APPLICATIONS OF GEOMORPHOLOGIC AND KINEMATIC WAVE MODELS TO WADIS IN SAUDI ARABIA

Achi M. Ishaq*

Department of Civil Engineering
King Fahd University of Petroleum & Minerals
Dhahran, Saudi Arabia

and

Mohamed N. Allam

Department of Civil Engineering
Cairo University
Cairo, Egypt

الخلاصـــة :

تعتبر السجلات والمعلومات المتوفرة الخاصة بعلم المياه (الهيدرولوجي) في المملكة العربية السعودية غير كافية لإجراء دراسة مفصَّلة عن تأثر الأحواض المائية بالأمطار . لذلك فإن الطرق التقليدية المبنية على تحليلات دقيقة لتاريخ الصرف السطحي (السيول) وسجلات هطول الأمطار تبدو غير جديرة . وهناك بديل جذاب نتيجة لتطور أنظمة التنبؤ بالصرف السطحي معتمداً على علم شكل أرضية (لوريان) دون الحاجة إلى سجلات الصرف السطحي للأمطار . وفي هذه الدراسة طُبِّقت أربع روايات لنظام وحدة التصرف اللحظي الجيومورفولوجي (GIUH) نظام الموجة المتحركة على ثلاثة وديان مجهزة بأدوات القياس . وقد دلت المحاكاة على أن المتغيرات مثل الصرف الأعلى والوقت اللازم لحصوله وشكل الرسم المائي شديدة التأثر بسرعة جريان الماء . وقد بيَّـن تطبيق نموذج الموجة المتحركة (DR3M) على الوديان الصغيرة مثل (وادي مذنب) أن سرعة الموجة المتحركة هي أفضل مايمثل سرعة جريان الماء . أما بالنسبة للوديان الكبيرة مثل (وادي خاط) و(وادي جوف) فإن نموذج التصرف اللحظي (GIUH) بيّـن أن سرعة الموجة الديناميكية أفضل مايكون للتمثيل . وبمقارنة التمثيل مع القياسات الحقيقية تبيّـن أن محاكاة نموذج التصرف اللحظي (GIUH) المبنى على فرض التوزيع الأسي لوقت انتقال المياه السطحية في الوديان مع تمثيل (فيليبس) لزيادة مياه الأمطار متطابقة مع نتائج القياسات الحقيقية للوديان المتوسطة والكبيرة . أما بالنسبة للوديان الصغيرة فقد حقق نموذج الموجة المتحركة (DR3M) تمثيلاً فائقاً .

*Address for correspondence:
KFUPM Box No. 39
King Fahd University of Petroleum & Minerals
Dhahran 31261
Saudi Arabia

ABSTRACT

The hydrologic records available in the Kingdom of Saudi Arabia are generally inadequate for detailed analysis of basin response to rainfall. Therefore, traditional runoff estimates, based on the detailed analysis of the historical runoff and rainfall records do not seem to be promising. Thus, an attractive alternative appears to be the development of runoff prediction models with dependence on the geomorphology of watersheds rather than rainfall runoff records. In the study reported herein, four versions of the Geomorphologic Instantaneous Unit Hydrograph (GIUH) Model and a Kinematic Wave Model have been applied to three gauged watersheds in Saudi Arabia. The simulations revealed that parameters such as peak discharge, time to peak, and the shape of the hydrograph were very sensitive to the streamflow velocity. The Kinematic Wave Model DR3M applications showed that, for small watersheds like Midhnab, the kinematic wave celerity is the most representative streamflow velocity. For larger watersheds, such as Wadi Khat and Jawf, however, the GIUH model applications show that the dynamic wave velocity is the most representative one. A comparison between the model simulations and observed hydrographs showed that the simulations of the GIUH model based on the exponentially distributed streamflow travel time, and rainfall excess as computed from Philip's infiltration expression [1], were in significant agreement with observed hydrographs for medium and large watersheds. For small watersheds however, the DR3M performed superior simulations.

APPLICATIONS OF GEOMORPHOLOGIC AND KINEMATIC WAVE MODELS TO WADIS IN SAUDI ARABIA

INTRODUCTION

Many regions throughout the world lack the hydrologic data required for a detailed analysis of a basin response to rainfall. Typical examples of this situation are the many ungauged Wadis in the Kingdom of Saudi Arabia. These Wadis respond to sporadic rainfall events, frequently causing considerable damage to villages and other developments in their surroundings. Effective utilization of these flood waters as well as planning and protection of these Wadis, require estimates of expected discharge from rainfall events of varying magnitudes. Traditional estimation techniques, based on regression analysis of the historic rainfall and runoff records, do not seem to be promising for the Kingdom due to the lack of hydrologic data. Historic records of rainfall cover a period of 23 years from 1968 to the present with a reasonable spatial density. Runoff records available however are deficient in terms of record length, spatial coverage, and accuracy requirements. Therefore, the major challenge for the hydrologists in the Kingdom appears to be the development of runoff prediction models with minimum dependence on historic runoff records.

There are several runoff prediction models available in the hydrology literature today. The last generation of these models are the nonlinear-distributed-catchment models which represent in detail the physical processes involved in rainfall–runoff transformation [2–7]. However, insurmountable difficulties are encountered in the calibration of these models. These are mainly due to (*i*) the requirement of physical parameters in "distributed" form throughout the watershed as opposed to a "lumped" form, and (*ii*) the nonlinearity, which generally amplifies the error in the input data. In the recent past two groups of models appear to have gained prominence. These models may be classified as those using the Geomorphologic Instantaneous Unit Hydrograph (GIUH) techniques and those routing models using the Kinematic Wave Approximations. In the case of the former convolution of the effective rainfall with the GIUH (computed from appropriate infiltration models) will result in the discharge hydrograph. In the case of the latter, the same excess precipitation (from planes and channels in the watershed) is routed to obtain the discharge hydrograph. The kinematic wave model chosen for the study is Distributed Routing Rainfall–Runoff Model (DR3M) developed by Alley and Smith [8].

The primary objective of this study has been to provide an efficient working tool for predicting the surface runoff hydrographs of the Wadis in the Kingdom. Prediction of these discharges is necessary for the design of appropriate infrastructures and for the efficient storage, distribution, control and use, *i.e.* the optimum management of water resources of the Kingdom

With this objective in mind, the above models were used to predict runoff in three Wadis in the Kingdom with limited runoff records. These Wadis are Wadi Khat (600 km^2) and Jawf (305 km^2) in the southwestern region, and Wadi Midhnab (20 km^2) in the Qassim (Central) region. The observed hydrographs of these Wadis were analyzed and compared with those simulated by the above models.

GEOMORPHOLOGIC INSTANTANEOUS UNIT HYDROGRAPH MODELS

Recent hydrology literature reveals that geomorphologic models have a greater potential for use in data deficient areas. Common practice in applied hydrology is the use of the linear systems theory to determine surface runoff discharges of watersheds. In this theory, transformation of rainfall to runoff is assumed to be linear. Given the Instantaneous Unit Hydrograph (IUH), then for a rainfall event the corresponding runoff discharge can be estimated *via* the convolution transformation. Rodriguez-Iturbe and Valdes [9], suggested a methodology for estimating the IUH based on watershed geomorphology. Gupta *et al.* [10] interpreted the IUH as the probability density function (pdf) of the travel time that a drop of water, landing anywhere in the watershed, takes to reach the outlet. It is assumed that the pdf of travel time in watershed streams is exponential [9]. The resultant IUH is called the Exponentially Distributed Geomorphologic Instantaneous Unit Hydrograph (ED–GIUH).

