Journal of Materials and Environmental Sciences
ISSN : 2028-2508

JMES, 2017 Volume 8, Issue 10, Page 3795-3808

http://www.jmaterenvironsci.com/

Rainfall-Runoff calibration for semi-arid ungauged basins based on the cumulative observed hyetograph and SCS Storm model: Application to the Boukhalef watershed (Tangier, North Western Morocco)

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Received 22 Nov 2016,
Revised 03 Apr 2017,
Accepted 09 Apr 2017

Keywords

- ✓ Rainfall-Runoff;
- ✓ HEC-HMS model;
- ✓ Cumulative rainfall;
- ✓ Boukhalef watershed;
- ✓ SCS-storm distributions

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Abstract

The aim of the present study is to design urban storm rainfall distribution curve for semi-arid ungauged basins by which storm runoff can be predicted accordingly. The rainfall-runoff modeling is based on the storm event which occurred on the 23th of October 2008 on the Boukhalef river basin (southwest of Tangier), using modern simulation tools, namely the Hydrologic model as well as Remote Sensing technic and Geographical Information System software (ArcGIS, HEC-GeoHMS). The study aims also to predict the design of peak flow for the 200-, 100-, 50-, 20-, 10-, and 5-years return periods. The problem most often encountered in this area is the need for estimating runoff from a watershed for which there are records of daily rainfall but no records of runoff. The objective of modeling the Boukhalef watershed is to set up the rainfall-runoff model using the HEC-HMS hydrological model and GIS. This model provides various meteorological and hydrological processes to obtain flood hydrographs. For this purpose, the determination of referential form of the hydrograph and hydrological parameters to predict frequency flows for different return periods was performed based on the concept of Curve Numbers of US Natural Resources Conservation Service (NRCS). The results of this study show that the SCS-24 Type I storm represents the best distribution to simulate the rainfall-runoff event for each return interval, because, during the same storm event, it is the most similar to the observed instantaneous rainfall at the neighboring gauged watershed called Kalaya.

1. Introduction

Floods are recurrent a problem in several densely populated Moroccan cities. They frequently result in considerable damage and, sometimes, in loss of life [1,2]. Most floods in Tangier city (Figure 1) are caused by torrential rain, which is characterized by its great volume and short duration due to the rugged topography of the study area. These floods affect larger areas due to the rapid urbanization of the river flood plain.

On 23 October 2008, Tangier city has experienced heavy flooding when uncontrolled spills caused by significant rainfall (more than 196mm of rain in less than five hours in October 2008) had caused a lot of damage and blocked the activity of the main industrial areas of the city. Following these floods, the Urban Development Program 2009-2013 of Tangier city mobilized a budget of 44 million Dollars to accompany the project of protection of Tangier against floods. The main objective is to implement the necessary infrastructure to protect neighborhoods and industrial areas against floods, to limit urbanization in areas bordering the important Rivers, but also to prevent the occurrence of natural disasters. This has consequences for local topographical features and the radical alteration of natural river systems was strongly artificialized and caused changes in land use by transforming infiltrated surfaces, paved surfaces and concrete water proofing and thus increasing downstream areas which will increase the volume and runoff.

