Article in Press: JJEES 16(2), June 2025.
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Surface Runoff Estimation Using GIS Data under HEC HMS: Wadi Laussif Subbasin, Algeria

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Received on 25 November 2023, Accepted on 2 February 2025

Abstract

This study is a part of the Kherzet Youcef deposit's hydrogeological investigation. Calculating hydrological balance requires knowing the magnitudes of infiltration and flow. One important consideration in hydrogeological research is the rate of infiltration. In this case, the hydrogeological model will make use of it.

In some watersheds, the lack of hydrological measurements, their insufficient or questionable quality, and their reliability limit the precision of hydrologists' forecasts of hydrologic quantities, such as runoff, sediment, and nutrients. This issue is especially serious in developing countries like Algeria, especially, in the Wadi Laussif subbasin's undetected watershed (sub-catchment) area. Furthermore, approaches that allow for accurate watershed estimations of these variables are needed. Because the HEC-HMS model is widely used in hydrology studies to simulate the volume of surface runoff and determine flood peaks, many researchers have used it in flood forecasting. To predict the discharge in the Wadi Laussif subbasin, an attempt has been made to combine a geographic information system (GIS) and the semi-distributed hydrological model HEC-HMS. First, a digital elevation model and the GIS icon on the model were used to determine the basin's characteristics.

Information on daily precipitation was gathered from 1986 to 2020. The hydrological model employs the SCS-CN method to calculate the direct volume of runoff, the SCS unit hydrograph method to convert enough precipitation to a runoff hydrograph, and the lag time approach to determine the channel flow routing. The runoff simulation in the

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Wadi Laussif subbasin is executed by utilizing rainfall data, basin features, and soil conservation services curve numbers (SCS CN).

In conclusion, the estimation of direct surface runoff at the watershed outflow was conducted using the HEC-HMS model. The result obtained is deemed satisfactory. The approximate value of the estimated correlation coefficient is 0.79. This study contributes to improved water resource management in Algeria by providing a reliable methodology for estimating surface runoff in ungauged basins, crucial for informed decision-making, related to flood control, irrigation planning, and drought mitigation.

Keywords*:* Surface runoff, Ungauged subbasin, HEC-HMS, Hydrological model, SCS CN, Kherzet Youcef deposit, Wadi Laussif subbasin.

1 Introduction

Water resource availability in Algeria, like many regions, is increasingly threatened by climate change, manifested in fluctuating precipitation patterns, rising sea levels, and shifting temperature averages (Asokan and Dutta, 2008). Accurate runoff estimation is crucial for effective water resource management, encompassing flood control, irrigation planning, and the design of drainage networks. However, the scarcity and unreliability of hydrological data in many Algerian watersheds pose significant challenges for hydrologists and water resource managers. This is particularly true in ungauged basins, where limited data hinders the accurate prediction of runoff, sediment transport, and nutrient loads.

This study addresses this critical challenge by developing a reliable methodology for estimating surface runoff in the ungauged Wadi Laussif subbasin, Algeria. Specifically, we aim to:

1. Demonstrate the applicability of the HEC-HMS model in simulating runoff in ungauged basins within the Algerian context.
2. Provide a practical approach for estimating runoff in data-scarce regions to contribute to improved water resource management in Algeria.

The findings of this study are highly relevant to Algeria, where a significant portion of the country's watersheds lack adequate hydrological data. By successfully applying the HEC-HMS model to the Wadi Laussif subbasin, this research provides valuable insights into:

- Improving flood forecasting and early warning systems.
- Optimizing water resource allocation for irrigation and other uses.
- Developing sustainable water management strategies in the face of climate change.
- Supporting informed decision-making related to water resources planning and development in Algeria.

This research contributes to a growing body of literature on the application of hydrological models in data-limited environments, particularly in developing countries. It provides a valuable case study for other ungauged basins in Algeria and can inform future research on improving hydrological modeling techniques in data-scarce regions.

The ability to depict landscape elements spatially has been made possible by recent developments in rainfall-based runoff models. The integration of precipitation data with these models, such as the widely used HEC-HMS model (El Hussein et al., 2022; Hamdan et al., 2021; Barik et al., 2017; Dariane et al., 2019; Thameemul Hajaj et al., 2019; Sai et al., 2017), provides a viable method for improving the accuracy of runoff estimation. While distributed models offer the advantage of simulating spatial variability, their implementation can be resource-intensive, particularly in data-scarce environments like Algeria (Piman and Babel, 2013).

The HEC-HMS model is specifically designed to simulate rainfall-runoff processes and predict streamflow within branched basin networks, encompassing diverse geographical regions from small watersheds to large river basins (Abushandi and Merkel, 2013; Verma et al., 2010). The model provides a range of options for hydrological modeling, with key components focusing on the computation of subbasin runoff hydrographs and their routing through channels to the basin outlet (Nag et al, 2024). Given the complexity of hydrological systems and data limitations, the use of rainfall-based runoff simulation models is essential. The combination of HEC-HMS with GIS and remote sensing techniques (Ibrahim-Bathis and Ahmed, 2016) offer a powerful approach to addressing these challenges. Consequently, this research focuses on assessing surface runoff in the Wadi Laussif subbasin utilizing the HEC-HMS model.

2 Material and methods

2.1 Presentation of the Chott Beida Watershed

The Ain Azel depression is part of a vast hydrological basin, Highlands Constantine, which spreads over more than 9580 km² from the region of Ain Beida in the east to that of El Eulma in the west. The National Agency of Water Resources of Algeria assigned it the number 07 under the name of the Constantine Highlands (Figure 1). The Ain Azel plain occupies the western subwatershed (s/BV), coded 07-01, Chott El Beida.

The Wadi Laussif subbasin is a small basin with an area of approximately 74 km².