Kirshen and Bras [11] proposed a time distribution based upon linearized equations of motion, the solution of which was developed by Harley [12]. The resultant IUH is called the Linear Routing Geomorphologic Instantaneous Unit Hydrograph (LR–GIUH). The resultant pdf of the travel time was found to be different from that of Rodriguez-Iturbe and Valdes [9]. Diaz-Granados *et al.* [13] modified the above two approaches to account for infiltration in watershed channels with a simple linear function of the surface runoff. After this modification, they applied them for various watersheds in Egypt and Puerto Rico. Both the ED−GIUH and LR−GIUH after the infiltration modification, yielded similar discharge hydrographs in terms of shapes, peak discharge, and time to peak. In this study, the four geomorphologic rainfall−runoff models used are the ED−GIUH and LR−GIUH with and without infiltration considerations.

The Exponential Distribution of Time of Travel Model (ED−GIUH)

Rodriguez-Iturbe and Valdes [9] proposed an exponential ditribution for the travel time in the streams given by:

$$f_{T(i)}(t) = \lambda_i \exp(-\lambda_i t) \qquad (1)$$

where $T(i)$ is the travel time in a stream of order i, $f_{T(i)}(t)$ is the pdf of $T(i)$, $\lambda_i = V/\bar{L}_i$, V is the streamflow velocity, $\bar{L}_i$ is the average length of the stream of order i and t is the time coordinate. This exponential travel-time distribution is equivalent to treating each stream as a linear reservoir.

The exponential distribution as given by Equation (1) will result, for a rainfall event, in a hydrograph which does not start at zero but at a positive ordinate. In order to overcome this problem, Rodriguez-Iturbe and Valdes [9] modified the distribution for the highest order stream as

$$f_{T(\Omega)}(t) = \lambda_\Omega^{*2} t \exp(-\lambda_\Omega^* t) \qquad (2)$$

where $\lambda^*_\Omega = 2\lambda_\Omega$ and Ω the order of the watershed. According to Strahler [14] this is the highest stream order. This distribution is equivalent to representing the highest-order stream by two linear reservoirs in series.

The Linear Routing Model (LR−GIUH)

Diaz-Granados *et al.* [13] presented an approximate linear solution of one-dimensional unsteady flow equations accounting for the infiltration losses in a wide rectangular channel. The solution defines the channel's response to an input at the channel's most upstream point. It is used in deriving the channel response to a uniform input along the channel length. This response is interpreted as the pdf of the time that a drop spends to travel to the outlet of the channel, which is in turn used in the derivation of the mathematical expression for the IUH. A complete derivation of the expression for the LR−GIUH and the ED−GIUH for fourth order basins has been provided by Allam *et al.* [15].

Computations of the Discharge Hydrograph

Having determined the ED−GIUH or LR−GIUH, then for a given storm with known effective rainfall intensity, the surface runoff discharge may be computed *via* the convolution transformation as:

$$Q(t) = A_\Omega \int_0^t I_e(\xi) h(t-\xi) \qquad (3)$$

where A_Ω is the area of the watershed, $Q(t)$ is the surface runoff discharge at time t, ξ is time into past, $I_e(t-\xi)$ is the effective rainfall intensity at time $t-\xi$ and $h(t-\xi)$ is the IUH ordinate at time $t-\xi$. The effective rainfall computation is performed using the Philip's [1] infiltration expression. It should be noticed however that if the infiltration losses are incorporated in the IUH [13], the gross rainfall instead of the effective one should then be considered in the above convolution.

Analytical solution of Equation (3) is possible, using the Laplace transform techniques, only if uniform rainfall intensity is assumed. Otherwise, a numerical solution may be obtained as:

$$Q_i = A_\Omega \sum_{i=1}^{j} I_i h_{j-1} \Delta t \quad j = 1, 2 \ldots$$

where Δt is the discretization time interval, used for discretizing the IUH and rainfall hyetograph.

Data Requirements

The input data of the four IUH models may be classified into two sets: (*i*) geomorphologic parameters which include number of streams of order; number of streams of order i which drain into streams of higher order j (N_{ij}, $i = 1, \ldots \Omega$), size of the watershed; and average drainage area, length and slope of each stream order; and (*ii*) hydraulic parameters which include the reference flow velocity and depth for each stream order and the infiltration coefficient. The geomorphologic data can easily be estimated from topographic maps, aerial photos and/or satellite imagery for the watershed concerned.

Effective Rainfall Computation

The effective rainfall computed is equal to the gross rainfall minus the infiltration losses. The interception losses and the depression storage are assumed to be negligible compared to the infiltration losses. The evapotranspiration is assumed to be negligible during the storm but significant between storms. The infiltration is presented with Philip's expression [1] as a function of soil parameters and soil moisture. Given that most watersheds have a mountainous nature, the watershed area is classified into two portions: mountainous and alluvial areas. For the mountainous area, a linear rainfall – runoff relationship is utilized. The resultant surface runoff is regarded as water depth on the alluvial area. The effective rainfall on the alluvium is computed equal to this water depth plus rainfall depth minus the infiltration losses as presented by Philip [1].

For the effective rainfall computation the following data is required:

1. Soil Data: Effective porosity of the soil, pore size distribution index and saturated effective hydraulic conductivity. These parameters can be determined from laboratory analysis of collected soil samples. Another input data here is the depth to the groundwater table which can be determined from field measurements.
2. Topographic Data: Size of the alluvial portion of the watershed; and size of the watershed. This data can be determined from topographic maps, aerial photos, or satellite imagery.
3. Climatological Data: Mean value of the rainfall depth and duration, mean value of the time between storms, mean value of the rainy season potential evaporation rate, and the hyetograph of the storm to be simulated. Long record of climatological data is required for computing the mean values of these parameters.
4. Hydrologic Data: Runoff coefficient of the mountains. The runoff coefficient may be determined from either field experience or from model calibration.

THE KINEMATIC WAVE MODEL

The kinematic wave model used in this study is the USGS Distributed Routing Rainfall – Runoff Model (DR3M). Since the late 1960s, the U.S. Geological Survey (USGS) has been developing simulation models of rainfall – runoff processes. Their first simulation model, a lumped-parameter rainfall – runoff model for small rural watersheds, was reported by Dawdy *et al.* [16]. Subsequent work by Dawdy *et al.* [6] produced a DR3M. This model was largely the product of incorporating the routing component from a version of the Massachusetts Institute of Technology catchment model [17] into the original USGS Model. Alley and Smith [8] subsequently expanded the DR3M Model by providing several numerical optimization and other options.

DR3M operates on two time intervals. The model provides detailed simulation of storm runoff during days for which short-time interval rainfall data are input to the program. These days are referred to as 'unit days', and it is only during unit days that flow routing is performed. Between unit days the model uses daily precipitation and daily evaporation data to provide a continuous daily accounting of soil moisture. Thus, the advantages of continuous simulation are combined with those of an event type model.

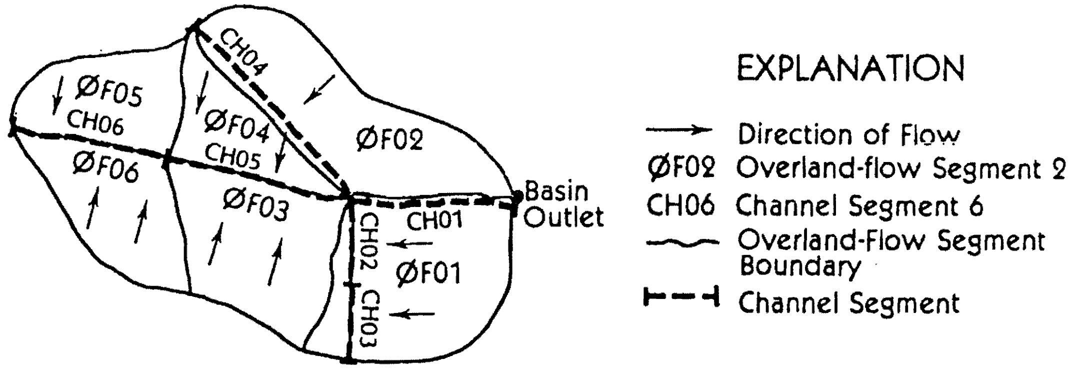
During the simulation of a period of storm runoff, the generation of rainfall excess and flow routing are treated independently. The time series of rainfall excess is determined first and then, in a second step, it is routed to the watershed outlet. The rainfall-excess is computed using the Philip's expression as in the case of GIUH models.