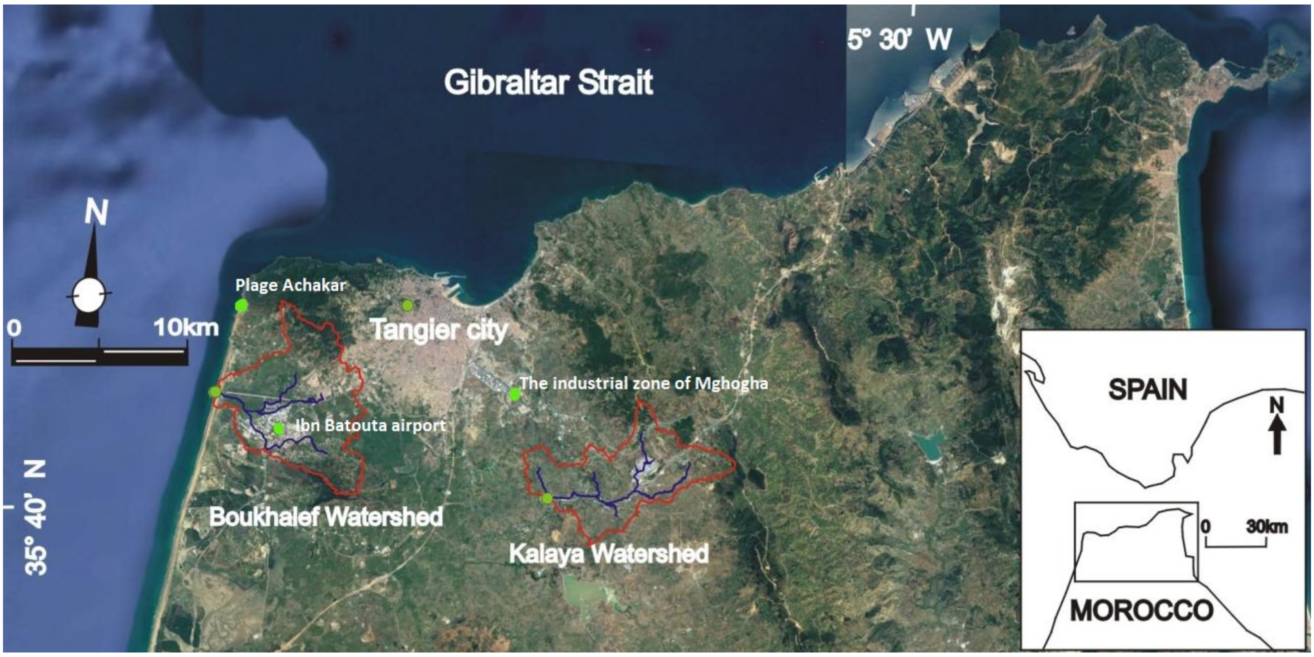

Figure 1: Geographical situation of the study area and location of the Boukhalef and Kalaya watersheds

The development of appropriate techniques for modeling flood events in ungauged basins remains a challenge for hydrologists. The Boukhalef watershed is considered "ungauged», so the determination of the flood peak flow at spatial-temporal scales is not allowed since he does not have instruments measuring and collecting rainfall and hydrological data [3]. In this case, a large quantity of rainwater could be lost without any benefit due to evaporation and loss of infiltration. For this purpose, it is necessary to develop new technical tools based on modern methods of numerical modeling allowing the digitization and collection of different physical components, with the aim of an integrated management of flood risks.

Flood modeling requires estimation of flood volumes and distributed model predictions to inform major decisions for development of management strategies, and for flood damage reduction, [4]. Hydrological modeling aims to reproduce the hydrological behavior of a watershed [5] during a rain event. For this purpose, the HEC-HMS Hydrologic model was used because it helps the understanding of natural phenomena such as the flashfloods, and attempts to simulate the complex hydrological processes that lead to the transformation of rainfall into runoff [6]. There are several HEC-HMS models to estimate runoff volume, peak flow, and the hydrograph for modeling hydrological process from a watershed. The selection of the model depends on the objective of the hydrological simulation as well as the available data of the basin. Natural Resource Conservation Service Curve Number (NRCS-CN) was chosen for this study since it is useful for ungauged watersheds [7,8]. This model computes the direct runoff volume of a given rainfall event and estimates the volumes and peak rates of surface runoff in agricultural, forest, and urban watersheds [9,10]. In case of lack of instantaneous rainfall data, Synthetic Unit Hydrograph procedures can be employed [11]. Considerable attempts have been devoted to the development of synthetic hyetographs for severe storm events in the past [12-14]. In 1967, Huff began the detailed analysis data of the temporal distribution based on the time quartile from observed heavy storms in the Illinois State (Chicago-USA) for a 12-year period (1955-1966). Developed hyetographs were presented in probability terms to provide quantitative measures variability and general characteristics of the temporal sequence of rainfall during the storm events, allowing for accurate management of flood risks.

On the other hand, using the detailed hydrological analysis techniques in the SCS TR-55 Bulletin (urban hydrology for small watersheds), rainfall is described in terms of total precipitation and depth of one of the four standard 24 hours temporal distribution of rainfall: type I, type IA, type II, and type III. This method was developed for the four storm types prepared for geographic regions of the United States. Types I and IA represent the Pacific maritime climate, with wet winters and dry summers. Type III for the Gulf of Mexico and Atlantic coastal areas, where tropical storms bring large amounts of precipitation within 24 hours. Type II represents the rest of the country (NRCS 1986). To apply the TR-55 procedure outside the US, a local distribution of synthetic storms must be developed. Many studies have been conducted to verify how type I and II SCS curves are compared with the observed events [15]. These types of distributions are available in case of ungauged stations that could store and accumulate the instantaneous rainfall used for calibration and validation of hydrological model.

