and basin relative perimeter, are in strong to very strong correlations with all the hydrological indices. A perfect linear correlation exists between the drainage basin area and runoff volume. This agrees with Melton’s (1957) conclusion to use the basin area to calculate the total amount of water entering the system during rainfall. Another very significant linear relationship exists between the time concentration and the basin length, where increasing the distance means increasing the required time until droplets reach the basin’s outlet.

Relief parameters

Slope parameters of drainage network are showing strong to very strong inverse correlations, while relief and slope parameters of the drainage basin are showing good to strong inverse correlations. The results meet with Horton’s (1932) suggestion of considering the slope parameters are one of the major factors that control the concentration-time of rainfall and flood magnitude. Only the hypsometric integral is showing weak correlations, which meets with Abdel-Fattah et al. (2017) findings.

Texture parameters

Parameters that depend on the length of streams per the drainage area, such as the drainage density and infiltration number, are showing good correlations with discharge peak and runoff volume, and strong correlations with time to peak. The constant of channel maintenance, length of overland flow, and drainage intensity show similar but inverse correlations as they have an inverse relation with the drainage density and thus with the length of streams.

Only texture ratio and topographic texture ratio are showing opposite influence, where strong correlations have been recorded with discharge peak and runoff volume, and good correlations with time to peak.
Fig. 6  Average values for the main morphometric parameters at sub-basin level for Billi drainage basin
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Drainage network parameters

Parameters that have a significant strong relation with the basin’s area, such as the number of streams, the number of streams of 1st order, and the Sum Stream length, are showing similar hydrological influence (very strong correlations with all hydrological indices). This meets with Schumm’s (1956) and Almasalmeh and Eizeldin (2019a) suggestions for a directly proportional relation between mean drainage basin area and means stream length and number.

The weighted mean bifurcation ratio showed stronger hydrological implication than the mean bifurcation ratio, with a strong correlation with discharge peak, good correlation with time to peak, while it is a weak correlation with runoff volume, while the mean stream length ratio showed...
stronger hydrological implication than the weighted mean stream length ratio, with good inverse correlation with peak and time to peak, and a weak inverse correlation with runoff volume.

The main channel width and standard sinuosity index showed a good correlation with discharge peak and a weak correlation with time to peak and discharge volume, while valley index, channel index, main channel length, and valley length showed weak inverse correlations. Only hydraulic sinuosity index and topographic sinuosity index showed very weakly and opposite correlations.

The morphometric parameters can be classified according to their hydrological contribution into four classes (Appendix Table 2). Only morphometric parameters that show a strong correlation are recommended for further study. The results are useful to optimize the accuracy of the hydrological models that are based on the morphometric characteristics to predict the flood hydrograph within ungauged drainage basins. Here, it is worth to mention that the KW-GIUH model was able to provide accurate results because of its mathematical equations depending on variables that represent the most influential morphometric parameters, such as total basin area, ith-order sub-catchment contributing area, ith-order stream number, mean ith-order stream length, ith-order overland and channel slope, and the overland and channel roughness.

Conclusions

This paper aims to develop a deep understanding of the hydrological response of ungauged wadis by analysing the relation between the morphometric and hydrological parameters. So, a database of 58 morphometric parameters for all aspects has been developed for Wadi Billi at the sub-basin level using GIS techniques. The KW-GIUH model has been used to investigate the hydrological response for the flash flood event of the 9th of March 2014. The statistical analysis, using Pearson correlation, applied only over five sub-basins that represent the extremist values and showed that only 21 parameters have a significant linear correlation with all the hydrological parameters, while other parameters considered insignificant. The results will enhance the accuracy of hydrological models, and they justify the accuracy of the KW-GIUH model as its equations depend on the most influential morphometric parameters. Also, they could be used to determine susceptible areas for flood risks and groundwater recharge depending on prioritizing the effect of the related morphometric parameters. The results are limited to the study area, and it is recommended to implement a comprehensive analysis of the Red Sea drainage basins to determine the standard correlations. Moreover, the use of ASTER DEM of 30 m resolution is not the best choice but it was the available one. More accurate DEMs that are based on LiDAR technology could give more accurate results.
## Appendix

