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# Modeling Hydrological Processes in A Wadi Basin in Egypt: Wadi Kharouba Case Study

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## *Abstract.*

*Wadi Flash Flood (WFF) is one of the most crucial problems facing the north-western coastal region in Egypt. Water harvesting (WH) approaches may be an effective tool to reduce the WFF risk while storing the runoff water for agricultural activities. In this study, the Agarma sub-catchment of the Wadi Kharouba was taken as a reference investigation site to study terraced WA systems. The main problem in this area is that local farmers independently build terraces using traditional knowledge to increase land availability. This frequently generates conflicts with farmers downstream, worried about not receiving enough water due to runoff being retained by the upstream terraces. There is a need to determine the potential area that can be irrigated by quantifying the runoff remaining for the farmers downstream. In this scope, this study aims to develop a modeling methodology for designing water harvesting systems at the watershed scale based on the Geomorphological Instantaneous Unit Hydrograph (GIUH) approach for runoff routing. GIUH predicts runoff and average transmission losses during a single rainfall event. A computer program was developed to systematically derive computed direct surface runoff hydrograph (DSRH), based on the Nash model. Computed DSRH was compared with observed DSRH derived from measurements at the Agarma outlet for rainfall events observed from Oct 2015 to Mar 2016. Geomorphologic information was derived from DEM of the basin and QGIS was used for data processing. The results showed that the efficiency of computed DSRH was 96.7 and 90.3 for the events of 16 Nov 2015 and 30 Dec 2015, respectively. The RMSE for the two events was 0.5 and 0.2, and the absolute average error was 0.3 and 0.06. In conclusion, GIUH proved to be an effective method for estimating the runoff volume for single rainfall events in Wadi Kharouba. This approach could be reused and expanded for other ungauged basins with similar geomorphology, namely, El-Safa and El-Raml.*

***Keywords.***
*Terraces - GIUH - Nash model - DSRH - Dryland.*

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## Introduction:

The northwestern coastal region of Egypt is considered one of the most promising lands for agricultural expansion beyond the Delta and Nile Valley, and agricultural development of the desert may play a significant role in promoting agricultural production (Elbeih, 2021). This expansion may come from water harvesting systems developed in Wadi basins, as they may increase water availability during dry seasons and reduce the harmful effect of flash flood risk. Wadi basins could be suitable for developing water harvesting strategies. In these areas, occasionally brief, but intensive rainfall events may generate flash floods. The flood water may be stored in the Wadi stream bed by modifying the natural ephemeral stream into a series of leveled terraces supported by regularly spaced dikes. These terraces slow down the water flow and provide a chance to seep into the alluvial bed (Oweis et al. 2001). When new wadi water harvesting systems are being developed, hydrologists, soil scientists, and agronomists alike need to determine the potential area that can be irrigated through data such as total annual runoff, its distribution in time, the peak flows, and the characteristics of the area. To develop a Wadi system for agricultural uses, it is important to understand the entire hydrology of the system and provide a detailed description of the soil properties. In the northwestern coast of Egypt, agricultural expansion is already based on similar water harvesting strategies, and local farmers took the initiative and started to construct cisterns, reservoirs, and cement dykes based on local and traditional knowledge to increase their land availability for crops (Yousif et al., 2022). However, this frequently generates conflicts with farmers downstream, worried about not receiving enough water as most of the runoff can be held by terraces built upstream. In this context, designing terrace water harvesting systems based on scientific methodologies may provide a good approach for calculating the number of terraces upstream and also quantifying the runoff remaining for the farmers downstream. The Agarma sub-catchment of the Wadi Kharouba can be considered a reference investigation site for terrace-based water harvesting systems. A rainfall-runoff database already exists, collected within the Matrouh Rural Sustainable Development Project (MARSADEV), aiming at reclaiming part of the wadi into cultivated terraces from a previously heavily eroded, abandoned, and degraded landscape. The database consists of weather data, measurements of distributed water content with detailed spatial and temporal data, and monitoring of runoff at the downstream section of the wadi. Specifically, a surface hydrological model known as GIUH (Geomorphological Instantaneous Unit Hydrograph) will be utilized for forecasting average transmission losses and runoff generated by a single rainfall event, both before and after developing the terraces (Rodriguez-Iturbe et al. 1979 a, b). This will enable us to determine the average water storage capacity for each rainfall event and assess the average water loss at the end section of a single rainfall event. Consequently, we can ascertain the number of terraces that can still be constructed in the wadi. Once calibrated and validated, the model parameters will be used to evaluate the hydrological behavior of two other similar wadis, ungauged basins, namely the El-Safa and El-Raml wadis. Therefore, this research aims to develop a modeling methodology for designing water harvesting systems at a watershed scale. The methodology is based on using the GIUH model to simulate runoff routing during a single rainfall event, both before and after developing the terraces, and estimate the possible number of terraces that still can be built.

## Materials and Methods:

### Study Area and Data Preprocessing:

Wadi Kharouba watershed is located west of Marsa Matrouh in the North-Western Coastal Region of Egypt (Fig.1a). It covers an approximate area of 16516 ha. The climate is characterized by a temperate Mediterranean climate with long periods of hot-dry summers, and brief cool rainy winters from November to February. Agarma sub-catchment experiences a sub-humid climate regime, and undergoes a dry period from May to September, while the period from October to March is characterized by higher humidity levels. The monthly average temperature fluctuates between 14.4°C and 26.8°C, while the annual rainfall ranges from 100 to 190 mm. The soil texture in the Wadi area is classified as sandy clay loam. Moreover, the slopes in this region are extensively covered by thin soils, often with outcropping bedrock. This study focuses on the Agarma, El-Safa, and El-Ramal sub-catchments of the Wadi Kharouba (Fig.1b).

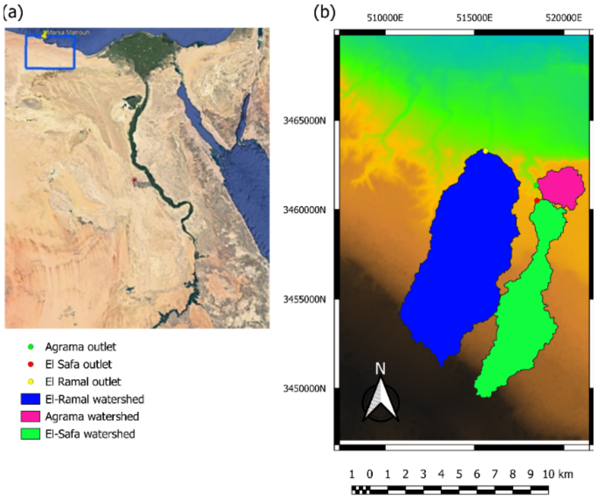

**Figure 1. (a) The study area location is shown over the map of Egypt. (b) Sub-catchments of Wadi Kharouba in the Northwestern coastal region overlayed on the DEM layer.**