2. Study Area

Tangier city is rich in watersheds that extend over 285 square kilometers; the hydrographic network consists mainly of the Mghogha, Souani and Mlaleh river basins flowing directly in the bay of Tangier [16]. There are also important Watershed Rivers pouring out in the Atlantic coast. Among them is the Boukhalef River, which is the chosen survey area. The "Boukhalef" basin is less studied compared to other areas of Tangier. That is why we chose it as the subject of this study, despite the scarcity and lack of some geomorphological and climatic data. We hope that this research will contribute to a better understanding of the problems associated with these natural phenomena, but also to predict the hydrological response of ungauged basins and their future behavior during flood events. The Boukhalef watershed topic of this study is part of the Moroccan Atlantic coast, and is located to the west of the bay of Tangier (NW of Morocco) between parallels 35°43' and 35°50' north and meridians 5°53' and 5°58'west (figure 1). The watershed has a total length of 14.192 Km and a geographical area of 48.34 km2, while its elevation ranges between 3m and 264m above the mean sea level, and the average slope is 10.4% (figures 4 and 5).
The region of Tangier is one of the rainiest regions of the country, the wet period lasts about six months and covers the period from October to April. For the whole basin, precipitation is relatively high. The average annual precipitation recorded in the study area for the last five years is approximately 750mm. About 90% of this rainfall occurs from October to April (Figure 2); during the period 1983-2013, the rainiest year was recorded in 1996 with a height of 1400 mm, while the driest year corresponds to 1994 with only 380 mm (Figure 4). Precipitation is concentrated in winter (between December and February) while the dry season coincides with the warm summer period (between July and August). The mean monthly rainfall increases gradually from October to its peak in November. It then declines reaching its minimum in July and August. From September onwards, it resumed its recovery (Figure 2).

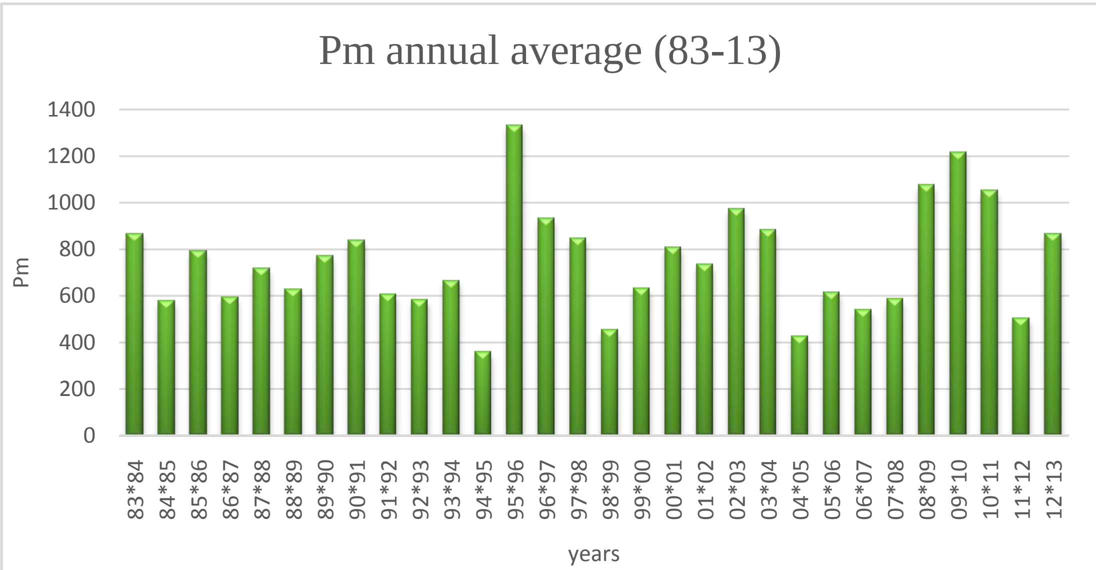

Figure 2 rainfall annual average history from Tangier station

The climate is typically Atlantic, influenced by the nearby Mediterranean Sea. Average temperatures reflect a relatively mild climate. The temperature difference during the day shows an average of 7-9°C, depending on the season. During the winter period, the minimum temperatures can often be below 4°C, especially in December, January, February, and March, but much more rarely below 0°C. Monthly averages range from 11.7°C to 26.2°C. January is the coldest month with an average temperature of 11.7°C, while the hottest is August with 26.2°C as monthly average (Figure 3).