| Morphometric parameters                                      | Formula                                                                 |
|-------------------------------------------------------------|-------------------------------------------------------------------------|
| **Drainage network**                                        |                                                                         |
| Stream order (Su)                                           | Hierarchical rank (Strahler system)                                     |
| 1st order stream (Suf)                                      | \( Suf = N_1 \)                                                        |
| Stream number (Nu)                                          | \( Nu = N_1 + N_2 + N_3 + \ldots + N_n \)                              |
| Stream LENGTH (Lu) [km]                                     | \( Lu = L_1 + L_2 + \ldots + L_n \)                                    |
| Mean stream length ratio (Lur)                              | \( Lur = \frac{L_u}{L_{u-1}} \)                                        |
| Weighted mean stream length ratio (Luwm)                    | Luwm = multiplying the stream length ratio for each successive pair of orders by the total numbers of streams involved in the ratio and taking the mean of the sum of these values. |
| Bifurcation ratio (Rb)                                      | \( R_b = \frac{N_j}{N_{j+1}} \)                                        |
| Mean bifurcation ratio (Rbm)                                | Rbm = average of bifurcation ratio of all orders                       |
| Weighted mean bifurcation ratio (Rbwm)                      | Rbwm = multiplying the bifurcation ratio for each successive pair of orders by the total numbers of streams involved in the ratio and taking the mean of the sum of these values. |
| Main channel length (Cl) [km]                               | The distance of channel course between the source and mouth. Measured directly using GIS software Analysis. |
| Main channel width (\( B_{ci} \))                          | \( B_{ci} = \frac{b_j \sum_i L_{ci}}{\sum_i L_{ci}} \)   |
| Valley length (Vl) [km]                                     | The valley length along a stream, the length of a line which is everywhere midway between the base of the valley walls. Measured directly using GIS software Analysis. |
| Minimum areal distance (Adm) [km]                           | The shortest air distance between the source and mouth of the stream. Measured directly using GIS software Analysis. |
| Channel index (Ci)                                          | \( Ci = Cl / Adm \)                                                    |
| Valley index (Vi)                                           | \( Vi = Vl / Adm \)                                                    |
| Rho coefficient (\( \rho \))                               | \( \rho = L_w / R_b \)                                                 |
| Basin geometry                                              |                                                                         |
| Length from Catchment's center to its mouth (Lcm) [km]       | Measured directly using GIS software Analysis.                          |
| Width of catchment at the center of mass (Wcm) [km]         | Measured directly using GIS software Analysis.                          |
| Basin length (Lb) [km]                                      | The longest dimension of a drainage basin parallel to the main drainage line. Measured directly using GIS software Analysis. |
| Basin width (Wb) [km]                                       | \( W = A / L_b \)                                                      |
| Basin area (A) [km²]                                        | The area in square kilometres of the outline of the watershed of a stream as projected onto the horizontal plane. Measured directly using GIS software Analysis. |
| Area ratio (Ar)                                             | \( A_r = \frac{A_i}{A_{i-1}} \)                                       |
| Mean area ratio (Arm)                                       | \( A_m = Am = Stream order wise mean area. \)                          |
| Weighted mean area ratio (Arwm)                             | Arwm = multiplying the mean area ratio for each successive pair of orders by the total number of streams involved in the ratio and taking the mean of the sum of these values. |
| Basin perimeter (P) [km]                                    | The length of the outer boundary of a drainage basin as projected onto the horizontal plane of the map. Measured directly using GIS software Analysis. |
| Basin relative perimeter (Pr)                               | \( P_r = A / P \)                                                      |
| Length area relation (Lar)                                  | \( Lar = 1.4 \times A^{0.6} \)                                        |
| Lemniscate (k)                                              | \( k = Lb^2 / A A \)                                                  |
Table 1 (continued)

