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EFFECT OF STORM KINEMATICS ON RUNOFF HYDROGRAPH IN ARID REGIONS USING A 2-D MODEL

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الملخص

إن التقدير الصحيح لأقصى تدفق من أحواض الصرف بسبب عاصفة معينة أمر مهم جداً. إستناداً إلى التدفق الأقصى الذي يتم تقديره تُصمم أنظمة التصريف وتُقترح نظم الحماية من الفيضانات. وتعد البيانات المتريولوجية (مثل خصائص العاصفة والفترة التكرارية لها) من العوامل الرئيسية التي تؤثر على هيدروجراف الجريان السطحي وأقصى تدفق من أحواض الصرف.

الهدف من هذا البحث هو دراسة تأثير ديناميكية العواصف مثل سرعة واتجاه العاصفة على هيدروجراف الجريان السطحي المنمذج بإستخدام نموذج ثنائي الأبعاد تم إنشاؤه بإستخدام برنامج Info Works (ICM). تم تقدير هيدروجراف الجريان السطحي لمخطط الدراسة ضمن سيناريوهات مختلفة

ABSTRACT

The right estimation of catchment peak flow due to a specific storm is very important. Based on the estimated peak flow, drainage systems are designed and flood protection systems are proposed. Meteorological data such as storm characteristics and storm return period are main factors that affect runoff hydrograph and peak flow discharging from a catchment.

The objective of this research is to study the effect of storm kinematics, such as storm speed and direction, on the modelled runoff hydrograph using a 2D model. It will be undertaken using InfoWorks Integrated Catchment Modeling (ICM) software.

The runoff hydrograph of the study catchment will be estimated under different scenarios such as:

- The catchment is subjected to a commonly used stationary rainfall storm (without spatial distribution).
- The catchment is subjected to a moving rainfall storm:
  - In the direction of flow (downstream)
  - Opposite to the direction of flow with the same speed (upstream)
  - In the direction of flow with higher speed (change in speed)

The catchment is subjected to a stationary rainfall storm (with spatial distribution)
Storm characteristics (such as rainfall total depth) will be kept the same for all scenarios. As-Sulai catchment, located in Riyadh, Kingdom of Saudi Arabia KSA, will be used as a case study.

INTRODUCTION

The movement of a rainstorm is a main important factor that affects rainfall hyetograph temporally and spatially; which consequently influences the temporal and spatial distributions of surface runoff. Commonly, runoff estimation assumes simple static storms ignoring the effects of storm kinematics which means that rainfall is assumed to be a function of time only and is averaged in space and uniformly distributed over the catchment. Since the design of drainage systems and flood protection measures depends mainly on surface runoff, it was found important to study the effects of storm movement on the modeled surface runoff for different scenarios using a 2D model. Many researchers have studied this idea using different techniques and for different case studies and gave a background about the expected effects of storm movement whether in the direction of flow or in the opposite direction.

LITERATURE REVIEW

Many methods have been used for studying moving rainstorms; empirical, numerical, experimental and analytical studies are presented in this section.

Empirical Studies

In studies following this method, rainfall data collected from a big number of rain gauges were used to develop hydrological analysis which is used for determining and studying the effect of storm movement.

Niemczynowicz (1984) measured the peak flow discharged from the study area in Lund at five outlets during 17 months. Rainfall data were extracted from a network of 12 advanced rain gauges distributed over a catchment with area of 20 km^2 in Lund. The study included 10 severe events of 550 rainfall events observed during the period from 1979 to 1980.

He concluded the error in simulated runoff peak discharge caused by using stationary storms as input will not be very important from a practical point of view.

Physical Study

Yen & Chow (1969) initiated this kind of studies on storm movement at the University of Illinois at Urbana-Champaign. They built up a laboratory Watershed Experimentation System (WES) to study the influence of rainstorm kinematics on the overland flow with an impervious surface.

Richardson & Julien (1989) validated a one dimensional application of the finite element runoff model which was developed for modeling the influence of rainstorm movement over a catchment of simple geometry using Yen & Chow's laboratory data. For this regard, nine storms moving in the crossway direction and eighteen moving in the longitudinal direction from Yen & Chow's data were used to validate the one dimensional numerical model of rainfall storm movement.

Xiong & Melching (2005) highlighted 5 limitations of the WES laboratory apparatus, in comparison with the real rainfall storms and catchment basins. They comprise: the short precipitation duration, the small experimental catchment, the low roughness of catchment surface, the 100% imperviousness without any initial abstraction and the simplicity of the catchment with one subarea and one collecting channel.