Agarma's channel was modified into leveled terraces for cultivation. The terraced area is about 13.5 ha. It was provided with a complete hydrological monitoring system consisting of a meteorological station, discharge measuring systems, and sensors for monitoring the spatial distribution of soil water content. This makes Agarma a good reference investigation site for developing guidelines for designing wadis in arid areas (Coppola et al. 2019). The total area of El-Safa and El-Raml sub-catchments were 6.69 Km2 and 144.35 km2 respectively. The main channel was modified, and the alluvium bed was transformed by building terraces. The soil texture within this region has been classified as sandy clay loam. The terraced area was 17.78 ha out of 350.75 ha for El-Safa. The mainstream of El-Raml was occupied by olive and fig trees, while the upstream part of the watershed remains reserved for rainfed agriculture and indigenous flora. Barley is the predominant winter crop cultivated within the basin, with the primary purpose being the provision of livestock fodder. A minor proportion of the land is designated for wheat cultivation. The crop production in the area is based on rainfall with no supplemental irrigation, no mineral fertilization, and a lack of crop rotation practices. In the last 20 years, Wadi El-Raml has faced significant land use changes. Total vegetation cover that protects soil from erosion has decreased to 28 % in the spring of 2015 which indicates vegetation degradation in Wadi El-Raml. High-resolution rainfall data for the study area has been acquired from Agarma meteorological station located in Wady Kharouba, which includes a reading every 30 minutes during the day, from 21 Oct. 2015 to 21 May 2016. The soil conservation service (SCS) curve number method was utilized to compute excess rainfall from total rainfall (Garen and Moore, 2005).

Data preprocessing of the Digital Elevation Model (DEM) and a database consisting of Rainfall data has been done to derive a Direct Surface Runoff DSRO hydrograph using the geomorphological, and climatological characteristics of a basin. Data processing of the watershed in this study was carried out using QGIS software (Version 3.30.0) to delineate the basins and draw the streamlines based on the elevation model using SAGA Next Gen tools. The Digital Elevation Model (DEM) for the study area was obtained from the Desert Research Center in Egypt. This DEM provides elevation data for the study region at a resolution of 20 meters per pixel. The listed steps were followed to delineate the three sub-catchments:

1. Fill Sinks by using wang and Liu (2006) method. This step is necessary when there are small depressions in the elevations.
2. Stream networks have been generated by Strahler's orders method (Strahler, 1957).
3. Flow Direction and Channel network were generated using the Channel Network and Drainage Basins tool. The D-8 drainage model was utilized to calculate the flow directions

connecting the central cell and its eight neighboring cells.

4. Flow accumulation was utilized to assess the precipitation amount received within a specific watershed. The output layer represents the amount of rain flowing through each cell and was used to determine the drainage pattern.

5. The outlet coordinates of 3 sub-catchments were extracted.

6. The upslope area tool was utilized to delineate the Watershed, and the generated watershed was converted from raster to vector layer to calculate the hydrologic area for the stream network, and hydrologic area for each order.

7. The channel network layer was clipped by the overlay layer that represents the generated watershed. Three channel network layers are styled for each watershed based on the value of each order, that value has been obtained from Strahler's orders method.

*8.* The length of the longest stream and the length of the highest-order stream were *measured* manually, while the order and number of streams were generated automatically.

## Hydrological model: Geomorphological Instantaneous Unit Hydrograph (GIUH)

The methodology was established to derive the direct surface run-off (DSRO) hydrograph for a single rainfall event by using a Geomorphological Instantaneous Unit Hydrograph (GIUH) based on the Nash model. Figure (2) represents the flow chart of the methodology used in this study.

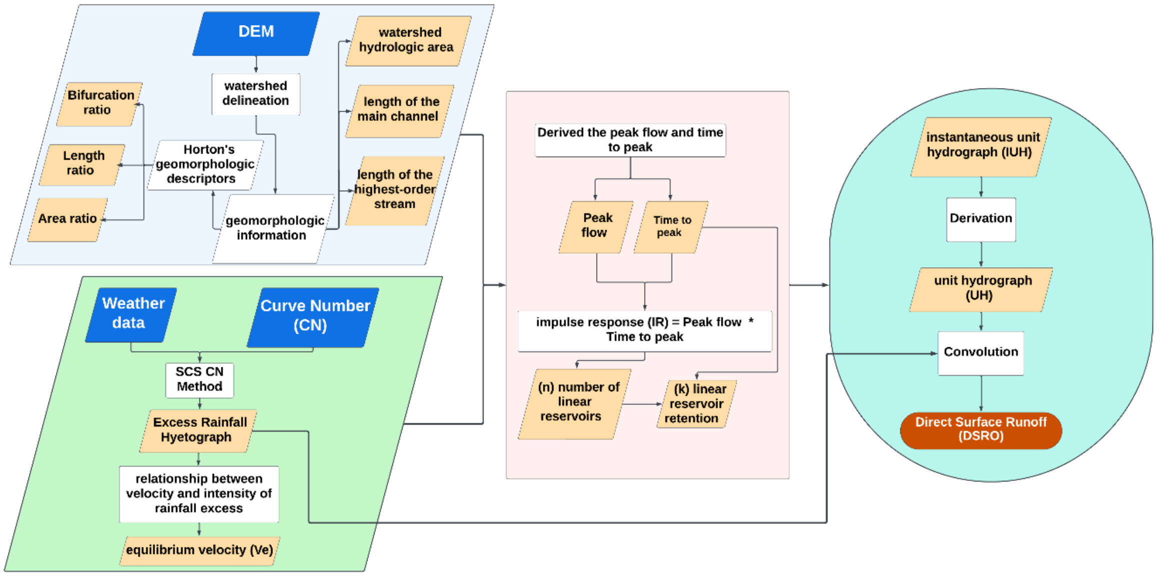

**Figure 2. Flow chart of the methodology used in the study.**

The primary idea of this method is to derive the instantaneous unit hydrograph (IUH) from Horton's laws of basin composition, which describe the architecture of the channel network. The resulting response function is known as a geomorphologic instantaneous unit hydrograph. Rodriguez-Iturbe et al. (1979) derived Equations (1) and (2) for the peak flow $q_p$ in units of an inverse hour and time to peak $t_P$ in an hour of the IUH as follows:

$$q_p = 1.31 R_L^{0.43} V / L_\Omega \qquad \text{Equation 1}$$

$$t_P = 0.44 (L_\Omega / V)(R_B / R_A)^{0.55} (R_L)^{-0.38} \qquad \text{Equation 2}$$

## Model Parameters

The parameters represent the geomorphologic details of the basin and the climatological characteristics. The geomorphologic parameters include the bifurcation ratio ($R_B$), the length ratio ($R_L$), and the area ratio ($R_A$), with values typically ranging from 3 to 5 for $R_B$, 1.5 to 3.5 for $R_L$, and

3 to 6 for $\boldsymbol{R_A}$ (Horton, 1945). Additionally, the mean length of streams ($\bar{L}_\omega$) and the average streamflow velocity in the catchment (v) are required as additional parameters. The estimation of peak velocity (V) involves establishing a relationship between the intensity of rainfall excess and velocity for a single rainfall event (Kumar et al., 2002).

