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Rainfall-Runoff Simulation for Ungauged Watershed: A Case of Bessre Watershed, Duhok Province, Iraq

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Keywords:
Watershed Modelling System (WMS); HEC-HMS; Rainfall-Runoff Simulation; GIS; Flood Management.

Highlights:

- *Stimulating a real rainfall event and predicting storm Return Period (RP) of 100 years.*
- *The Hydrologic Engineering Center-Hydrologic Modeling System on the Ungauged Bessre Valley watershed was used.*
- *Comparisons between the HEC-HMS model and the Rational method.*
- *The HEC-HMS calibration process illustrated a high-level precision with the Nash-Sutcliffe efficiency (NSE) value of 0.895.*
- *Watershed Modelling System (WMS) applied to deliver support as a platform.*

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Abstract: The scarcity of measured hydrological data poses a challenge in many developing countries, stemming from insufficiently established gauging stations. Due to the mentioned issue, it is crucial to develop models capable of conducting reliable simulations of runoff behavior, particularly for ungauged catchments. Understanding the intricate relationships in rainfall-runoff modeling is essential for estimating peak flows, a critical aspect in formulating water resources management strategies, which can aid in water resource management and planning. In areas prone to floods performing, an extensive hydrological study becomes necessary. This study determined the outflow discharge at the outlet point of the Bessre Valley Ungauged Catchment (41.4 km2) using the Watershed Modeling System, used by reliable hydrological standards as a graphical interface integrating with the Hydrologic Modeling System (HEC-HMS). Bessre Valley watershed is one of the flood-prone watersheds in the Duhok governorate, mainly due to the terrain's steep slopes at the upper north and east of the catchment. The catchment was delineated by a Geographic Information System (GIS). Its properties were extracted from a 12.5 m × 12.5 m Digital Elevation Model (DEM), which evaluates the hydrological response of a watershed to two significant storm events: a real rainfall event in March 2020 and a hypothetical 100-year return period event by dividing the watershed into ten sub-basins. Achieving a Nash-Sutcliffe efficiency of 0.895 indicates a high accuracy between observed and simulated peak flows of the real rainfall event of March 2020, underscoring the model's reliability for hydrological predictions. Also, comparing the HEC-HMS model and the Rational Method of (100 YRP event) for calculating peak discharges revealed a mere 2.2% error. Furthermore, the study explores the potential for building additional dams based on discharge volumes from specific sub-basins to enhance flood control and water storage capabilities.

محاكاة هطول الأمطار والجريان السطحي لمستجمعات المياه غير المقيسة: حالة حوض بيسري، محافظة دهوك، العراق

هندرين محمد نظيف

معهد ئارارات التقني الخاص / دهوك - العراق.

الخلاصة

تشكل ندرة البيانات الهيدرولوجية المقاسة تحديا في العديد من البلدان النامية، ناجم عن عدم كفاية محطات القياس المنشأة. ونظرًا للمشكلة المذكورة، يصبح من الضروري تطوير نماذج قادرة على إجراء عمليات محاكاة موثوقة لسلوك الجريان السطحي، خاصة بالنسبة لمستجمعات المياه غير المقاسة. إن فهم العلاقات المعقدة في نمذجة جريان مياه الأمطار أمر ضروري لتقدير تدفقات الذروة، وهو جانب حاسم في صياغة استراتيجيات إدارة الموارد المائية. وهذا يمكن أن يساعد في إدارة الموارد المائية والتخطيط. وفي المناطق المعرضة للفيضانات، يصبح من الضروري إجراء دراسة هيدرولوجية واسعة النطاق. حددت هذه الدراسة تصريف التدفق الخارجي عند نقطة مخرج مستجمع وادي بسري غير المقيس (41.4 كم^{2}) باستخدام نظام نمذجة مستجمعات المياه (WMS)، والذي تم استخدامه من خلال معايير هيدرولوجية موثوقة كواجهة رسومية تتكامل مع نظام النمذجة الهيدرولوجية (HEC-HMS). يعد مستجمع مياه وادي بسري أحد مستجمعات المياه المعرضة للفيضانات في محافظة دهوك، ويرجع ذلك أساسًا إلى المنحدرات التضاريسية الشديدة في الجزء العلوي الشمالي والشرقي من مستجمع المياه. تم تحديد مستجمع المياه بواسطة نظام المعلومات الجغرافية (GIS) وتم استخراج خصائصه من نموذج الارتفاع الرقمي (DEM) 12.5 م × 12.5 م الذي يقيم الاستجابة الهيدرولوجية لمستجمع المياه لحدثين مهمين من العواصف: حدث هطول أمطار حقيقي في مارس 2020 وحدث فترة عودة افتراضية مدتها 100 عام، من خلال تقسيم مستجمع المياه إلى عشرة أحواض فرعية. يشير تحقيق كفاءة Nash-Sutcliffe البالغة 0.895 إلى مستوى دقة عالٍ بين تدفقات الذروة المرصودة والمحاكاة لحدث هطول الأمطار الحقيقي في مارس 2020، مما يؤكد موثوقية النموذج للتنبؤات الهيدرولوجية. كما تكشف المقارنة بين نموذج HEC-HMS وRational Method (فترة العودة 100 عام) لحساب ذروة التصريف الذي أعطى الخطأ بنسبة 2.2٪ فقط. علاوة على ذلك، تستكشف الدراسة إمكانية بناء سدود إضافية بناءً على أحجام التصريف من أحواض فرعية محددة، بهدف تعزيز قدرات التحكم في الفيضانات وتخزين المياه.

الكلمات الدالة: نظام نمذجة مستجمعات المياه (WMS)، HEC-HMS، محاكاة هطول الأمطار والجريان السطحي، نظم المعلومات الجغرافية، إدارة الفيضانات.