This data from Yen and Chow`s laboratory were used later by Lee and Huang in 2007 to verify the non-linear numerical kinematic-wave model which was developed to model the influence of rainstorm movement on achievement of the equilibrium discharge resulting from both an overland plane and a V shaped catchment. Even though experimental studies give important insights for hydrologists, the limitation of the size of the laboratory apparatus is an obstacle against a complete awareness about the subject (Lee & Huang, 2007).

Numerical Studies

Results of numerical models often require physical models for verifying these results which could improve the study of storm kinematics and their effect on runoff (Richardson & Julien, 1989).

Niemczynowicz (1984) used the Storm Water Management Model (SWMM) to investigate the correlation between rainstorm characteristics and the extent of the directional bias on a plain watershed storage model depending on a both Manning's equation and the continuity equation. He also used this simulation model in the same year on actual urbanized watershed in Lund city, Sweden.
Singh (2002) developed analytical solutions for runoff discharging out of rainstorms moving upstream and downstream a plane using an infiltration plane which was completely and partially covered.

Xiong & Melching (2005) investigated the degree of precision of usual hydrologic and hydraulic routing models specifically SWMM and the Dynamic Watershed Simulation Model (DWSM) by evaluating them using data from an experimental system (the Watershed Experimentation System, WES) of Yen & Chow`s laboratory developped in 1969. Based on that evaluation, Xiong and Melching concluded that the precision of the kinematic wave routing (DWSM) was much better than the nonlinear reservoir routing SWMM, particularly for rainfall storms that have short durations which do not attain an equilibrium discharge.

Lee & Huang (2007) simulated the effect of rainstorm movement on the achievement of equilibrium discharge an overland catchment and from a V-shaped catchment by developing non-linear models based on kinematic wave equations.
Seo (2012) came up with a study of the influence of rainfall storm on the peak runoff flow by comparing moving rainfall storm with the Equivalent Stationary Storm (ESS). This study concluded that, although the drainage networks in urban areas have different configurations of networks and they can be greatly inefficient in terms of drainage time compared with natural channel networks, the result showed that inefficient networks are less sensitive to rainstorm movement and as a consequence, they potentially contribute to mitigate the effect from rainstorm movement in urban catchments. His research evaluated the effect of rainstorm movement and also reproduced the discharge hydrograph based on the network configuration.

In this research, simulation scenarios have been developed to measure the effect of storm movement direction, speed or spatial distribution. Both catchment characteristics and rainstorm characteristics shall be the same for all scenarios to prevent factors other than storm kinematics from affecting simulation results. The first novelty of this research is that we used the full 2D hydrodynamic model in the rainfall-runoff simulation; the second is that we implement the characteristics of real storm events that occurred in arid regions and no theoretical shapes were assumed.

METHODOLOGY

The aim of the study is to compare rainfall storms in both stationary and moving scenarios. For a stationary storm, a 100-yr event derived hyetograph is used. This storm profile is assumed in order to distribute the storm maximum rainfall depth over the storm period which was assumed as well. This is assumed for stationary and moving storms and thus its impact is neutralized. In the scenario of stationary storm, which is commonly used for the design, the effect of storm movement is not considered and the storm rainfall depths are averaged over the entire study area catchment. On the other hand, for moving storm simulation, there are many scenarios that could be investigated by changing storm kinematic characteristics such as direction and speed. The moving storm is simulated by introducing a different rainfall hyetograph for each of the subdivisions of the study area catchment based on the tested storm movement scenario.

3.1 Simulation of Moving Storm:

The main idea of simulating the moving storm depends on preparing a storm input with its characteristic shape and then applying it over the catchment. The location of the center of this storm shall change with time to represent storm movement. Storm movement starts when the storm is out of the study area and then after constant time steps it moves through the catchment gradually until it exits the catchment. During storm movement at each time step, rainfall intensity changes at each part of the catchment. In order to simulate the above, the following steps were followed:

- **Simulation of Storm rainfall spatial distribution:**

The available storm shape used was extracted from one of March 2015 Radar images. It is well known that storm shape may change with time. However, it is assumed that storm shape is the same throughout the storm duration.