## Derivation of instantaneous unit hydrograph using Nash model

Kumar *et al.* (2007) mentioned the possibility of deriving the complete shape of GIUH by linking the peak flow and time to peak with Nash parameters such as n and k. The product of the $\boldsymbol{q_p}$ and $\boldsymbol{t_p}$ is an impulse response (IR), which is a dimensionless quantity representing the hydrologic similarity coefficient. This IR value is derived from the geomorphological characteristics of the watershed.

$$IR = q_{p^*}t_p = \frac{(n-1)}{\Gamma n}\mathrm{e}^{-(n-1)} \cdot (n-1)^{n-1} \qquad \textbf{Equation 3}$$

$$t = t_p = k(n-1) \qquad \textbf{Equation 4}$$

$$k = \frac{t_p}{(n-1)} \qquad \textbf{Equation 5}$$

where:

$q_{p^*}t_p$: $is$ a non-dimensional term

$n$: number of linear reservoirs (Dimensionless)

$k$: linear reservoir retention (hr)

The Nash model facilitates the derivation of an instantaneous unit hydrograph by routing the instantaneous inflow through a series of (n) identical linear reservoirs. These reservoirs are characterized by a storage coefficient (k) measured in hours. The outflow from the initial reservoir serves as the inflow for the subsequent reservoir, and this sequence continues until the final reservoir is reached. To determine the complete shape of GIUH using the following generalized expression of Nash IUH model:

$$u(t) = \frac{1}{k\Gamma_{(n)}}(t|k)^{n-1}\mathrm{e}^{-t/k} \qquad \textbf{Equation 6}$$

where:

$u(t)$: IUH ordinates in hr $^{-1}$

## Derivation of UH using instantaneous unit hydrograph.

The Unit Hydrograph for a specified duration (D) per unit area can be derived by utilizing equation 7, which relates the Instantaneous Unit Hydrograph (IUH) to the Unit Hydrograph (UH) of a D-hour duration.

$$U(D,t) = \frac{1}{D}\Big(I\big(n_, t|k\big) - I(n,(t-D)|k)\Big) \qquad \textbf{Equation 7}$$

where:

$U(D,t)$: ordinates of UH of D-hour duration in hour$^{-1}$

$t$: is sampling time interval in hour.

$\boldsymbol{I}$: (n, t k$^1$): incomplete $\gamma$ function of order n at (t k-1)

D: is the duration of UH in hour.

## Derivation of the Direct Surface Runoff DSRO, using UH.

The direct surface runoff (DSRO) hydrograph was obtained by combining the excess rainfall hyetograph with the previously derived unit hydrograph (UH) through convolution.

## Sensitivity analysis

Sensitivity Analysis serves as a method for evaluating the influence of changes in the values of independent variables on a specific dependent variable, within a predetermined set of assumptions. This analytical tool is applicable across diverse systems and operates based on the fundamental principle of "modifying the model and observing its resultant behavior." After designing GIUH model for Agarma, 5 technical parameters including the cumulative excess rainfall, manning’s roughness coefficient, the slope of the outlet, water depth, and width of the outlet were chosen to assess sensitivity by applying the "one-at-a-time" method. The observation has been done for total runoff volume per 1% change in the selected parameters.

## Model calibration

Model calibration was done using runoff measurements and two rainfall events, and this calibration process involved altering the most sensitive parameters by applying an optimization technique. The goal of this calibration was to ensure that the computed DRSO hydrograph closely matched the observed hydrographs at the wadi's outlet. Six objective functions were used to assess the computed DSRO hydrographs. These functions include Efficiency (EFF), Average error in volume (AEV), Percentage error in peak (PEP), Percentage error in time to peak (PETP), Root mean square error (RMSE), and Absolute average error (AAE) (Kumar et al. 2007).

## Simulation

During the rainy season of 2015-2016, hydrological processes were simulated under two different scenarios, scenario 1: simulations were conducted after the construction of terraces, and scenario 2: simulations were performed before the construction of terraces. These simulations involved adjusting input data parameters, including curve number CN, Initial abstraction (Ia), Width of the channel (m), the slope of the main channel (m/m), and Manning’s roughness coefficient. For each rainfall event during the rainy season, DSRO hydrograph was estimated, and the runoff volume was calculated by determining the area under the curve. To assess the accuracy of the GIUH model during the rainy season, a percentage of error calculation was used. This involved comparing the computed total runoff volume for the rainy season of 2015-2016 with the total runoff volume measured during the monitoring campaign in 2015.

## Scaling out the methodology

The methodology was extended to the El-Safa and El-Ramal watersheds, both of which share similar geomorphological characteristics with the Agarma watershed. This extension involved the reuse of GIUH based on Nash model. In these new areas, hydrological processes were simulated, by adjusting input data parameters analogous to scenario 2. Additionally, specific parameters such as the width of the channel (m), the slope of the main channel (m/m), bifurcation ratio, length ratio, area ratio, length of the highest-order stream (km), and length of the main channel (km) were modified based on data extracted from digital elevation model (DEM). For each rainfall event that occurred during the rainy season of 2015-2016, DSRO hydrograph was estimated, and the runoff volume was determined. To calculate the number of terraces that could be built in El-Safa and El-Raml, two key pieces of information need to be known, the runoff volume for the rainy season and the storage capacity of the terrace. The equation for calculating the capacity of the terrace is as follows:

$$\text{Capacity of the Terrace} = \text{Length (m)} * \text{Width (m)} * \text{Depth (m)} * \text{Soil Porosity } \theta \qquad \textbf{Equation 8}$$

After obtaining the capacity of the terrace in cubic meters ($m^3$), the number of terraces could be calculated according to the following equation:

$$\text{Number of Terraces} = \text{Runoff Volume for Rainy Season} / \text{Capacity of the Terrace} \qquad \textbf{Equation 9}$$

# Results and Discussion

## Watershed Delineation

The coordinates of the outlet points for Agarma, El-Safa, and El-Ramal were extracted as shown in Table 1. After extracting the coordinates, the stream networks for the three basins were generated and styled for each watershed based on the value of each order as shown in Figure (3). The watershed area was generated and converted from raster to vector layer to calculate the hydrologic area for the stream network, and hydrologic area for each order.

**Table 1. Latitude and longitude for the outlets of Agarma, El-Safa, and El-Ramal.**

| Sub-catchments of Wadi Kharouba | X-coordinates | Y-coordinates |
|---|---|---|
| Agarma | 518467.123 | 3461368.502 |
| El-Safa | 518495.112 | 3460509.29 |
| El-Ramal | 515614.405 | 3463279.163 |