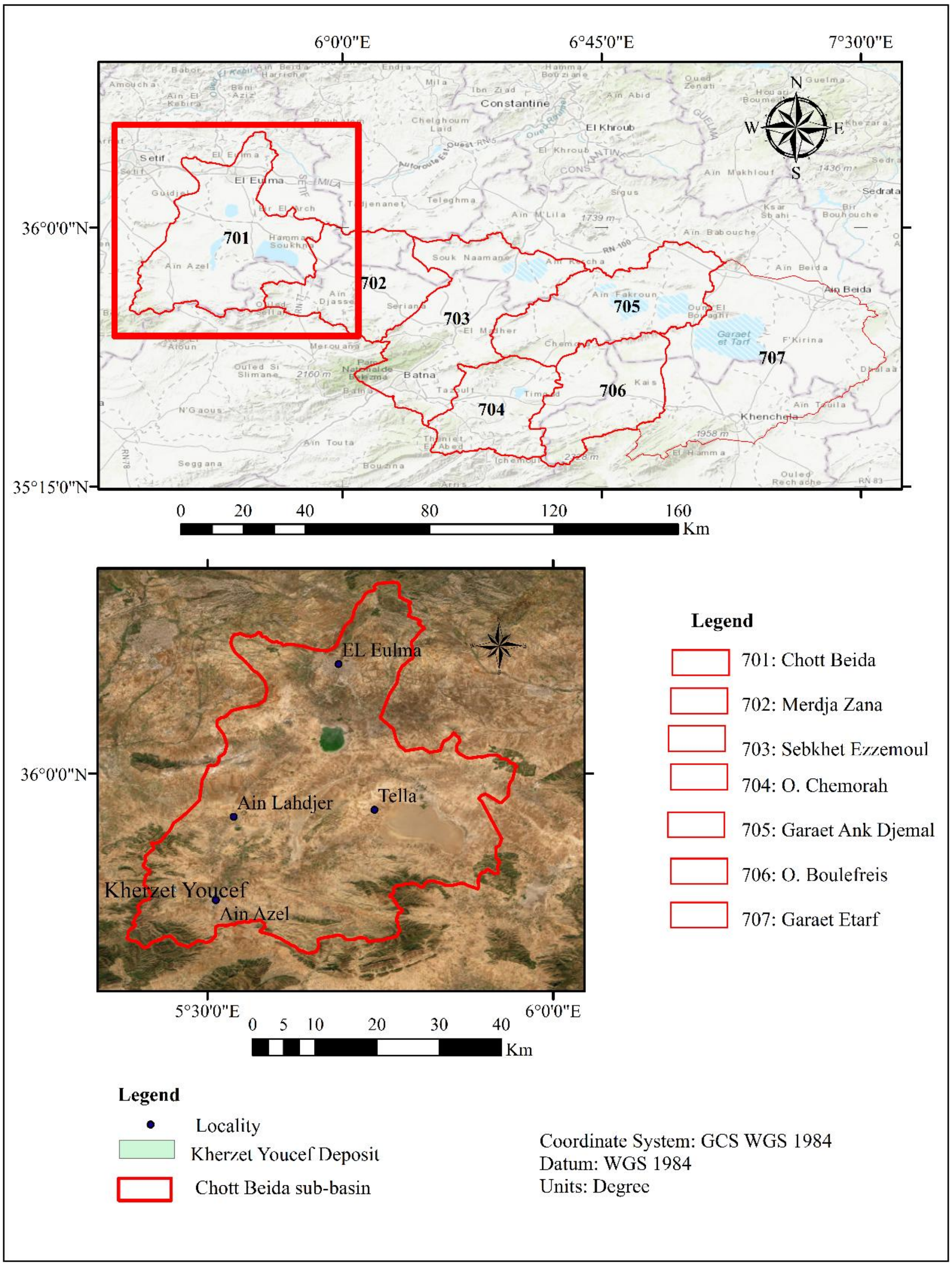

Figure. 1: Geographic location of the Wadi Laussif subbasin

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The slope is calculated using the slope module of GIS to present the topographic area of the subbasin. Then, the obtained slope is reclassified into categories, as shown in Table 1. The slope categories are chosen according to the classification proposed by Hagerty and Kingston (1992). The obtained result is presented in Figure 2.

