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# Simulating the 1-hr Unit Hydrograph for the Ungauged Watershed of Swaqa

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**Abstract:** This study uses QGIS-3.28 to extract the geomorphological features for the ungauged watershed of Swaqa and employs SWMM-5.2 to simulate its 1-hr unit hydrograph (UH). Visualizing the watershed as an impervious surface of virtual curve number equals 100 subjected to an effective rainfall of 1cm depth, the SWMM has successfully simulated the 1-hr UH after computing the watershed width as this study proposes. The simulated 1-hr UH follows the common pattern of synthetic UHs. It has peak flow of 133m$^3$/s which requires 4.5 hours to attain its value after the runoff has begun. The watershed has lag-time of 4 hours and it drains rainwater to around 45 hours. The derived UH is useful to obtain storm hydrograph for flood analysis and rainwater harvesting studies in the arid region of Swaqa. From regression analysis, a strong relationship was observed between the UH peak flow and the geomorphological attributes of the watershed. Based on that, this study introduces a general equation to predict the UH peak flow given the watershed area, stream length, surface roughness and slope. The predicted peak flow is close to the SWMM simulated value; therefore, this equation is useful to construct synthetic UHs for ungauged watersheds.

**Keywords: SWMM, ungauged watershed, unit hydrograph, watershed width.**

## 1. Introduction

The majority of watersheds in Jordan discharge winter flows into natural channels with no direct streamflow measurements. The term ungauged watershed refers to the watershed that lacks direct streamflow measurement (Grimaldi et al., 2012). After Sherman (1932) introduced the concept of the unit hydrograph (UH), it has become a valuable tool to estimate the entire ordinates of the hydrograph generated by the watershed due to rainfall (James et al., 1987). The UH is defined as the direct runoff hydrograph resulting from 1cm depth of excess rainfall distributed uniformly over the watershed for an effective duration (Chow et al., 1988). Given the historical rainfall-runoff data for a gauged watershed, the UH ordinates can be derived easily (Hosseini et al., 2016); however, for ungauged watersheds the derivation of the UH is not an easy task (Ghumman et al., 2017). In literature, several methods from simple empirical to complex conceptual or physical-based models are used to relate the watershed runoff to the rainfall (Pumo et al., 2016). Generally, the conceptual models like the geomorphological UH (GUH) and the geomorphological instantaneous UH (GIUH) employ spatial modelling techniques offered by the geographic information systems (GIS) to model the rainfall-runoff process, so they are preferable for ungauged watersheds (Hosseini et al., 2016; Ghumman et al., 2017). Basically, the GUH or GIUH models relate the hydrological response of the ungauged watershed to its geomorphologic characteristics which ultimately provide simple rainfall-runoff model (Kumar, 2015). In literature, extensive efforts have been made to accurately predict the runoff hydrograph ordinates given the geomorphologic characteristics of the ungauged watershed in Jordan and worldwide (Kumar, 2015; Hosseini et al., 2016; Ghumman et al., 2017; Bamufleh et al., 2020; Obeidat et al. 2021; Ogassawara et al., 2022; Shatnawi and Ibrahim, 2022).

Storm water management model software (SWMM), developed by the United States Environmental Protection Agency (EPA), has been used to model the response of urban and natural watersheds to rainfall events (e.g. Khaleghi et al., 2020; Hossain et al., 2019; Bai et al., 2019). This study uses QGIS-3.28 to divide the ungauged watershed of Swaqa into 13 sub-watersheds (SW) and extract their geomorphological characteristics, and later the SWMM-5.2 is used to derive the 1-hour UH for the ungauged watershed of Swaqa. Furthermore, the characteristics of the derived UH will be related to the watershed geomorphological attributes. The derived UH is useful to estimate the peak flow and the time to peak for flood analysis and compute the surface runoff volume for water harvesting studies in the arid region of Swaqa. The use of computer simulation models to derive the runoff hydrograph for ungauged watersheds is an attractive option because field data is either limited or not existed (Gou and Urbonas, 2009).

## 2. Materials and Methods

Briefly, the QGIS-3.28 was used to delineate the watershed of Swaqa and extract its geomorphological features. The tool SRTM-downloader in the QGIS was used to download 1 arc-second digital elevation model (DEM) for Swaqa region in Jordan from NASA Earth-Data service. The downloaded DEM layers were re-projected according to the coordinate reference system WGS84/UTM zone 36N that covers the study region. The re-projected DEM layers were processed to remove sinks following the algorithm proposed by Wang and Liu (2006), eventually the watershed was delineated. Fig. 1 shows Swaqa watershed drainage area, channels network and elevations.