The characteristic shape of storm in the radar images can be presented in DBZ unit which stands for decibel relative to Z. It is a logarithmic dimensionless technical unit used in radar, mostly in weather radar, to compare the equivalent reflectivity factor (Z) of a radar signal reflected off a remote object (in mm^6 per m^3) to the return of a droplet of rain with a diameter of 1 mm (1 mm^6 per m^3). DBZ values were converted to rainfall intensity values using Equation 1:

$$\text{Rainfall Intensity (mm/h)} = \left(\frac{10^{\left(\frac{dBZ}{10}\right)}}{200}\right)^{5/8} \qquad \text{Equation 1}$$

In order to simulate the spatial distribution of storm rainfall, the study area catchment was divided into 21 polygons for which we can calculate the average DBZ over each polygon at each time step (Figure 1).

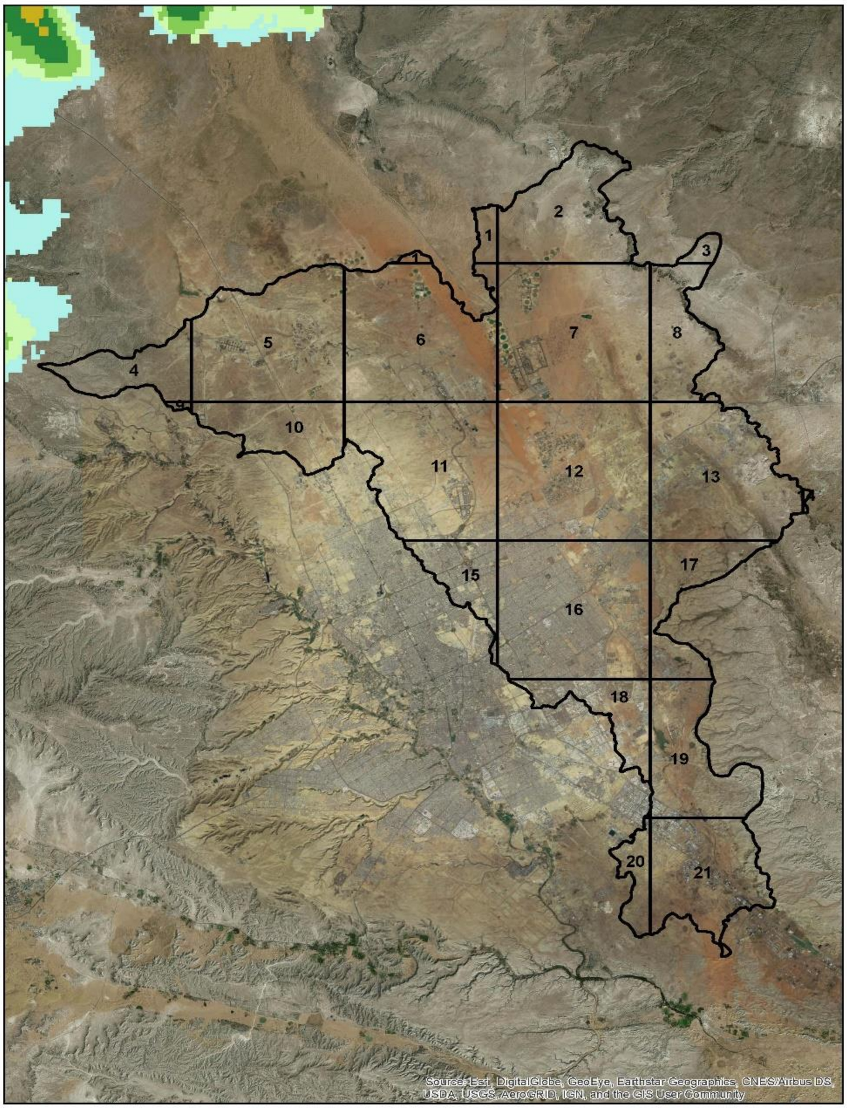

Figure 1 Case Study Catchment Area Subdivisions

- **Assume storm speed and direction and developing rainfall intensity hyetographs**

We assume a certain storm speed and direction which differ in each of the investigated simulation scenarios. Using ArcGIS, the average DBZ over each subdivision can be extracted from the storm layer at each time step based on storm location at this time step. For each scenario, using the tables representing rainfall intensities for all of the subdivisions covered by the storm at each of the time step, a table representing rainfall intensity hyetographs for each subdivision has been developed. Hence, 21 rainfall intensity hyetograph tables have been prepared representing the temporal variation of rainfall intensity over each subdivision.