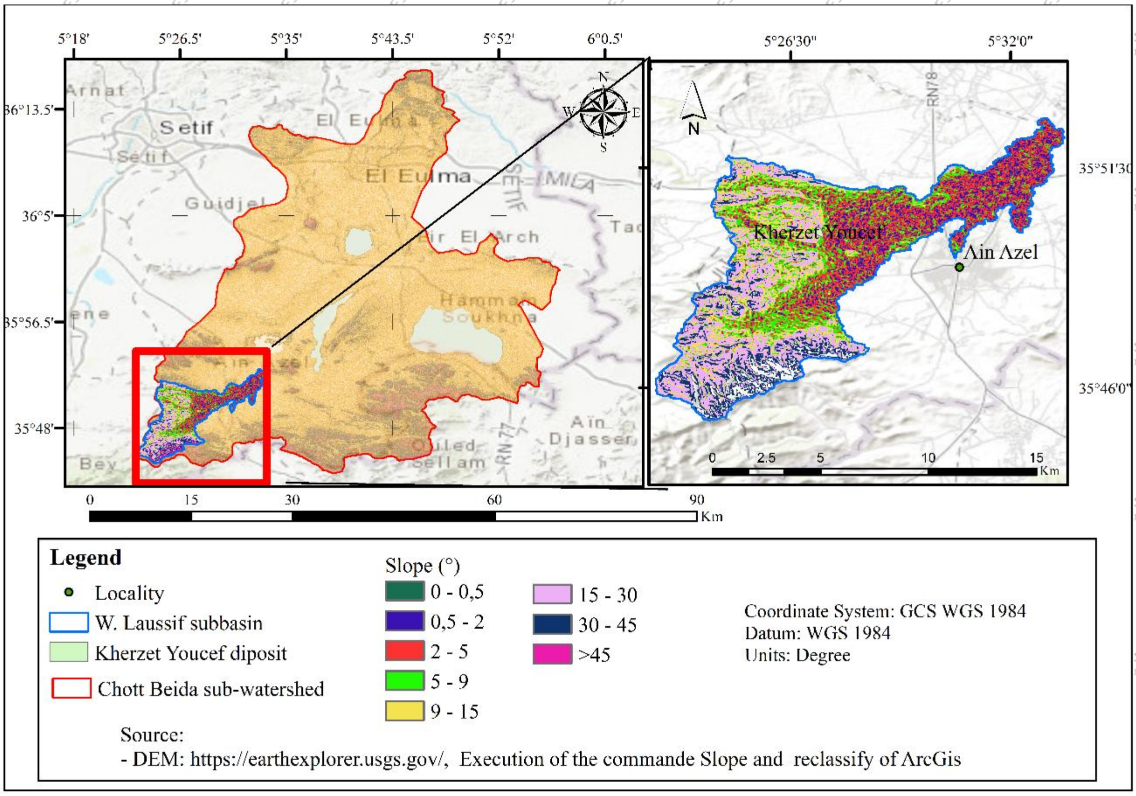

Figure 2. Slope map

Each category's area, expressed in km² and percentage, is shown in Table 1. There is a minor slope (less than 15%) over 41% of the Wadi Laussif subbasin.

Table 1. Slope category (Hagerty and Kingston, 1992)

Category	Slope percentage (%)	Description	Occupied area (km²) Chott Beida	(%)	(km²) W. Laussif subbasin	(%)
A	0 – 0.5	Plat	100	6.25	0.75	1.018
B	0.5 - 2	Almost plat	255	15.93	8.45	11.424
C	2 – 5	Very slight slope	568	35.48	19.12	25.834
D	5 – 9	slight slope	326	20.36	12.55	16.953
E	9 – 15	Medium slope	149	9.31	10.13	13.689
F	15 – 30	Steep slope	140	8.77	16.13	21.802
G	30 – 45	Very steep slope	63	3.90	6.87	9.279

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One aspect that can be incorporated into the subbasin element is the canopy, which can symbolise the existence of plants in the landscape. The amount of precipitation that reaches the ground surface is decreased by plants' ability to intercept it. Water that has been intercepted evaporates in between storms. Transpiration is another way that plants draw water from the earth. Evapotranspiration is the term used to describe the combination of transpiration and evaporation.

Selecting a canopy method is optional but should be used for continuous simulation applications.

Table 2 shows the area occupied by each theme, and Figure 3 displays the land use/land cover map.

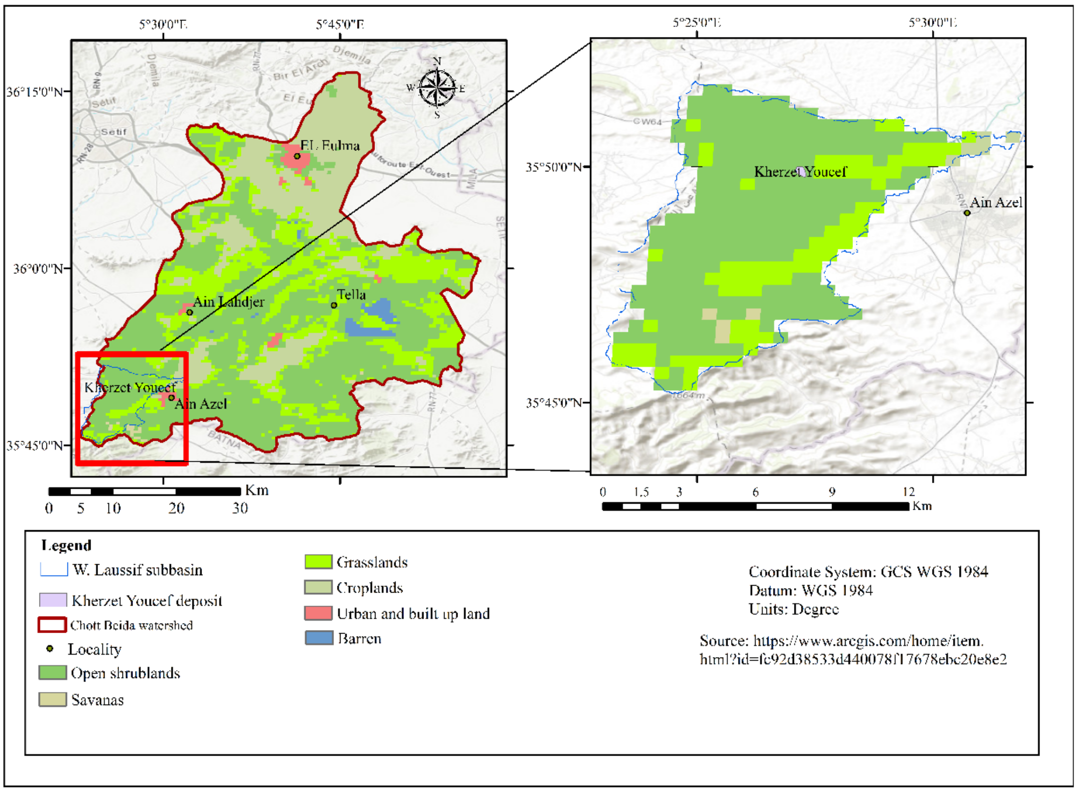

Figure 3. Land use/land cover, Chott Beida watershed

Table 2. Land use/land cover

Theme	Area occupied. (km²)	Area occupied. (%)
Open shrublands: Dominated by perennials (1 – 2 height), 10 – 60% cover	791	49.40
Savannas: Tree cover, 10 -30%, canopies >1Km	5	0.28
Grasslands: Dominate by herbaceous annuals	404	25.24

Croplands: At least 60% of the area is cultured croplands	358	22.36
Urban and built-up land: At least 30% impervious surface area, including building materials, asphalt, and vehicles.	22	1.38
Barren: At least 60% of the area is covered by permanent water bodies.	21	1.33

Infiltration rates vary with rainfall intensity, runoff, and vegetation conditions (Luo et al., 2020). In Chott El Beida watershed, according to Table 3, the land is covered by open shrublands, grasslands, and croplands, representing 49%, 25%, and 22%, respectively. Overall, the cropland effect drove in the same direction as climate change, increasing crop water requirements (3%) and actual evapotranspiration (11%), while decreasing net primary productivity-based water intensity (−15%), according to Vila-Traver et al. (2022).