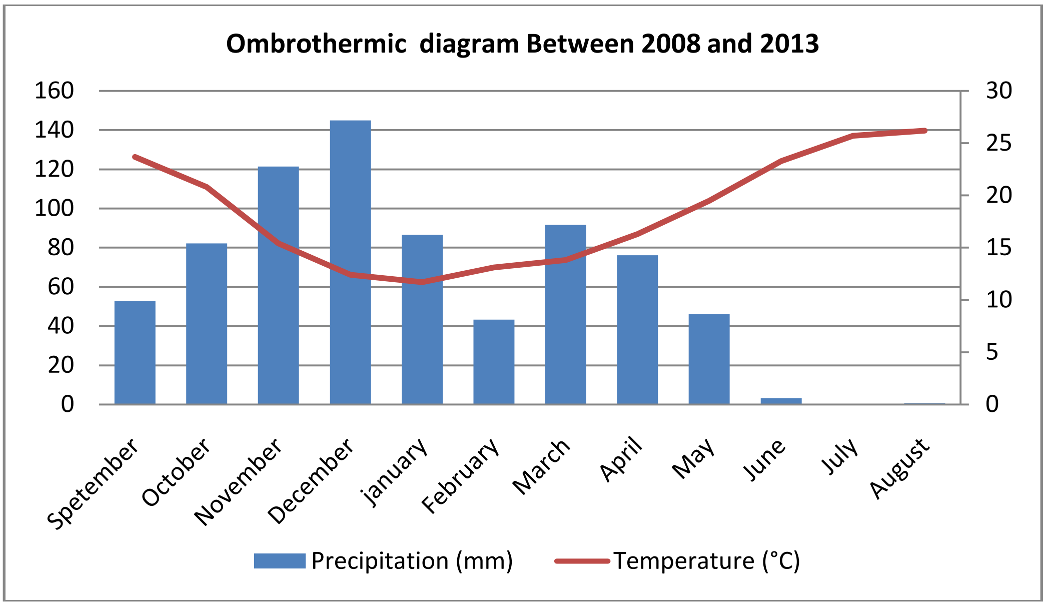

Figure 3: Ombrothermic diagram (2008-2013) based on monthly annual rainfall (P) and mean monthly air temperature (T) recorded at the meteorological station of Boukhalef.

3. Materials and Methods

3.1 Tools used

Many methods, techniques, and software have been used to estimate the peak flow and runoff hydrograph such as the technical release-55 model (TR-55), the Remote Sensing (RS), Geographical Information System (GIS), and Hydrologic Modeling system (HEC-HMS). In this study, the ASTER-DEM (30m) has been used to delineate the watershed boundary and to extract its geomorphological and physical characteristics. Spot imagery (2.5m) was used for the generation of the land use map. Soil map and hydrologic soil group map were prepared according to soil characteristics mentioned in the pedological and geotechnical map of Tangier city. The daily rainfall data from meteorological station of Boukhalef (provides only the daily rainfall data) have been used in order to deduce the maximal annual rainfall indispensable data for the estimation of the peak flow for various return periods using the Statistical Analysis [17] Hyfran plus.

3.2. Soil Conservation Service–Curbe Number (SCS-CN) method

For basins where monitoring activity doesn't exist, the SCS-CN method can be used to estimate the depth of direct runoff from the rainfall depth, providing an index describing runoff response characteristics. To describe these curves mathematically, the model assumes proportionality between the ratio of actual retention (F) to potential maximum retention (S), and the ratio of actual runoff (Q) to potential maximum runoff (P) (expressed as rainfall Pminus initial abstraction Ia).

$$\frac{F}{S} = \frac{Q}{P - I_a} \quad (1)$$

Where:

F = actual retention (mm)

S = potential maximum retention (mm)

Q = accumulated runoff depth (mm)

P = accumulated rainfall depth (mm)

After runoff has started, all additional rainfall becomes either runoff or actual retention.

$$F = P - I_a - Q \quad (2)$$

$$I_a = 0.2S \quad (3)$$

Combining equations (1), (2) and (3) gives an expression for

$$Q: Q = \frac{(P - 0.2I_a)^2}{P + 0.8S} \quad (4)$$

Eq. (4) is valid for P>Ia, otherwise, Q= 0. The equation for the potential maximum retention is defined as:

$$S = \frac{25400}{CN} - 254 \quad (5)$$

The Curve Number parameter is dimensionless and varies between 0 (maximum infiltration) and 100 (zero infiltration). It is determined by the look-up table mentioned in the technical report 55 (TR-55) (SCS, 1986). Low CN values mean that the surface of the basin has a high potential to retain water, whereas high values indicate that the rainfall could only be stored to a limited extend [18,19]. As illustrated in table 1, the moisture conditions are grouped in 3 classes: AMC-I for dry, which has the lowest runoff potential (lower limit of moisture or upper limit of S), AMC-II for moderate (normal or average soil moisture condition), and AMC-III for wet conditions, which has the highest runoff potential (upper limit of moisture or lower limit of S), respectively [20]. The AMC is based on 5-day antecedent precipitations, it was derived from accumulated rainfall measurements during the preceding five days. However, in the present study, CN values were considered for AMC-II (Table 1).