1.INTRODUCTION

Catchment management is an important plan of action utilized to mitigate and control the effects of flooding in a designated region through strategic planning of soil characteristics, water flow dynamics within a watershed, and land-use patterns, so the purpose of watershed management is to control and reduce the potential for flooding [1]. The soil conservation implementation practices to prevent soil degradation, afforestation, and structure construction like control dams are complementary components of catchment management that take part in attenuating the volume and velocity of water during heavy rainfall [2]. The addressed endeavors in catchment management not only minimize the flash flood threats but also support strength over an extended period by applying water resource engineering sustainability approaches. Managing and understanding the aspects that cause runoff in the watershed can provide a proactive way of controlling floods and preventing excessive water accumulation and adverse impacts on the infrastructure within and around the streams of the watershed [3]. To sum up, the dams' significance in any watershed is located in their multi-faceted contributions to the prevention of flooding, ecological and environmental well-being, and storage of water as a reservoir, emphasizing their crucial importance in managing water resource engineering [4]. The importance of hydrological models, which are specific to simulate excess flow on the watershed during a storm event, depends on their ability to understand how different aspects contribute to the runoff simulation, assisting users in creating effective methods for catchment management. Accurate runoff execution is critical for flood forecasting in any storm event, considering the environmental conservation efforts. More distant, hydrological models speed up scenario analysis and allow users to anticipate the impacts of climate change (global warming), land use changes, or other human activities that harm the environment on the watershed [5, 6]. Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) is a main ingredient of hydrological models, particularly in rainfall-runoff simulations within watersheds. HEC-HMS, which was developed by the United States Army Corps of Engineers, integrates various data inputs, including topographical, meteorological, and land use data in complex hydrological processes for a comprehensive simulation within a watershed, providing reliable and accurate runoff simulation for researchers, decision-makers, and water resource engineers [7]. The importance of HEC-HMS in runoff simulation is versatile. First, it is substantial for operative catchment management, allowing users to burgeon strategies that optimize water resource recruitment and reduce flood risks. Another point to consider, HEC-HMS enables simulation scenario analysis, enabling users to assess the possible effects of land use transformations, climate change due to warming means the air can hold more moisture, and infrastructure developments on runoff streams. This Anticipatory ability is important for adjusting to changeable conditions of the environment [8,9]. While population growth, urbanization, and industrialization require further water resource management, obtaining river discharge data remains challenging [10]. Reviews global research on the HEC-HMS model, developed by the USACE for transforming rainfall into runoff, highlight its effectiveness in runoff prediction and usefulness in water resource planning and decision-making under various hydrological conditions. Furthermore, flood risk management is vital in water resources engineering, addressing sudden events like heavy rainfall in upstream river tributaries. Engineers need precise tools for flood risk management, made possible by advancements in computer technology enabling credible mathematical models [11]. Studying flood risks is crucial for near rivers-city safety. A flood analysis study on Tikrit used Tigris River data to manage flood risks. Using HEC-RAS and HEC-HMS software for calibration proposes, Manning's coefficient (n) was adjusted to 0.031, representing the region's nature, with Nash-Sutcliff Error (NSE) of 0.93, ensuring accurate flood scenario simulations. The results indicated higher vulnerability to flooding on the eastern riverbanks due to lower ground levels [12]. The historical evolution of hydrologic modeling for runoff estimation in watersheds reflects a remarkable progression marked by the development and refinement of influential models. The mid-20th century witnessed a surge of conceptual models aimed at representing watershed dynamics through simplified abstractions of physical processes, such as the Soil Conservation Service Curve Number (SCS-CN) method, which prepared the scene for quantifying runoff in agricultural landscapes and is considered an early systematic approach [13]. In the late 20th century, a paradigm shift occurred with the development of empirical models that explicitly incorporated basic physical principles governing hydrological processes. In 2000, the United States Army Corps of Engineers (USACE) introduced the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) as a typical model example for water resources engineering applications, presenting a wide and precise framework for runoff simulations by integrating topographical, meteorological, and Routing methods and, land-use data [14]. Moreover, in 1998, the Soil and Water Assessment Tool (SWAT) was introduced as a flexible and integrated model tool for land-use planning and watershed management, which combines physical and conceptual-based approaches for explicit spatial representation of hydrological processes [15]. The combination of contemporary technologies, specifically Geographic Information Systems (GIS) and Remote Sensing (RS), was introduced in an era of transforming hydrologic modeling capabilities for runoff simulations in catchments. GIS assists in analyzing and integrating varied geospatial data information for model validation and parameterization. Also, RS is an effective strategy for obtaining high-spatial data resolution, giving precise and detailed delineation of topography, land cover, and afforestation (vegetation dynamics) inside a watershed [16-19]. Likewise, the interaction between the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and contemporary advancements in technology allows for more flexible and precise methods of hydrological simulation modeling, assisting in hypothetical scenario analysis and real-time monitoring. Consequently, the mentioned combination between modern technologies and HEC-HMS not only improves the accuracy of rainfall-runoff simulation predictions but also defines the HEC-HMS model as a multipurpose and strong tool for decision support and efficient management of watershed in the continuous phase of evolving needs of environmental obstacles [19-23]. This study primarily aims to find the total volume and discharge of runoff within the ungauged Bessre Valley watershed to its outlet by stimulating a real singular rainfall event and Storm Return Period (RP) of 100 years by utilizing the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and a suggestion of building two subsequent dams on the watershed at particular locations for flood management and other use purposes.

2.METHODOLOGY

Watershed Modeling System (WMS) and Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) are crucial tools in catchment analysis, providing sophisticated accomplishments in water resource engineering management and hydrological modeling. Watershed Modeling System powerfully combines spatial data, such as GIS data and remote sensing information, with hydrological models, which facilitate comprehensive catchment analysis, enabling tasks such as automated basin delineation, floodplain mapping, and stormwater system design as an interface program for the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). In contrast, HEC-HMS is one of the hydrological models in Watershed Modeling System software simulating the rainfall-runoff processes of complex watershed systems [24]. HEC-HMS is commonly utilized for examining the effects of flood forecasting, land changes, spillway design of reservoirs, and catchment drainage using various rainfall-runoff simulation methods, such as Rational Method for peak discharge in small urban watersheds, Unit Hydrograph (UH) Method, involving (SCS hydrographs and Snyder), and Soil Conservation Service (SCS) Curve Number Method for simplicity in limited data scenarios. However, for complicated analyses, it has been used the ModClark Method for GIS-integrated and spatially detailed modeling as well as Kinematic Wave Routing and Green-Ampt (GA) model that assumes a homogeneous soil with constant hydraulic conductivity and initial water content, which are used for infiltration and deep flow studies [25]. The WMS assists as a platform for combining various critical inputs, including land cover use data, soil type classification information, Digital Elevation Model (DEM) with a resolution of (12.5 x 12.5) m, rainfall stations data for the ungauged basin, and the precise locations of dams and outlet within the catchment. The HEC-HMS model was then configured by providing detailed information for stream transform, routing methods in the channel, and each dam in the basin, including storages, elevations, and discharge curves of their reservoirs to execute the hydrological processes and gives directional runoff, rainfall-runoff losses as a part of outputs data. The HEC-HMS model was executed several times, and then the observed data were compared with the executed HEC-HMS model results for calibration for the known rainfall event. For more confirmations, the rational method, empowered by Intensity Duration Frequency (IDF) curves specific to Duhok city, was employed and compared with the HEC-HMS results of 100 Years Return Period (YRP) of a rainfall event. This comprehensive approach aims to ensure the reliability and accuracy of the hydrological simulations by integrating different data sources and model parameters, as shown in Fig. 1.

2.1.Study Area Data Description

This study is dedicated to meticulously examining runoff volume within the ungauged catchment area of Bessre Valley (41.4 km²), primarily emphasizing determining the maximum discharge at the watershed outlet for a 100-year return period. The investigation relies on a comprehensive dataset encompassing 28 years of meticulously recorded rainfall data from three gauged stations, which are outside of the watershed: Duhok Center Station, Zawita Station and rainfall satellite recorded data from Kamaka Village obtained through satellite technology (NASA/POWER CERES/MERRA2 Native Resolution Daily Data), as shown in Fig. 2. Explained in Section (3.3.4. Meteorological Model) in more details.

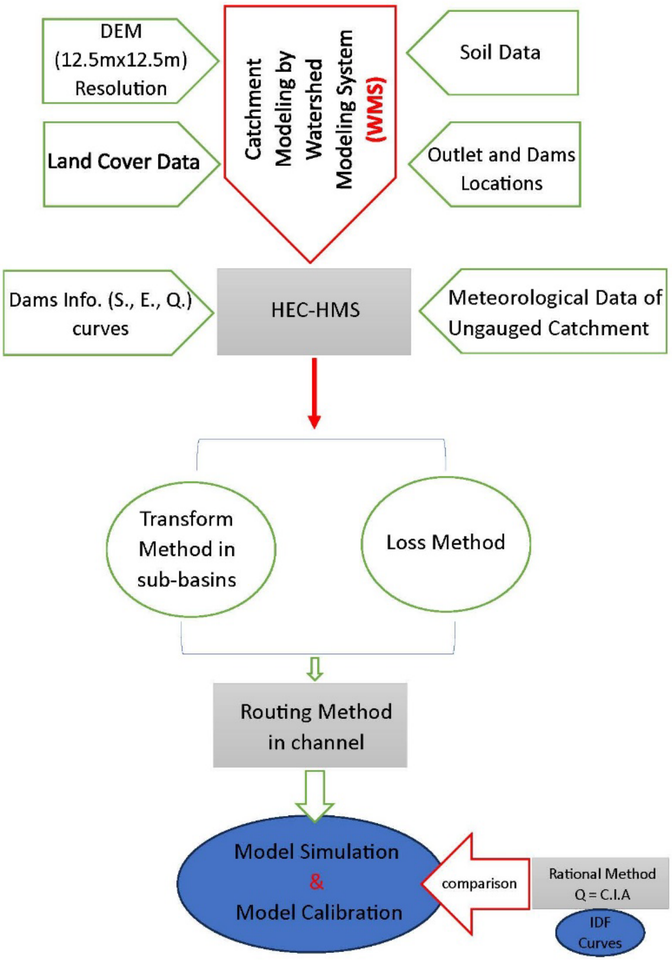

Fig. 1 Methodology Flow Chart.