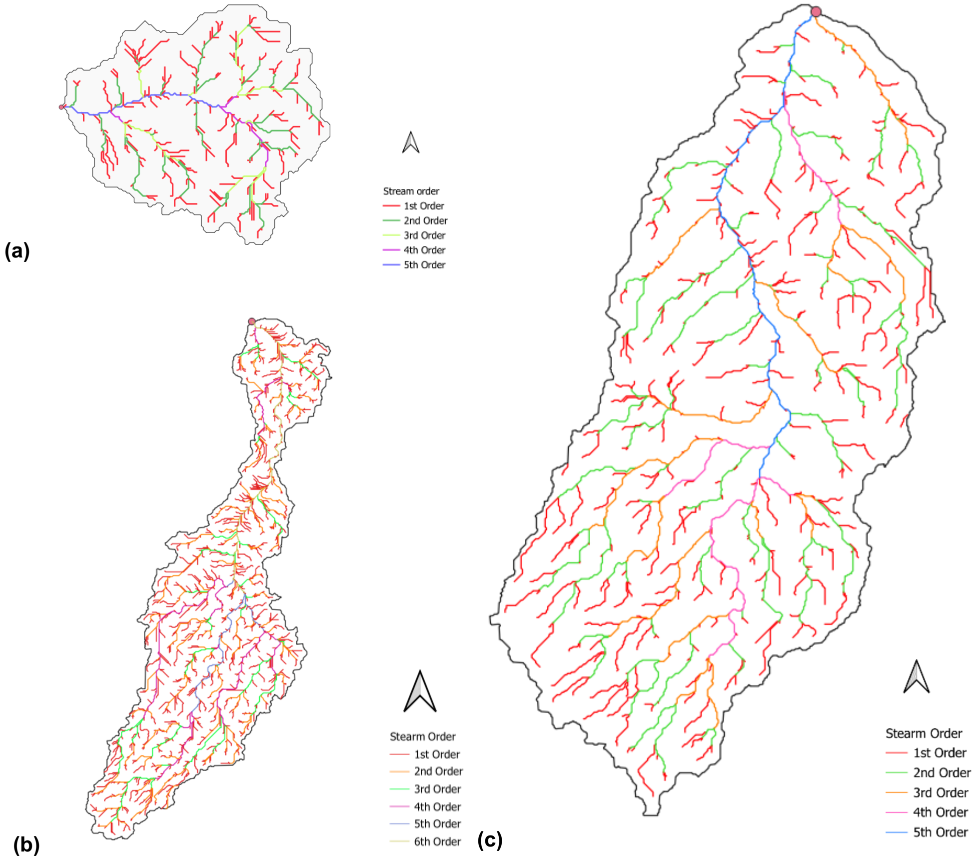

**Figure 3. Drainage pattern and stream order of a) Agarma, b) El-Safa, and c) El-Ramal.**

## The geomorphological information of the three basins.

Agarma and El Safe are medium watersheds, while El-Ramal is considered a large watershed due to the area and time of concentration. Horton's Ratios are derived from fitting best-fit lines to graphs representing the number of streams, average length of streams, and average area of streams as a function of their respective order as shown in Figures 4, 5, and 6. Table (2) was generated to provide the details of Order, Number of Streams, Average Length (m), Average Area ($m^2$), Bifurcation ratio, Length ratio, and Area ratio for the sub-catchments of the Wadi Kharouba.

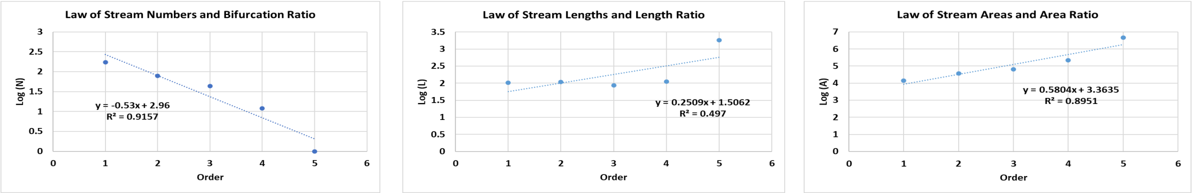

**Figure 4. Horton's Ratios of Agarma sub-catchment.**

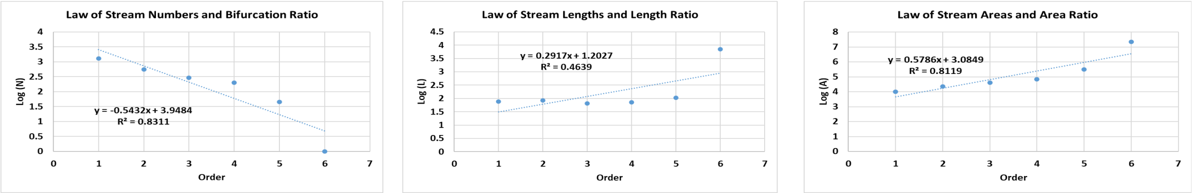

**Figure 5. Horton's Ratios of El Safa sub-catchment wadi Kharouba.**

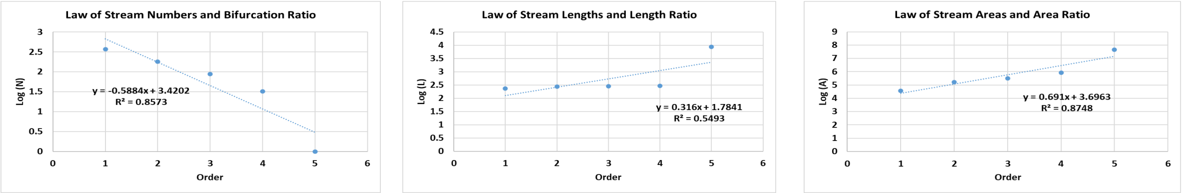

**Figure 6. Horton's Ratios of EL Ramal sub-catchment wadi Kharouba.**

**Table 2. Details of Number, Average Length, and Average Area for streams of various orders. Bifurcation ratio, Length ratio, and Area ratio for sub-catchments of the Wadi Kharouba.**

| Order | Number of Streams | Average Length (m) | Average Area (m$^2$) | log(N) | log(L) | log(A) | Bifurcation ratio | Length ratio | Area ratio |
|---|---|---|---|---|---|---|---|---|---|
| **AGARMA sub-catchment wadi Kharouba** | | | | | | | | | |
| 1 | 174 | 102.87 | 13896.04 | 2.24 | 2.01 | 4.14 | 3.39 | 1.78 | 3.76 |
| 2 | 79 | 108.96 | 36964.65 | 1.90 | 2.04 | 4.57 | | | |
| 3 | 43 | 86.56 | 64695.29 | 1.63 | 1.94 | 4.81 | | | |
| 4 | 12 | 111.00 | 221896.08 | 1.08 | 2.05 | 5.35 | | | |
| 5 | 1 | 1831.96 | 4284434.97 | 0.00 | 3.26 | 6.63 | | | |
| **El Safe sub-catchment wadi Kharouba** | | | | | | | | | |
| 1 | 1296 | 75.39 | 10232.87 | 3.11 | 1.88 | 4.01 | 3.49 | 1.96 | 3.79 |
| 2 | 559 | 83.44 | 23139.98 | 2.75 | 1.92 | 4.36 | | | |
| 3 | 294 | 65.41 | 41672.30 | 2.47 | 1.82 | 4.62 | | | |
| 4 | 200 | 71.85 | 68637.39 | 2.30 | 1.86 | 4.84 | | | |
| 5 | 45 | 104.23 | 305091.77 | 1.65 | 2.02 | 5.48 | | | |
| 6 | 1 | 7132.69 | 22121370.82 | 0.00 | 3.85 | 7.34 | | | |
| **EL Ramal sub-catchment wadi Kharouba** | | | | | | | | | |
| 1 | 367 | 232.79 | 36135.70 | 2.56 | 2.37 | 4.56 | 3.88 | 2.07 | 4.91 |
| 2 | 182 | 277.72 | 163495.87 | 2.26 | 2.44 | 5.21 | | | |
| 3 | 88 | 280.70 | 315957.94 | 1.94 | 2.45 | 5.50 | | | |
| 4 | 32 | 292.03 | 816351.97 | 1.51 | 2.47 | 5.91 | | | |
| 5 | 1 | 8630.34 | 46122901.45 | 0.00 | 3.94 | 7.66 | | | |

