Tikrit Journal of Engineering Sciences (2023) 30 (2): 80-93
DOI: http://doi.org/10.25130/tjes.30.2.9

IRAQI Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

Developing an Empirical Relations between Nash Model Parameters and Watersheds Topographical Characteristics for Predicting Direct Runoff Hydrograph

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Keywords:

Parameters, Nash Instantaneous Unit Hydrograph, Direct Runoff, Ungauged, Watershed.

ARTICLE INFO

Article history:

Received	01 Mar. 2023
Accepted	07 May 2023
Received in revised form	18 May 2023
Final Proofreading	19 May. 2023
Available online	25 June 2023

Citation: Khidir KM. Developing an Empirical Relations between Nash Model Parameters and Watersheds Topographical Characteristics for Predicting Direct Runoff Hydrograph. *Tikrit Journal of Engineering Sciences* 2023; **30**(2): 80-93.

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Abstract: The limited availability of the recorded rainfall-runoff data for many watersheds restricts the development and management of different activities of water resources. To overcome this limitation, the Natural Resources Conservation Service (NRCS) for estimating storm excess rainfall and momentum and optimization methods were combined in a mathematical model to estimate the optimal parameters of Nash Instantaneous unit hydrograph (IUH) and resulting direct runoff hydrograph (DRH), using a developed computer program in MATLAB. The available recorded data of 14 storms (out of 18) of four watersheds in northern Iraq have been applied in the calibration stage. An empirical relationship was developed between the average of each IUH optimal parameter (obtained by optimization as an optimal method according to the applied tests) and the effective watershed topographical characteristics. The developed empirical relations were used in the verification stage to estimate the IUH parameters and DRH for the verification storms and compare with that resulted from Haan's empirical relations and optimization method. The statistical tests showed that the developed empirical relations efficiency was better than that of Haan's method and close to that of the recorded storm by optimization method, where the average value of the Nash-Sutcliffe Efficiency for the four watersheds resulted from applying the optimization method, Haan's method and the developed empirical relations were 0.925, 0.587, 0.883 respectively. The results indicated the developed model's ability to estimate the IUH and direct runoff hydrograph for ungauged watersheds in northern Iraq.

تطوير علاقات تجريبية بين معلمتي نموذج ناش والخصائص الطبوغرافية للأحواض المائية للتنبؤ بهيدروغراف الجريان السطحي المباشر

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الخلاصة

إن التوافر المحدود لبيانات جريان الأمطار المسجلة للعديد من الاحواض المائية، يقيد تطوير وإدارة الأنشطة المختلفة للموارد المائية. للتغلب على هذا القيد، تم الجمع في نموذج رياضي بين طريقة خدمة حفظ الموارد الطبيعية (NRCS) لحساب المطر المؤثر مع طريقتي الزخم والأمثلية لا يجاد المعلمتين المثاليتين لهيدروغراف ناش القياسي ومن ثم هيدروغراف الجريان السطحي المباشر للعاصفة، باستخدام برنامج حاسوبي أعد باستخدام MATLAB. تم تطبيق البيانات المسجلة المتوفرة لـ 14 عاصفة (من أصل 18) من أربعة مستجمعات مائية تقع في شمال العراق في مرحلة المعايرة. تم تطوير علاقة تجريبية بين متوسط كل معلمات هيدروغراف ناش القياسي اللحظي المثلى (تم الحصول عليها بطريقة الامثلية وفقًا للاختبارات المطبقة) والخصائص الطبوغرافية الفعالة للأحواض المائية. تم استخدام العلاقات التجريبية في مرحلة التحقق لتقدير معلمات الهيدروغراف القياسي اللحظي ومن ثم هيدروغراف الجريان السطحي المباشر لعواصف التحقق المرصودة التي لم تدخل في مرحلة المعايرة. قورنت قيمتا المعلمتين مع تلك الناتجة عن كل الطريقة الامثلية من بيانات العاصفة الخاصة وطريقه هان التجريبية. أظهرت الاختبارات الإحصائية أن كفاءة العلاقات التجريبية لحساب المعلمتين أفضل من طريقة هان التجريبية وتقترب من قيم طريقة الأمثلية للعواصف المرصودة، حيث يبلغ معدل قيم اختبار ناش-ساكليف للعواصف الاربعة الناتجة عن طرق الامثليه، هان التجريبيه والعلاقتين التجريبيتين 0.925 و0.587 و0.883 على التوالي. تشير النتائج إلى قدرة النموذج المطور المعد على ايجاد هيدروغراف ناش اللحظي وهيدروغراف الجريان السطحي للأحواض المائية غير المرصودة في شمال العراق.

الكلمات الدالة: معالم، الهيدروغراف القياسي اللحظي، الجريان المباشر، الحوض المائي غير المرصود.

1.INTRODUCTION

Watershed Runoff estimation represents an essential part of surface hydrology for water resources planning, development, and management [1]. The watershed acts as a hydrological system transforming input rainfall hyetograph into an output runoff hydrograph. The transfer functions contain a mathematical characterization of the process that relates the inputs and outputs. Based on this system's transformation approach, numerous conceptual rainfall-runoff models have been developed to simulate the rainfall-runoff process of transformation [2]. Nash´s model of the Instantaneous Unit Hydrograph (IUH) is one of the most efficient conceptual rainfall-runoff models, used to predict direct runoff resulting from occurring storms over the watershed [3], where its parameters (number of reservoirs (n) and storage coefficients (k)) describe the Instantaneous Unit Hydrograph shape. The derivation of the Nash Instantaneous Unit Hydrograph has been addressed by many researchers, such as [4-11]. Nash model parameters are significant in estimating the instantaneous unit hydrograph and are determined based on the recorded rainfall-runoff gauged watersheds. For ungauged watersheds, serious difficulties arise due to a lack of recorded rainfall-runoff data, and then the Nash model parameters have to be estimated using information from other sources. Three methods have been intensified towards using it for estimating the instantaneous unit hydrograph (IUH) parameters coupled with a conceptual model's approach for predicting the direct runoff [12]. The first method is to obtain the parameters' values by applying geomorphological approaches to overcome the need for hydrological data, where these data straightforwardly can be obtained from GIS, topographic maps, or even tabulated values [13]. The second method is done by directly using the parameters estimated on gauged watersheds with similar characteristics [14]. In the third approach, the parameters can be derived by empirical relations from readily available recorded data through a regionalization process [15].The first method can only be used to obtain physically-based parameters, such as the area of a watershed or the Curve Number, depending on land use and soil type maps [16, 17], which can be biased due to outdated data. The second method raises the question of how to ensure the similarity of two watersheds [18, 19]. The last method is promising because it links non-physically based parameters to watershed characteristics [20]. In his study on some watersheds in the United Kingdom, Nash established two relations for estimating IUH parameters and showed a good correlation between these two parameters and the three watershed characteristics represented by the length of mainstream, slope, and area [21]. Various relationships have been proposed for estimating these two parameters [8, 22-24]. The relations developed by the references [24-27] are unsuitable as they relate the IUH parameters with the flow characteristics, which are unavailable for ungauged watersheds. The objective of this research is to develop relationships between Nash IUH's parameters and the effective topographical characteristics. The available recorded storms rainfall-runoff data for some watersheds in the north of Iraq were used to predict direct runoff hydrograph for ungauged watersheds in the north of Iraq, where generally the watersheds within it have similar topographical and meteorological characteristics.