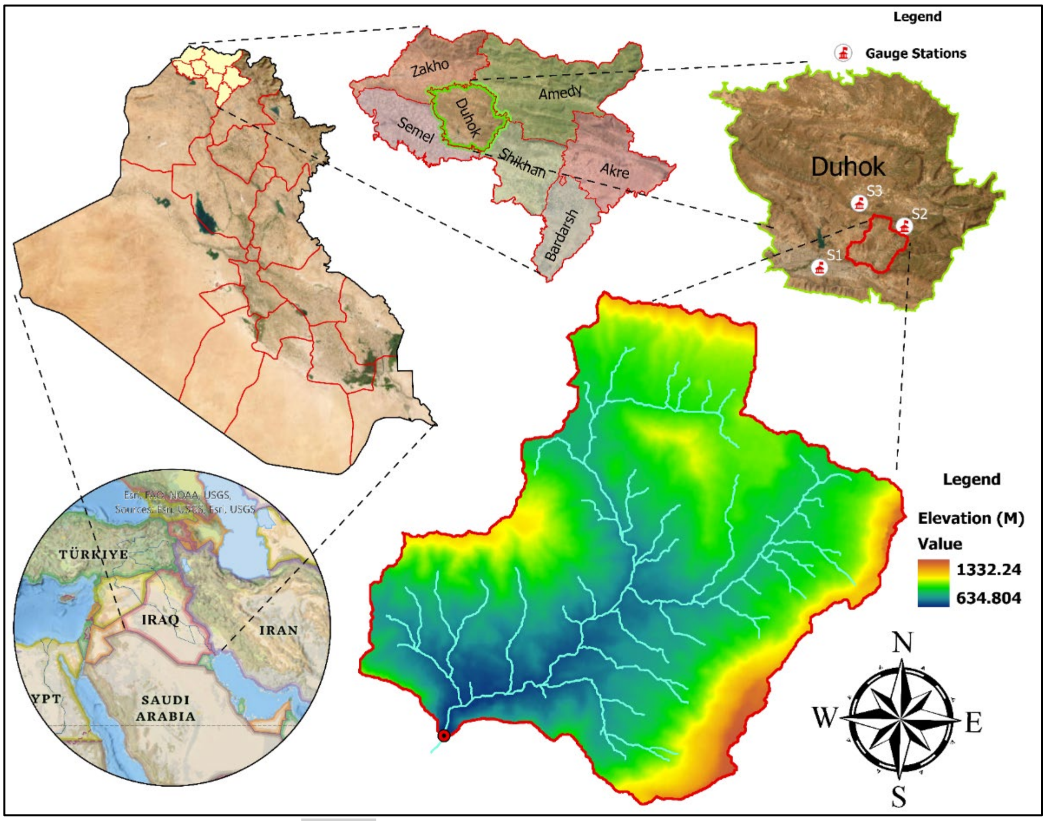

Fig. 2 Study Area at Duhok Province.

2.1.1.Soil Types and Land Use

Ecological infrastructure, such as vegetation cover type, soil characteristics, plant, and settlement densities, affects the infiltration characteristics and runoff behavior. Derived from enhanced Landsat imagery, the study area's land use categories were classified into several classes, distributed into agricultural fields, green spaces, waterbodies, undeveloped lands, residential areas, and transportation roads, as shown in Fig. 3.

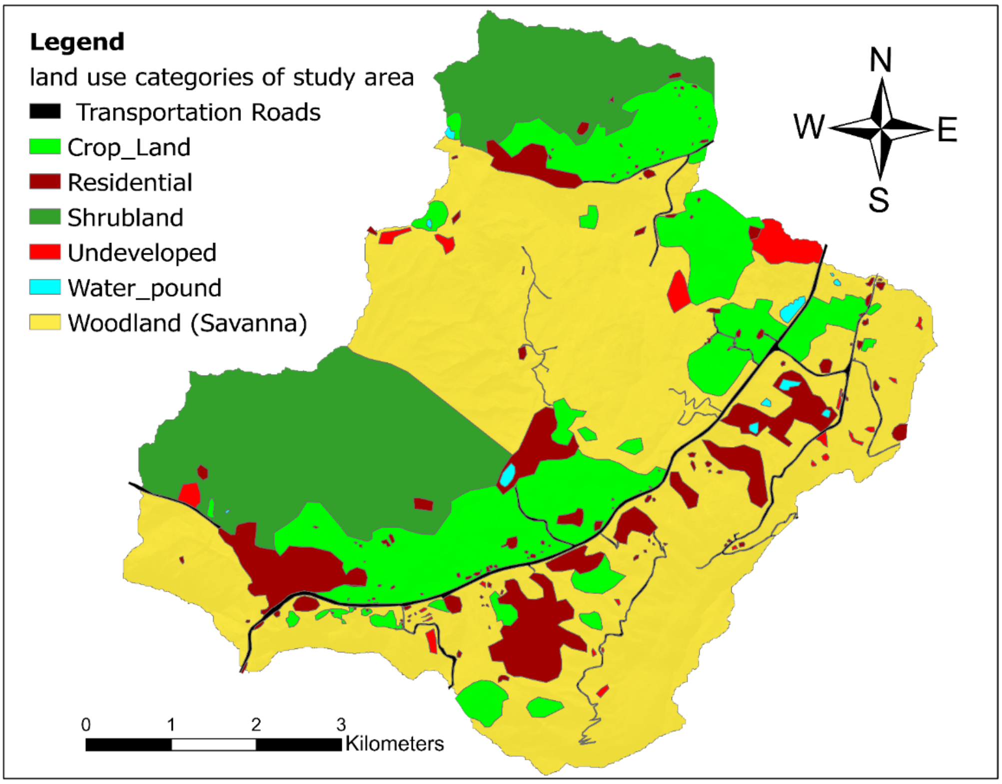

Fig. 3 Land Use Categories of Study Area.

The distribution of land use areas and their corresponding percentages are detailed in Table 1.

Table 1 Land Use Categories of Study Area.

#	Land uses	Area (km²)	Percentage %
1	Water pound	0.230754	0.56%
2	Residential	3.436	8.30%
3	Transportation Roads	2.929	7.07%
4	Cropland	6.602	15.95%
5	Undeveloped	1.573	3.80%
6	Shrubland	10.218	24.68%
7	Woodland (Savanna)	16.412	39.64%
Total		41.4	100%

The soil types at Duhok Province, having seven districts, are classified into clay, clay loam, loam, and silty loam; however, within the study area is classified as clay loam [26] with a coordinate system of (36°52'46.76" N, 43° 5'59.98" E). Soil physical properties and their relationship to soil moisture have important implications for water flow potential. Spatial soil physical properties of clay loam in the study area with a percentage combination of sand 26%, silt 39%, and clay 35% are obtained from the soil texture properties in the terrain database developed by FAO and UNESCO, as shown in Fig. 4. In watershed management, the physical properties of clay loam, as delineated by the USDA Soil Conservation Service (SCS) soil classifications, play a crucial role in shaping the response to rainfall and runoff events. Clay loam, falling under the Hydrologic Soil Group (HSG) of type D, as shown in Table 2, is characterized by a notable combination of sand, silt, and clay particles, as mentioned. Exhibiting a high runoff potential, indicating that it is prone to surface water runoff. This propensity is closely tied to the minimum rate of infiltration and low water transmission rate associated with clay loam [27-31].