- **Developing rainfall hyetographs equivalent to the stationary storm:**

Since the research aim is to compare runoff peak flow hydrographs for stationary and moving storms, it is important to multiply the rainfall hyetograph tables by a suitable factor so that the overall catchment is subjected to the same rainfall amount in all of the compared scenarios (i.e. Rainfall volume which equals the Total rainfall depth multiplied by the catchment area) is constant for all of the simulated scenarios and the difference between scenarios is the distribution of the rainfall depth spatially and temporally.

3.2 Rainfall Runoff Transformation

In order to get the excess rainfall hyetograph from rainfall hyetograph for each of the simulated storm scenario, the Curve Number method has been used for transforming rainfall to runoff, based on Equation 2 and Equation 3:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad \text{Equation 2}$$

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \qquad \text{Equation 3}$$

3.3 Hydrodynamic Model Software

In order to simulate the different scenarios, hydrodynamic 2D modeling software has been used. InfoWorks ICM has been considered for developing, simulating, and producing study area 2D flood model results. InfoWorks ICM (Integrated Catchment Modelling) is an integrated modelling platform to incorporate both urban and river catchments. With full integration of 1D and 2D hydrodynamic simulation techniques, both the above- and below-ground elements of catchments can be modelled to accurately represent all flow paths. InfoWorks ICM has many capabilities such as applying full hydrodynamic equations, flexible meshing, different mesh sizes in one model.

WADI AS-SULAI IN RIYADH CITY

The case study of this research was chosen to be located in an arid region, namely the catchment of Wadi As-Sulai in Riyadh city, Saudi Arabia. Wadi As-Sulai extends from Northwest of King Khaled International Airport KKIA to Al Rafaeaa area southeast of Riyadh City over a total length of 176 Km reaching Al-Kharj Town. The Wadi is considered the natural rainwater drainage basin for east of Riyadh, Saudi Arabia. Figure 2 and Figure 3 show the general location and alignment of the Wadi within Riyadh City context.

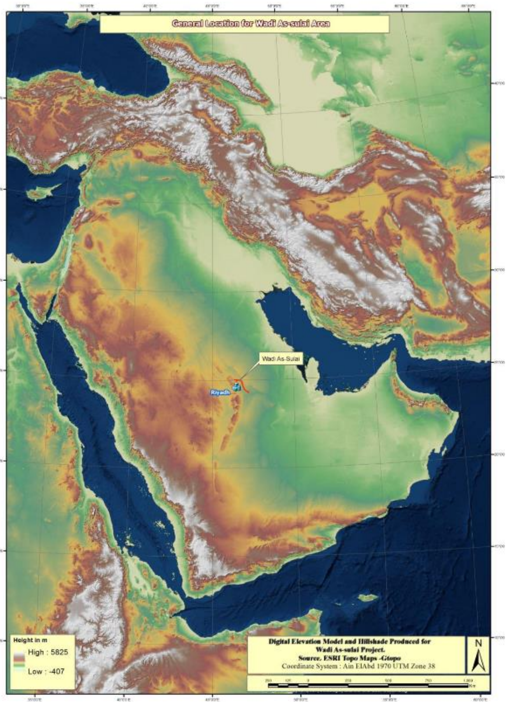

Figure 2 Location of Wadi As-Sulai

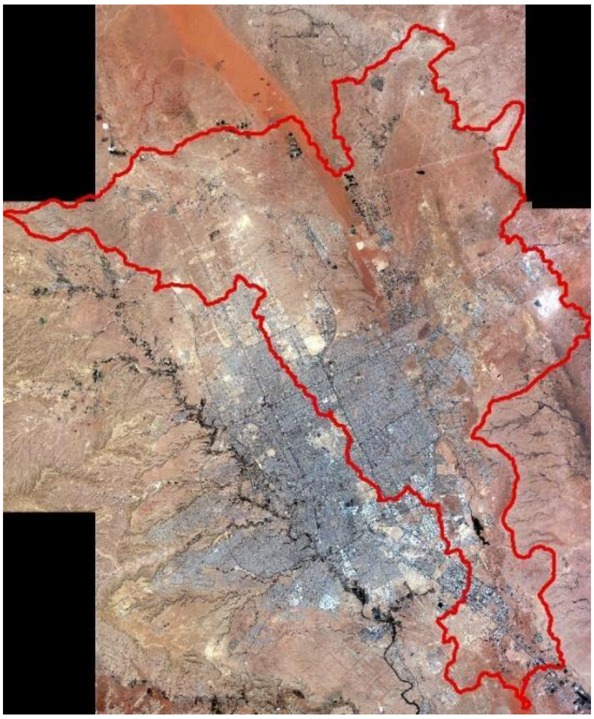

Figure 3 As-Sulai Catchment Location

Vast amount of data were collected for the study area which included the following:

LIDAR Data, Satellite Imagery and Landuse data:

Lidar data with 1m resolution for almost the full area of Wadi As-Sulai within Riyadh City. Satellite imagery with high resolution was used to show existing land use covering the whole catchment of Wadi As-Sulai. Riyadh City Master Plan for the year 1442 Hijri was used, to decide the future.

Meteorological data:

Maximum daily rainfall depths for different return periods in Riyadh city were obtained from Riyadh guidelines, as shown in Table (1). Radar rainfall image for the rainfall event that occurred in March 2015 is also available and was used in order to represent the spatial variation of rainfall depths over the storm area and it was important for the simulation of storm movement in different simulation scenarios as shown in Figure 4.

Table 2: Maximum daily rainfall depths for different return periods in Riyadh City

Return Period (Year)	**Maximum daily rainfall depth (mm)**
2	20.26
5	31.43
10	38.53
20	45.15
25	47.20
50	53.44
100	59.50
200	65.42

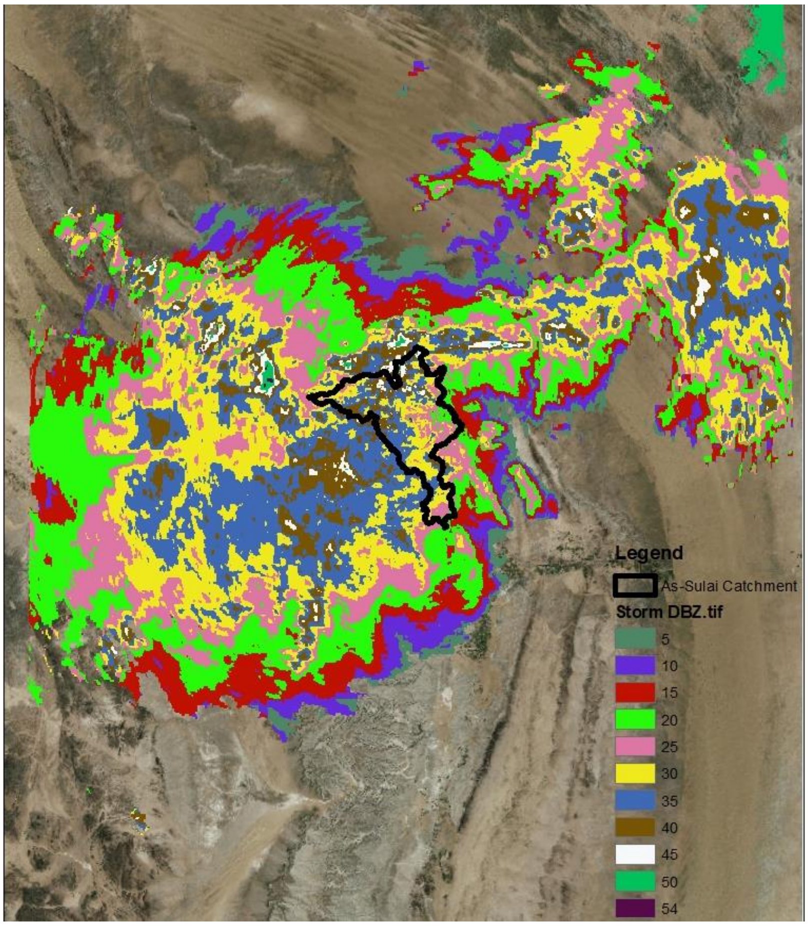

Figure 4 Radar Image for March 2015 Storm

RESULTS AND DISCUSSION

This section describes in detailed steps the analyses performed on different simulation scenarios which are used to understand and evaluate the impact of considering storm movement on modeled runoff hydrographs as well as the results of these analyses. In addition, comparisons between these results are evaluated.