2. DESCRIPTION OF THE SELECTED WATERSHEDS

The study area is in northern Iraq, bounded between (41° – 46°) E longitudes and (35° – 38°) N latitudes. The climate in the north of Iraq is considered arid to semi-arid. This climate is distinguished by low precipitation and high evaporation rates [28]. The mean annual rainfall ranges between 35° and 1000 mm [29]. Direct runoff monitoring for the watersheds in Iraq is usually scarce, which hampers the description of hydrological processes for the watersheds. Only four watersheds are distributed in different locations in the study area, as shown in Fig. 1, and have recorded data for runoff flow induced by rainfall for some storms. A digital elevation model (DEM) with a resolution of 30 m was downloaded to delineate the boundary of each watershed and derive its characteristics. The land uses and soil types are estimated using Satellite images from Landsat-8, then WMS version 10.1 Software and ERDAS Imagine 2015 software were used to build, manage, and generate various layers and maps, which have been developed for each watershed. The watershed characteristics, such as area, slope, etc., were calculated, as shown in Table 1. The watersheds understudy (Fig. 1) has various characteristics and include various types of land use and land cover classification, as listed below:

Table 1. The Watersheds Understudy Characteristics

Watershed	Watershed Characteristics							
	Area (km)	perimeter (Km)	Average Slope	Max flow distance (km)	Shape factor (A/L)	Basin Ratio ($L/S^{0.5}$)	Time Lag T_L hr	Time of concentration Tc hr
Goiza-Dabashan	2.02	6.72	0.125	3.20	0.197	8.67	0.21	0.35
Khoshanan	36.3	41.42	0.04	10.77	0.142	80.00	0.86	1.42
Yousifka	20.9	28.39	0.08	10.87	0.178	38.43	0.66	1.11
Solag	52.46	54.65	0.07	22.83	0.101	86.29	1.23	2.05

Solag watershed is located northeast of Sinjar city, which lies northwest of Iraq. The watershed is located between 410 41' 12″ - 410 46' 08″ E (Longitude) and 36° 21' 55 - 360 12' 01″ N (Latitude). The watershed soil contains high plastic clay with saline soils, as well as sandy loam containing organic matter. As for land uses, they are fields of various crops and pastures [30, 31, 32]. Yousifka watershed is located northeast of Sinjar city in northwest Iraq, where the watershed represents the upper feeding part of the Solag watershed. The watershed is confined between 41° 41' 12″ and 41° 46' 08″ E (Longitude) and 36° 21' 55 and 36° 15' 01″ N (Latitude). The soil is alluvial, with high permeability eroded by surface runoff [31, 32]. Khoshaban watershed is one of the feeding branches of the seasonal Al-Khawser River, located about 25 km northeast of Mosul city. The watershed is located between 43° 18' 20″ 15 and 43° 11' 35″ (Longitude) and 360 28 ' 30 ' and 36° 32' 15" (Latitude). Based on the previous geological studies results on the area and the field tests conducted[33], it was found that the soil of the watershed ranged from alluvial clay soil to Alluvial clay in addition to the limits of 5% of the area, which is a solid rocky stone that contains a percentage of cracks [34]. Goizha-Dabashan watershed is located in the northeast of Iraq, near Al-Sulymaniah city. Geographically, the watershed is located between 45°27´00" and 45°28´30" E (Longitude) and 35°35´00" and 35°36´00" N (Latitude). The watershed elevation varies from 1490 m to 947 m above mean sea level. The upper part of the watershed consists of limestone; however, the lower parts are composed of sandstone and green marl. The average soil porosity is 0.57, and the actual infiltration capacity ranges from 0.3 to 1.68 mm/day [35].

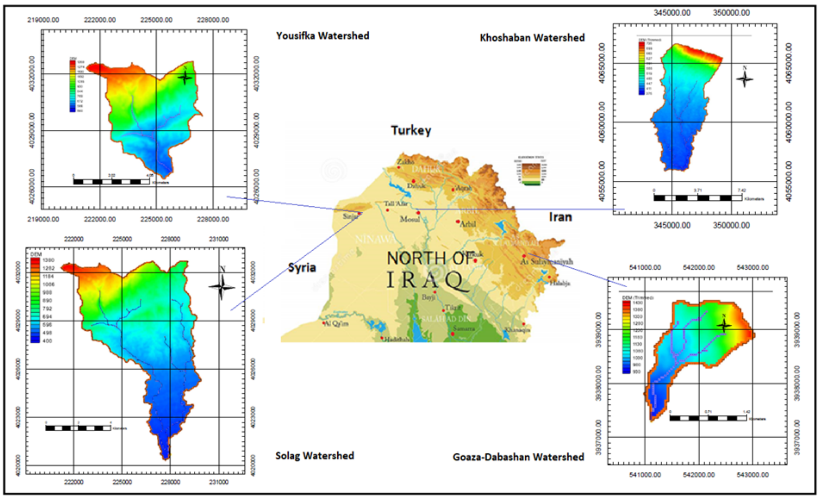

Fig.1 Location of the Studied Watersheds in the North of Iraq.

3. THEORETICAL BACKGROUND

3.1. Temporal Distribution of Storm Excess Rainfall

The excess rainfall temporal distribution for each storm event was estimated in this research using Natural Resources Conservation Services (NRCS) method. The (NRCS) method is known as soil conservation service (SCS). It is developed by the Soil Conservation Service in the USA [17] mostly for estimating the excess rainfall in small watersheds, which depends on the category of soils, land use, and the antecedent moisture condition before the considered rainfall storm occurs. All these factors were considered in a dimensionless parameter named curve number (CN) [36-38]. NRCS has prepared a table for estimating the dimensionless curve number for normal soil moisture conditions (N_{II}). Antecedent moisture condition (AMC) of the storm refers to the amount of moisture content found in the soil at the beginning of the storm. Both initial abstraction and infiltration are governed by AMC [17]. NRCS has prepared a table for estimating the dimensionless curve number for normal soil moisture conditions (N_{II}), depending on the hydrologic soil group, cover type, and antecedent moisture condition. The value of CN under dry conditions (CN_I) and wet conditions (CN_{III}) can be estimated from CN under normal conditions using Eqs. (1) and (2) [36]:

$$CN_I = \frac{4.2\ CN_{II}}{10-0.058\ CN_{II}} \quad \textbf{(1)}$$

$$CN_{III} = \frac{23\ CN_{II}}{10+0.13\ CN_{II}} \quad \textbf{(2)}$$

The accumulated abstraction depth (F_a) in (mm) can be estimated at each time interval using the following relationship [36, 18]:

$$F_a = \frac{S\cdot(P-I_a)}{P-I_a+S} \quad P \geq I_a \quad \textbf{(3)}$$

$$S = \frac{25400}{CN} - 254 \quad \textbf{(4)}$$

$$I_a = \lambda.S \quad \textbf{(5)}$$

where:

P = Accumulated rainfall depth in mm.
S= Potential maximum retention (mm)
I_a=Initial abstraction in mm.
λ =Initial abstraction coefficient.