Table 2 Hydrological Soil Categories and Their Corresponding Soil Textures [32].

Soil Group (HSG)	Runoff Description	Soil Texture
A	Reduced runoff potential due to high rates of infiltration	Sand, Loamy sand, and sandy loam
B	Moderate infiltration rates resulting in moderate runoff potential	Silty loam and loam
C	High to moderate runoff potential due to slow rates of infiltration	Sand clay loam
D	High runoff potential due to very low infiltration rates	Clay loam, silty clay loam, sandy clay, silty clay, and clay

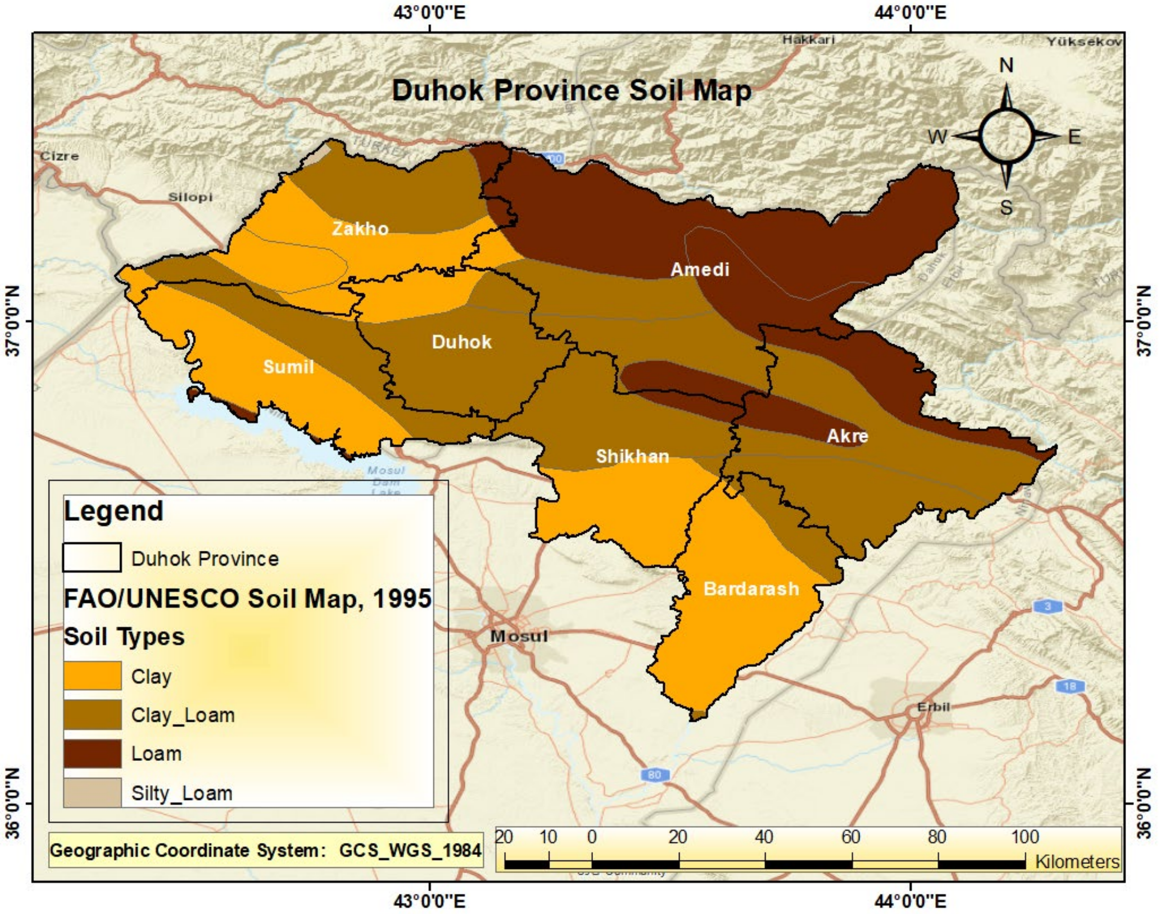

Fig. 4 Duhok Province Soil Map.

2.1.2.Meteorological Model

As shown in Table 3 and Fig. 2, all three stations are outside the study area's catchment; therefore, it is called the ungauged watershed.

Table 3 Gauge Stations.

Gauge Stations	Station Names	Coordinate System	
		Longitude	Latitude
S1	Duhok Center	43°0'3.00"E	36°51'1.00"N
S2	Zawita	43°8'33.85"E	36°54'21.13"N
S3	Kamaka Village	43°3'56.33"E	36°56'7.15"N

The rainfall data obtained from Directorate of Meteorology & Seismology – Duhok for Duhok Center station and Zawita station; however, the Kamaka rainfall records were taken from satellite technology (NASA/POWER CERES/MERRA2 Native Resolution Daily Data) for 28 years, as shown in Fig. 5. This utilization represents a novel strategy within the field of hydrological studies, introducing an alternative and advanced approach to data collection. Adopting satellite-derived rainfall information signifies a pioneering step in enhancing the precision and comprehensiveness of runoff analysis in ungauged catchments, underscoring the study's commitment to advancing methodologies in this dynamic field of research [33]. The maximum flow discharge of the outlet point with the coordinate system of (36°51'15.61 "N, 43° 3'41.23 "E) was recorded in 2020. It was used for calibration as an observed record and compared with HEC-HMS peak discharge at the outlet using Nash-Sutcliffe Efficiency (NSE), which is a pivotal statistical tool used in hydrologic modeling, particularly with HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System), to evaluate the accuracy of runoff simulations. This method measures the predictive model accuracy between the observed discharge data and simulated discharge values from the model. Nash-Sutcliffe Efficiency (NSE) of 1 refers to an ideal pairing between observation and simulation data, while a value of zero or lower than zero indicates poor model execution [34]. Nash-Sutcliffe Efficiency (NSE) is important in hydrologic modeling for validating and calibrating HEC-HMS models, ensuring their reliability for flood risk and water resource management. NSE is calculated from:

$$\mathbf{NSE = 1\text{-}} \left(\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right) \qquad \mathbf{(1)}$$

where $\boldsymbol{Y_i^{sim}}$ is the $\boldsymbol{i}$th simulated value, $\boldsymbol{Y_i^{obs}}$ is the $\boldsymbol{i}$th observation value, $\boldsymbol{n}$ is the total number of observation samples, and $\boldsymbol{Y^{mean}}$ is the mean of observed data for the evaluated elements. The data of annual maximum daily rainfall of three stations were recorded, as shown in Fig. 5. Then the data were analyzed in HYFRAN-PLUS software to predict 100 years of the return period (RP) maximum daily rainfall for each station, as shown in Fig. 6, using Gumbel, Lognormal, Weibull distribution theories for Duhok, Zawita, and Kamaka Stations. Then, the event was simulated to know the maximum runoff flow on the watershed in the HEC-HMS model and compared the 100 RP runoff results with the Rational Method (Duhok IDF Curves) outputs to validate the data.