## Rainfall analysis

During the rainy season between 2015 and 2020, 22 rainfall events were recorded and 15 rainfall events were able to create flash floods as shown in Table (3). The excess rainfall hyetograph was computed using the Soil Conservation Service Curve Number (SCS-CN) Method, where the curve number for Agrama was 85. On 11/16/2015, the Initial abstraction (Ia) was equivalent to 18% of the Maximum soil storage depth. Conversely, on 12/30/2015, the Initial abstraction (Ia) was found to represent 20% of the Maximum soil storage depth. This shift in percentage occurred due to the filling of the terraces with water from prior rainfall events. Excess rainfall begins to accumulate when the total rainfall exceeds the total abstraction. Specifically, 2 mm of cumulative excess rainfall (Pe) was obtained when 18.6 mm of cumulative rainfall per 15 minutes was observed. The excess rainfall hyetograph was computed for two rainfall events during the rainy season 2015-2016 are shown in Figure 7.

**Table 3. Rainfall-runoff events through the period between 2015 and 2020.**

| Event Number | Date | Rainfall (mm) | Duration (hr) | Rainfall Intensity (mm/hr) | Excess rainfall (mm) | Duration (hr) | Excess rainfall Intensity (mm/hr) |
|---|---|---|---|---|---|---|---|
| 1 | 10/26/2015 | 14.6 | 3 | 4.87 | 0.8 | 1 | 0.83 |
| 2 | 11/16/2015 | 15.2 | 1.5 | 10.13 | 1.0 | 1 | 0.98 |
| 3 | 12/30/2015 | 12.2 | 3.5 | 3.49 | 0.2 | 2.5 | 0.09 |
| 4 | 1/23/2016 | 26.2 | 8.5 | 3.08 | 5.22 | 8.50 | 0.61 |
| 5 | 11/30/2018 | 12.4 | 1.5 | 8.27 | 0.38 | 0.75 | 0.51 |
| 6 | 12/1/2018 | 18.6 | 0.25 | 74.40 | 2.00 | 0.25 | 8.01 |
| 7 | 12/11/2018 | 16.2 | 1 | 16.20 | 0.40 | 0.50 | 0.81 |
| 8 | 1/2/2019 | 18.4 | 1.25 | 14.72 | 1.94 | 0.75 | 2.58 |
| 9 | 1/3/2019 | 20.8 | 1 | 20.80 | 2.82 | 0.75 | 3.76 |
| 10 | 1/20/2019 | 18.6 | 1 | 18.60 | 0.45 | 0.50 | 0.89 |
| 11 | 2/6/2019 | 14.0 | 3 | 4.67 | 0.21 | 1.00 | 0.21 |
| 12 | 2/26/2019 | 19.4 | 3.75 | 5.17 | 2.29 | 1.75 | 1.31 |
| 13 | 2/17/2020 | 13.4 | 2.75 | 4.87 | 0.6 | 1.75 | 0.32 |
| 14 | 3/12/2020 | 14.6 | 2 | 7.30 | 0.8 | 1.25 | 0.66 |
| 15 | 3/13/2020 | 17.2 | 2.75 | 6.25 | 1.5 | 1.25 | 1.24 |

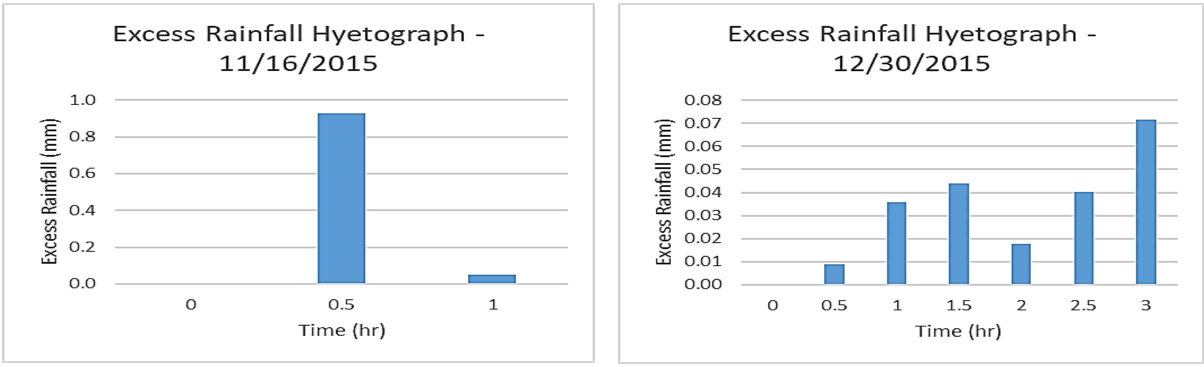

**Figure 7. Excess rainfall hyetograph derived from two rainfall events.**

## Dynamic velocity

The GIUH-based Nash model was run by adopting a peak velocity of 0.85 m/s for the Agarma. This velocity value was determined based on the correlation between equilibrium velocity and excess rainfall intensity. In this case, Manning's roughness coefficient was established at 0.012, the outlet slope was set at 0.00045 m/m, and the outlet width was determined as 10 meters for the Agarma. A Code was developed to link equilibrium velocity to excess rainfall intensity. Consequently, equilibrium velocity can be computed automatically by changing excess rainfall intensity.

## Design the GIUH model based on the Nash model.

The geomorphological information and Peak velocity are used to derive the peak flow in units of an inverse hour $(q_p)$ and time to peak in an hour $(t_P)$ of the IUH. For Agarma, the peak flow is 0.78 in units of an inverse hour, and the time to peak is equal to 0.71 hour. To derive the complete shape of GIUH, the peak flow and time to peak were linked with Nash parameters such as n and k. For Agarma, the impulse response is equal to 0.556607. IR was utilized to calculate (n) the number of linear reservoirs that represent the shape factor and the degrees of freedom. For Agarma, (n) number of linear reservoirs is equal to 3.105750263. These series of linear reservoirs are characterized by a storage coefficient (k) measured in hours. The parameter "K" is related to velocity inversely. K for Agarma is equal to 0.338.

The generalized expression of Nash IUH model has been utilized to determine the complete shape of GIUH, where $(t)$ is the sampling time interval in 0.25 hours. The output of the generalized expression is IUH ordinates obtained in cm/hr. IUH ordinates were converted to (m/s) and multiplied in the area of the watershed ($m^2$) to obtain IUH ordinates in $m^3$/s. The ordinates of UH of a specific duration are calculated by using the relationship between IUH and UH, while t is the sampling time interval in 0.25 hours. DSRO was derived by convoluting unit hydrograph with excess rainfall hyetograph for a single rainfall event. The time of concentration is the duration it takes for runoff to travel from the most distant point within the watershed. DSRO hydrograph was lagged by 0.5 hr. lag time represents 0.6 of the time of concentration (Tc)= 0.84 hr. Figure (8) shows IUH, UH, for agarma and DSRO during a rainfall event.