Table 1: Total five days antecedent rainfall (mm) considered for Boukhalef watershed (AMC-II).

AMC	Dormant Season	Growing Season
I	<12.7	< 35.6
II	12.7 – 27.9	35.6 – 53.3
II	> 27.9	> 53.3

3.3 input data used

The Digital Elevation Model (DEM) is a fundamental dataset for the simulation of the stream network; it is useful for the delineation of the watershed and for the illustration of the topographic variations of the area [21-24]. DEM data was obtained from The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) at a horizontal spatial resolution of 30 meters, mosaicked and processed. The slope map was completed from surface analysis of the DEM using the 3DAnalyst tools in ArcGIS. The DEM and slope maps of the Boukhalef watershed are presented in (figure 4 and 5):

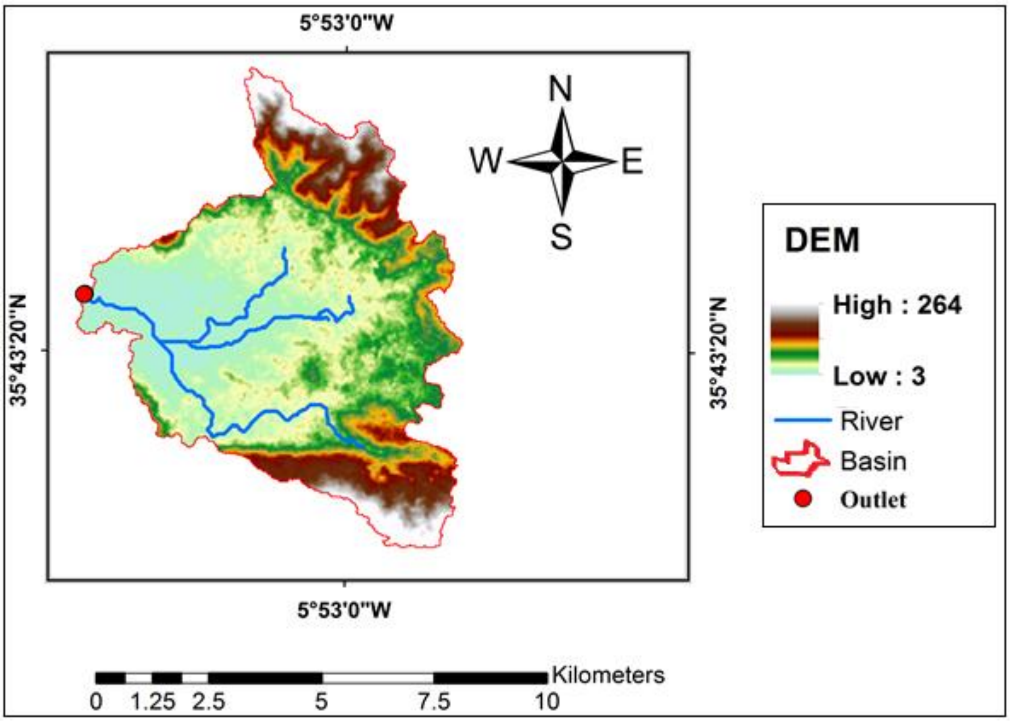

Figure 4: Digital Elevation Model (DEM) of the Boukhalef watershed.