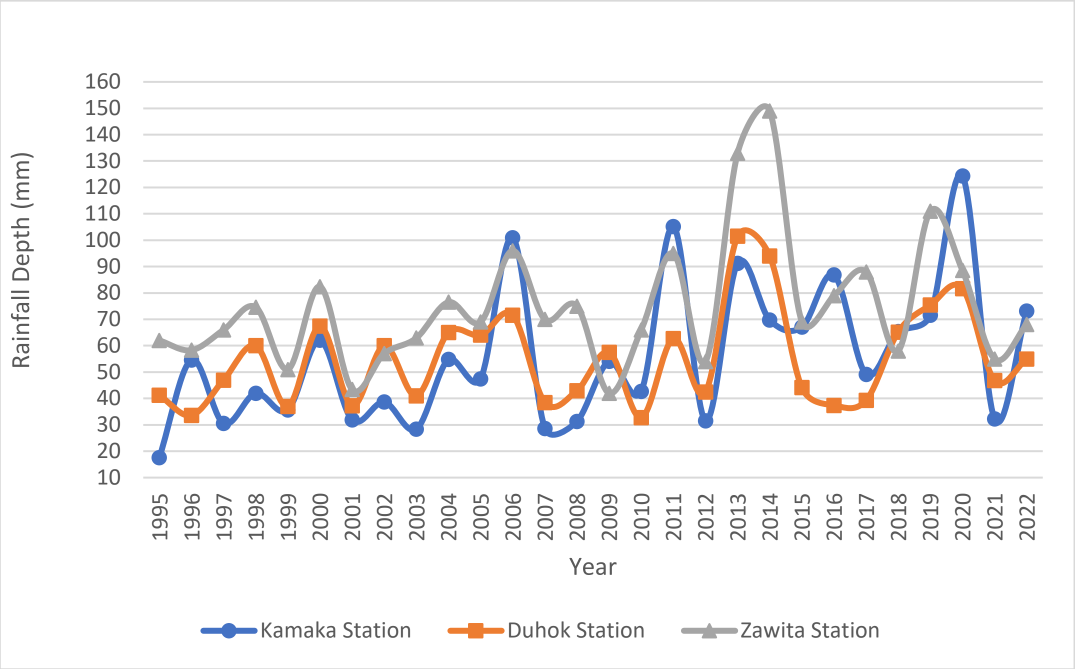

Fig. 5 Recorded Annual Maximum Daily Rainfall of Three Stations.

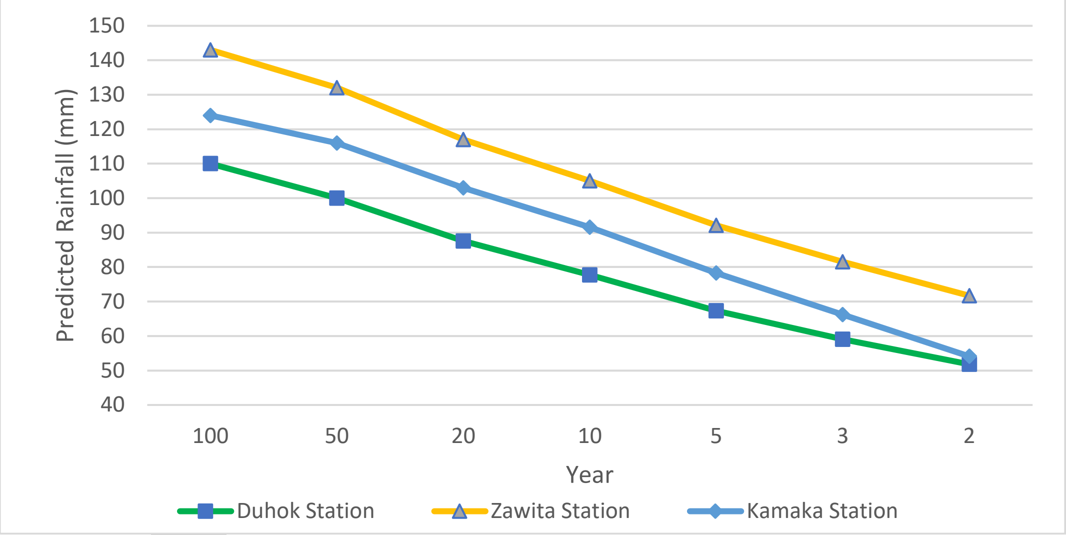

Fig. 6 100 Years of Return Period (RP) Maximum Daily Rainfall.

2.2.Modeling Watersheds Using HEC-HMS

HEC-HMS is a hydrologic modeling software developed by the US Army Corps of Engineers-Hydrologic Engineering Center. It is designed to simulate the rainfall-runoff processes in extensive geographic areas, such as flooding, water supply, large river basin to small urban, and natural watershed runoff [28]. For building the rainfall-runoff model of the case study watershed, version 4.8 of HEC-HMS was used. In the present study and with the new features of the 4.8 version, the basin model was developed and delineated using the GIS tool in the HEC-HMS Model. The ten (10) sub-basins within the study area were adopted, as illustrated in Fig. 7. The sitting-up dams' locations at the catchment are shown in Fig. 8.

All dams information were then defined and built on the watershed for flood control purposes as an input in the HEC-HMS model, as shown in Table 4. Also, the main hydrologic elements in HEC-HMS, i.e., elevation, storage, and Discharge Curves of all dams, must be added as an input to illustrate the dam capacity during the storm event on the watershed. Reservoirs (Dams) play a crucial role in attenuating and delaying storm flows by temporarily storing excess runoff and releasing it gradually, thereby reducing peak flows downstream and mitigating flood risks. Including reservoir information enables HEC-HMS to simulate how reservoir operations influence the timing, magnitude, and distribution of runoff within the watershed during storm events.

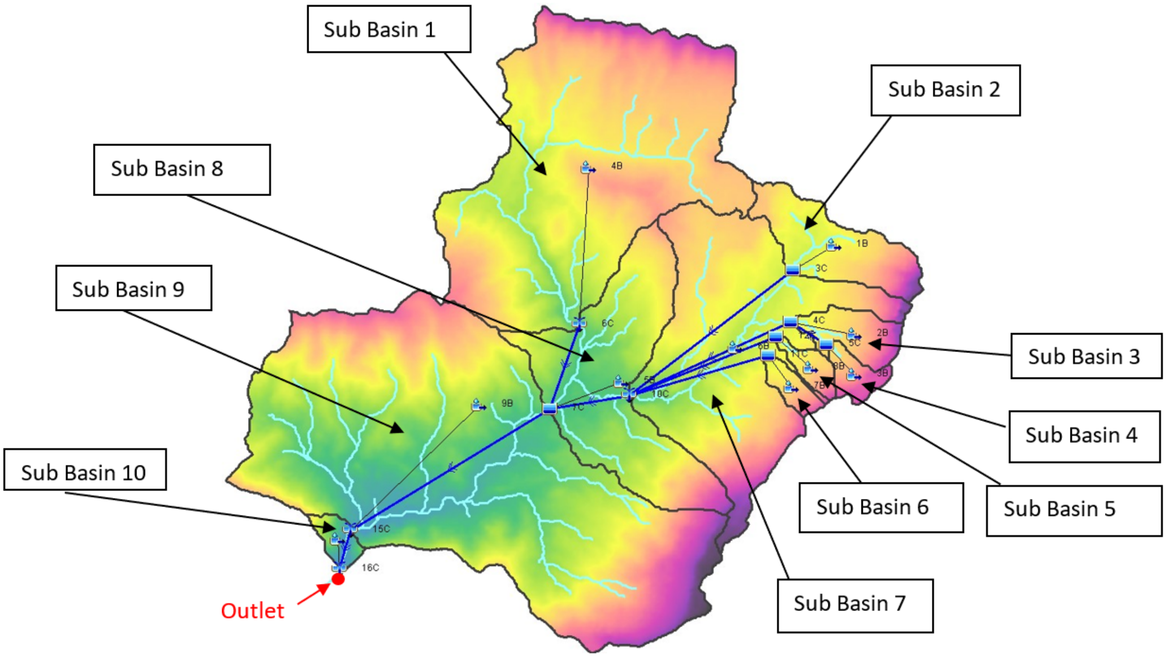

Fig. 7 HEC-HMS Sub-Basins Model.