| Morphometric parameters | Formula |
|-------------------------|---------|
| Form factor ratio (Rf)  | $F_f = A/L_b^2$ |
| Shape factor ratio (Rs) or inverse shape form (Sv) | $S_f = S_v = L_b^2/A$ |
| Elongation ratio (Re)   | $R_e = \left( \frac{2\sqrt{A/\pi}}{L_b} \right)$ |
| Ellipticity index (Ie)  | $I_e = \pi \cdot V_l^{2/3} \cdot A$ |
| Circularity ratio (Rc)  | $R_c = 4 \cdot \pi \cdot A/P^2$ |
| Circularity ration (Rcn) | $R_{cn} = A/P$ |
| Texture ratio (Rt)      | $R_t = N_{1/P}$ |
| Topographic texture ratio (T) | $T = N_t/P$ |
| Compactness coefficient (Cc) | $C_c = 0.2841 \ast \left( \frac{P}{\sqrt[3]{A}} \right)$ |
| Fitness ratio (Rf)      | $R_f = C_l/P$ |
| Wandering ratio (Rw)    | $R_w = C_l/L_b$ |
| Watershed eccentricity (τ) | $\tau = \frac{[L_{cm}^2 - W_{cm}^2]^{1/3}}{W_{cm}}$ |
| Centre of gravity of the watershed (Gc) | Measured directly using GIS software Analysis. |
| Hydraulic Sinuosity Index (HSI) [%] | $HSI = \left[\frac{C_l+5}{C_l+1}\right] \cdot 100$ |
| Topographic Sinuosity Index (TSI) [%] | $TSI = \left[\frac{10+1}{C_l+1}\right] \cdot 100$ |
| Standard Sinuosity Index (SSI) | $SSI = C_l/V_i$ |
| Longest dimension parallel to the principle drainage line (Clp) [km] | Measured directly using GIS software Analysis. |
| Basin shape index (Ish) | $I_{sh} = 1.27A/L_b^2$ |
| Compactness ratio (SH)  | $SH = Pr/2\sqrt{\pi \cdot A}$ |
| Drainage texture        | $F_s = \sum_{i=1}^{k} N_i/A$ |
| Stream frequency (Fs)   | $D_d = \sum L_u/A$ |
| Drainage density (Dd) [km/km²] | $c = 1/D_d$ |
| Constant of channel maintenance (C) [km2/km] | $D_i = F_s/D_d$ |
| Drainage intensity (Di) | $F_N = F_s \cdot D_d$ |
| Infiltration number (FN) | Analysed qualitatively using GIS software Analysis using DEM |
| Drainage pattern (Dp)   | Length of overland flow (Lg) | $L_g = \frac{1}{2\cdot D_d} = \frac{L_u}{2\cdot A}$ |
| Drainage pattern (Dp)   | Relief characteristics | Maximum elevation of the basin (Z) | Elevation of highest summit. Measured directly using GIS software Analysis using DEM |
| Minimum elevation of the basin (z) | Elevation of Basin Mouth. Measured directly using GIS software Analysis using DEM |
| Total basin relief (H) [m] | $H = Z - z$ |
| Relief ratio (Rh)       | $R_{rh} \left( \frac{H}{Z} \right)$ |
| Absolute relief (Ra) [m] | $R_{a} = Z$ |
| Relative relief ratio (Rhp) | $R_{hp} = \frac{H + 100}{F}$ |
| Dissection Index (Dis)  | $Dis = H/I_{r}Ra$ |
| Ruggedness number (Rn)  | $R_n = R_f \cdot D_d$ |
| Melton ruggedness number (MRn) | $MR_{n} = H/I_{r}A^{0.5}$ |
| Channel gradient (Cg) [m/km] | $C_g = \frac{Z_{\text{max}} - Z_{\text{min}}}{L_u}$ |
| Gradient ratio (Rg)     | $R_g = \frac{Z_{\text{max}} - Z_{\text{min}}}{L_u}$ |
| Watershed slope (Sw)    | $Sw = H/L_b$ |
| Total contour length (Cl) [km] | Measured directly using GIS software |
| Contour interval (Cin) [m] | Measured directly using GIS software |
Table 1 (continued)