The accumulated excess rainfall (direct runoff) for each time interval of the storm duration can be estimated by subtracting the accumulative abstraction depth and initial losses from the accumulated rainfall (P) at that interval. The excess rainfall (direct runoff) at any time interval of the storm duration can be estimated as the difference between the accumulated excess rainfall at the end and the accumulated excess rainfall at its beginning. The effect of the initial abstraction value of the threshold, i.e., λ= 0.2, used by NRCS is still being actively debated by several studies, which have shown considerable differences between handbook-tabulated CN values based on land cover/use and those estimated from watershed observations of rainfall-runoff storms [39, 40]. These studies have found that λ of value 0.05 or 0.01 is much more representative than λ=0.2. Nevertheless, essentially all handbook CN table values correspond to λ = 0.2. The corresponding S and then CN for λ = 0.05 is different from that for λ = 0.2; hence, the resulting runoff values are different. The adjustment of CN value from λ = 0.2 to λ = 0.05 has been adopted by the Task Group on Curve Number Hydrology [39], which recommends a new relation of the form:

$$S_{0.05} = 1.42 S_{0.2} \quad \textbf{(6)}$$

and leads to:

$$CN_{0.05} = \frac{100}{1.42-0.0042 CN_{0.2}} \quad \textbf{(7)}$$

Two cases of the composite CN values were adopted (using initial abstraction coefficient λ =0.2 and 0.05) to choose the most suitable composite CN value for the watershed (after comparing with the calibrated optimal CN value) for estimating the direct storm runoff hydrograph. These two cases were selected to study the effect of (λ) in adjusting and modifying the tabulated CN value used by NRCS for estimating the excess rainfall.

3.2. Nash Instantaneous Unit Hydrograph and Methods of Estimating its Two Parameters

In 1957, Nash developed a conceptual model based on identical linear reservoirs in series to derive the instantaneous unit hydrograph (IUH) for a natural watershed [3]. Nash IUH model has two parameters: (n) the number of reservoirs and (k) the storage coefficient [8], [41]. The final form of the Nash IUH model is:

$$IUH(t) = \frac{1}{k.\Gamma(n)} \left(\frac{t}{k}\right)^{n-1} e^{-t/k} \quad \textbf{(8)}$$

where:

IUH(t) = Instantaneous unit hydrograph ordinate at time t in m^3/sec.
t = Time in hr.
Γ(n) = Gamma function.

Gamma Function Γ(n), developed by Nemes [42], will be used in this research. The Eq takes the following form:

$$\Gamma(n) = \sqrt{\frac{2\Pi}{n}} \left(\frac{n}{e}\right)^n \left(1 + \frac{1}{15n^2}\right)^{\frac{5}{4}n} \quad \textbf{(9)}$$

where n is any positive real number (dimensionless). In this research, the Nash model parameters (n and k) are estimated for storms using the following three methods:

3.2.1. Momentum Method

Nash found a relationship between the parameters n, k, and the moments for the storms of the recorded excess rainfall hyetograph (ERH) and direct runoff hydrograph (DRH) [21]. These relationships are:

$$n \cdot k = MQ_1 - MI_1 \quad \textbf{(10)}$$

$$n \cdot (n+1) \cdot k^2 + 2 \cdot n \cdot k \cdot MI_1 = MQ_2 - MI_2 \quad \textbf{(11)}$$

where:

MI_1 = First momentum of the ERH about the time origin divided by the total excess rainfall.

MI_2 = Second momentum of the ERH about the time origin divided by the total excess rainfall.

MQ_1 = First momentum of the DRH about the time origin divided by the total direct runoff.

MQ_2 = Second momentum of the DRH about the time origin divided by the total direct runoff.

The moments of the ERH and the DRH are determined as follows:

$$MI_1 = \frac{\Delta T}{2} \cdot \frac{\sum_{t=1}^{nr} (2t-1) \cdot ER(t)}{\sum_{t=1}^{nr} ER(t)} \quad \textbf{(12)}$$

$$MI_2 = \frac{\Delta T^2}{4} \cdot \frac{\sum_{t=1}^{nr} (2t-1)^2 \cdot ER(t)}{\sum_{t=1}^{nr} ER(t)} \quad \textbf{(13)}$$

$$MQ_1 = \frac{\Delta T}{2} \cdot \frac{\sum_{t=1}^{nq} (2t-1) \cdot \frac{Q_t + Q_{t+1}}{2}}{\sum_{t=1}^{nq} \frac{Q_t + Q_{t+1}}{2}} \quad \textbf{(14)}$$

$$MQ_2 = \frac{\Delta T^2}{4} \cdot \frac{\sum_{t=1}^{nq} (2t-1)^2 \cdot \frac{Q_t + Q_{t+1}}{2}}{\sum_{t=1}^{nr} \frac{Q_t + Q_{t+1}}{2}} \quad \textbf{(15)}$$

where:

Q_t = Ordinate of the direct runoff hydrograph at time$(t) = 1, nq$ in m^3/sec.

$ER(t)$ = Depth of excess rainfall throughout the time interval (ΔT) between the ordinates t and $t+1$ in mm/hr.

nr = Number of interval duration of the excess rainfall.

nq= Number of ordinates of the Direct runoff hydrograph.

The first momentum (MI_1 and MQ_1) and the second momentum (MI_2 and MQ_2) amounts can be estimated using Eqs. (12- 15), then the n and k values for a given storm can be calculated.

3.2.2 Optimization Method

The efficient calibration of the rainfall-runoff model, which has a parameter that cannot be directly measured in the watershed, represents a difficult issue. The model, however, can be inferred by the calibration process, where the unknown parameters were estimated indirectly by minimizing the discrepancy between the direct recorded and estimated model hydrograph. The success of the calibration of such hydrological models depends on the calibration degree achieved and the choice of suitable calibration strategies [43]. During the last decade, several pieces of research that compared optimization algorithms applied to model calibration were published to prove or disprove the efficiency of a particular modern or historical method. Nevertheless, the Rosenbrock algorithm [44] has been successfully used to estimate the parameters of different hydrological models and has proven surprisingly efficient compared to modern algorithms [45]. The Rosenbrock algorithm was used in this research to estimate the parameters of the developed model. The optimization between the recorded and estimated direct runoff hydrograph was measured by applying the objective function. The objective function of the Sum of Squared Residual given in Eq. (16) was used in this research. The sum of Squared Residual is the sum of squared deviation of recorded and estimated direct runoff [46].

$$F^2 = \text{Min} \sum_{i=1}^{nq} (Q_r - Q_e)^2 \quad \textbf{(16)}$$

where:

Q_r = Recorded value of direct runoff hydrograph ordinates in m^3/sec.

Q_e = Estimated value of direct runoff hydrograph ordinates from the IUH models in m^3/sec.

nq= Number of the direct runoff hydrograph ordinates.

3.2.3 Haan's Empirical Method

The values of n and k parameters for a given watershed in the case of the unavailability of the recorded direct runoff hydrograph produced by the storm cannot be estimated by the momentum or optimization method. Haan [25] developed an empirical relation to estimate the above parameters and used Eq. (17) to estimating the parameter k. While Haan [25] suggested Eq. (18) to estimate the parameter n:

$$n = 1 + 6.5 \left(\frac{Q_p T_p}{V_t}\right)^{1.92} \quad \textbf{(17)}$$

$$k = \frac{T_p}{n-1} \quad \textbf{(18)}$$

where:

Q_p = peak discharge in ft^3/sec.