The developed scenarios are presented below:

I. Commonly Used Rainfall Storm (Without spatial Distribution and not considering storm movement)

II. Moving Rainfall Storms:
   a) In the Direction of Flow
   b) Opposite to the Direction of Flow (Change in Direction)
   c) In the Direction of Flow with Higher Speeds (Change in Speed)

III. Stationary Rainfall Storm (With spatial Distribution)

Scenario (1): Commonly Used Rainfall Storm (Without spatial Distribution and not considering storm movement)

In this scenario, the storm is simulated by applying the same rainfall intensity hyetograph resulting from the IDF of Riyadh city. This scenario neglects the effect of storm spatial distribution as well as storm movement. This method of simulation is the easy and is commonly used for simulation and design of most of storm drainage systems. The resulting flow hydrograph at the outlet is presented in Figure 5. The resulting flow hydrograph shows that the peak discharge at the catchment outlet is 140 m3/s.

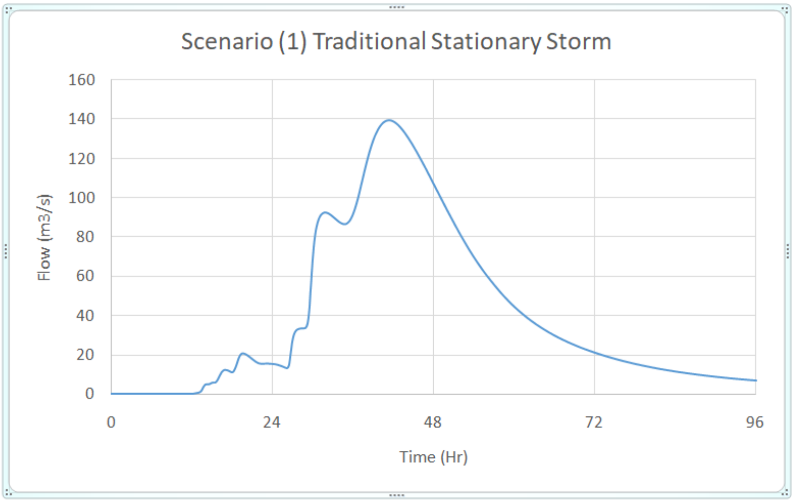

Figure **Error! No text of specified style in document.**: Flow Hydrograph at Catchment Outlet Resulted from Scenario (1) Simulatio***n***

Scenario (2): Moving Storm in the Direction of Flow

In this scenario, the storm is simulated by applying different rainfall hyetograph for each subdivision of the study area catchment so that the rainfall storm movement is simulated. The direction of storm movement is assumed to be in the direction of flow in the catchment`s main river (South East) and the storm speed is assumed to be 15 km/hr. The resulting flow hydrograph at the outlet is presented in Figure 6, showing a peak discharge at the catchment outlet of 160 m3/s

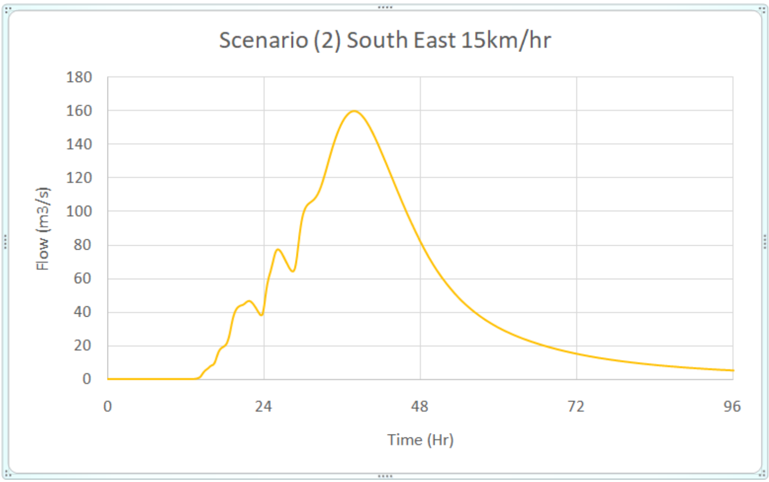

Figure 6: Flow Hydrograph at Catchment Outlet Resulted from Scenario (2) Simulatio***n***

Scenario (3): Moving Storm Opposite to the Direction of Flow

In this scenario, the direction of storm movement is assumed to be opposite to the direction of flow in the catchment`s main river (North West) in order to evaluate the impact of storm direction on the runoff hydrograph, with a storm speed iof 15 km/hr, similar to the previous scenario. The resulting flow hydrograph at the outlet is presented in Figure 7, with a peak discharge at the catchment outlet of 156 m3/s.