DR3M approximates the complex topography and geometry of a watershed as a set of segments which jointly describe the drainage features of the basin. The purpose of this approach is to reduce the rainfall-excess routing problem to the hydraulic problem of unsteady flow over uniform planes and channels.

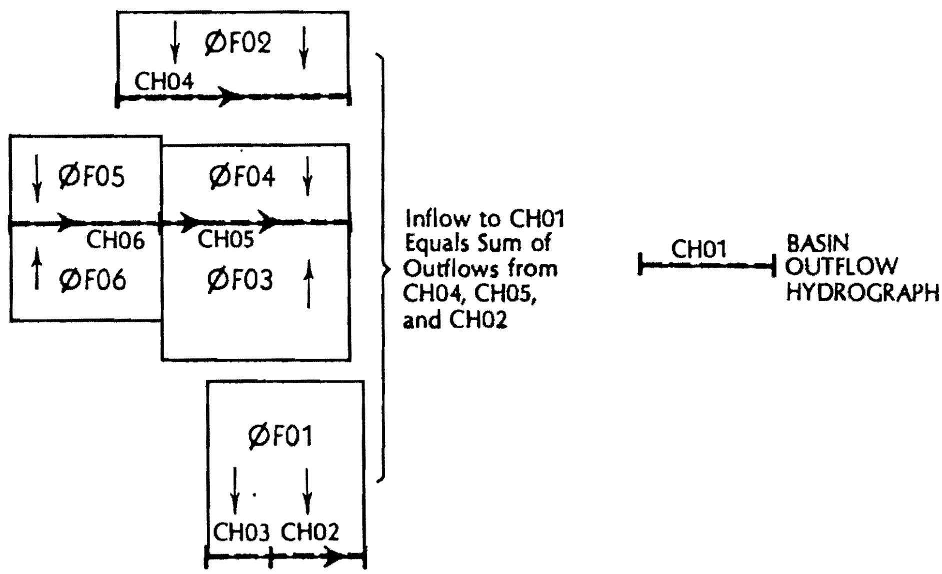
A schematic illustrating the relationships between channel and overland-flow segments is shown in Figure 1. Kinematic wave theory is applied for both overland-flow and channel routing. Unsteady free-surface flow is governed by the equations of continuity and momentum, commonly referred to as the Saint-Venant or shallow-water equations. These equations have been solved using the method of characteristics and finite difference techniques.

Model Limitations

In applying this model the assumptions behind the kinematic wave equations for channel and overland-flow routing should be recognized. The kinematic wave solution is based on the assumption



(a) PLAN VIEW OF DRAINAGE BASIN



(b) SCHEMATIC REPRESENTATIONS OF MODEL SEGMENTS

Segment	Inflow to Segment	
	Lateral Inflow	Upstream Inflow
ØF01	Rainfall Excess	—
ØF02	" "	—
ØF03	" "	—
ØF04	" "	—
ØF05	" "	—
CH01	—	CH02, CH04, CH05
CH02	ØF01	CH03
CH03	ØF01	—
CH04	ØF02	—
CH05	ØF03, ØF04	CH06
CH06	ØF05, ØF06	—

(c) SEGMENT INTERRELATIONSHIPS

Figure 1. Discretization of Watershed into Overland Flow and Channel Segments.

that disturbances are allowed to propagate only in the downstream direction. Therefore, the model does not account for backwater effects or flow reversal. In addition to the assumptions behind the kinematic wave routing, other major assumptions are listed below:

Rainfall excess is assumed to be uniformly distributed over an overland flow segment;

Pervious and impervious parts of a segment are assumed uniformly distributed over the segment;

The complex uneven topography of the natural catchment can be approximated by planes;

Rainfall excess does not infiltrate as it moves overland (once rainfall excess is computed, it must end up in a channel);

Lateral inflows to channels are assumed uniformly distributed;

Changes in flow from laminar to turbulent or *vice versa* will not occur.

WATERSHED DESCRIPTIONS

Selection of Wadis for Model Calibration and Applications

According to the Ministry of Agriculture and Water [18] the Kingdom is classified into nine hydrological areas as shown in Figure 2. After analyzing the hydrologic records of these areas, three Wadis (Jawf, Khat, and Midhnab) were found to be suitable for model calibration and application. Geomorphologic analysis of the selected Wadis was performed and the geomorphologic parameters were determined.

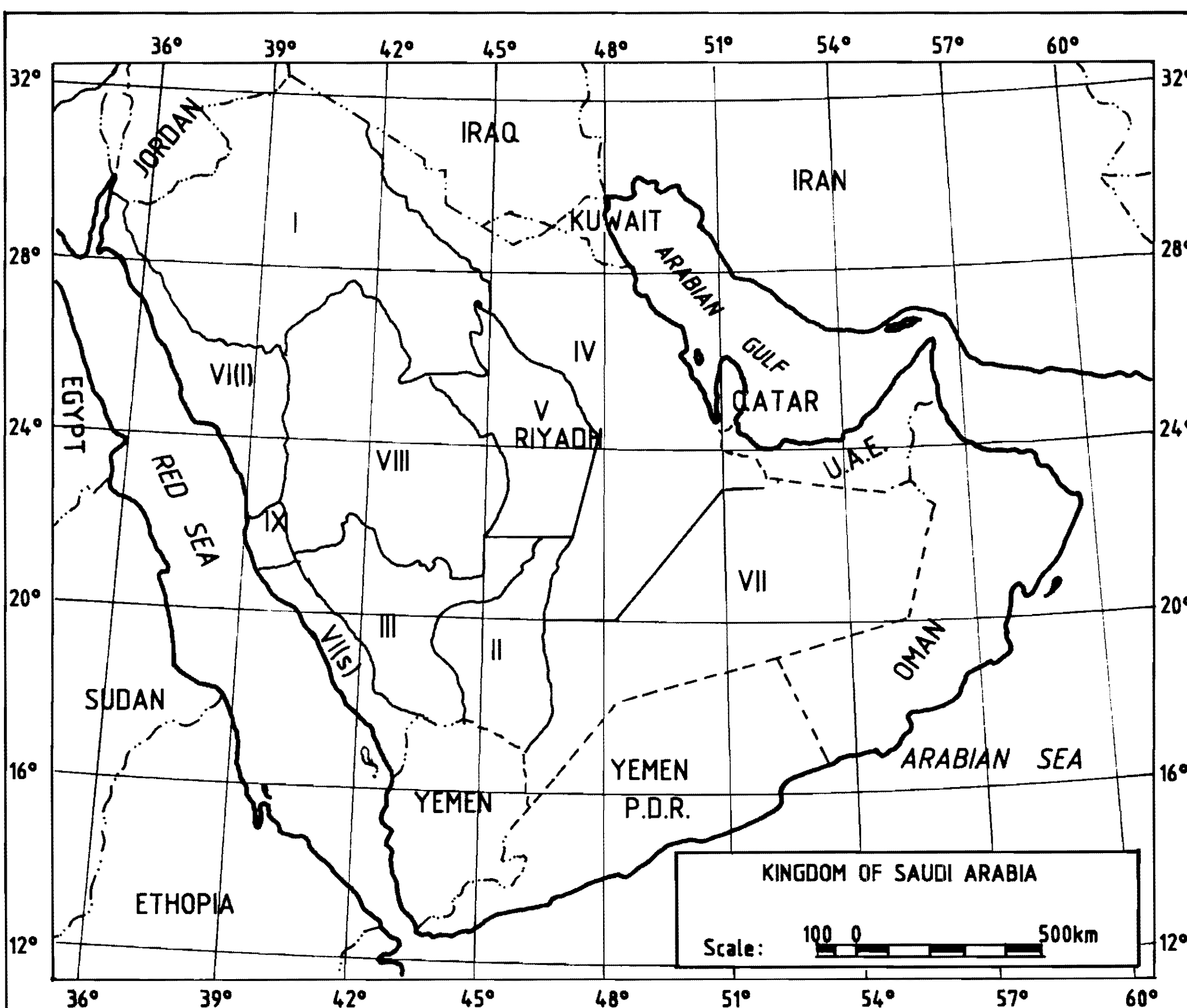


Figure 2. Map of Hydrological Areas of the Kingdom of Saudi Arabia.