T_p = Time to peak in hr.

V_t = total volume of the excess rainfall in ft^3.

The unit parameters of n and k in Haan's empirical method are dimensionless and hour respectively . Q_P and T_P amounts were estimated using the dimensionless unit hydrograph method [47]. This unit hydrograph has a point of inflection approximately 1.67 times the time to the peak, while the time to the peak is about 0.2 of the time base. The peak discharge was calculated using the English system using the following equations:

$$Q_P = \frac{484.A}{T_P} \quad \textbf{(19)}$$

$$T_P = \frac{D}{2} + T_{Lag} \quad \textbf{(20)}$$

where:

Q_P= peak discharge in ft^3/sec.

A = watershed area in $mile^2$.

D= Duration of excess rainfall in hr.

T_{Lag} = Watershed lags time in hr.

T_c = Time of concentration in hr.

The watershed lag time is calculated as [48, 49]:

$$T_{Lag} = \frac{0.00136\,(L)^{0.8} \left(\frac{S}{25.4}+1\right)^{0.7}}{\propto^{0.5}} \quad \textbf{(21)}$$

where:

L=Length of main stream in m.

∝= Average slope of the watershed.

S= Potential maximum retention (mm) as shown after Eq. (4).

In the case of applying the NRCS method to estimate the excess, the watershed lag time is calculated as [48, 49]:

$$T_C = 1.666667 T_{Lag} \quad \textbf{(22)}$$

The potential maximum retention (S) in Eq. (21) is in mm and can be calculated from the CN using Eq. (4).

3.3. Estimating the Unit Hydrograph and Direct Runoff Hydrograph

The derivation of 1hr- UH from IUH is conducted using the following equation [50]:

$$(1\text{-}\mathrm{hr\ UH})_t = \frac{1}{2}[(\mathrm{IUH})_t + (\mathrm{IUH})_{t-1}] \quad \textbf{(23)}$$

Then 1-hr UH can be used to estimate the ordinates of any D-hr UH by the S-Curve method. The Direct Runoff Hydrograph (DRH) ordinate can be estimated anytime by employing the D-hr UH and excess rainfall hyetograph in the de-convolution method [50].

4. STATISTICAL METHODS TO EVALUATE THE DEVELOPED MODEL ACCURACY

The criteria for the developed model evaluation involves the following tests:

a. Nash-Sutcliffe Efficiency Test (NSE)

NSE is calculated from [51]:

$$\mathrm{NSE} = 1 - \frac{\sum_1^{nq}(Q_r - Q_e)}{\sum_i^{nq}(Q_r - Q_{avr})} \quad \textbf{(24)}$$

where:

Q_r = Recorded value of direct runoff hydrograph ordinates in m³/sec.

Q_e = Estimated value of direct runoff hydrograph ordinates from the IUH models in m³/sec.

Q_{avr}= Average of the recorded runoff data in m³/sec.

nq= Number of the direct runoff hydrograph ordinates.

b. Root of Mean Square Error (RMSE)

RMSE is calculated as [8]:

$$\mathrm{RMSE} = \sqrt{(1/N)\sum_{i=1}^{nq}(Q_r - Q_e)^2} \quad \textbf{(25)}$$

c. Relative Mean Error (RME)

RME is calculated as [52] :

$$\mathrm{RME} = (1/nq)\sum_{i=1}^{nq}\frac{(Q_r - Q_e)}{Q_r} \quad \textbf{(26)}$$

d. Percentage Error of Estimated Peak (PEP):

PEP is calculated as [53]:

$$\mathrm{PEP}\ \% = \frac{(Q_{pe} - Q_{pr})}{Q_{pr}} \ \mathrm{x} \quad 100 \ \textbf{(27)}$$

where:

Q_{pr}=Recorded peak storm runoff in m³/sec

Q_{pe}= Estimated peak storm runoff in m³/sec

PEP %= Percentage error of estimated peak storm runoff.

The peak storm runoff error percentage indicates the error in predicting the peak storm runoff. A negative percentage indicates an underestimate and a positive percentage indicates an overestimate.

e- Time to Peak Error (TPE):

Time to peak is calculated as [53]:

$$\mathrm{TPE} = \left((\mathrm{TP_E} - \mathrm{TP_R})\right) \ \mathrm{x\ TINT} \quad \textbf{(28)}$$

where:

TP_E=Esitmated time to peak(hours)

TP_R= Recorded time to peak (hours)

TINT= Data time interval (hour)

TP_E measured the error in time to peak in an hour. A negative value indicates an underestimate and a positive value indicates an overestimate.

f- Percentage Error of Estimated Direct Runoff Volume (PEV)

PEV is calculated as [52]:

$$\mathrm{PEV}\ \% = \frac{(V_r - V_e)}{V_r} \ \mathrm{x}\ 100 \ \textbf{(29)}$$

where:

V_r=Recorded Volume storm runoff in m³

V_e= Estimated Volume of storm runoff in m³

PEV %= Percentage of performance of Estimated runoff volume.

The best method to be chosen for the first test will be that has the maximum outcome of the efficiency value, and the best method to be chosen for the tests RMSE, RME, PEP, and PEV will be that has the least outcome value of the test.

5. THE DEVELOPED MATHEMATICAL MODEL

The general flowchart in Fig. 2 shows the different steps followed in executing the procedure for the developed model prepared for estimating the Instantaneous Unit Hydrograph (IUH) and its two parameters and Direct Runoff Hydrograph (DRH) resulting from the occurring storm rainfall over the watershed. A computer program in MATLAB has been prepared to develop a mathematical model according to this procedure, and the prepared program can be used for both gauged and ungauged watersheds to estimate the excess rainfall and for both calibrating processes to estimate n and k parameters or operating processes to estimate the IUH and DRH.

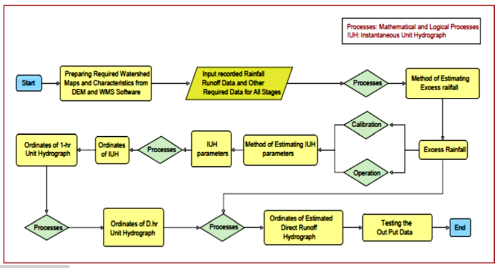

Fig. 2 The Developed Mathematical Model Flowchart.

6. APPLICATION OF THE DEVELOPED MODEL AND RESULTS

6.1 Estimation of the Composite Curve Number

The CN represents a soil hydrologic group and cover treatment and is used to estimate the excess rainfall (direct runoff) from the watershed at any time interval of storm duration. Landsat satellite imagery with a resolution of 30 meters downloaded from the Landsat-8 was used to develop the land use map and soil type maps of the watersheds understudy. With the aid of (WMS) software, land use, and soil type maps were conformed to obtain a unified map to find the composite CN value for each watershed. To understand, besides the aim of this study, the effect of the initial abstraction (λ), two cases of the composite curve number have been investigated according to two values of the initial abstraction, i.e., λ value =0.2, which depended on the Soil Conservation Service, and adjusting λ value =0.05 by applying the relations 6 and 7. The composite CN values for these two cases are shown in Table 2.