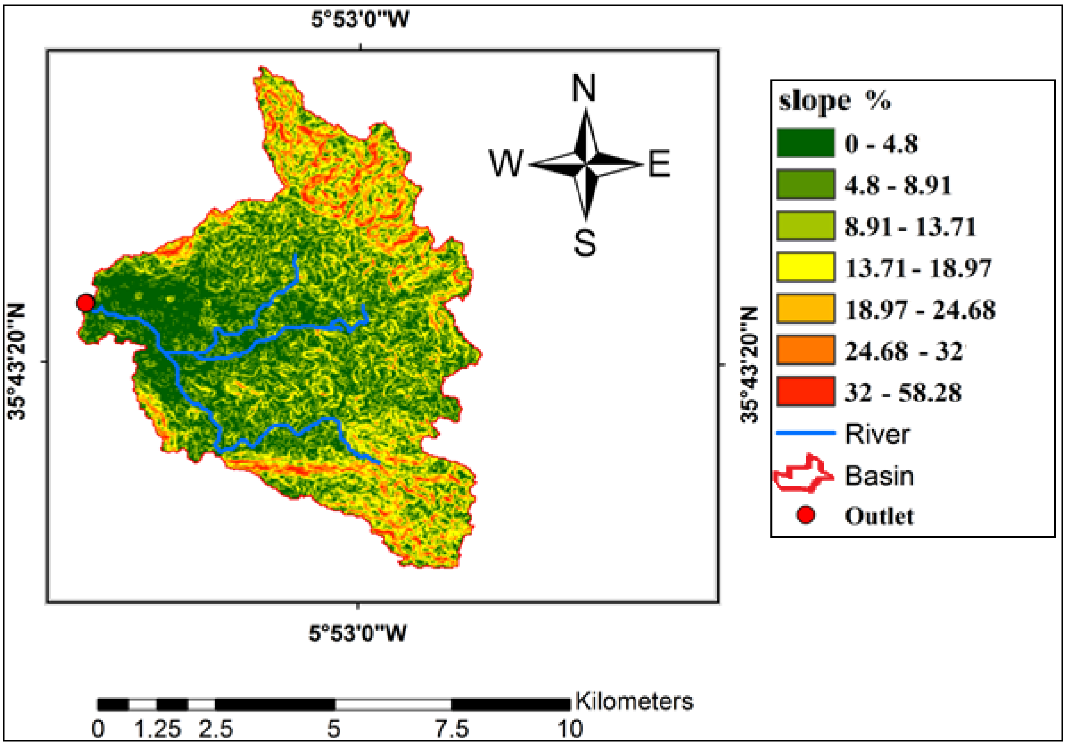

Figure 5: Relief slopes of the Boukhalef watershed.

The HEC-GeoHMS and ArcHydro are extensions for ArcGIS, which analyses and derives the necessary parameters that can later be imported into HEC-HMS to develop a hydrologic model. HEC-GeoHMS is also used for catchment delineation, terrain pre-processing, and basin processing to develop a number of hydrologic modeling inputs for the study area (Table 2). Basin characteristics such as area, length, slop, lag time, and initial abstraction will be used as the input parameters of the Rainfall-Runoff model for the HEC-HMS model.

Table 2: Geographical and Hydrologic features of Boukhalef watershed.

Geographical components			**Loss Method (SCS Curve Number)**		**Transfer (SCS Unit Hydrograph)**
Area (Km2)	**Basin Slope (%)**	**Length (Km)**	**Initial Abstraction**	**Mean CN**	**Lag Time**
48.34	10.4	53.87	17.04	74.88	2.48

On the other hand, technique of Remote Sensing was performed through ERDAS IMAGINE software to generate land use classification. By means of the multispectral image satellite Spot 5 (launched on 09/11/2005) at resolution of 2.5 m, the supervised classification method with maximum likelihood clustering was employed for image classification. Remote sensing technique and geographic information system (GIS) are used to extract and integrate the spatially distributed land use for the computation of the CN values.

2. Results and discussion

In hydrological processes, land use is used to describe how people use an area of Land, including a variety of human uses such as urban, agriculture, bare soil, forest, pasture, and Water body [25]. Infiltration losses of the soil are related to the land use and differ greatly between forested, agricultural, and urban areas [26]. Land use units of the Boukhalef watershed were delineated and they are primarily identified as agricultural, forest, urban and bare soil areas (figure 6).