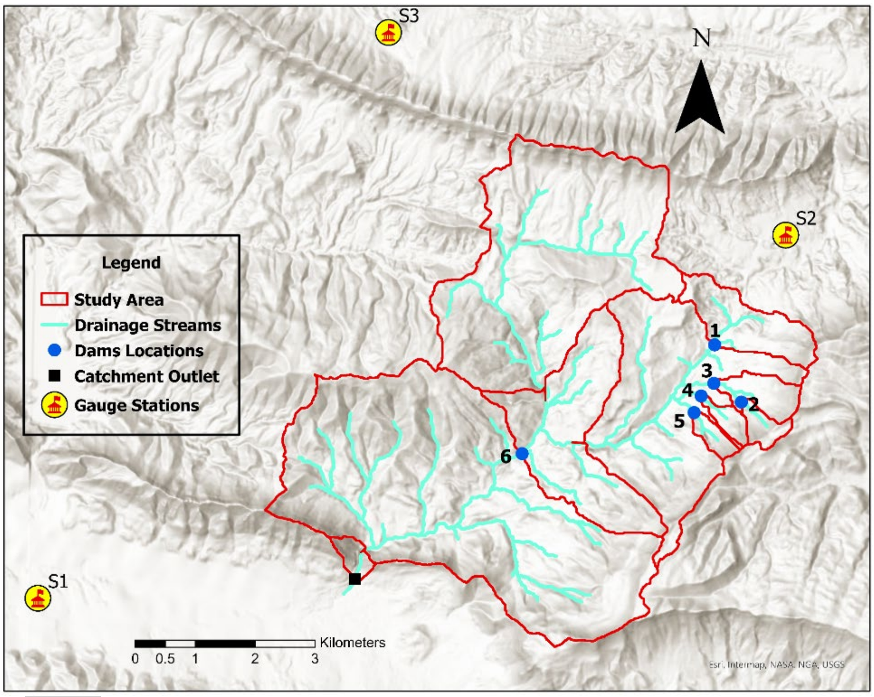

Fig. 8 Dams' Locations, Outlet, and Gauge Stations of the Study Area.

Table 4 Dams Information.

Dam Label No. at Fig.6	Dams Names	Coordinate System		Storage (m3)	Dam Height (m)
		Longitude	Latitude		
1	Zawita	43° 7'40.11"E	36°53'27.11"N	38000	12
2	Babblo 1	43° 7'58.05"E	36°52'54.37"N	10000	7.4
3	Babblo 2	43° 7'38.71"E	36°53'4.25"N	18000	10
4	Babblo 3	43° 7'31.01"E	36°52'58.03"N	11500	8
5	Babblo 4	43° 7'26.47"E	36°52'49.83"N	12000	8.3
6	Bari Bhar	43° 5'33.61"E	36°52'25.38"N	120000	13

2.3.Selection of Modeling Methods and Parameters

All sub-basins employ consistent modeling methods, meaning that the Loss Model and Transform Model utilize identical approaches across all sub-basins. This uniformity also extends to the Routing and Meteorological Model. Subsequent paragraphs provide a more detailed description of the Loss, Transform, and Routing Models.

2.3.1.Loss Model

The model evaluates runoff by calculating total losses from overall precipitation. In this research, the Soil Conservation Service (SCS) Curve Number was chosen for the loss method. This approach involves predicting the curve number, imperviousness percentage, and initial abstraction for each sub-basin. The SCS established a relationship between initial abstraction (Ia) and storage (S) through numerous analyses on small experimental watersheds (Sub-Basins), as outlined below [35]:

$$I_a = 0.2 * S \qquad (2)$$

The total excess (accumulated) precipitation will be:

$$Pe = \frac{(p-0.2*S)^2}{(p+0.8*S)} \qquad (3)$$

The relationship between the curve number (CN) and the maximum retention (S) is expressed as follows:

$$S = \frac{(25400-254\mathrm{CN})^2}{\mathrm{CN}} \qquad (4)$$

To accommodate the various ground types and land use within the watershed, a composite curve number (CN) can be determined as follows:

$$CN_{composite} = \frac{\Sigma CN_i A_i}{\Sigma A_i} \qquad (5)$$

Where $CN_{composite}$ is the composite number for runoff computations, CN_i is CN of subdivision i, i is the index of watershed subdivision for uniform land use and ground type, and A_i is the area of subdivision i. The curve number depends on soil type, land use, and antecedent moisture conditions. To obtain land use data, satellite imagery, specifically Synthetic Aperture Radar (SAR), was employed. Subsequently, the data was digitalized using ARC-GIS Pro, resulting in a shapefile, as illustrated in Fig. 3. Furthemore, Based on data from the Food and Agriculture Organization (FAO), soil information was acquired for further analysis and classification, as depicted in Fig. 4.

2.3.2.Transform Model

The Soil Conservation Service (SCS) introduced a parametric unit hydrograph model to estimate transforming surplus precipitation into direct runoff. The SCS unit hydrograph requires only a time parameter to reach its peak, associated with the duration of the excess precipitation event, as described in [35]:

$$T_p\frac{\Delta t}{2}+t_{lag} \qquad (6)$$

In ungauged watersheds, the SCS establishes a connection between concentration time and lag time as follows [35]:

$$t_{tag}=0.6\,t_c \qquad (7)$$

The time of concentration refers to the period needed for water to move from the most distant point within a watershed to the outlet of the watershed. It is determined using Giandotti's formula, articulated as follows: [36]:

$$t_{tag}=\frac{4.\sqrt{A}+1.5L}{0.8.\sqrt{H_m-H_E}} \qquad (8)$$

Where t_{lag} is the time difference between the peak of the Unit Hydrograph and the center of mass of excess rainfall, Δt is the excess precipitation duration, A is the sub-watershed surface area, t_c is the concentration-time, H_{med} is the medium elevation, H_{min} is the minimum elevation, and L is the length of the mainstream.

2.3.3. Routing Channel Flow Model

The Saint Venant equations, consisting of the momentum and continuity equations, serve as the foundational equations for modeling open channel flow [35]. The continuity equation accounts for the volume of water within the reach, encompassing outflow and stored water. The momentum equation, on the other hand, describes the forces acting on the water body in an open channel context [37].

In a one-dimensional context, these equations can be expressed as:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=q_L \qquad (9)$$

$$S_f=S_o-\frac{\partial y}{\partial x}-\frac{v}{g}.\frac{\partial v}{\partial g}-\frac{1}{g}.\frac{\partial v}{\partial t} \qquad (10)$$

where S_f is the friction slope, S_o is the bottom slope, A is the wetted surface, q_L is the lateral inflow per unit length of the channel, x is the distance along the flow path, y is the hydraulic depth, V is velocity, t is time, g is the acceleration due to gravity, $\partial y/\partial x$ is the pressure gradient, $\frac{1}{g}\frac{\partial v}{\partial t}$ is the local acceleration, and $\frac{v}{g}\frac{\partial v}{\partial x}$ is the convective acceleration [35]. The momentum and continuity equations were formulated based on the following assumptions:

- A trapezoidal channel geometry
- A constant Strickler roughness coefficient along the mainstream
- The water surface remains horizontal, and velocity remains constant for all channel sections
- Neglect vertical acceleration
- Gradual and varied flow regime