Table 2 Watersheds Composite Curve Number (CN) for Two Cases of Initial Abstraction Adjustment .

Watershed	Values of Composite Curve Number (CN) for different application cases			
	CN_{II}		CN_{III}	
	CN_{II} without adjusting $\lambda=0.2$	CN_{II} adjusted for $\lambda=0.05$	CN_{III} without adjusting $\lambda=0.2$	CN_{III} adjusted for $\lambda=0.05$
Goeza-Dabashan	69.10	88.52	83.72	94.66
khoshaban	62.06	86.26	79.00	91.89
Yousifka	67.21	87.89	81.50	92.79
Solag	59.83	85.56	7.1	91.23

6.2 Model Application and Results

The records of rainfall-runoff data for the four watersheds used in this research were available for five storms in the water years 2002 and 2006 for Goeza-Dabashan Watershed [35], three storms in the water years 2004 for the Khoshaban watershed [30], and for five storms in the water years 1991 and 1992 for both Yousifka and Solag watersheds [31]. The available recorded data for the storms mentioned above were applied in the developed model to determine the optimal Nash IUH parameters for each watershed. The applied storms covered a wide range of rainfall depth and intensity. The area, slope, max flow distance, soil type, land use, and composite curve number for each watershed were estimated firstly, as shown in the previous paragraph. Each watershed's different methods and case application were divided into two stages, i.e., calibration and verification stages, to reassess and estimate the applied methods and cases' accuracy. In the calibration stage, the first four storms were used for each of the watersheds; Goeza-Dabashan, Yousifka, and Solag, while the two first storms were used for the Khoshaban watershed. The last storm for each watershed was used in the verification stage. The calibration process was performed for the CN parameter in the case of the applied momentum method and for CN and the two parameters (n, k) in the case of the applied optimization method, using the recorded data of both rainfall and direct runoff for each storm until obtaining the optimal calibrated CN, n and k values according to the statistical tests results in each storm and method. For comparison, it is better to express the objective function (F^2) value by the non-dimensional relation using the Nash-Sutcliffe efficiency test. The priority in the optimization process was given to the most important parameter, where the optimization was done first for the parameter that significantly affects the acceptance criterion. Therefore, in the case of the optimization method, the optimization was done first for the curve number and then for the parameters n and k. The constraints of each parameter were chosen and put within the real physical limits, and the initial parameters values were assumed to approach the expected optimal values for them. For example, the curve number is placed within a range of values not less than the minimum value of the curve number according to the previous humidity condition. It does not exceed 100 as a maximum. Table 3 shows the storms' number and dates applied in the calibration stage for each watershed, in addition to its rainfall depth and runoff coefficient, which have been estimated using NRCS. Table 4 shows the estimated optimal Nash IUH parameters (n, k) for each storm and its average for each watershed, obtained by applying momentum and optimization methods. The estimated direct runoff hydrographs for each storm were tested using the tests: Nash-Sutcliffe Efficiency, root mean square error, relative mean error, standard error of estimate, time error to the peak between estimated and recorded runoff, % error of estimated to recorded peak direct runoff storm, and percentage error, i.e., the estimated to recorded direct runoff volume. Table 5 shows the statistical test results between the recorded and estimated direct runoff hydrograph for the watersheds understudy storms.

Table 3 Storms Numbers, Dates, Rainfall Depth, and Resulted in Runoff Coefficient Watershed used in the Calibration Stage for each Watershed.

	Watersheds															
	Goeza-Dabashan				Khoshaban				Yousifka				Solag			
Storm No.	Storm Date	Rainfall Depth mm	Runoff Coffs. *	**	Storm Date	Rainfall Depth mm	Runoff Coffs. *	**	Storm Date	Rainfall Depth mm	Runoff Coffs. *	**	Storm Date	Rainfall Depth mm	Runoff Coffs. *	**
1	13/2/2002	20.9	0.034	0.035	19/2/2003	16	0.13	0.12	2/1/1991	7.1	0.28	0.31	2/1/1991	5.52	0.25	0.32
2	30/3/2002	18.5	0.071	0.074	22/2/2003	12.3	0.03	0.10	14/10/1991	4.2	0.22	0.17	14/10/1991	7.4	0.18	0.11
3	12/4/2002	13.8	0.042	0.048					14/11/1991	4.7	0.11	0.28	14/11/1991	5.4	0.09	0.22
4	2/4/2006	16.4	0.047	0.043					18/2/1992	12.0	0.31	0.29	14/2/1992	11.8	0.37	0.27

Table 4 Values of the Optimal Parameters (n, k) for each Storm and its Average for each Eatershed by Applying both Momentum and Optimization Methods in the Calibration Stage.

Watershed	Method of Estimating Nash IUH Parameters	IUH Parameter	Storm Number and Its IUH Parameters (n and k) Values 1	2	3	4	Average n and k
Goeza-Dabashan	Moment	n	3.606	2.487	2.615	.270	2.995
		k	0.698	1.512	0.967	.065	1.061
	Optimization	n	4.230	2.818	1.890	4.429	3.342
		k	0.686	1.298	1.549	0.716	1.062
Khoshaban	Moment	n	2.939	2.700			2.820
		k	1.469	1.477			1.473
	Optimization	n	7.828	3.793			5.811
		k	0.435	1.003			0.719
Yousifka	Moment	n	2.05	2.533	1.912	1.234	1.932
		k	1.157	0.949	1.122	1.869	1.274
	Optimization	n	1.227	1.428	1.827	1.097	1.395
		k	1.629	1.871	1.196	1.817	1.628
Solag	Moment	n	4.229	4.074	4.475	1.731	4.259
		k	0.959	0.828	0.782	1.798	0.856
	Optimization	n	3.399	3.399	3.40	2.782	3.246
		k	1.265	1.091	1.107	1.130	1.148

Table 5 Tests Results of the Applied Storms for the Watersheds Understudy in the Calibration Stage.