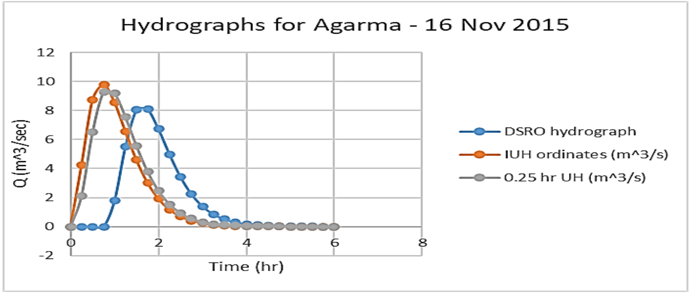

**Figure 8. UH, IUH, and DSRO Hydrographs for agarma.**

## Sensitivity analysis

This analysis observes the impact on total runoff volume for 1% change in the selected parameters. The parameters that were selected for variation in the model include cumulative excess rainfall, Manning's roughness coefficient, slope of the outlet, water depth, and width of the outlet. The higher the sensitivity figure, the more sensitive the total runoff volume is to any change in that input and vice versa. The results of this sensitivity analysis carried out by considering total runoff volume as the main output are summarized in Table (4). Figure (9) provides a graphical representation of the sensitivity coefficient values derived from a 1% change in the parameters. Cumulative Excess Rainfall and Manning's Roughness Coefficient are the most sensitive parameters. Consequently, the calibration was focused on two parameters.

**Table 4. The results of this sensitivity analysis**

| Output (Y) | Inputs (X) | Optimal value (Y) | Percentage change in the input | Percentage change in the output | sensitivity coefficient |
|---|---|---|---|---|---|
| Total runoff volume | Cumulative Excess Rainfall | 321083 | 0.01 | 32.11 | 3210.8 |
| | Manning's Roughness Coefficient | | 0.01 | -2.99 | -298.7 |
| | Slope of the outlet | | 0.01 | 1.44 | 143.9 |
| | Water depth | | 0.01 | 1.84 | 184.1 |
| | Width of the outlet | | 0.01 | 0.01 | 0.7 |

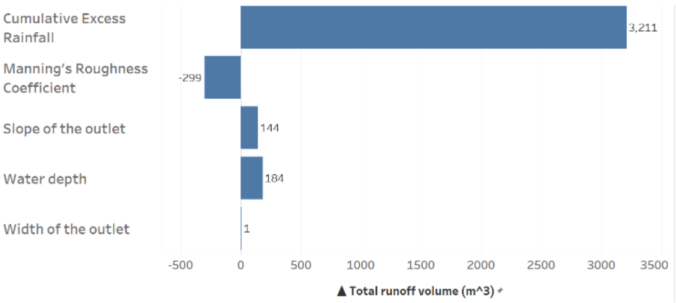

**Figure 9. Sensitivity coefficient values derived from a 1% change in the parameters.**

## Model calibration

The model was calibrated to ensure that the computed DRSO hydrograph closely matched the observed hydrographs at the outlet of the Wadi. The process involved the use of two rainfall events, with a focus on adjusting the most sensitive parameters through an optimization technique. Among these parameters, the cumulative excess rainfall and Manning's roughness coefficient emerged as the most sensitive. It's important to note that the cumulative excess rainfall cannot be directly altered, but changes in the excess rainfall can be influenced by adjusting the Initial abstraction (Ia) percentage. This percentage of initial abstraction (Ia) can be modified based on the availability of air-filled porosity or water-filled porosity (capillary porosity) within the soil (soil was partially saturated). calibration started with an initial abstraction (Ia) set at 20%. After conducting tests, it was determined that for Agarma, the optimal value for Manning's roughness coefficient is 0.012. This determination was made while considering that the outlet type is lined with concrete, and a range of values between 0.012 and 0.017 were examined during the calibration process. Throughout the calibration procedure, adjustments were made to the cumulative excess rainfall value to minimize the area under the curve between the computed and measured DSRO hydrographs. This area under the curve is indicative of the total runoff volume. The dynamic variables such as the depth of water (m), Excess Rainfall (ie) (mm/hr), Peak velocity (m/s), peak flow (inverse hour), time to peak (hr), Linear reservoir retention (hr), and Excess rainfall hyetograph (mm) are subject to change based on the specific rainfall event being measured, reflecting the variable nature of precipitation and runoff within the modeling framework. Figures 10 and 11 show DSRO hydrographs developed by using the GIUH based on Nash model and the measured hydrographs for two rainfall events.

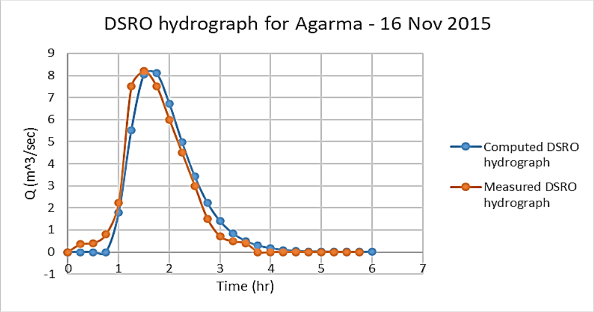

**Figure 10. DSRO hydrograph for Agarma – 16 Nov 2015.**

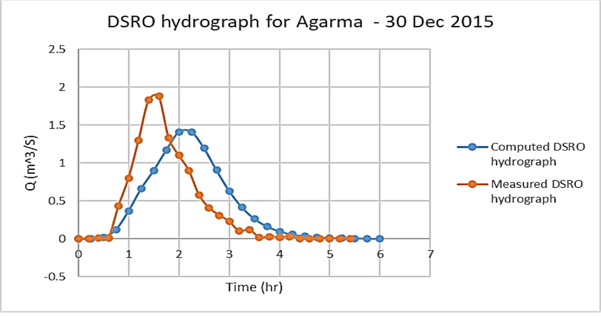

**Figure 11. DSRO hydrograph for Agarma – 30 Dec 2015.**

## Objective functions for evaluating the computed DSRO hydrographs.

Six objective functions were used to assess the accuracy and performance of the computed DSRO hydrographs. Table (5) presents the computed values of objective functions. For computed DSRO hydrographs, their EFF scores are notably high, measuring at 0.95 and 0.89, affirming the model's effectiveness in replicating these specific hydrological conditions. Indeed, Smaller Average error in volume (AEV) values, such as -25.81 and -24.94 for computed DSRO hydrographs are indicative of better model performance. The negative values signify that the model is slightly underestimating the runoff volume compared to the observed data. PEP values indicate model overestimation. Lower PEP values signify better peak flow accuracy. Percentage error in time to peak (PETP) values of 0 and 6.25 offer insights into timing prediction accuracy, with smaller values indicating better precision and larger values revealing greater timing discrepancies. Recorded Absolute average error (AAE) values of 0.36 and 0.06 reflect error magnitude. A lower AAE signifies better model performance with smaller absolute errors. (AAE) is less sensitive to outliers than Root Mean Square Error (RMSE), making it useful for extreme values.