Cross-sectional areas of representative streams in each Wadi were surveyed for estimating kinematic wave parameters necessary for the DR3M applications. Soil samples were collected and analyzed in the laboratory for estimating the saturated hydraulic conductivity ($K(I)$), the effective porosity (n) and the pore size distribution index (m). Measurements for the depth of the groundwater table in most of the Wadis were reported. Size of the alluvial coverage, and evaluation of the vegetation density were obtained. Hydrologic descriptions of the selected Wadis are provided.

Wadi Jawf and Wadi Khat

Wadi Jawf (305 km^2) and Wadi Khat (600 km^2) are subcatchments of Wadi Yiba, a major basin in the southwestern region of the Kingdom.

Topographic maps with 1:50 000 scale, which cover both Wadis were used to determine the stream networks of these Wadis. These are shown in Figures 3 and 4 for Wadis Khat and Jawf, respectively. Both Wadis have flat alluvial flood plains with a slope range of 0 − 8%. The flood plains are surrounded with mountains varying in slope from 30 to 100%. The steep mountains are characterized with relatively fractured rocky outcrops. The length, drainage area and slope of each stream of both Wadis are computed from the topographic maps. The mean values for each stream order were calculated. The initial and transitional probabilities of surface runoff in both Wadis are provided in Table 1.

Wadi Midhnab

Wadi Midhnab (19.4 km^2) is located in the Qassim region in a sedimentary formation (Khuff

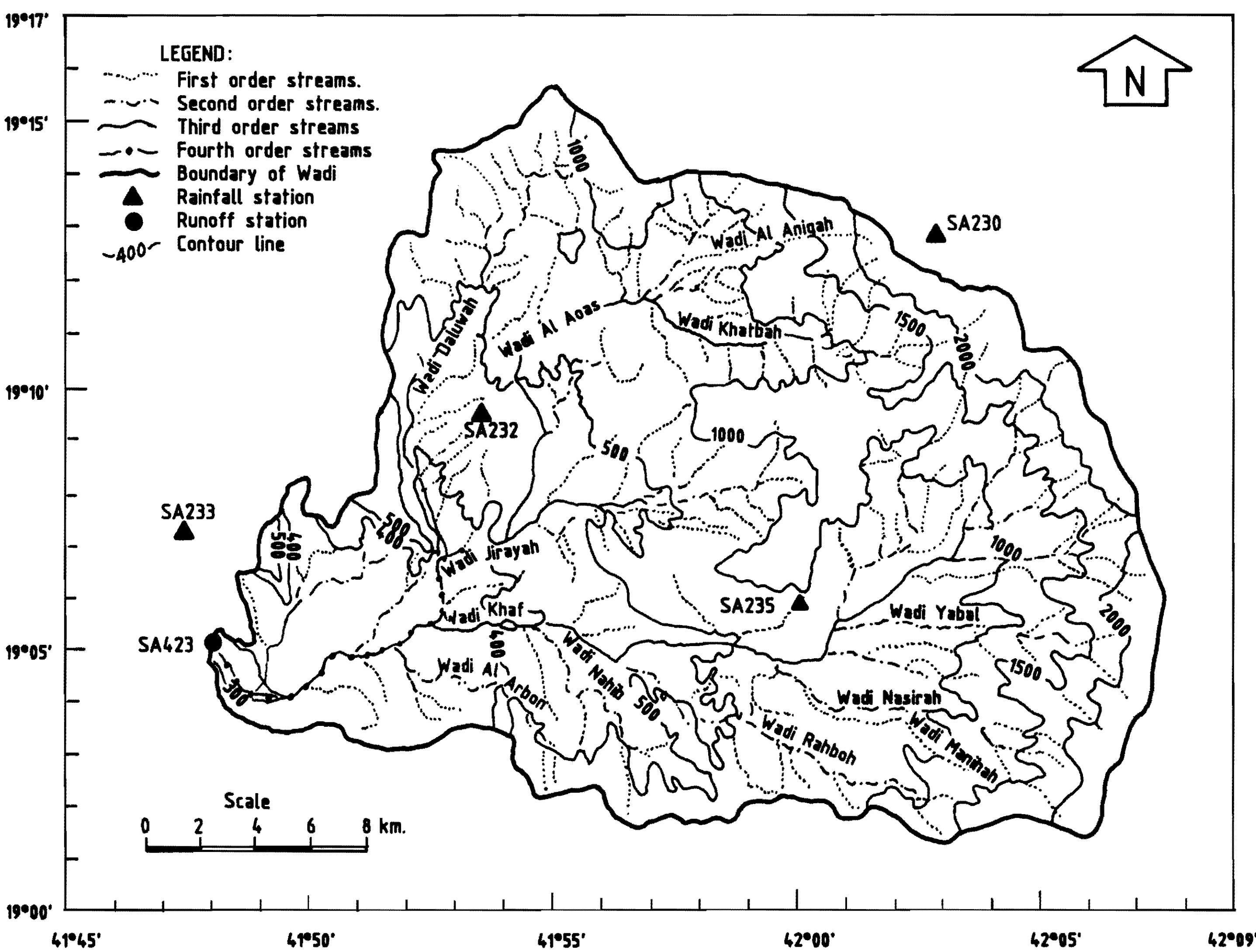


Figure 3. Topographic Map of Wadi Khat (SA-423).

limestone). This Wadi has gently sloping drainage areas with a few hills at the upstream. No agricultural activity exists in Wadi Midhnab. The topographic maps, scale 1:50 000, which cover the drainage areas of this Wadi was analyzed to determine the drainage network of this Wadi and is shown in Figure 5. As seen, this is a third order watershed.

The length, slope and drainage area of each stream of the Wadi was determined. The initial and transitional probabilities of surface runoff in the Wadi is provided in Table 1. The alluvium covers about 60% of the Wadi.

Wadi Midhnab is equipped with one rainfall station (U-217) and a runoff gauging station (U-404). The annual precipitation at the Wadi is in the order of 150 mm. Rainfall-runoff data covering a three-year period (1982–84) for the Wadi, has been reported by the MAW [18]. For Wadi Midhnab, the rainfall data is given in half-hour intervals while the runoff data is given in the form of discharge hydrographs. During the period 1982–84, this Wadi was subjected to 19 flooding storms, out of which only 5 were selected for model calibrations and applications.