Watershed	Storm No.	Tests Results for Storms													
		NSE		RMSE		RME		Standard Error of Estimate		Time error of estimated peak to Recorded Runoff (hr)		% Error of Peak Estimated to Recorded Runoff storm		% Error of estimated to recorded Runoff Volume	
		*	**	*	**	*	**	*	**	*	**	*	**	*	**
Goeza-Dabashan	1	0.81	0.87	0.007	0.006	-0.06	-0.06	0.009	0.007	1	0	-11.16	-5.93	0.08	0.02
	2	0.83	0.82	0.008	0.009	-0.07	-0.03	0.009	0.010	0	1	-0.24	-13.5	0.04	0.04
	3	0.78	0.79	0.006	0.005	-0.012	-0.09	0.006	0.006	0	0	16.1	10.30	0.08	*0.04*
	4	0.70	0.71	0.009	0.009	0.019	-0.08	0.010	0.010	0	0	-34.13	-28.4	0.07	007
Khoshaban	1	0.96	0.95	0.69	1.496	0.102	-0.64	0.737	1.593	0	1	-13.79	-19.92	0 .05	-0.06
	2	0.96	0.98	0.04	0.03	4.831	2.794	0.043	0.003	0	0	-14.90	-8.65	0.05	0.05
Yousifka	1	0.75	0.83	0.416	0.336	0.011	-0.07	0.2	0.382	1	1	5.05	-2.02	0.01	-0.06
	2	0.81	0.86	0.220	0.191	0.037	0.216	0.254	0.221	0	0	7.07	7.21	0.07	001
	3	0.91	0.89	0.204	0.220	-0.06	-0.01	0.231	0.249	1	1	-2.41	12.35	0.05	0.12
	4	0.93	0.95	0.182	0.154	0.034	0.218	0.206	0.175	0	0	11.29	13.17	0.11	0.14
Solag	1	0.86	0.83	0.253	0.126	0.037	-0.03	0.281	0.138	0	0	24.46	-4.9	0.13	0.02
	2	0.95	0.97	0.082	0.061	-0.08	0.016	0.094	0.069	1	1	10.53	3.21	0.06	0.02
	3	0.97	0.98	0.084	0.075	-0.01	0.012	0.094	0.093	0	0	6.10	-1.03	0.02	0.04
	4	0.96	0.98	0.094	0.074	0.115	-0.012	0.102	0.081	0	0	-0.52	2.97	0.21	0.18

*** Applying Moment method   ** Applying optimization method**

6.3 Empirical Relations for Estimating Nash IUH Parameters (n and k)

The topographical characteristics usages are a basic tool in hydrologic science for estimating the IUH and DRH due to the lack of recorded data for the watersheds. The topographical characteristics and features of the watershed have a significant effect on its hydrological behavior. Watershed different topographical factors significantly affected the flow characteristics and the direct runoff hydrograph shape resulting from falling the storm over the watershed, like the area, slope, main stream length, and lag time, besides its shape factor and basin ratio. The watershed shape influences the time for water from the remote parts of the watershed to arrive at the outlet. Therefore, its value significantly affected the peak occurrence time and hydrograph shape. The mainstream slope controls the flow velocity in the channel and has had a pronounced effect on the recession limb of the hydrograph. The intensity and the duration of the storm are important factors that affected the shape of the direct runoff hydrograph rising limb and its peak; however, these effects can be indirectly considered by the calibration process and estimating n and k values for the gauged watershed, in addition to the fact that the ungauged watersheds have not a recorded runoff data to use them in any empirical relation. Empirical relationships have been developed in this study between each of the average optimal IUH's parameters values of the watersheds, i.e., using n and k estimated by optimization method due to its best tests results, as depended parameters versus the area, slope, the mainstream length, and shape factor and basin ratio of the watershed as independent parameters. The developed empirical relations, using an optimization computer program in MATLAB, take the forms:

$$n = \frac{0.00016 \ L^{11.34402} \qquad S_f^{3.98374}}{A^{6.67542} \ S^{3.99766} \ B_r^{0.16890}} \quad \textbf{(30)}$$

$$k = \frac{85.85378 \ S^{14.49451} \qquad S_f^{12.09089} \ B_r^{26.31441}}{A^{11.87496} \ L^{2.66178}} \quad \textbf{(31)}$$

where:

A=Area of the watershed in Km²
L=length of the main stream in Km.
S=Slope of the watershed
S_f=Shape factor of the watershed (A/L^2).
B_r=Basin Ratio of the watershed(L/S^0.5).

These independent parameters easy estimation from the topographical map of the watershed, encourages using it in the empirical relationships. Table 6 shows the developed empirical relations statistical tests. The developed empirical relations can be used for estimating Nash IUH Parameters. Then the direct runoff hydrograph, resulting from occurring any storm over any ungauged watershed within the area under study, can be estimated where the watersheds within it have generally similar topographical characteristics.

Table 6 Values of the Statistical Tests for the Empirical Relationships between Nash IUH Parameters and Watershed Characteristics.

Dependent Parameter of the Developed Empirical relation	Tests Results				
	Nash-Sutcliffe efficiency (NSE)	Root Mean Square error RMSE	Mean Absolute Deviation SABSE	Standard Error of Estimate (SEE)	Objective Function F^2
n	0.9645	8.743047×10^{-02}	9.374493×10^{-01}	4.181638×10^{-03}	3.497219×10^{-01}
k	0.9999	1.562442×10^{-08}	4.613996×10^{-04}	1.767734×10^{-04}	6.249766×10^{-08}

6.4 Verification of the Developed Empirical Relations and the Applied Model

Estimating the empirical relationship's objective is to evaluate its accuracy and the possibility of applying and adopting it to estimate the Nash IUH parameters and then direct runoff hydrograph resulting from the occurring storm over the ungagged watershed in the north of Iraq. The developed model was used in the verification stage by applying these empirical relationships to estimate the IUH parameters and the direct runoff hydrograph of one recorded storm, which was not applied in the calibration stage of each watershed under study. The estimated direct runoff hydrograph was compared with the recorded direct runoff hydrograph, which was obtained by applying both the optimization method and Haan's empirical relations for the storm data. Table 7 shows the applied statistical test results. Figs. (3, 4, 5, 6) show the recorded and estimated direct runoff hydrographs of the verification storm by the three reported methods for each watershed.

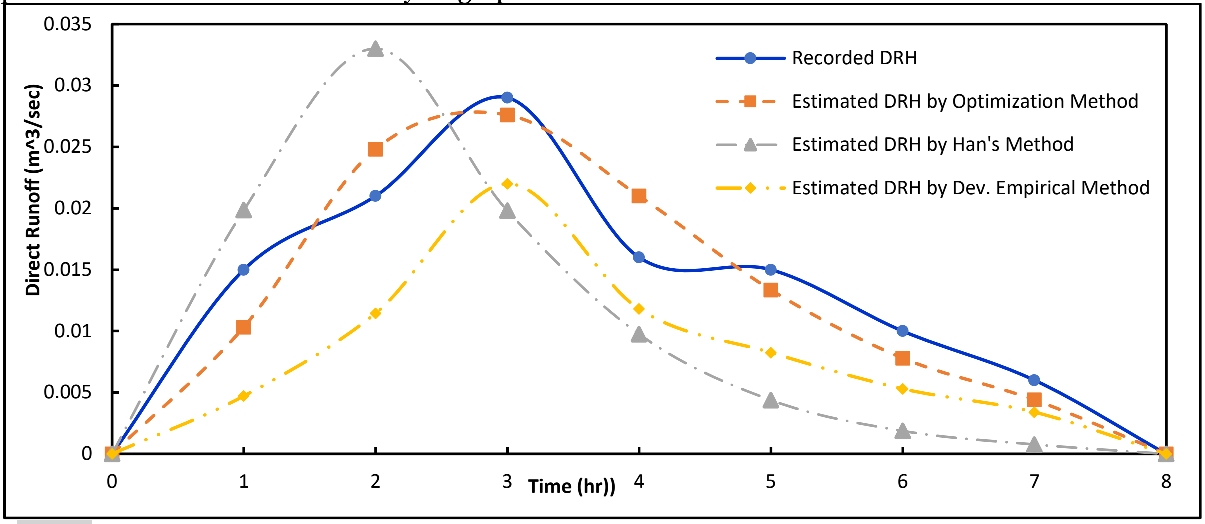

Fig. 3 Recorded and Estimated DRH for the Verification Storm using Optimization and Haan's and Developed Empirical Relations Methods for the Goeza-Dabashan Watershed.