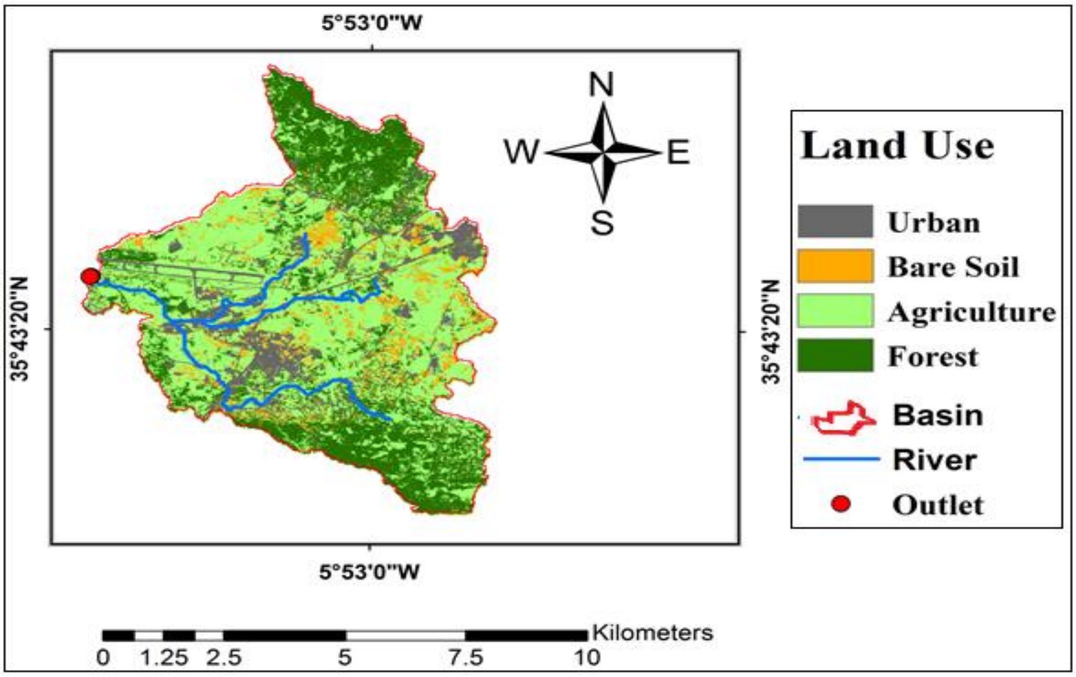

Figure 6: Land use types of Boukhalef watershed.

The land uses and their corresponding percentages are shown in Table 3:

Table 3: Land use classification in the study area.

Land Use	**Surface Area**	
	In sq.km	**%**
Urban	6.05	12.5
Bare Soil	3.91	8.1
Agricultural	23.87	49.38
Forest	14.51	30.02
Total	48.34	100

Regarding the soil texture classification of Boukhalef River watershed, it was derived from the pedologic map of the region, scale 1:100.000, digitized in ArcGIS Desktop 9.3, and assigned to represent different soil categories such as vertisols, paravertisols, lithosols, salins, and alkalines [27]. In this regard, soil types were simplified and reclassified as soil textures, including silt, sand, clay, and loam in order to determine the hydrologic soil group classifications map (figure 7 and Table 4). The soil texture classifications were reclassified to SCS Soil Types A, B, C, and D [28], depending on soil infiltration. Type A has the highest infiltration rate, while type D has the lowest infiltration rate.

Once the data has been gathered, the process for estimating the CN values for a drainage area of the Boukhalef watershed was completed. Using the SCS Technical Report 55 (TR-55), the CN is calculated trough the union processing attributes combined to one of the land and hydrologic soil group. With the help of HEC-GeoHMS, the creation of the curve numbers values for different combinations of soil hydrologic groups and land uses has been made (Table 5).

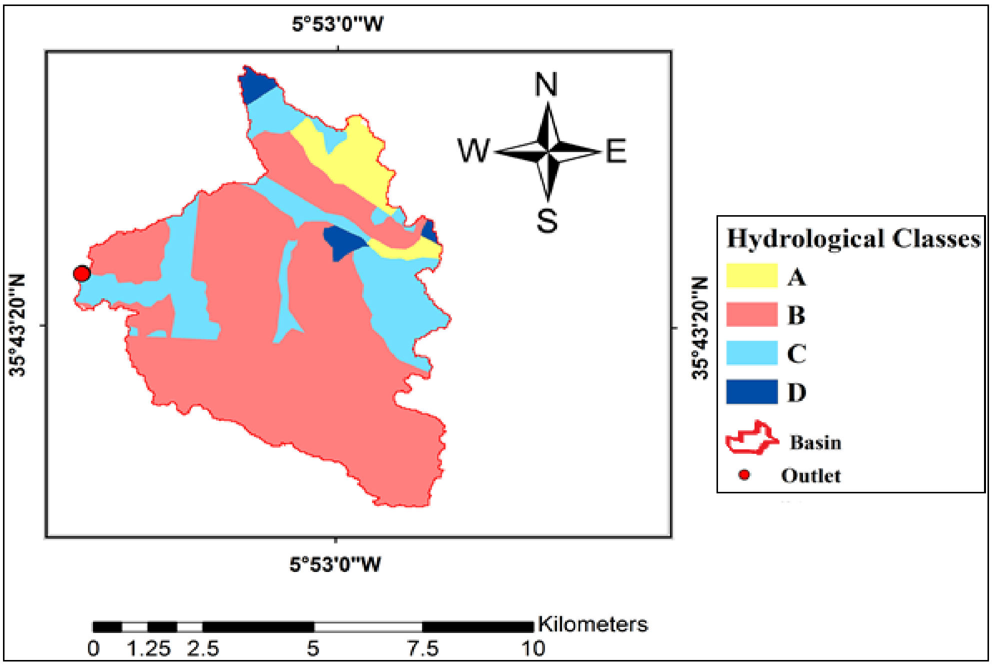

Figure 7: Hydrologic soil groups of Boukhalef watershed.

Table 4: Surface definition of HSG in the Boukhalef watershed.