The redirection of the overall runoff from the sub-basin outlets to the entire basin outlet was achieved by employing the Muskingum Model. The Muskingum-Cunge model is grounded in the diffusion form of the momentum equation, as stated in [38]:

$$S_f=S_o-\frac{\partial y}{\partial x} \qquad (11)$$

By combining the mentioned equation with the continuity equation, the equation of convective is obtained [38]:

$$\frac{\partial Q}{\partial t}+C\frac{\partial Q}{\partial x}=\mu.\frac{\partial^2 Q}{\partial Q^2}+Cq_L \qquad (12)$$

Where μ is the hydraulic diffusivity, and c is the celerity wave

$$\mu=\frac{Q}{2BS_o} \qquad (13)$$

$$C=\frac{dQ}{dA} \qquad (14)$$

Where B is the maximum width of the water surface. Considering these assumptions, the Muskingum-Cunge hydraulic model relies on approximating the continuity equation by applying a straightforward finite difference approach [35]:

$$Q_t=Q_1 I_{t-1}+C_2 I_t+C_3 O_{t-1}+C_4\,(q_L\Delta x) \qquad (15)$$

The coefficients are

$$C_1=\frac{\frac{\Delta x}{k}+2*x}{\frac{\Delta t}{k}+2*(1-x)} \qquad (16)$$

$$C_2=\frac{\frac{\Delta x}{k}-2x}{\frac{\Delta t}{k}+2*(1-x)} \qquad (17)$$

$$C_3=\frac{2*(1-x)-\frac{\Delta t}{k}}{\frac{\Delta t}{k}+2*(1-x)} \qquad (18)$$

$$C_4=\frac{2(\frac{\Delta x}{k})}{\frac{\Delta t}{k}+2(1-x)} \qquad (19)$$

X and K are coefficients expressed in terms of flow, channel, and finite difference cell parameters as [39–42]:

$$X=\frac{1}{2}(1-\frac{Q}{BS_o c\Delta x}) \qquad (20)$$

$$K=\frac{\Delta x}{c} \qquad (21)$$

Where Δx is the space increment, Q is the flow, and S_o is the channel's bed slope.

3. RESULTS AND DISCUSSION

Two storm events- a recorded real rainfall event and a 100-year return period event- were considered to determine the maximum flow at the outlet and discharge volume on the watershed's outlet. The watershed was divided into ten sub-basins, as shown in Table 5, to anticipate it in different aspects and recommend suitable watershed management.

Table 5 Sub-basins HEC-HMS Model Parameters.

Model Parameters	Area (Km²)	Curve Number	Lag Time (Min.)
Sub-basin 1	10.9634	84.04	43.2780
Sub-basin 2	1.6932	88.89	14.5440
Sub-basin 3	0.7226	87.56	10.2780
Sub-basin 4	0.3672	84.02	9.3840
Sub-basin 5	0.2927	82.45	11.3640
Sub-basin 6	0.2909	82.55	8.6340
Sub-basin 7	6.5750	83.80	34.2840
Sub-basin 8	4.4894	83.17	27.1560
Sub-basin 9	16.0321	84.31	36.0180
Sub-basin 10	0.2972	87.67	6.9420

Table 6 displays the total amount of water flowing downstream from each sub-basin, as shown in Fig.7, during a severe storm that occurs once every hundred years (100-year return period storm), as calculated by HEC-HMS. This data is crucial for deciding whether to build new dams, considering the shape of the position if it is suitable, and recommending more explorations. In the study area, six dams are along the right bank of the watershed, chosen for their steep upstream slopes near the dams. These dams are defended as outlets of Sub-Basins 2, 3, 4, 5, 6, and 8 in HEC-HMS to assess their effectiveness in reducing flood risks and storing water. Furthermore, Sub-basins 1 and 9 were proposed as suitable locations for building two additional dams. While primarily aimed at storing water, these new dams also had the potential to significantly aid in flood control on the watershed's left bank, based on the water volume flowing through their designated outlets.

3.1.The Model Calibration

As shown in Fig. 5, the outlet point is defined as 16C Junction with the coordinate system of (36°51'15.61" N, 43° 3'41.23" E). To compare the simulated and observed peak flow at outlet point 16C, the meteorological data of Duhok, Zawita, and Kamaka Village stations on 18/03/2020 were considered; the maximum daily rainfall at the mentioned storm event date were 81.7 mm, 88.5 mm, and 124.3 mm, respectively, for calibration purposes, as shown in Fig. 9. As shown in Table 7, the Nash-Sutcliffe efficiency (NSE) is 0.895 for comparing observed and simulated peak flow at the outlet and discharge volume in the study area's watershed**.** Six dams on the watershed of the case study, as illustrated in Fig. 8 and Table 4, cause the runoff event that delays the flood, as shown in Table 8. Despite of dam's construction on the watershed and the attenuation that happens because of the dams' capacities, the flood effect on the downstream of the watershed, as shown in Fig.10.

Table 6 Total Volume of Water at the Downstream Outlet of Each Sub-Basin for (100 YRP) Storm.

#	Sub-basin names	Total Volume (1000 m^3)	Outlet Coordinate System	
			Longitude	Latitude
1	Sub-basin 1	1004.1	43° 5'45.55"E	36°53'1.52"N
2	Sub-basin 2	176.6	43° 7'39.73"E	36°53'27.18"N
3	Sub-basin 3	110.4	43° 7'38.35"E	36°53'3.89"N
4	Sub-basin 4	33	43° 7'56.76"E	36°52'54.18"N
5	Sub-basin 5	26.5	43° 7'31.01"E	36°52'57.80"N
6	Sub-basin 6	26.1	43° 7'26.12"E	36°52'49.33"N
7	Sub-basin 7	984.2	43° 6'11.48"E	36°52'29.55"N
8	Sub-basin 8	2481	43° 5'33.33"E	36°52'25.49"N
9	Sub-basin 9	3882	43° 3'46.33"E	36°51'31.10"N
10	Sub-basin 10	3942.8	43° 3'41.23"E	36°51'15.61"N

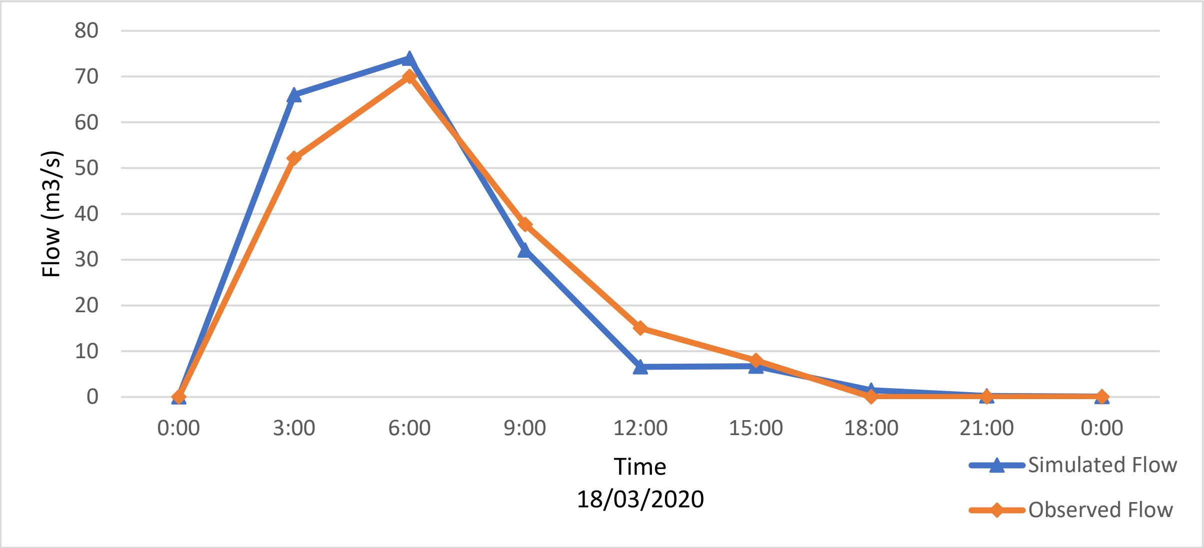

Fig. 9 Observed Vs. Simulated Peak Flow at Outlet on the Watershed.