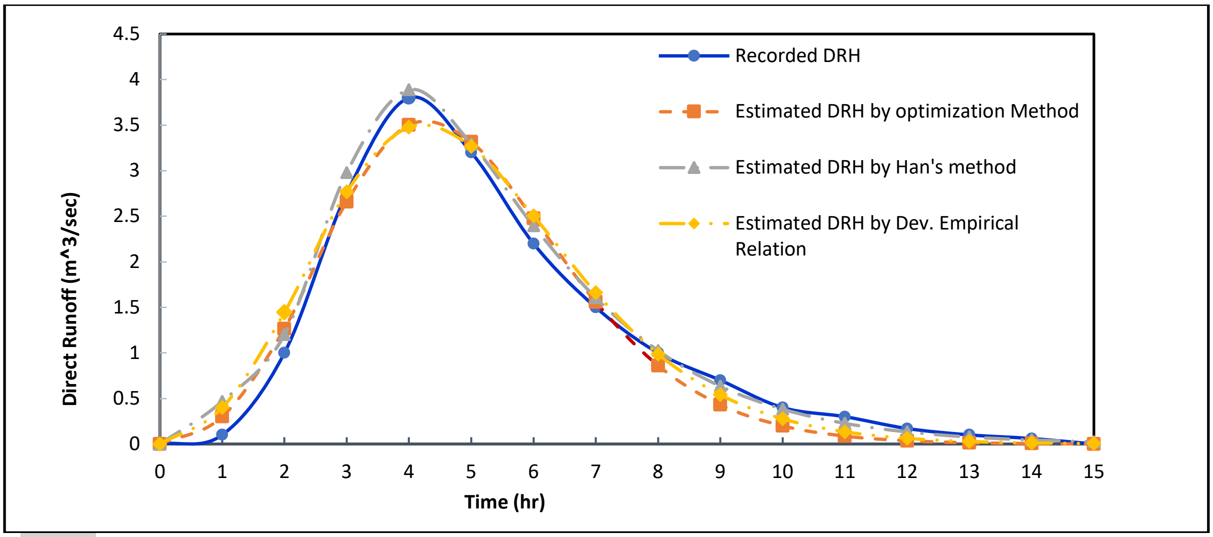

Fig. 4 Recorded and Estimated DRH for the Verification Storm using Optimization and Haan's and Developed Empirical Relations Methods for the Khoshaban Watershed.

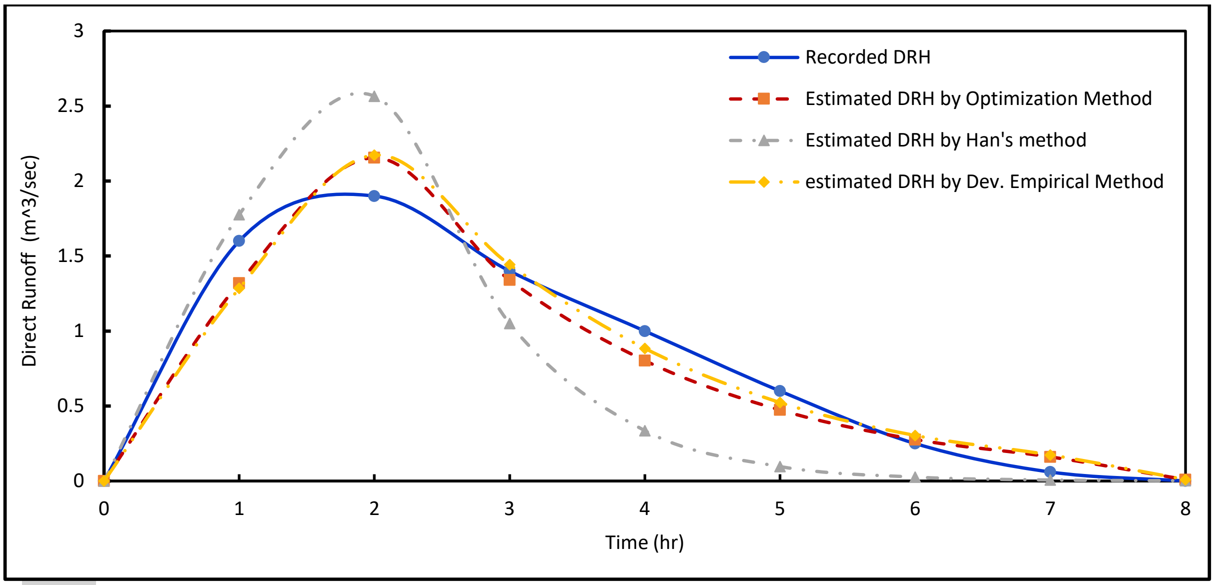

Fig. 5 Recorded and Estimated DRH for the Verification Storm using Optimization and Haan's and Developed Empirical Relations Methods for the Yousifka Watershed.

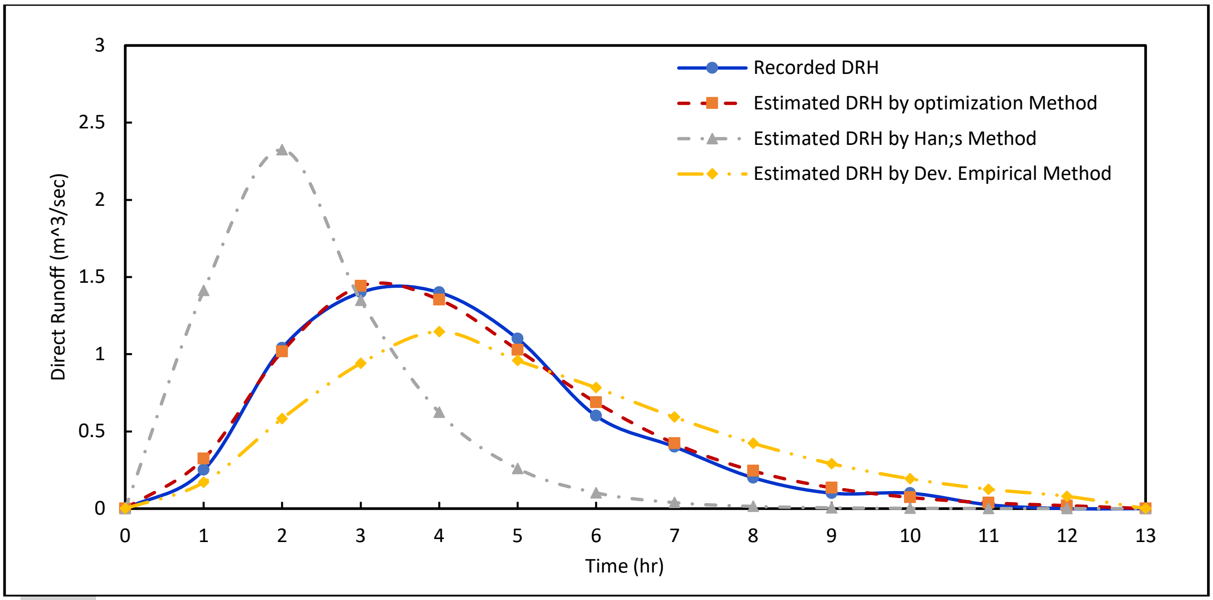

Fig. 6 Recorded and Estimated DRH for the Verification Storm using Optimization and Haan's and Developed Empirical Relations Methods for the Solag Watershed.