| Morphometric parameters                                      | Formula                                                                 |
|--------------------------------------------------------------|------------------------------------------------------------------------|
| Length of two successive contours (L1+L2) [km]               | Measured directly using GIS software                                    |
| Slope analysis (Sa)                                          | Generated through DEM analysis using GIS software                        |
| Mean slope of overall bain (Θs)                              | Θs = \frac{\sum(Cin*Cin)}{A}                                             |
| Slope ratio                                                 | r_s = \frac{s_s}{s_c}                                                   |
|                                                             | s_s: average slope of ground surface                                   |
|                                                             | s_c: average slope of stream-channels                                   |
| Tangent ratio                                               | r_t = \frac{tan s_s}{tan s_c}                                           |
| Hypsometric integral (Hi) [%]                               | Area under the hypsometric curve                                        |
| Erosional integrals (Ei) [%]                                | Area above the hypsometric curve                                        |
| Clinographic analysis (Cga)                                 | Tan Q = Cin/Awc                                                         |
| Erosional surface (Es) [m]                                  | Superimposed Profiles                                                   |
| Surface area of relief (Rsa) [km²]                          | Composite Profile:                                                      |
|                                                             | Area between Composite Curve and Horizontal Line                        |
| Composite profile area (Acp) [km²]                          | Area between Composite Curve and Horizontal Line over distance equal to |
|                                                             | the distance of projected profile                                      |
| Minimum elevated profile area as projected profile (App) [km²] | Area between Minimum Elevated Profile as Projected Profile and Horizont |
| Erosional affected area (Aea) [km²]                         | Aea = Acp – App                                                         |
| Longitudinal profile curve area (A1) [km²]                  | The numerically integrated area that lies between the profile curve and |
|                                                             | a straight line connecting the profile endpoints                        |
| Profile triangular area (A2) [km²]                          | The triangular Area created by that Straight Line and above the Horizont |
| Concavity Index (Ca)                                        | Ca = A1/A2                                                              |
Table 2 The hydrological importance of different morphometric parameters

| No | Significant correlation (> 1.95) with all hydrological indices (rainfall-runoff) | Significant correlation (> 0.65) for each hydrological index |
|----|-----------------------------------------------------------------|-------------------------------------------------|
|    | With peak value | With concentration time | With runoff volume |
| 1  | Basin area | Length area relation | Sum stream length | Basin area | High |
| 2  | Length area relation | Number of streams of 1st order | Basin length | Length area relation | |
| 3  | Number of streams | Number of streams | Basin perimeter | Number of streams | |
| 4  | Number of streams of 1st order | Basin area | Basin area | Number of streams of 1st order | |
| 5  | Sum stream length | Sum stream length | Infiltration number | Sum stream length | |
| 6  | Main channel slope | Basin relative perimeter | Length area relation | Basin perimeter | |
| 7  | Channel gradient | Circularity ration | Drainage density | Basin relative perimeter | |
| 8  | Basin perimeter | Texture ratio | Number of streams | Circularity ration | |
| 9  | Melton ruggedness number | Topographic texture ratio | Number of streams of 1st order | Basin length | |
| 10 | Relative relief | Mean basin width | | | |
| 11 | Relief ratio | Basin perimeter | | | |
| 12 | Watershed slope | Weighted mean bifurcation ratio | | | |
| 13 | Gradient ratio | | | | |
| 14 | Ruggedness number | | | | |
| 15 | Total basin relief | | | | |
| 16 | Basin length | | | | |
| 17 | Maximum elevation | | | | |
| 18 | Absolute relief | | | | |
| 19 | Basin relative perimeter | | | | |
| 20 | Circularity ration | | | | |
| 21 | Overland slope | | | | |

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Declarations

Conflict of interest The authors declare no competing interests.

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