**Table 5. Objective functions for evaluating the computed DSRO hydrographs.**

| Rainfall event | EFF | AEV | PEP | PETP | RMSE | AAE |
|---|---|---|---|---|---|---|
| 11/16/2015 | 0.95 | -25.81 | 1.94 | 0 | 0.55 | 0.36 |
| 12/30/2015 | 0.89 | -24.94 | 52.02 | 6.25 | 0.19 | 0.06 |

## Assessing GIUH Model Accuracy for Rainy Season.

The accuracy of the GIUH model during the rainy season was assessed using a percentage error calculation, which involved comparing the total runoff volume computed for the rainy season of 2015-2016 with the total runoff volume that was measured during the monitoring campaign in 2015. Where excess rainfall (Pe) of 7.25 mm was calculated using the Soil Conservation Service (SCS) curve number method. The terraced area covered 267,000 $m^2$, resulting in a total volume of excess rainfall for the rainy season at 1,936 $m^3$. A total rainfall of 207.2 mm was recorded, equivalent to a volume of 55,323 $m^3$ for the entire season. To determine the stored water, the volume of excess rainfall was subtracted from the total rainfall, resulting in a stored water volume of 53,387 $m^3$. Additionally, the evaporation volume was computed at a 5 cm soil depth, totaling 5,874 $m^3$. This calculation considered the terraced area's soil volume, which was 13,350 $m^3$, and had a soil porosity of 0.44. After deducting the evaporation volume from the total stored water, the remaining stored water in the soil profile (5-100 cm depth layer) at the end of January was determined to be 47,513 $m^3$. Coppola et al. (2019) mention that terraces have the potential to retain as much as 50,000 $m^3$ of water at the end of January. The study involved the collection of data from 20 terraces during a monitoring campaign conducted between October 2015 and July 2016. Percentage error was used to evaluate the accuracy of the calculation by comparing it to a known value. The percentage error between the computed and actual values was found to be -4.97%, indicating an underestimation of approximately 4.97%.

## Simulation

Comparing the hydrological scenarios between 2 rainfall events, while considering the presence and absence of terraces provides valuable insights into how terrace construction influences water flow and excess rainfall management. For each rainfall event, DSRO hydrograph was estimated, and the runoff volume was calculated. Figure (12) represents the simulated and computed DSRO hydrographs for Agarma during two rainfall events, and Table (6) shows the simulation outputs. The results show that terraces have helped reduce peak flow rates from 1.26 m/s in (Scenario 2) to 0.85 m/s in (Scenario 1). Terraces have tended to delay the time to reach the peak flow, In Scenario 1, the time to peak was longer (1.75 hours in November and 2.25 hours in December) compared to Scenario 2, where it remained constant at 0.75 hours. This could be beneficial for controlling floods and preventing soil erosion. The total volume of excess rainfall was lower in (Scenario 1) after terrace construction, compared to Scenario 2. This demonstrates that terraces are effective in capturing and storing excess rainfall, reducing the potential risk of wadi flash floods.

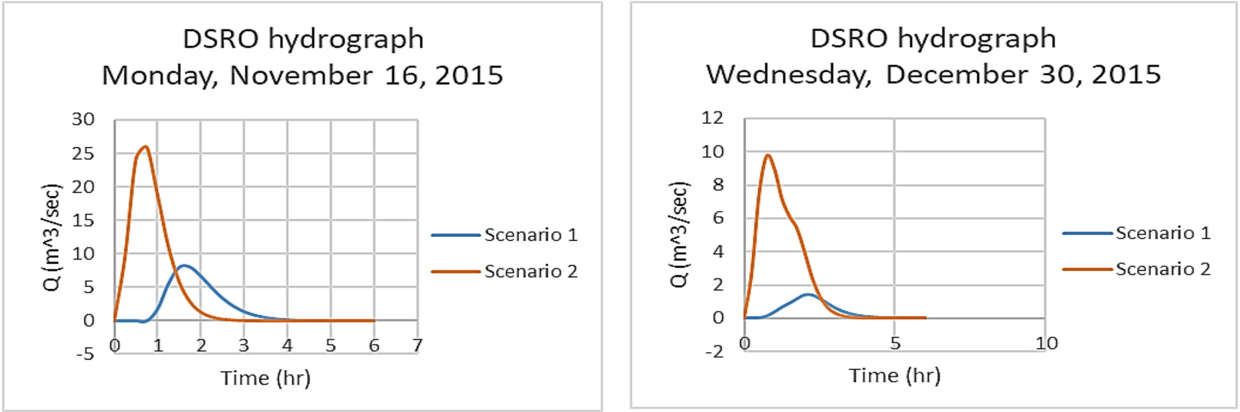

**Figure 22. Simulated and computed DSRO hydrograph for Agarma**

**Table 6. Simulation outputs.**

| Output | Monday, November 16, 2015 | | Wednesday, December 30, 2015 | |
|---|---|---|---|---|
| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
| Peak velocity (m/s) | 0.85 | 1.26 | 0.85 | 1.26 |
| Peak flow in units of an inverse hour | 8.1 | 25.9 | 1.4 | 9.8 |
| Time to peak in an hour | 1.75 | 0.75 | 2.25 | 0.75 |
| Total volume of Excess Rainfall (m^3) | 39849 | 90415 | 8865 | 51095 |

## Scaling out the methodology

The methodology was extended to the El Safa and El Ramal watersheds. In these new areas, hydrological processes were simulated, by adjusting input data parameters to Scenario 2, which included the curve number (CN) = 88, Initial abstraction (Ia)= 9% of Maximum soil storage depth (mm), and Manning's roughness coefficient = 0.04. Additionally, specific parameters such as the width of the channel (m), the slope of the main channel (m/m), bifurcation ratio, length ratio, area ratio, length of the highest-order stream (km), and length of the main channel (km) were modified based on data extracted from digital elevation model (DEM). The Instantaneous Unit Hydrograph and Unit Hydrograph were estimated as shown in Figures 13 and 14.

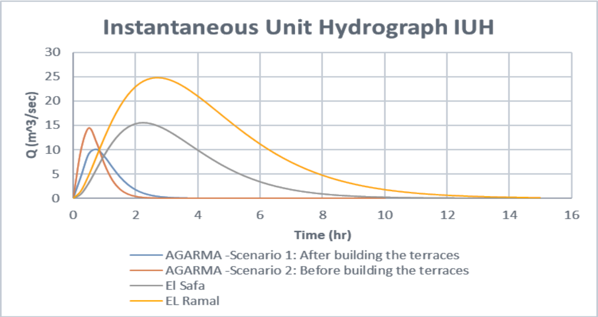

**Figure 13. Instantaneous Unit Hydrograph IUH for Agarma, El Safe, and El-Ramal.**

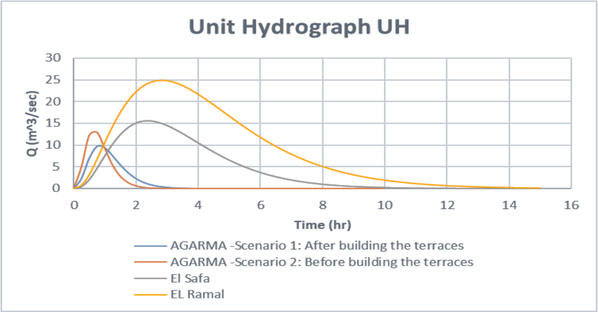

**Figure 14. Unit Hydrograph UH for Agarma, El Safe, and El-Ramal.**

For each rainfall event that occurred during the rainy season of 2015-2016, DSRO hydrograph was estimated as shown in Figures 15 and 16. and the runoff volume was determined as shown in Table 7.