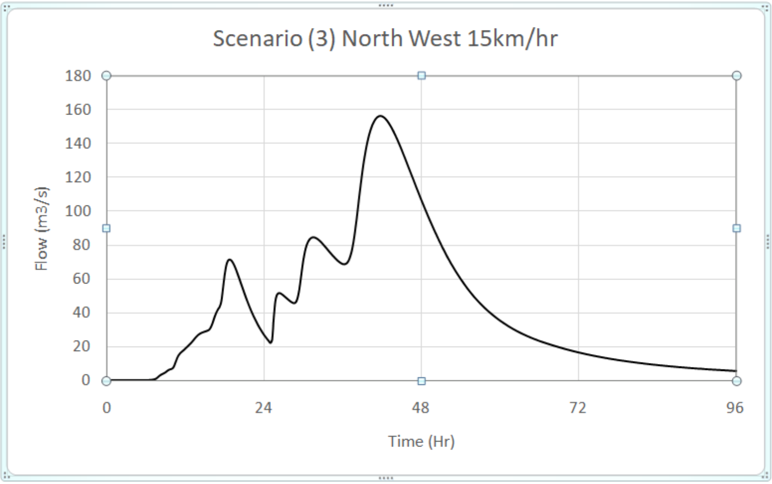

Figure 7: Flow Hydrograph at Catchment Outlet Resulted from Scenario (3) Simulation

Scenario (4): Moving Storm in the Direction of Flow with Higher Speed

In this scenario, the direction of storm movement is south east (same as Scenario 2) but with a doubled speed (30 km/hr) in order to evaluate the impact of storm speed on the runoff hydrograph. The resulting peak discharge at the catchment outlet is 182 m3/s.

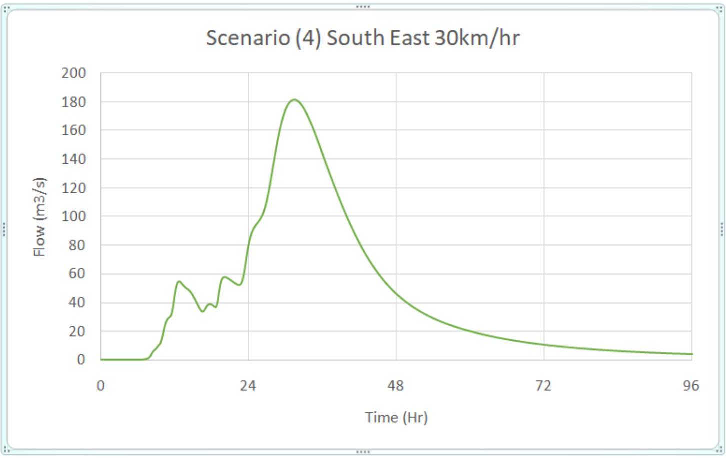

Figure 8: Flow Hydrograph at Catchment Outlet Resulted from Scenario (4) Simulation

Scenario (5): Stationary Rainfall Storm (With spatial Distribution)

In this scenario, the rainfall storm shape of Figure (4) was used to represent the spatial distribution of rainfall on the catchment. It was assumed that the storm is static and that the catchment is in the center (eye) of the storm. In order to make sure that only the spatial distribution effect was taken, the total rainfall volume (rainfall depth over the whole catchment area on the day) was kept the same as scenario (1) and only the distribution of this rainfall was changed based on the storm shape and location. The resulting flow hydrograph at the outlet is presented in Figure 9 with a peak discharge at the catchment outlet is 165 m3/s.

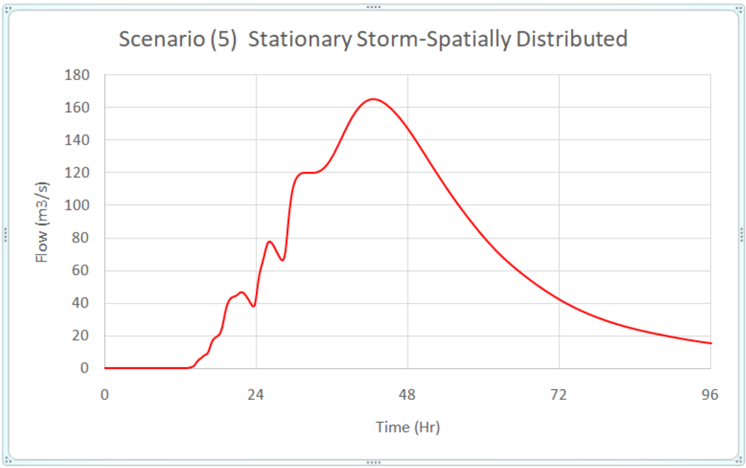

Figure **Error! No text of specified style in document.**9: Flow Hydrograph at Catchment Outlet Resulted from Scenario (5) Simulation

Comparison between Results of Simulated Scenarios:

The results from simulated scenarios were compared as shown in Figure 10. The conclusions and recommendations based on these comparisons are presented in the following section.