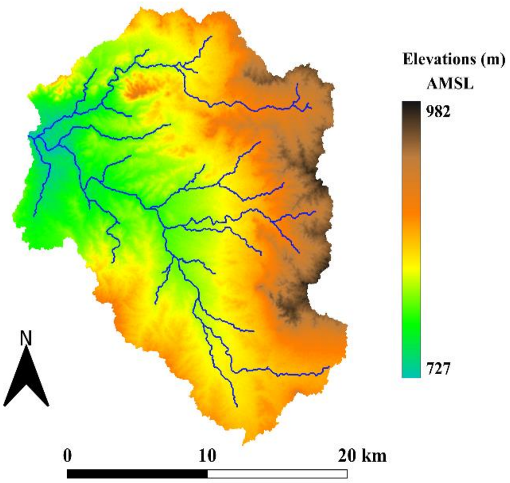


**Figure 1.** The watershed of Swaqa

Swaqa watershed is located in the western part of the Jordanian desert, approximately 63km south of Amman and 50km east of the Dead Sea. It has an area of 454.42 km$^2$ and drains rainwater from the eastern and southeastern high plains towards the western lowlands through streams of orders 1 – 8 at the outlet. Generally, the watershed is characterized by arid regions climate which is the dominant pattern in the Jordanian desert. The SWMM-5.2 will be used to generate the 1-hr UH for the ungauged watershed of Swaqa given the geomorphological features of the 13 SWs extracted using QGIS. Fig. 2 shows the SWMM model layout considering the 13 SWs of Swaqa.


**Figure 2.** The 13 sub-watersheds of Swaqa and the SWMM model layout.

In concept, the SWMM treats any watershed as a nonlinear reservoir that receives inflow (*i*) in the form of precipitation, stores water in depressions ($d_s$) and releases water as surface runoff (*q*) and losses as infiltration (*f*) and evaporation (*e*). Once the water depth (*d*) in the nonlinear reservoir exceeds the maximum depression storage ($d_s$), the surface runoff (*q*) per unit area (*A*) of the watershed will be generated (Rossman and Huber, 2016). The SWMM conceptualizes the watershed as a rectangular channel of width (*W*) that discharges runoff of uniform depth equals $d - d_s$ at an average slope (*S*). Given the Manning roughness (*n*) of the watershed surface, the runoff *q* is computed as (Rossman and Huber, 2016):

$$q = \frac{W\,(d-d_s)^{\frac{5}{3}}\sqrt{S}}{n\,A} \qquad (1)$$

The most important parameters in Eq.1 that requires an accurate estimation is the watershed width (*W*). The user manual of the SWMM suggests an initial value for *W* to be twice the length of the flow path from the farthest point to the watershed outlet; however, such an initial value must be adjusted given the watershed observed flow and rainfall data (Rossman and Huber, 2016) which is not utilized for the case of ungauged watersheds. This study follows the procedure developed by Gou and Urbonas (2009) to estimate the best value of *W* with slight modification to account for the existence of branching channels. The sub-watershed width is computed as:

$$W = L_s(1.5 - Z)\left[2.286\frac{A}{\bar{L}^2} - 0.286\left(\frac{A}{\bar{L}^2}\right)^2\right] \qquad (2)$$

where $L_s$ is the total length of branching channels, *Z* is the watershed skew factor, *A* is the watershed area and $\bar{L}$ is the average length of branching channels.

## 3. Results and Discussion

Equation 2 was used to compute the individual sub-watersheds width (*W*) which is an important input in the SWMM. The computed *Z* values for the 13 SWs fluctuate between 0.5 and 0.69 which indicates that areas contributing surface runoff are nearly distributed evenly around the main channel. The computed shape factor $\boldsymbol{A/\bar{L}^2}$ for the 13 SWs in Swaqa is between 0.1 for the elongated sub-watershed S11 and 0.6 for the equant sub-watershed S5. For the SWMM to simulate the 1-hr UH, the watershed is visualized as an impervious surface of zero depression storage and infiltration which can be achieved by assigning a virtual curve number (CN) of 100 to the watershed. Here, once the watershed is exposed to rainfall of 1cm depth in 1-hr duration, the excess rainfall depth becomes 1cm and the resulted SWMM hydrograph is the watershed 1-hr UH. In the SWMM, all the SWs were assumed to have surface roughness (*n*) of 0.03 which is close to *n* values adopted by previous research (e.g. Agnew et al., 1995) conducted in the eastern Jordanian desert. Other sources like the HEC-RAS suggests *n* value of 0.03 for barren lands which is similar to the case of Sawqa watershed. A first run of the SWMM gave initial estimations of the surface runoffs generated from individual SWs due to the 1cm excess rainfall and routed flows to the outlet of the watershed. Channels dimensions were re-adjusted accordingly in subsequent SWMM runs such that no rainwater was flooded or stored in the system.

The SWMM uses the dynamic wave routing technique to route individual flows of the 13 SWs to the main watershed outlet. Fig.3 shows the SWMM derived 1-hr UH at the outlet of Swaqa watershed. The UH has peak flow of 133m$^3$/s which requires 4.5 hours to attain its value after the runoff has begun. The watershed keeps draining rainwater to around 45 hours, after that the flow becomes negligible. Given that the storm causing the flow has 1-hour duration, the watershed lag-time is 4 hours (Fig.3).