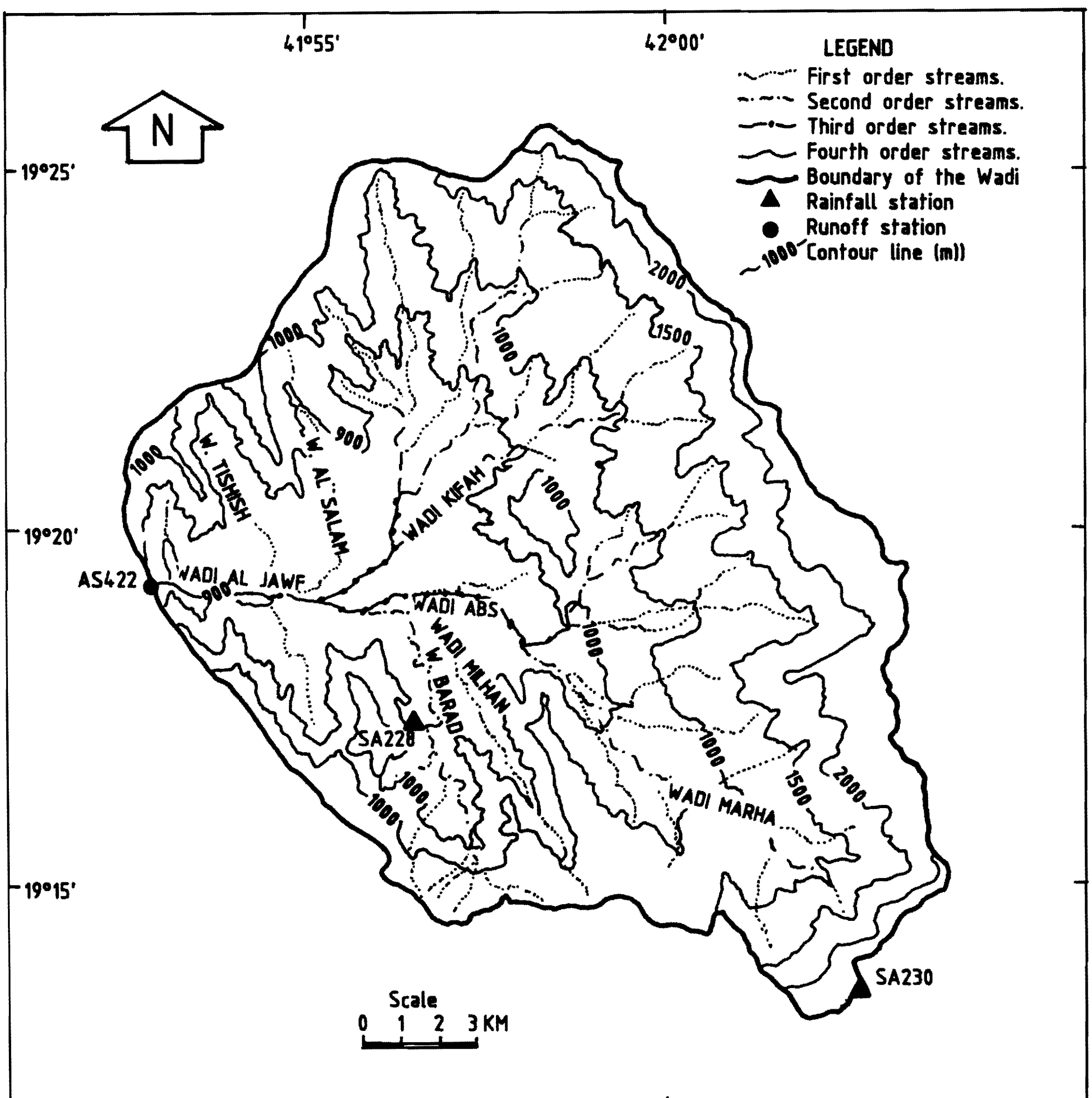


Figure 4. Topographic Map of Wadi Jawf (SA-422).

MODEL APPLICATIONS

The ED – GIUH Model Simulations

The initial simulations using the GIUH models were performed in order to determine the most representative streamflow velocities in Wadis Midhnab, Khat, and Jawf. In the ED – GIUH model, four different streamflow velocities, the flood dynamic wave velocity at the peak discharge time, (V_{wp}), the flood kinematic wave velocity at the peak discharge time (C_{wp}), the mean dynamic wave velocity (V_{wm}), and the mean kinematic wave velocity (C_{cm}) were used. In the case of LR – GIUH applications only two velocities V_{wp} and V_{wm} were used. The procedure suggested by Troutman and Karlinger [19] has been used to compute velocities. For each storm, four discharge hydrographs corresponding to these velocities were simulated. The closeness of the simulated hydrographs of all five models to the observed ones were used as the criteria to distinguish the most representative streamflow velocity.

Table 2 shows the geomorphologic, soil, and climatic input data for these three Wadis. The annual precipitation in Wadi Midhnab is about 150 mm, and that in Wadi Khat and Jawf is approximately 400 mm. The runoff coefficient of the three Wadis is 0.10, 0.10, and 0.03 respectively. During the period of 1982 – 1984, Wadi Midhnab was subjected to 16 storms, whereas Wadi Khat and Jawf were subjected to about 26 storms each since 1984. Of these storms for model applications, only five storms for Midhnab, six for Khat, and five for Jawf were selected.

A summary of the rainfall – runoff characteristics of the selected events are shown in Table 3. It provides for each storm: the rainfall depth, the surface runoff depth, the observed peak discharge (Q_p) and time to the peak discharge from the beginning of the storm (T_p). The mean streamflow depth (y_m) and the depth at the peak discharge time (y_p) are also presented in the table. Table 4 shows the values of the streamflow velocities: mean velocity (V_m), peak velocity (V_p), the mean and peak kinematic wave velocities (C_{wm} and C_{wp}), and the mean and peak wave velocities (V_{wm} and V_{wp}). The $K(I)$ values shown in Table 4 are the calibration values where the observed runoff depths is equal to the effective rainfall depths.

The Philip's infiltration expression was used to compute effective rainfall of the studied storms.

Table 1. The Initial and Transitional Probabilities of Surface Runoff Movement in Wadis Khat, Jawf, and Midhnab.

Probability	Khat	Midhnab	Jawf
Θ_1	0.64	0.54	0.73
Θ_2	0.19	0.22	0.04
Θ_3	0.14	0.24	0.07
Θ_4	0.03	–	0.16
P_{12}	0.76	0.88	0.86
P_{13}	0.21	0.12	0.03
P_{14}	0.03	–	0.11
P_{23}	0.96	1.00	1.00
P_{24}	0.04	–	0.00
P_{34}	1.00	–	1.00

Table 2. Geomorphologic, Soil, and Climatic Input Data for Wadis Khat, Jawf, and Midhnab.

	Wadi Khat	Wadi Jawf	Midhnab
Geomorphologic Data			
$\bar{A}_1$, km^2	2.81	6.01	1.32
$\bar{A}_2$, km^2	4.10	1.65	1.41
$\bar{A}_3$, km^2	13.74	10.88	4.60
$\bar{A}_4$, km^2	21.26	49.48	–
$\bar{A}_\Omega$, km^2	600.74	305.25	19.40
$\bar{L}_1$, km	2.47	3.44	1.40
$\bar{L}_2$, km	3.79	6.19	1.15
$\bar{L}_3$, km	12.10	5.60	4.00
$\bar{L}_4$, km	9.50	4.70	–
$\bar{L}_\Omega$, km	40.50	23.00	7.60
N_1	138	37	8
N_2	28	7	3
N_3	6	2	–
A_a	0.14	0.11	0.60
α_m	0.80	0.80	0.80
Soil Data			
n_e	0.35	0.35	0.35
m	0.70	0.70	0.30
Z, m	2.00	4.00	1.00
Climatic Data			
m_{tr}, h	7.40	7.40	1.40
m_{tb}, h	240.00	240.00	156.00
m_i, mm/h	2.00	2.00	3.30
e_p, mm/h	0.40	0.40	0.38