Grasslands and open shrublands cover the Wadi Laussif subbasin; however, the soil is represented by leptosols (Figure 4).

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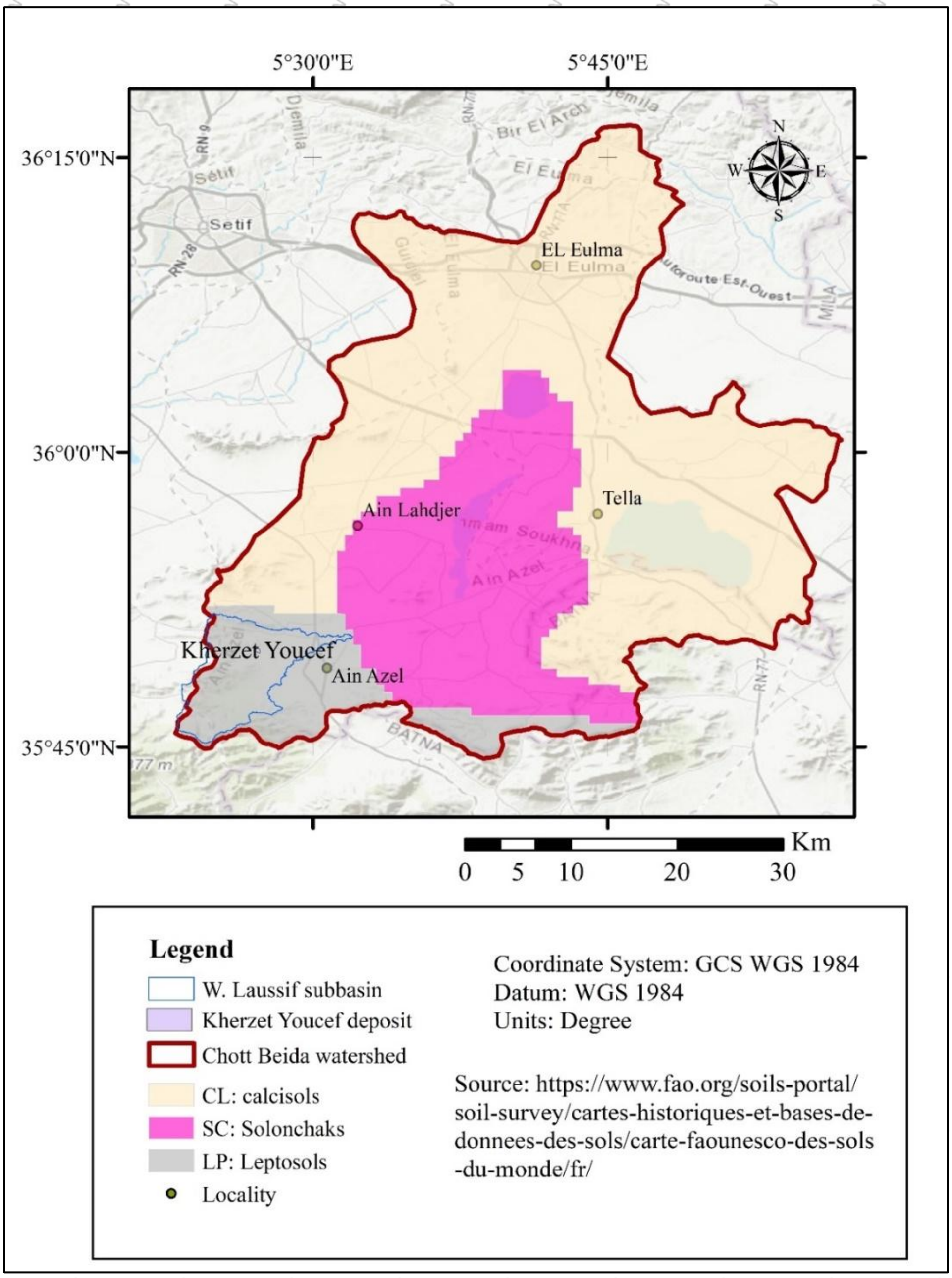

Figure 4. Soil type, Chott Beida watershed

2.2 Hydrological model

The rainfall-runoff model was generated using the HEC-HMS model. It is a semi-distributed, event-based model that divides the catchment into subbasins, computes the runoff response in each subbasin, and routes the river flow to the outlet. HEC-HMS has been extensively used in runoff estimation and land use change impacts on run-off (Yahia et al., 2018; Al-Samawi et al., 2021; Chanchala et al., 2022).

HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, direct runoff, and models of base flow (Mokhtari et al., 2016). The SCS-CN method was chosen to estimate the rainfall-runoff model for the loss methods. Channel flow was calculated using the lag time method.

2.2.1 SCS curve number

Assuming that the ratio of actual direct runoff to maximum possible runoff is equal to the ratio of actual infiltration to potential maximum retention and that the amount of initial abstraction is a fraction of the potential maximum retention, the SCS-CN method (NRCS, 2008) is a popular rainfall-runoff model that is based on the water balance calculation.

This method is given by Equations (1), (2), and (3). (In Dahdouh et al., 2018)

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \quad (1)$$

$$S = \frac{25400}{CN} - 254 \quad (2)$$

$$I_a = \lambda S \quad (3)$$

Where Q is the runoff depth (mm); P is the gross rainfall depth (mm); I_a is the initial abstraction (mm); and S is the potential retention (mm); λ is the initial abstraction coefficient.

The only parameter, curve number (CN), relates to land cover, soil type, and antecedent moisture condition. At the same time, the constant λ value should be fixed to 0.2, as found in documentation.