Table 7 Observed and Simulated Peak Flow and Discharge Volume During Calibration.

	Simulated	Observed	Difference
Volume (1000 m^3)	2151.3	1973.5	177.8
Peak Flow (m^3/s)	74	70	4
Time of Peak	18-Mar-20, 06:00	18-Mar-20, 06:00	0 hrs.

Table 8 Dam Capacity and Attenuation of the Simulated Model of the 18/03/2023 Storm Event.

Dams	Dam Storage (1000M^3)	Initial Storage (1000 M^3)	Inflow to the Reservoir (1000 M^3)	Outflow from Reservoir (1000 M^3)
Zawita	38	2.5	100.3	64.8
Babblo 1	10	3.3	18	11.3
Babblo 2	18	2.9	52.2	37.1
Babblo 3	11.5	6.5	13.4	8.4
Babblo 4	12	7	13	8
Bari Bhar	120	7.6	1357.7	1245.3

Fig. 10 Downstream of the Watershed (Heshkaro River), Date: 18/03/2020.

3.2.HEC-HMS Model Vs. Rational Method: A Comparative Analysis

Comparing data from the Rational Method with software-generated data allows for validating the software model's performance and accuracy against a widely used method, i.e., (Rational Method). The 100-year return period (YRP) rainfall data of Duhok, Zawita, and Kamaka Village stations were 110 mm, 143 mm, and 124 mm, respectively. The HEC-HMS simulated storm's runoff volume and discharge at the watershed outlet were 3942.8 m^3 and 161.9 m^3/s, respectively. Fig. 11 shows the mentioned storm event at 24 hours. The outlet Discharge with a Rational Method using intensity-duration-frequency (IDF) curves of Duhok city with a Return Period of 100 years was calculated and then compared with the 100 YRP peak discharge of the HEC-HMS simulated storm. Q_p=C.i.A, where Q_p is the peak runoff discharge (ft^3/s), C is a runoff coefficient, i is the rainfall intensity (Inch/Hour), and A is the catchment area (Acre). To Calculate the Runoff Coefficient (C), the area of each land use was calculated with its runoff coefficient to find the total weight of C on the watershed.

$$\textbf{Weighted C} = \frac{C1.A+C2.A+Cn.A}{A} \qquad \textbf{(22)}$$

Each land has its runoff coefficient according to land use, as shown in Table 9.

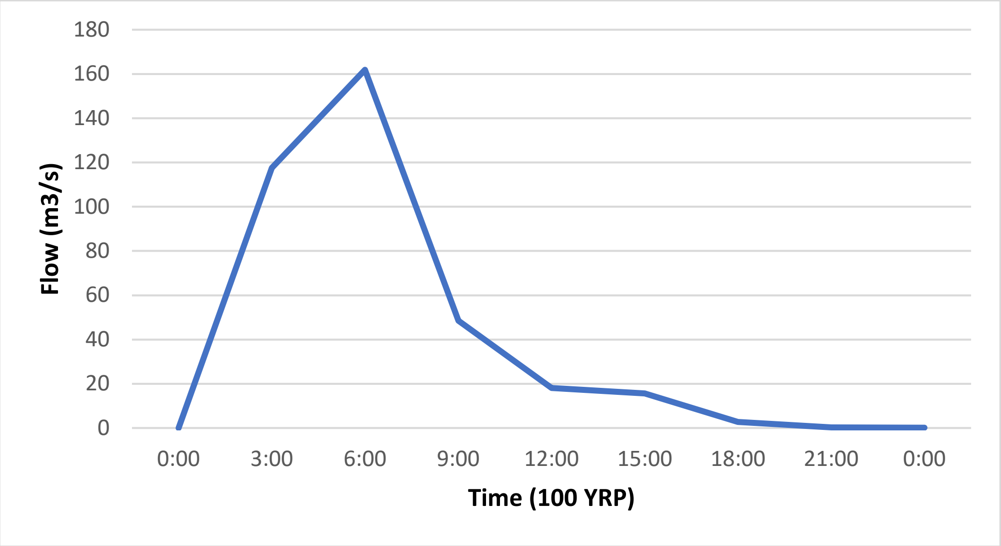

Fig. 11 HEC-HMS Storm Discharge at the Outlet of a Watershed for 100 YRP.

Table 9 Runoff Coefficients of Case Study Land Use [43].

#	Land Uses	Runoff Coefficient (C)	Area (Acre)
1	Water pound	-	-
2	Residential	0.45	849.054
3	Transportation Roads	0.8	723.771
4	Cropland	0.3	1631.389
5	Undeveloped	0.3	388.696
6	Shrubland	0.45	2524.922
7	Woodland (Savanna)	0.42	4055.493
Total Area			10173.33

$$C = \frac{0.45x849.054+0.8x723.771+0.3x1631.389+0.3x388.696+0.45x2524.922+0.42x4055.493}{10173.33} = 0.43$$

Taken from the Watershed Modeling System (WMS 11.1), the concentration time was 1.83 hours for a 100-year Return Period. The rainfall intensity is determined from [44].

$$i = \frac{239.95T_r^{0.246}}{t_c^{0.667}} \qquad \textbf{(23)}$$

i is intensity (mm/hr.), T_r is the Return Period in Year, and t_c is the Time of Concentration in minutes.

$$i = \frac{239.95(100)^{0.246}}{(1.83x60)^{0.667}} = 32.436\,\frac{mm}{hr} = 1.277\,\frac{inch}{hr}$$

So, C= 0.43, I=1.277 $\frac{inch}{hr}$, and A =10173.33 Acre

Q_p= C.I.A = 0.43 x 1.277 x 10173.33 = 5586.277 ft^3/s = 158.186 m^3/s

The simulated discharge by the HEC-HMS model and Rational method at the outlet of the watershed were 161.9 m^3/s and 158.186 m^3/s, respectively, i.e., 2.2% as the percentage error between both approaches.

4.CONCLUSIONS

The primary focus of the study is to determine the total volume and discharge of runoff within the ungauged Bessre Valley watershed following a real rainfall event and a storm return period of 100 years. The present work suggests new locations for constructing dams due to the high flow rate passing through the outlets of these two sub-basins. The model calibration process demonstrated a high level of accuracy, as indicated by the Nash-Sutcliffe efficiency (NSE) value of 0.895, suggesting that the simulated peak flows closely matched observed values. This calibration process ensures the model's reliability in predicting peak flows and discharge volumes within the watershed. Comparisons between the HEC-HMS model and the Rational method give more credibility to the study, with a minimal percentage error of 2.2% between the simulated discharge values, underscoring the HEC-HMS model utility in accurately predicting runoff volumes and peak discharges for effective watershed management and flood control planning. Furthermore, this study recommends several open-ended questions for future researchers. Whereas the present study concentrates on evaluating the influence of existing dams in flood attenuation, more consideration may be needed to explore the optimum design of the newly mentioned dams' locations within the catchment. Secondly, the current study mainly used satellite remote sensing data for sorting soil types and land uses as input into the HEC-HMS Model. However, in future works, utilizing more advanced satellite remote sensing techniques, such as a combination of hyperspectral imaging and Light Detection and Ranging (LiDAR), could improve the simulation precision. This research supports ongoing studies in flood management and hydrological modeling strategies, confirming the importance of comprehensive data inputs and solid modeling mechanisms for efficient catchment management and flood risk mitigation. Future research in this field can be conducted to advance our comprehension of catchment dynamics and provide supported information on flood-based management practices and policies.

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