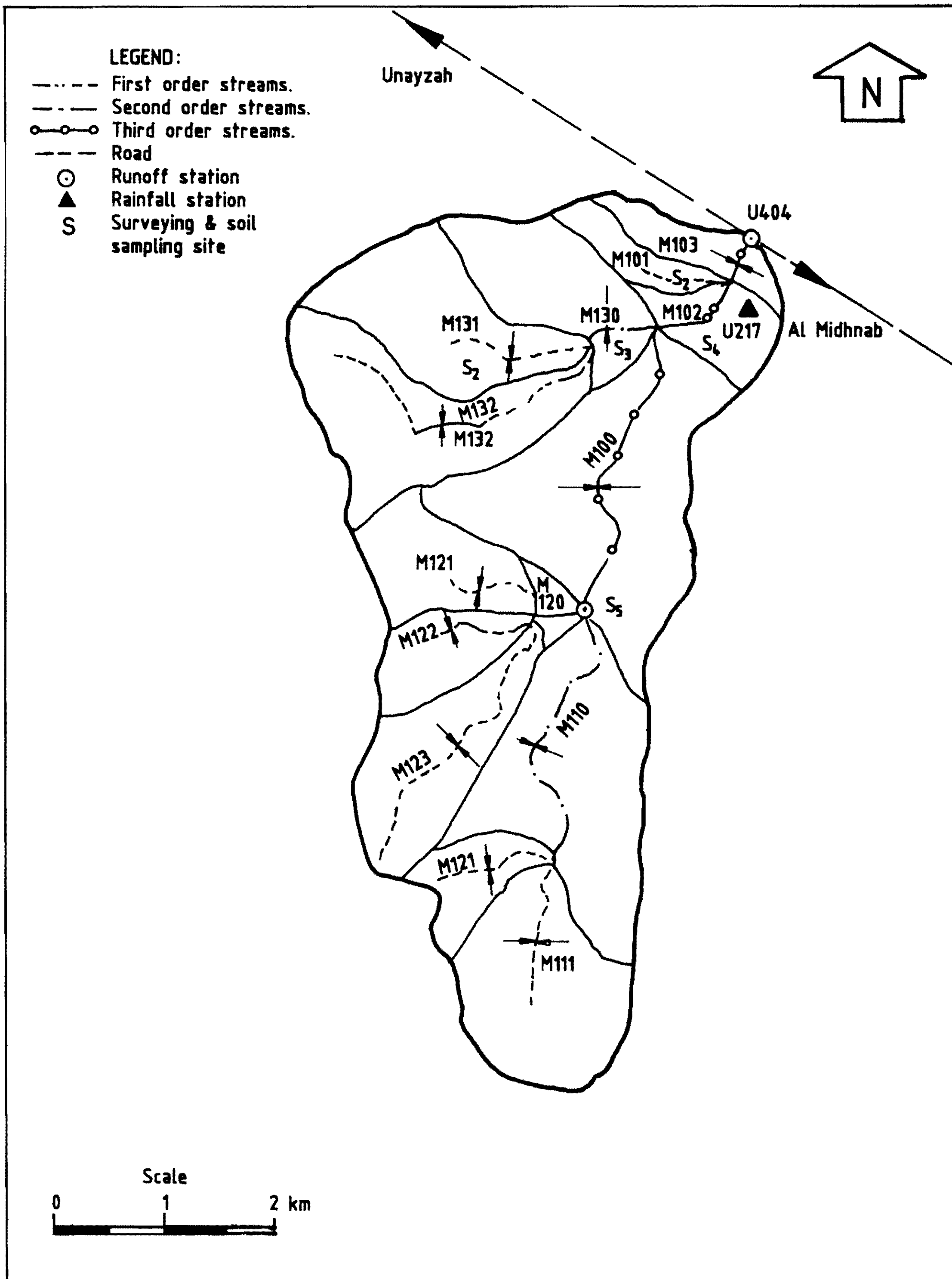


Figure 5. The Stream Network and Drainage Pattern of Wadi Midhnab (Qassim Region).

Table 3. Characteristics of the Selected Rainfall – Runoff Events for the Three Wadis of Midhnab, Jawf, and Khat.

Wadi	Storm No.	Date	Rainfall Depth(mm)	Runoff Depth(mm)	Q_p (m^3/sec)	T_p (hr)	Q_m (m^3/sec)	Y_m (m)	Y_p (m)
Midhnab	1	1.3.82	13.20	3.66	10.3	1.6	2.82	0.29	0.63
	2	12.5.82	7.20	0.7	1.87	1.6	0.57	0.11	0.23
	3	10.11.82	16.95	2.82	9.0	1.5	2.77	0.29	0.6
	4	28.3.84	9.20	1.0	2.3	2.0	0.92	0.15	0.26
	5	3.11.84	15.00	1.37	6.4	1.5	1.64	0.21	0.48
Khat	1	12.5.84	25.50	1.58	205	3.8	60	1.3	1.85
	2	19.8.84	14.50	1.67	133	2.8	34	1.16	1.6
	3	5.4.85	38.95	4.05	290	3.9	95	1.47	2.07
	4	11.4.85	11.50	1.12	100	3.0	36	1.17	1.5
	5	16.4.86	13.40	1.66	145	4.4	42	1.2	1.65
	6	7.6.86	27.30	2.49	232	3.8	80	1.4	1.9
Jawf	1	5.4.85	41.20	1.96	100	5.0	24	1.2	1.8
	2	1.5.85	13.80	1.18	112	2.4	18	1.3	1.9
	3	12.5.85	7.60	0.5	36	1.8	12.8	1.05	1.65
	4	17.5.85	14.60	0.76	41	1.9	9.5	1.2	1.75
	5	22.5.85	27.50	0.87	83	3.4	1.6	1.2	1.78

Table 4. The Computed Streamflow Velocity for the Selected Storms for the Three Wadis of Midhnab, Khat, and Jawf.

Wadi	Storm No.	Date	V_p (m/sec)	V_m (m/sec)	C_{wp} (m/sec)	C_{wm} (m/sec)	V_{wp} (m/sec)	V_{wm} (m/sec)	$K(I)$ (cm/h)
Midhnab	1	1.3.82	0.89	0.55	1.34	0.83	3.39	2.23	0.58
	2	12.5.82	0.62	0.58	1.93	0.87	2.12	1.62	0.29
	3	10.11.82	0.78	0.54	1.17	0.81	3.20	2.23	0.86
	4	28.3.84	0.62	0.48	0.93	0.72	2.22	1.69	0.43
	5	3.11.84	0.73	0.50	1.10	0.75	2.90	1.94	0.50
Khat	1	12.5.84	3.00	1.00	4.50	1.50	7.26	4.57	5.18
	2	19.8.84	2.30	1.11	3.45	1.67	6.26	4.48	1.44
	3	5.4.85	3.10	1.45	4.65	2.18	7.60	5.25	5.58
	4	11.4.85	1.70	0.80	2.55	1.20	5.50	4.18	0.61
	5	16.4.86	2.40	1.00	3.60	1.50	6.40	4.43	1.04
	6	7.6.86	3.05	1.40	4.58	2.10	7.37	5.10	4.18
Jawf	1	5.4.85	2.10	0.70	3.15	1.05	6.30	4.13	10.22
	2	1.5.85	2.35	1.00	3.53	1.50	6.67	4.57	3.60
	3	12.5.85	0.95	0.67	1.43	1.00	4.97	3.88	1.44
	4	17.5.85	0.90	0.66	1.35	0.99	5.04	4.09	2.41
	5	22.5.85	1.80	0.68	2.70	1.02	5.98	4.11	12.13

A separate routine was used for this purpose. Four hydrographs (one for each velocity) were simulated for each of the sixteen storms. A summary of these simulations is shown in Tables 5 and 6. Table 5 shows for each storm the simulated values of Q_p and T_p, corresponding to different streamflow velocities, C_{wm}, C_{wp}, V_{wm}, and V_{wp}. Table 6 shows the simulation errors in Q_p and T_p when using the different streamflow velocities.