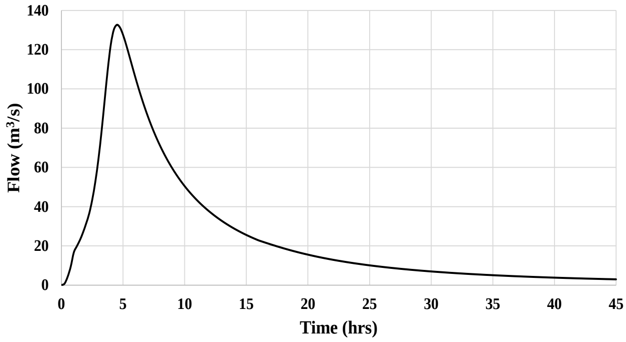


**Figure 3.** The SWMM derived 1-hr UH at the outlet of Swaqa watershed.

The derived 1-hr UH for the ungauged watershed of Swaqa is positively skewed which is a common characteristic of most hydrographs including synthetic unit hydrographs (Collischonn et al., 2017). The rising limb of the derived 1-hr UH is steeper than the recession limb which is simply attributed to the positively skewed watershed width function, i.e. considerable portion of the drainage area, including channeling system, exists relatively near the watershed outlet.

The peak flow ($Q_p$) is an important feature of the UH; therefore, the relationship between $Q_p$ and the geomorphological features of the ungauged watershed was investigated for the ease of constructing synthetic UH in Swaqa or similar regions. From regression analysis, it has been found that the peak flow is directly proportional to the width ($W$), average slope (S) raised to the power 0.5 and inversely to the roughness ($n$), simply $Q_p$ α $W \times S^{0.5}/n$. Fig.4 shows a strong relationship between $Q_p$ and the term $W \times S^{0.5}/n$. For Swaqa watershed, the individual SWs skew factor $Z$ is close to 0.5 and the shape factor ($\boldsymbol{A/\bar{L}^2}$) is always much below 1, then technically Eq.2 is reduced to $W \approx 2.286 L_s \times \boldsymbol{A/\bar{L}^2}$. Replacing $W$ by its equivalent terms, the general regression equation that can be used to predict the 1-hr UH peak flow is:

$$\boldsymbol{Q_p = C\frac{2.286\, A\, L_s \sqrt{S}}{n\, \bar{L}^2}} \qquad (3)$$

where $C$ is the regression coefficient (0.309 for Swaqa watershed), $A$ in km$^2$, $L_s$ and $\boldsymbol{\bar{L}}$in km and $S$ expressed in decimal. For validation, Eq.3 was used to reproduce the peak flow of Swaqa 1-hr UH and the result is compared to the SWMM simulated value. Given the watershed area A= 454.42 km$^2$, average slope $S$ = 0.05, $L_s$ = 68km, $\boldsymbol{\bar{L}}$ = 34km and $n$ = 0.03, the predicted peak flow using Eq.3 is 141m$^3$/s which is so close to the SWMM simulated value (133m$^3$/s). In general, Eq.3 is useful to obtain the peak flow of the 1-hr UH in Swaqa or similar ungauged watersheds.

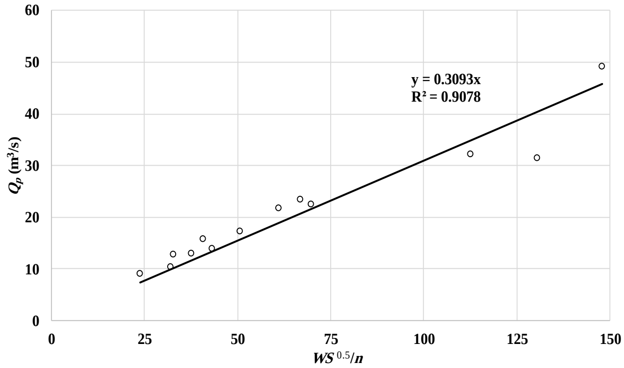


**Figure 4.** The relationship between the sub-watershed peak flow and its geomorphological attributes.

## 4. Conclusions

As a function of the ungauged watershed area and stream lengths, this study presents a general equation that can be used to estimate the watershed width which is an important input parameter for the SWMM to simulate the unit hydrograph. Conceptualizing the ungauged watershed as an impervious surface of virtual curve number equals 100 subjected to 1cm depth of an effective rainfall, the SWMM simply simulates the 1-hr UH. The derived 1-hr UH for Swaqa has peak flow of 133m$^3$/s which requires 4.5 hours to attain its value after the runoff has begun. It can be used to produce runoff hydrograph in Swaqa region which is valuable to analyze floods and study rainwater harvesting. For ungauged watersheds of skew factor near 0.5 and shape factor much below 1, this study introduces a general equation that can be used to predict the peak flow of the 1-hr UH as a function of the watershed area, streams length, surface roughness and slope. The predicted peak flow value of the 1-hr UH agrees well with the SWMM simulated value. Such an equation is useful to construct synthetic UHs in ungauged watersheds similar to Swaqa.

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