2.2.2 Lag time

Hydrometeorological factors (such as rainfall and runoff), watershed features (such as slope, land cover, soils, drainage density, and storage), and stream channel geomorphology all have a direct impact on concentration time (TC) and lag time (TL). In practice, TC and TL are most estimated from those variables using empirical approaches. According to Gericke and Smithers (2014), practically every technique created globally is empirically grounded and represents a constant trait for a particular watershed.

To calculate the TC, the Kirpich equation (in Dagnenet et al., 2022). This equation is used for channel flow and developed for small drainage basins.

$$Tc = 0.0663 \times L \times S^{-0.385} \quad (4)$$

Where:

- Tc is a time of concentration (h),
- L is the primary channel length (Km),
- S is the primary channel slope (m/m).

For the lag time, the next equation is used:

$$TL = 0.6 \times Tc \tag{5}$$

2.3 Method

This study employed HEC-HMS integrated with GIS techniques to estimate surface runoff within the ungauged Wadi Laussif subbasin, Algeria. Data acquisition included a 30-meter resolution Digital Elevation Model (DEM) from the SRTM 1 Arc-Second Global data, LULC and soil maps for CN estimation using the SCS-CN method, and 34 years of daily rainfall data (1986-2020). The 34-year rainfall dataset, sourced from the Algerian Ministry of Water Resources, was complete and of high quality. The SCS-CN method was selected due to its established reliability and widespread use in hydrological modeling. A hypothetical storm approach was utilized to provide consistent input for runoff simulations. The HEC-HMS model was then used to process the DEM, delineate the basin, and simulate surface runoff. Recognizing the data limitations in ungauged basins, the study addressed data quality concerns, implemented gap-filling techniques, and conducted sensitivity analyses to assess the impact of data uncertainties on model predictions. While rigorous calibration was not feasible, model parameters were adjusted within reasonable ranges based on expert judgment and literature values. The results of this analysis provide valuable insights into surface runoff characteristics within the Wadi Laussif subbasin and contribute to improved water resource management in data-scarce regions of Algeria.

Figure 5 presents the method used in this work.

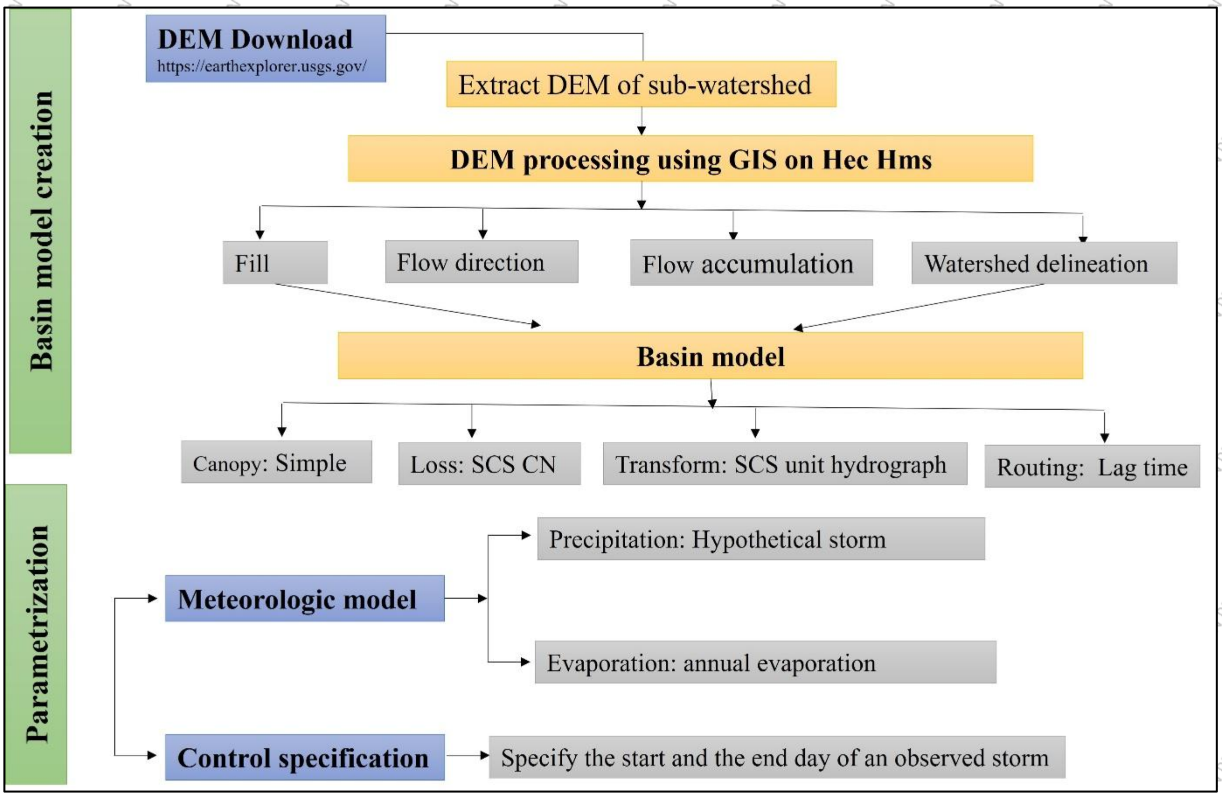

Figure 5. Chart of methodology

3 Results and discussion

3.1 Sub watersheds creation

A digital elevation model (DEM), downloaded from the United States Geological Survey site (USGS), with a 30 m resolution, was processed and used to generate the stream network and to define the sub-catchments with the GIS tools available under the GIS menu. First, we use the tool "Preprocess Sinks" after creating a basin model and adding the terrain (DEM). This tool will run a pit removal algorithm on the terrain data assigned to the selected basin model and produce a new, hydrologically corrected DEM and a raster indicating the location of sinks and the depth at which they were filled. These two new rasters are added to the map layer list as "sink fill" and "sink locations." The Preprocess drainage tool is then used, which will use an algorithm to ascertain the accumulation and flow direction of each grid cell in the terrain data raster. The hydrologically corrected DEM will be used in this method if the Preprocess Sinks command is executed first. Otherwise, the terrain data component's default elevation dataset or, if available, the reconditioned elevation dataset will be used. The Map Layers

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list now includes both generated rasters under the names "Flow Direction" and "Flow Accumulation."