Table 7 Statistical Tests Results between the Recorded and Estimated Direct Runoff Hydrographs for the Verification Stage.

Watershed	Method of Estimating Nash Coefficients	Nash IUH Coefficient		Tests					
		n	k	NSE	RMSE	RME	Standard Error of Estimate	% Error of Peak Estimated Storm Runoff to Peak Recorded Storm	% Error of Runoff Volume (Estimated /Recorded Storms)
Goeza-Dabashan	Optimization Method for Recorded Storm	3.150	0.952	0.81	0.0041	-0.057	0.0048	-4.74	002
	Haan's Empirical Relations	2.050	0.565	0.73	0.0084	0.051	0.0049	28.98	0.13
	Developed Empirical Relations	3.414	1.062	0.78	0.0086	-0.377	0.0099	-51.60	0.26
Khoshaban	Optimization Method for Recorded Storm	6.980	0.691	0.97	0.172	0.869	0.184	-7.84	0.04
	Haan's Empirical Relations	3.06	2.03	0.60	0.903	0.645	0.908	-53.21	0.07
	Developed Empirical Relations	5.847	0.719	0.94	0.205	2.362	0.218	-6.01	0.05
Yousifka	Optimization Method for Recorded Storm	1.164	1.750	0.95	0.156	0.143	0.178	13.44	0.03
	Haan's Empirical Relations	2.047	0.651	0.70	0.387	0.342	0.387	35.06	0.13
	Developed Empirical Relations	1.819	1.628	0.92	0.166	0.072	0.188	8.04	0.09
Solag	Optimization Method for Recorded Storm	3.400	1.112	0.97	0.075	-0.012	0.081	2.97	0.01
	Haan's Empirical Relations	2.032	0.867	0.32	0.614	0.079	0.435	66.94	0.11
	Developed Empirical Relations	2.843	1.148	0.89	0.085	0.030	0.092	-2.98	0.02

7. DISCUSSION:

From the calibration stage, it was found that: The values of each parameter, i.e., n and k, for the most applied storms (Table 4) of each watershed (except Khoshaban) were close in case of applying the momentum or optimization method. The average values of n and k for each watershed by the two methods were also close. Although the results of all tests for both momentum and optimization methods were close and acceptable, the Nash-Sutcliffe efficiency test values for the optimization method were slightly higher than the momentum method. The same can be said for the other tests, as shown in Table 5. The optimal calibration CN values of each storm resulted from both the momentum and optimization methods for each watershed were very close to each other, as compared to the n and k coefficients values, which reflects that the degree of accuracy of both methods is right. The results showed that the topographical characteristics effect on the n and k values was greater than the rainfall characteristics effect. The results encourage correlating the average of each IUH parameter (for the best method) in empirical relationship with the topographical characteristics to facilitate using it to estimate the two parameters for Hundreds of ungauged watersheds distributed in different positions north of Iraq. As a second result, the average optimal calibrated curve numbers for the storms of the Goeza-Dabashan watershed were 76.7 and 81.92 for CN_{II} and CN_{III}, respectively. The average optimal calibrated curve number for the storms of the Khoshaban watershed was 87.7 for CN_{II}, where the two storms applied were of the antecedent moisture condition type II. While for Yousifka and Solag watersheds, the average optimal calibrated curve numbers for the storms were 86.8 and 91.3, respectively, for CN_{II}, and the average optimal calibrated curve numbers for the storms were 94.21 and 92.7 for CN_{III}- respectively, which means that applying the NRCS method for Goeza-Dabashan Watershed, the CN_{II} value needs minor correction when λ=0.05, while CN_{III} requires no correction. However, for the other watersheds, both CN_{II} and CNI_{III} need correction when λ=0.05 in applying the NRCS method. From the verification stage, it was found that: The higher values of Nash-Sutcliffe efficiency tests for the developed empirical relations [30, 31] and the minimum values of the other tests reflect their high compatibility and the possibility of it for the ungauged watersheds in the north of Iraq. The application of relations 30 and 31 to estimate the Nash coefficients for each watershed for the recorded storm, which was unused in the calibration stage, showed that the estimated values of coefficients n and k were close to those obtained by applying the optimization method as compared to coefficients obtained by Haan's method. The statistical test values shown in Table 7 showed that the NSE test values of the developed empirical relations were higher than that of Haan's method for all studied watersheds, where the NSE average value for the four watersheds resulted from applying the optimization method. Haan's method and the developed empirical relations were 0.925, 0.587, and 0.883, respectively. The same can be said for the other tests. This result showed the watershed topographical characteristics' significant effect on estimating the IUH parameter values.

8. CONCLUSION:

The limited availability of the recorded rainfall-direct runoff data for many watersheds in the north of Iraq restricts the development and management of different activities of water resources. To overcome this limitation, the DEM, Nash IUH, and NRCS methods were combined in a developed mathematical model to estimate the Nash model coefficients and direct runoff hydrograph for different recorded storms using momentum, optimization method, Haan's relations, and the developed empirical relations in both the calibration and verification stages for the four gauged watersheds under study. From the developed mathematical model's applications, tests, and results, the following noticeable findings can be concluded:

a- The initial abstraction (I_a) in estimating the composite curve number of the watersheds should be adjusted for $\lambda = 0.05$ in estimating the curve number (CN) type II and III for the Khoshaban, Yousifka, and Solag watersheds; while the Goeza-Dabashan watershed results exhibited no need to adjust the λ value from 0.2 to 0.05 to estimate CN_{III}; however, to estimate CN_{II}, the λ value needs a correction between λ values of (0.2-0.05).

b- The momentum and optimization methods have close estimated values of IUH parameters. Also, their tests' results were satisfied, with no significant difference, though with slightly more acceptance of the optimization method, where the results of the IUH parameters were used with five important watershed topographical characteristics to develop two empirical relations for estimating the IUH parameters for the ungauged watershed. The developed empirical relations applications showed a higher efficiency than Haan's method when it is applied to verify estimating the direct runoff hydrograph for a recorded storm for each of the four watersheds.

c- The developed empirical relations were more appropriate than Haan's empirical method to estimate the Nash IUH parameters and the direct runoff hydrograph for the ungauged watersheds with no hydrometric station in the north of Iraq. It is worth mentioning that the application of Haan's empirical relations (17 and 18) to estimate the IUH parameters required previously applying Eqs. (19 and 20) to estimate the storm peak discharge and time to peak.

d- The developed empirical relations and model application limitations were within the studied areas' topographical characteristics limitations, unit hydrograph, and the Natural Resources Conservation Services (NRCS) method.

e- The statistical tests indicated the ability of the developed model to estimate the IUH and direct runoff hydrograph for ungauged watersheds in northern Iraq in case storm rainfall data were available.

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