It can be seen from the simulated hydrographs for Wadi Midhnab that in terms of shape, Q_p and T_p, they are generally in good agreement with the observed ones, when using C_{wp} for the surface runoff velocity. On the other hand, differences in shape and over estimations of Q_p result when the streamflow velocity was taken to equal to V_{wm} or V_{wp}. The velocity C_{wm} results in under estimates of Q_p and over estimates of T_p. Apparently a velocity between C_{wm} and C_{wp} would result in a better estimate of Q_p and the hydrograph shape. But such a velocity would result in a higher error in T_p compared to the velocity C_{wp}. In the case of Wadi Khat, as can be seen from Tables 5 and 6, the best simulations for Q_p were obtained when using V_{wm} as the representative velocity. However in terms of T_p, the best simulation results were obtained when using C_{wp}. Probably a velocity between V_{wm} and V_{wp} would result in a better estimate of hydrograph shape and Q_p but with a higher error in T_p, compared to the velocities V_{wm} or C_{wp}. Tables 5 and 6 also show that the dynamic velocities V_{wm} and V_{wp} result in better estimates of Q_p, T_p and hydrograph shape for Wadi Jawf, compared to the kinematic wave velocities C_{wm} and C_{wp}.

Reviewing all these results it may be concluded that the kinematic wave velocity results in best hydrograph simulations for Wadi Midhnab while the dynamic wave velocity is found more representative to the streamflow movement in Wadis Khat and Jawf.

The LR – GIUH Model Simulations

The input data of the LR – GIUH model is the same as the input data of the ED – GIUH in addition to the streamflow depths (y_m and y_p) in the various order streams. In order to compare the results of the models with those of the ED – GIUH models, the streamflow depths in all stream orders are assumed to be the same and equal to the depth at the runoff gauge station in the mainstream. The simulation error in Q_p and T_p, corresponding to the velocities V_{wm} and V_{wp}, are listed in Table 7.

Table 5. Simulated Q_p and T_p Corresponding to Different Stream-Flow Velocities.

Wadi	Storm No.	Date	Peak Discharge (Q_p), m³/s				Time to Peak (T_p), h			
			C_{wm}	C_{wp}	V_{wm}	V_{wp}	C_{wm}	C_{wp}	V_{wm}	V_{wp}
Midhnab	1	1.3.82	7.9	12.6	18.83	26.24	2.0	1.4	1.20	1.00
	2	12.5.82	1.60	1.67	2.90	3.81	2.1	2.0	1.40	1.30
	3	10.11.82	6.10	9.0	15.64	21.76	2.5	2.0	1.70	1.60
	4	28.3.84	1.90	2.5	4.53	5.93	2.7	2.4	1.90	1.70
	5	3.11.84	2.8	3.9	6.90	10.17	2.0	1.8	1.30	1.10
Khat	1	12.5.84	67	165	166.84	211.96	4.5	2.5	2.40	2.20
	2	19.8.84	45	105	125.49	164.12	3.8	2.4	2.00	1.50
	3	5.4.85	168	315	339.13	426.93	4.5	3.5	3.40	3.20
	4	11.4.85	30	60	85.67	100.82	5.0	2.9	2.20	1.80
	5	16.4.86	48	111	132.56	184.10	5.0	3.0	2.80	2.50
	6	7.6.86	108	211	231.65	310.74	3.8	2.6	2.50	2.30
Jawf	1	5.4.85	24.68	72.80	91	137	6.50	4.50	4.3	4.0
	2	1.5.85	21.70	50.43	65	92	3.70	2.50	2.4	2.1
	3	12.5.85	7.64	10.92	29	37	4.70	4.0	2.5	2.4
	4	17.5.85	9.30	12.67	37	46	4.70	3.90	2.3	2.1
	5	22.5.85	10.80	28.29	41	60	4.60	2.70	2.4	2.0

The simulated hydrographs for Wadi Midhnab are relatively superior to the simulated hydrographs by the ED – GIUH model when using V_{wm} and V_{wp}. The simulation errors in Q_p are much less and the shape of the simulated hydrographs are closer to the shape of the observed ones. For Wadi Khat, the simulated hydrographs using V_{wm}, the LR – GIUH resulted in much higher error in Q_p (29.6% compared to 10.7% of the ED – GIUH model) and less error in T_p (11.4% compared to 29.3% of the ED – GIUH model). In terms of hydrograph shape, the ED – GIUH simulations are better than those of the LR – GIUH model. For Wadi Jawf, most of the LR simulations are poor in terms of shape, Q_p and T_p, compared to either the observed hydrographs or the simulated ones *via* the ED – GIUH model. This is perhaps due to the linearization procedure of the equations of motions not being applicable to watershed routing problems particularly in the arid and semi-arid regions. It is assumed that the perturbations in the streamflow depth and velocity due to the floods are very small compared to steady state flow conditions. But in Saudi Arabia as well as in most of arid and semi-arid regions where the streams are usually dry before and after the storms the above assumptions become invalid.

The DR3M Simulation

Wadi Midhnab is divided into 28 subcatchment and channel segments as shown in Figure 5. Wadi Jawf is divided into 96 subcatchment and channel segments and similar sequence as Midhnab was adopted. The flow sequence of Wadi Midhnab upto the outlet M103 is shown in Table 8, and the computational sequence along with corresponding kinematic wave parameters α and *m* and the roughness coefficient of each segment are also shown in Table 8.

Table 6. Simulated Errors in Q_p and T_p Corresponding to Different Streamflow Velocities.

Wadi	Storm No.	Date of Storm	Error in $Q_p = \frac{Q_{p_o} - Q_{p_s}}{Q_{p_o}}$ %[a]				Error in $T_p = \frac{T_{p_o} - T_{p_s}}{T_{p_o}}$ %[b]			
			C_{w_m}	C_{w_p}	V_{w_m}	V_{w_p}	C_{w_m}	C_{w_p}	V_{w_m}	V_{w_p}
Midhnab	1	1.3.82	23.3	−22.3	−83	−155	−25	12.5	25	37.5
	2	12.5.82	14.4	10.7	−55	−104	−31	−25	12.5	18.7
	3	10.11.82	32.2	0	−74	−142	−66.7	−33.3	−13.3	−6.7
	4	28.3.84	17.4	−8.7	−103	−158	−35	−20	5.0	15.7
	5	3.11.84	56.3	39.1	−7.8	−58.9	−33.3	−20	13.3	26.7
	Average[c]		28.7	16.2	64.6	123.6	32	18.5	11.5	17.4
Khat	1	12.5.84	67.3	19.5	18.6	−3.4	−18.4	34.2	36.8	42.1
	2	19.8.84	66.2	21.0	5.8	−23.4	−35.7	14.3	28.6	46.4
	3	5.4.85	42.1	−8.6	−16.9	−47.2	−15.4	10.3	12.8	17.9
	4	11.4.85	70	40	14.3	0.0	−66.7	0.0	26.7	40.0
	5	16.4.86	66.9	23.4	8.6	−26.9	−13.6	31.8	36.4	43.2
	6	7.6.86	53.4	9	0	−33.9	0	31.6	34.2	39.5
	Average		61	19.2	10.7	22.5	25	20.4	29.3	38.2
Jawf	1	5.4.85	75.3	27.2	9	−37	−30	10	14	20
	2	1.5.85	80.6	55	42	17.9	−54	−4.2	0	12.5
	3	12.5.85	78.8	69.7	19.4	−2.8	−161.1	−122.2	−38.9	−33.3
	4	17.5.85	77.3	69.1	9.8	−12.2	−147.4	−105.3	−21.1	−10.5
	5	22.5.85	87	65.9	50.6	27.7	−35.3	20.6	29.4	41.2
	Average		79.8	57.4	26.2	19.5	85.6	52.4	20.7	23.5

[a] Q_{p_o} = Observed peak discharge; Q_{p_s} = Simulated peak discharge;
[b] T_{p_o} = Observed time to peak discharge; T_{p_s} = Simulated time to peak discharge.
[c] Average absolute error.