Finally, we use the delineate element tool to delineate basins (Figure 6).

Hydrologic and topographic parameters were calculated as the model inputs.

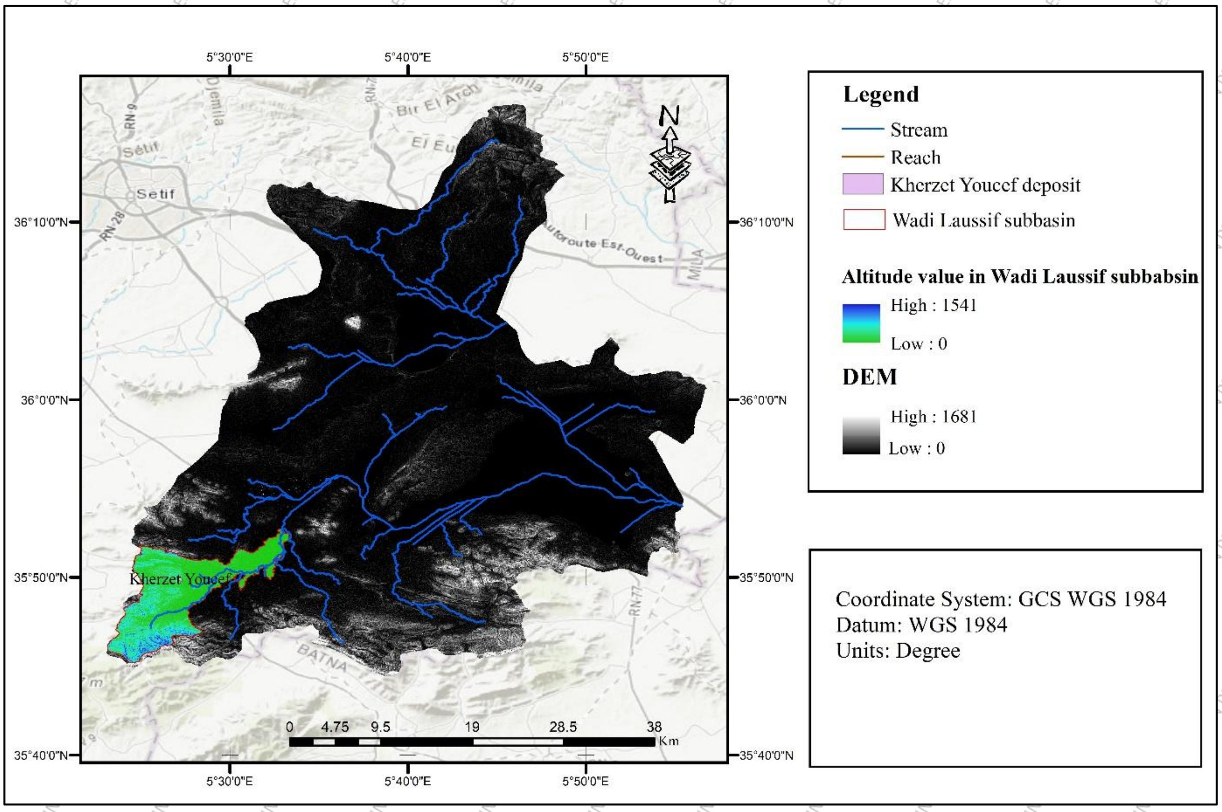

Figure 6. Wadi Laussif subbasin delineation

We compared the area of the subbasin with the area of the subbasin delineated on a topographic map, and the results are shown in Table 3.

The subbasin area, obtained from HEC-HMS, is near the natural area by approximately 3%. This discrepancy primarily stems from the use of different geodetic systems: a local system for the map and the global WGS84 system for the DEM.

Table 3. Wadi Laussif subbasin area

Parameter	From HEC HMS (km^2)	From topographic map (km^2)	Difference (km^2)	Difference (%)
Area	78.50	73.77	4.73	3.10

3.2 Climate data analyses

The fitting of the time series of maximum daily rainfall for the station of Ain Azel shows that the lognormal distribution is the most appropriate (Figure 7). This is given by the following formula of equation 6:

$$F(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{z^2}{2}} dx;\ z = aLog(x - x_0) + b. \qquad (6)$$

The maximum daily rainfall values calculated, using HYFRANPLUS software, for the return periods of 5, 10, 50, 100, and 200 years at the station (Table 4), correspond well to the precipitation recorded during the historical floods observed in the region of Ain Azel.

These results show the reliability of the statistical fit to the lognormal distribution. For the return period of 5 years, a rainfall of 44 mm is calculated.

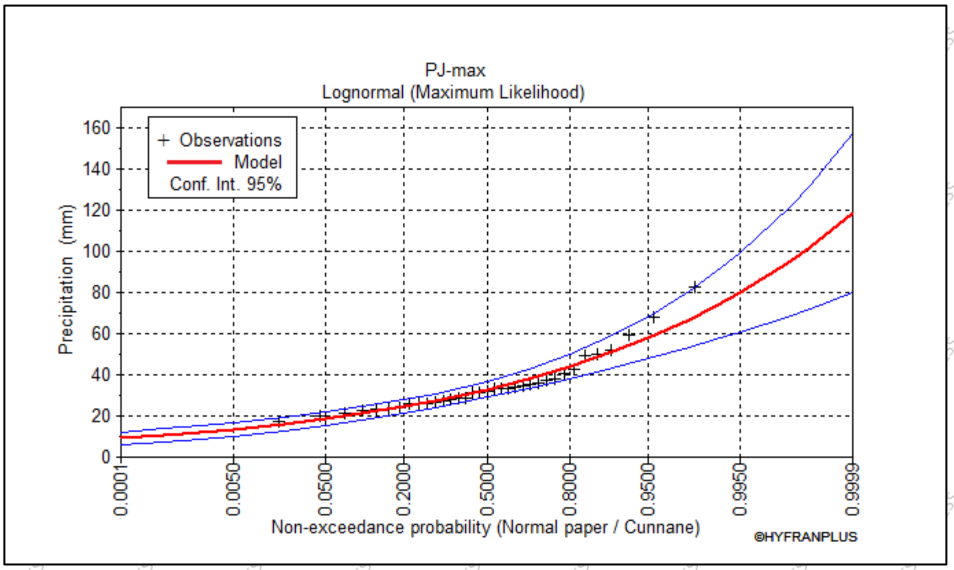

Figure 7. Adjustment of lognormal to the maximum daily rainfall (period 1986-2020)

Table 4. The maximum daily rainfall values calculated for different return periods.