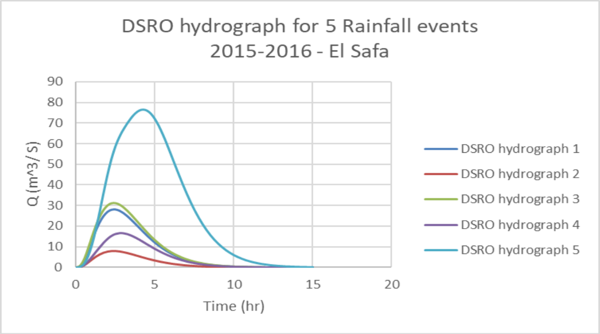

**Figure 15. DSRO hydrograph for El Safe during the rainy season.**

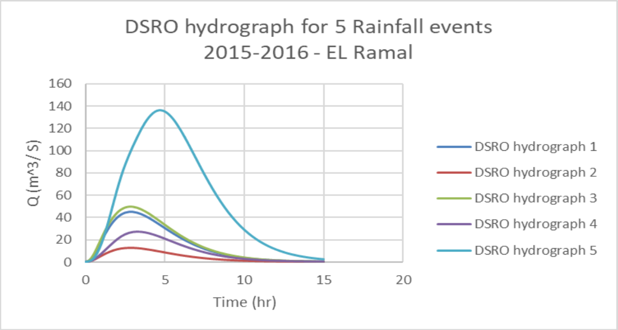

**Figure 16. DSRO hydrograph for El Ramal during the rainy season**

**Table 7. Runoff volume for El Safa and El Ramal during the rainy season.**

| Rainfall event | Excess rainfall (mm) | El Safa | EL Ramal |
|---|---|---|---|
| | | Total Runoff Volume (m^3) | Total Runoff Volume (m^3) |
| 10/26/2015 | 2.02 | 401,248 | 835,202 |
| 11/4/2015 | 0.57 | 114,209 | 237,733 |
| 11/16/2015 | 2.23 | 443,311 | 922,773 |
| 12/30/2015 | 1.26 | 250,512 | 521,223 |
| 1/24/2016 | 7.33 | 1,459,631 | 3,029,941 |
| Total | 13.41 | 2,668,912 | 5,546,873 |

The data demonstrates a significant variation in excess rainfall among the recorded events. Excess rainfall ranged from 0.57 mm (on 11/4/2015) to 7.33 mm (on 1/24/2016), indicating that the intensity of rainfall events varied over the season. The total runoff volume is directly proportional to the excess rainfall received. During the entire rainy season, El Ramal generated approximately 2.08 times more runoff volume than El Safa, reflecting differences in watershed size and characteristics. Over the entire rainy season (2015-2016), the cumulative excess rainfall amounted to 13.41 mm.

To calculate the number of terraces that could be constructed in El-Safa and El-Raml, the runoff volume for the rainy season, and the storage capacity of the terrace must be determined. The capacity of the terrace was 5000 $m^3$ when the length of the terrace was 50 m, the width was 100 m, the depth was 1 m, and the soil porosity was 0.44. Once these values are available, the number of terraces can be calculated by dividing the Runoff Volume for the Rainy Season by the Capacity of the Terrace. To ensure the saturation of the entire soil profile within the terrace, a proposed method involves constructing a cement dam with a height of 20 centimeters. This dam is specifically designed to enable the infiltration of up to 1,000 $m^3$ of water into the soil. The terrace's soil texture is classified as Sandy Clay Loam (SCL). Terrace dimensions are adaptable to the Wadi bed's width and slope. Additionally, the number of terraces could be modified based on these dimension changes. Table 8 provides runoff volumes, terraces' capacity, and recommended terrace numbers for AGARMA, El Safa, and El Ramal sub-catchments.

**Table 8. The number of potential terraces.**

| Sub-catchments | Total Runoff Volume ($m^3$) | Terraces capacity ($m^3$) | N. of Terraces |
|---|---|---|---|
| AGARMA | 544441 | 5000 | 108.888284 |
| El Safa | 2668912 | | 533.782326 |
| EL Ramal | 5546873 | | 1109.3745 |

Agarma sub-catchment has a relatively small total runoff volume compared to El Safa and El Ramal. El Safa sub-catchment has a significantly larger total runoff volume than AGARMA. El Ramal has the largest total runoff volume among the three sub-catchments. The number of terraces (1,109) is substantial and should have a significant impact on runoff management, especially with the available terraces' capacity.

## Conclusion

The Geomorphological Instantaneous Unit Hydrograph (GIUH) based on Nash model proposed in this study offers a valuable approach for calculating the DSRO hydrograph and calculating total runoff volume during a single rainfall event. DSRO hydrograph has been derived based on the integration of hydrologic characteristics of a catchment with geomorphologic parameters. In utilizing (GIUH) based on Nash model, a high-resolution Digital Elevation Model (DEM) enables to accurately derive geomorphological parameters for watersheds. Furthermore, the availability of high-resolution rainfall data, collected at frequent intervals as every 30 minutes throughout the day, has enabled the generation of an excess rainfall hyetograph for a specific rainfall event. Nash model facilitates the derivation of an instantaneous unit hydrograph and unit hydrograph. Convolution is a valuable technique for deriving a DSRO hydrograph by combining the excess-rainfall hyetograph with the Unit Hydrograph. Sensitivity analysis provided valuable insights into the relationships between model parameters and their effects on model behavior. Objective functions were used to assess the computed DSRO hydrographs such as efficiency (EFF), Average error in volume (AEV), percentage error in peak (PEP), percentage error in time to peak (PETP), root mean square error (RMSE), and absolute average error (AAE). Hydrological processes were simulated in two scenarios: post-terrace construction and pre-terrace construction, enabling a comparative analysis of watershed dynamics. The methodology used was adapted to encompass the El Safa and El Ramal watersheds, both of which exhibit similar geomorphological characteristics to the Agarma watershed. To determine the potential number of terraces that could be constructed in El-Safa and El-Raml, it is essential to have access to two critical pieces of information: the runoff volume during the rainy season and the storage capacity of each terrace. The result showed that cumulative excess rainfall and Manning's roughness coefficient are the most sensitive parameters. The efficiency of computed DSRH was 96.7 and 90.3 and the RMSE was 0.5 and 0.2 for events of 16 Nov 2015 and 30 Dec 2015, respectively.

Simulations demonstrate that after terrace implementation (Scenario 1) a substantial reduction in peak flow rates by 32% was observed, with peak flow dropping from 1.26 m/s (Scenario 2) to 0.85 m/s. Additionally, it delayed the time to peak flow, with a significant increase from 0.75 hours to 1.75-2.25 hours. Most notably, the total excess rainfall volume was consistently lower in Scenario 1, with a 20% reduction compared to Scenario 2. These findings underscore the beneficial influence of terrace construction in effectively managing water runoff. In conclusion, GIUH proved to be an effective method for estimating the runoff volume for single rainfall event in Wadi Kharouba. Consequently, enables the determination of the potential area that can be irrigated based on the available water. This approach could be reused and expanded for other ungauged basins with similar geomorphology.

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