Rainfall–runoff simulations have been carried out for Wadi Jawf and Wadi Midhnab and were compared with the observed hydrographs and with the ED – GIUH model simulations, using wave celerity C_{wp}. A comparison of the peaks and time to peak are shown in Table 9. As shown in the table, the simulated Q_p of both models for Wadi Midhnab are very close to each other and to the observed values. The differences in the simulated values of T_P are within the range of 0 to 35%. The simulated values of T_p are in reasonable agreement with the observed values. When plotted, there was good agreement between the shape of the simulated hydrographs of the DR3M and the ED – GIUH, respectively. These findings would indicate that the exponential distribution assumption for the streamflow travel time in the ED – GIUH, is a good one.

Regarding Wadi Jawf, as shown in Table 9, the simulated hydrographs of the DR3M as well as of the ED – GIUH (when using the velocity C_{wp}) are in significant disagreement with the observed ones. This is probably, as explained earlier, due to the invalidity of the kinematic wave assumptions for this watershed. The GIUH simulations, using V_{wp}, were much better in terms of Q_p, T_p as well as the hydrograph shape.

CONCLUSIONS AND DISCUSSIONS

From this limited study, the following three conclusions may be drawn regarding ED – GIUH rainfal – runoff model:

1. Hydrograph parameters such as peak discharge, time to peak discharge and shape of the hydrograph are very sensitive to the streamflow velocity.
2. The most representative streamflow velocity is watershed dependent. In the case of wide streams with many stream junctions, the dynamic wave velocity will be more representative than the kinematic wave celerity and *vice versa.* As shown in the DR3M applications that for small watersheds like Midhnab, the kinematic wave celerity is a more representative streamflow velocity. For

Table 7. The LR – GIUH Simulation Errors in Q_p and T_p.

Wadi	Storm No.	Date of Storm	$Q_p(m^3/s)$		$T_p(h)$		% Error in Q_P		% Error in T_P	
			V_{wm}	V_{wp}	V_{wm}	V_{wp}	V_{wm}	V_{wp}	V_{wm}	V_{wp}
Midhnab	1	1.3.82	12.7	19	1.3	1.2	−23.3	−84.5	18.8	25
	2	12.5.82	2.7	2.8	1.4	1.3	−44.4	−49.7	12.5	18.8
	3	10.11.82	9.6	12.5	2.3	1.9	−6.7	−38.9	−43.8	−26.7
	4	28.3.84	3.4	4.3	2.5	1.9	−47.8	−86.9	−25	
	5	3.11.84	4.8	6.7	1.6	1.4	25	−4.7	−6.7	
	Average*						29.4	52.9	21.36	
Khat	1	12.5.84	112.5	212	3.3	2.1	45.1	−3.4	13.2	[illegible]
	2	19.8.84	100	176	2.8	1.8	24.8	−32.3	0	35.7
	3	5.4.85	310	483	4.0	3.2	−6.9	−66.6	−2.6	17.9
	4	11.4.85	55	100	3.8	2.0	45	0	−26.6	33.3
	5	16.4.86	90	190	4.0	2.6	37.9	−31	10	40.9
	6	7.6.86	190	350	3.2	2.3	18.1	−50.9	15.8	39.5
	Average*						29.6	30.7	11.4	35.3
Jawf	1	5.4.85	48	118	6.0	4.2	52	−18	−20	16
	2	1.5.85	44	94	3.4	2.2	60.7	16.1	41.7	8.3
	3	12.5.85	15	24	4.4	3.6	58.3	33.3	−144.4	−100
	4	17.5.85	19	24	4.4	3.6	53.7	41.5	−131.6	−89.5
	5	22.5.85	22	54	4.0	2.8	73.5	34.9	−17.6	17.6
	Average*						59.6	28.8	71.1	46.28

*Average absolute error.

larger watersheds, such as Wadi Khat and Jawf, the dynamic wave velocity is more representative. In both cases however, the peak velocity will be over-estimating the peak discharge and under-estimating the time to peak. This is due to the use of a constant value for the streamflow velocity, equal to its maximum value, while the velocity actually changes during the storm from zero at the beginning to its maximum during the storm, then back to zero at the end of the storm. On the other hand, the mean velocity under-estimates the peak discharge and over-estimates the time to peak. For safe design of the hydraulic structures, the peak velocity C_{wp} or V_{wp} may be recommended.

3. The exponential distribution assumption for the time of travel seems to be a good one. The shape of the simulated hydrographs are in good agreement with the DR3M simulations as well as the observed hydrographs for Wadi Midhnab, when using the veolcity C_w. Using the velocity V_w, the shape of the simulated hydrographs are in good agreement with the observed ones for Wadis Khat and Jawf.

With respect to the LR – GIUH model, three conclusions can be made:

1. It is much more complicated than the ED – GIUH model in terms of its mathematical derivation and its numerical solution.
2. It is applicable only to the watersheds in which the dynamic wave conditions are applicable.
3. The simulated hydrographs are inferior to the ED – GIUH simulations.

Table 8. Computational Sequence and the Corresponding Kinematic Wave Parameters of the Various Segments in Wadi Midhnab.

Computational Sequence		Kinematic Wave Parameters		Roughness Parameter $\times 10^{-1}$
Index	Segment	α	M	
1	F111	5.27	1.670	0.20
2	F112	8.10	1.670	0.13
3	F123	6.25	1.670	0.16
4	F122	6.25	1.670	0.16
5	F121	6.25	1.670	0.16
6	F110	5.89	1.670	0.16
7	F120	5.89	1.670	0.16
8	F100	4.08	1.670	0.20
9	F132	5.13	1.670	0.13
10	F131	5.13	1.670	0.13
11	F130	3.62	1.670	0.13
12	F102	3.62	1.670	0.13
13	F101	3.62	1.670	0.13
14	F103	3.62	1.670	0.13
15	M111	3.26	1.330	0.16
16	M112	3.26	1.330	0.16
17	M110	2.91	1.330	0.16
18	M123	3.81	1.330	0.13
19	M122	3.81	1.330	0.13
20	M121	3.10	1.330	0.16
21	M120	2.85	1.330	0.16
22	M100	2.52	1.330	0.16
23	M132	2.06	1.330	0.16
24	M131	2.06	1.330	0.16
25	M130	1.43	1.330	0.16
26	M102	1.37	1.330	0.16
27	M101	1.37	1.330	0.16
28	M103	1.37	1.330	0.16

Table 9. A Comparison Between the DR_3M and the GIUH Model in Terms of Q_p and T_p.

Wadi	Storm No.	Peak Discharge (Q_p), m^3/s			Time to Peak (T_p), h		
		Observed	DR_3M	GIUH	Observed	DR_3M	GIUH
Midhnab	1	10.3	12.00	12.60	1.6	2.25	1.40
	2	1.87	1.70	1.67	1.6	1.80	2.00
	3	9.0	9.75	9.00	1.5	2.20	2.00
	4	2.3	2.10	2.50	2.0	2.40	2.40
	5	6.4	4.40	3.90	1.5	1.50	1.80
Jawf	1	100	84	72.80	5.0	4.75	4.50
	2	112	39.3	50.43	2.4	3.00	2.50
	3	36	15.00	10.92	1.8	3.50	4.00
	4	41	21.70	12.67	1.9	3.25	3.90
	5	83	25.90	28.29	3.4	3.25	2.70

With respect to the DR3M simulations, the following conclusions can be drawn:

As shown in case study applications and as recommended by Alley and Smith [8], the model is applicable only for small watersheds like Wadi Midhnab and its simulations are superior to that of ED − GIUH or LH − GIUH simulations. For larger watersheds such as Wadi jawf, the simulated hydrographs are in a significant disagreement with observations. This may in part be explained by the kinematic waved solution based on the assumption of "no backwater effects" which are likely to be predominant in larger watersheds like Wadies Jawf and Khat than in smaller ones like Midhnab.

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