Return period (year)	Maximum daily rainfall (mm
5	44
10	51.2
20	58
50	66.8
100	73.4

3.3 The unit hydrograph

After preparing all the required parameters for the loss method (Soil Conservation Service – curve number – SCS-CN), the method obtains the subbasin's direct runoff and peak discharge. Figure 8 illustrates the simulated unit hydrographs for return period of 5 years.

For this return period, the peak discharge is estimated to be 85.6 m^3/s; the loss volume is approximately 23.09 mm, the direct runoff volume is 20.91 mm, and the baseflow is approximately 9 mm (Figure 9).

Bibliographical research was carried out, and previous works on the area estimated the runoff value starting by applying empirical formulas based on monthly data averages (Djenba, 2015). The runoff value was estimated at 15.15 mm, and the infiltration was estimated at 8.4 mm.

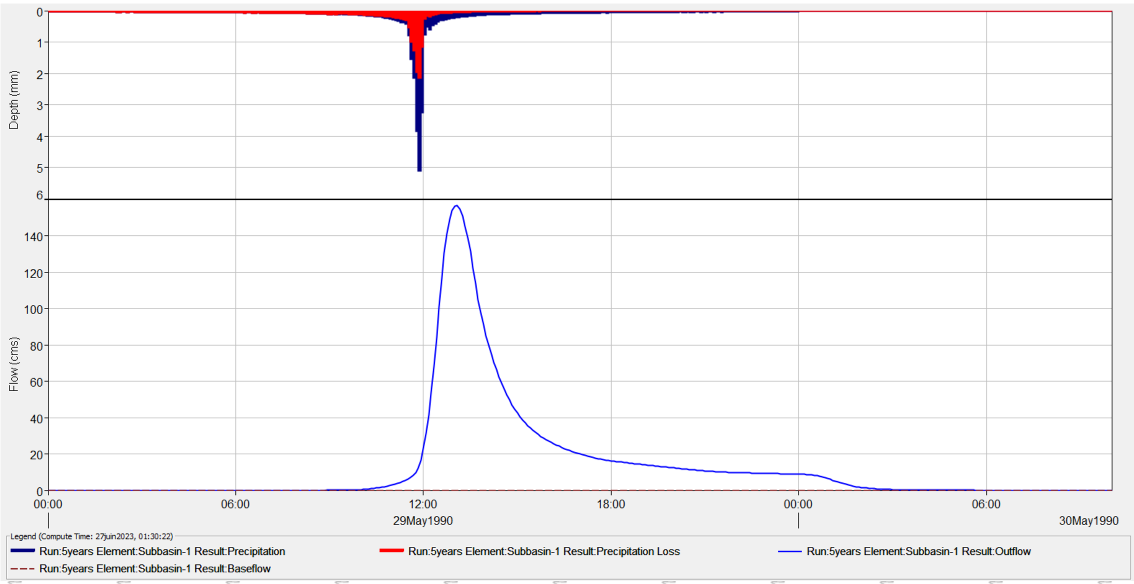

Figure 8. Flood hygrograph for a return period of 5 years

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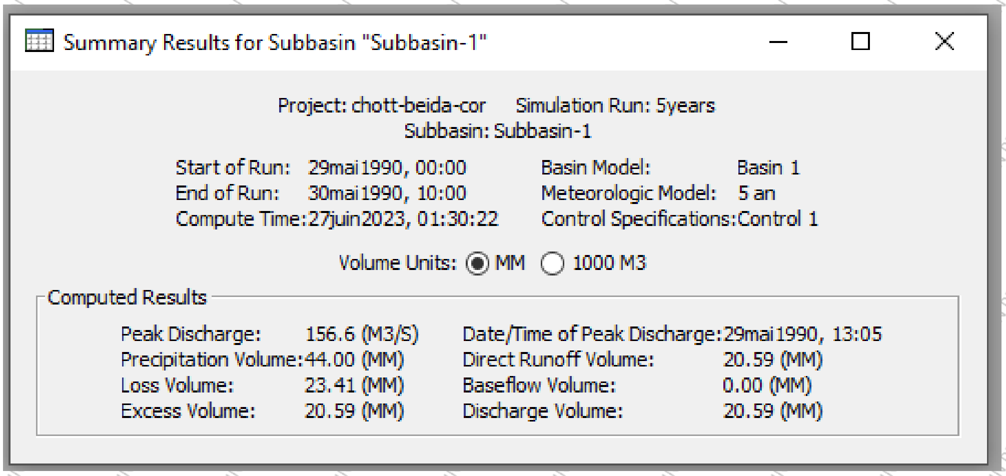

Figure 9. Summary results for a return period of 5 years

3.4 Statistical analysis

This section aims to analyze the model's sensitivity toward the values of the parameters implied in the simulations. To evaluate the flexibility of the rainfall-runoff model in this study case, we used the correlation coefficient (R) (In Dahdouh et al., 2018). It is calculated using the following formula in Equation 5:

$$R = \frac{\sum_{i=1}^{n}(Q_{i,obs}-\bar{Q}_{obs})(Q_{i,sim}-\bar{Q}_{sim})}{\sqrt{\sum_{i=1}^{n}(Q_{i,obs}-\bar{Q}_{obs})^2(Q_{i,sim}-\bar{Q}_{sim})^2}} \quad (6)$$

where:

- $Q_{i,sim}$ is the simulated value at time t=i,
- $Q_{i,obs}$ is the observed value at time t=i,
- $\overline{Q_{obs}}$ is the average value,
- n is the number of observations.