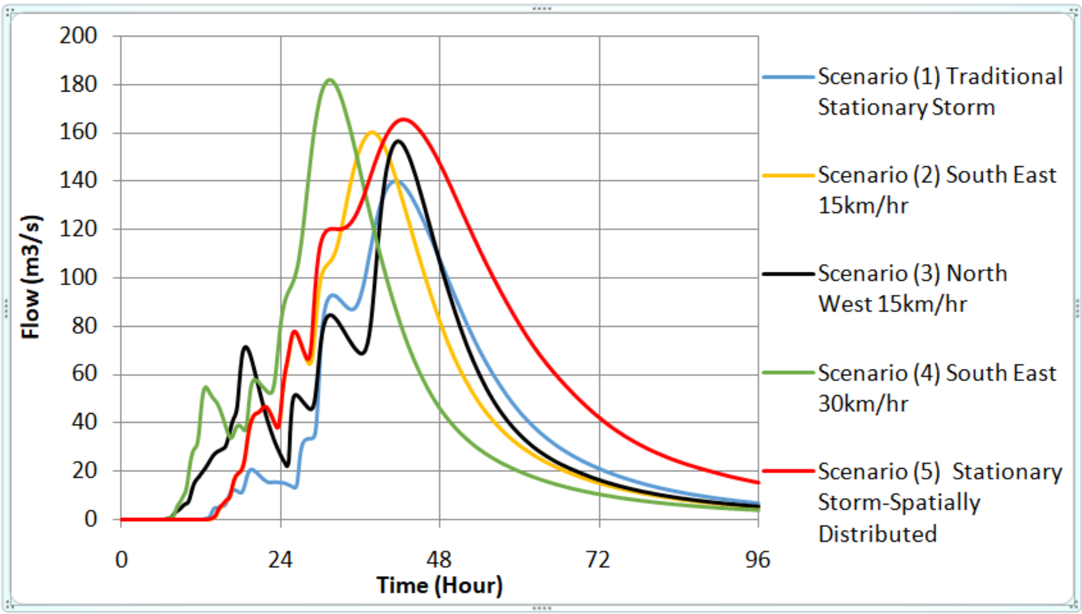

Figure 10: Comparison between Flow Hydrograph Resulted from the 5 Scenarios

CONCLUSIONS AND RECOMMENDATIONS

Based on the analyses performed for each of the simulated scenarios, results of these analyses, comparison between results and outcomes presented in Chapter 5, the following conclusions were attained based on the used case study data:

1. Considering storm movement has an obvious effect on the modeled runoff hydrograph.
2. In all of the simulated scenarios, the resulting peak runoff discharge increases mainly due to simulating the spatial distribution of the storm and the movement of this storm.

3. Spatial distribution of storm has the major effect on the simulated storm as shown as a result of scenario simulating static storm located at the same location relative to the study area catchment. This case may be theoretical as the storm is positioned – without movement – in a critical location with respect to the catchment. However, this scenario it indicates that the effect of storm spatial distribution should somehow be considered.
4. A 10 to 15 % increase in the resulting peak discharge – compared to the commonly used static storm – was noticed whether the storm direction was opposite or with the flow direction. However, the impact of the storm speed was the most important factor of the peak discharge.
5. Throughout all of the simulated moving storm scenarios it was found that the percentage of increase of peak runoff discharge ranges between 11% and 30 %.

The previously presented conclusions are based on the used case study data and the approximations considered, the following is recommended for further studies:

1. More simulation scenarios could be developed with different storm depths in order to investigate their impacts on the outcomes.
2. More simulation scenarios could be developed with different rainstorm movement angles relative to flow directions.
3. Since the rainstorm shape was assumed unchanged for all of the simulated scenarios, it is recommended to modify the shape to study the effect of this change shall be evaluated.
4. This study is recommended to be applied on different case studies and the influence of the change in terrain data and meteorological data to be evaluated.

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