The correlations between simulated and observed runoff (Figure 10) give linear relationships but with acceptable correlation coefficients ranging from 0.79. This can be explained by the fact that the observed runoff on 29th May 1990 does not necessarily correspond to the rain falling during the same period and that the underground flows can indeed support the surface runoff due to the rain of that day or the previous day.

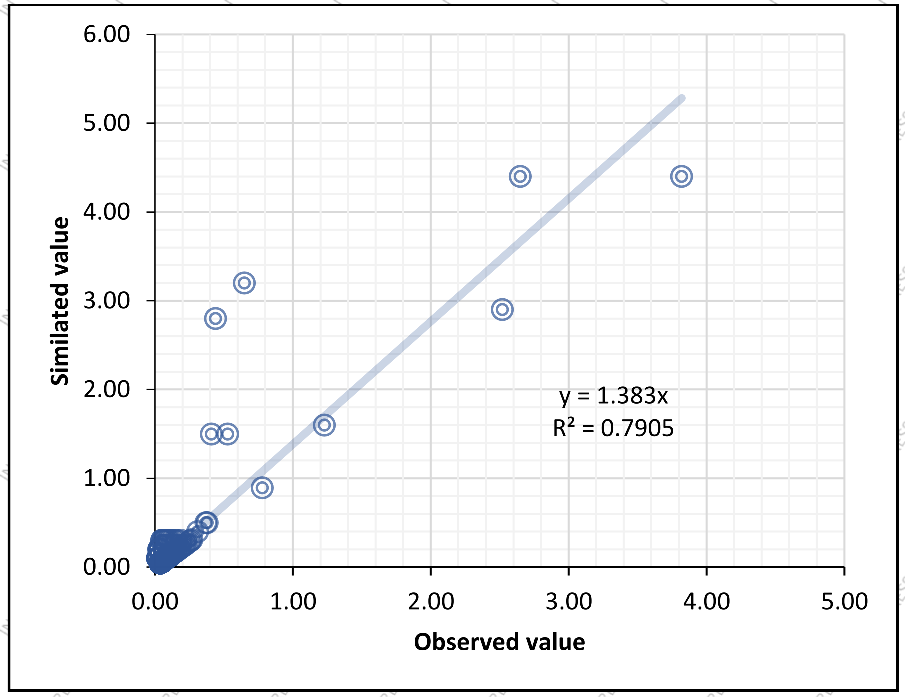

Figure 10. Comparison of simulated discharge and observed runoff in the Wadi Laussif subbasin

Another validation method is used. It visually compares simulated and observed runoff (Figure 11).

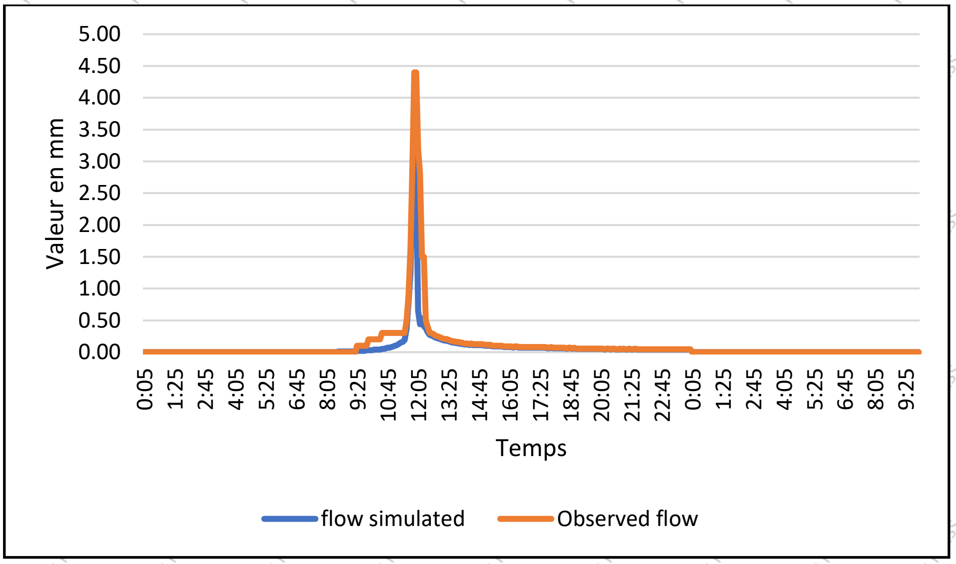

Figure 11. Comparison between observed and simulated runoff

An explicit assumption should be noted.

5. CONCLUSION

This study successfully applied the HEC-HMS model to simulate surface runoff in the ungauged Wadi Laussif subbasin, a crucial component of the Kherzet Youcef deposit hydrogeological study. By integrating a 30-meter resolution SRTM DEM with the HEC-HMS model and utilizing the SCS-CN method for loss estimation, this research demonstrates a viable approach for runoff estimation in data-scarce environments. Key findings include a satisfactory correlation coefficient of 0.79 between simulated and observed runoff values, demonstration of the model's ability to capture specific hydrological events, e.g., peak flows, time to peak. These results align with previous studies in the region while providing a more robust and spatially distributed assessment of the runoff generation. This study significantly contributes to improved water resource management in the region by providing a reliable methodology for runoff estimation in ungauged basins, supporting the development of a comprehensive hydrogeological model for the Kherzet Youcef deposit, and informing decision-making related to water resource planning, flood control, and drought mitigation in the Wadi Laussif subbasin and potentially other ungauged basins in Algeria. This research emphasizes the importance of integrating GIS and hydrological modeling techniques for effective water resource management in data-limited environments.

5. ACKNOWLEDGMENTS

The authors thank the national non-ferrous company's technical and administrative staff, Kherzet Youcef's unit. Also, our gratitude goes to the administrative staff of the Algerian Water Resource Ministry.

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