HSG	**Surface Area**	
	In sq.km	**%**
A	8.18	16.92
B	26.72	55.28
C	11.23	23.23
D	4.57	2.21
Total	48.34	100

HSG: Hydrological Soil Group.

Table 5: Different combinations of soil hydrologic groups and land uses.

CN look-up Table				
Lund Use Components	**Hydrologic Soil Groups**			
	A	**B**	**C**	**D**
Urban	77	85	90	92
Bare Soil	77	86	91	94
Agricultural	64	75	82	85
Woods	43	65	76	82

The SCS CN table provides CN for different combinations of land use and HSG. The CN values for each map unit are aggregated for the whole catchment by mean of GIS to obtain an average CN value. The values of CN of the Boukhalef Watershed are between 94 and 43 and the average CN is 74.883 (figure 8):

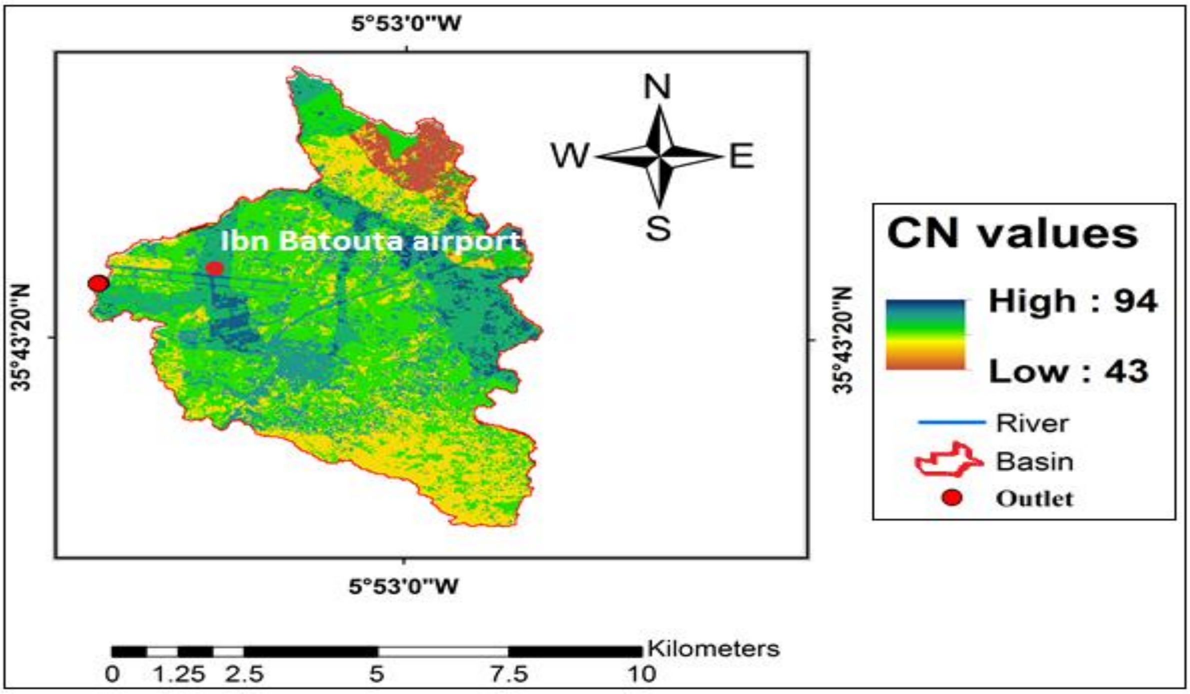

Figure 8: CN Grid map of Boukhalef basin.

As recommended by Kerr [29], the instantaneous rainfalls were converted into their dimensionless mass curves and the cumulative precipitation depth. Therefore, the mass curves transform a precipitation event to a dimensionless curve with cumulative fraction of storm time on the horizontal axis, and cumulative fraction of total precipitation on the vertical axis. The analysis used in the current study is similar to Huff [13] and Hogg [14] with the exception that the time increments are not equal due to insufficient storm events data. The rainfall of the only storm observed is expressed as a cumulative percentage of the total rainfall of the storm. These observed cumulative rainfalls are superimposed on one graph with the heights of the cumulative rainfall obtained through the SCS storm method on HEC-HMS.

The construction of the hydrograph from the metrology model can also be done through the method SCS storm that offers four types of temporal distributions of dimensionless precipitation 24 times to represent the rainfall event (type I, type IA, type II and type III). In order to simulate the hydrological response of the Boukhalef basin, the curves of the cumulative rainfall amounts for the four distributions of 4 types of SCS-24 hours were compared with the observed distribution of rainfall at the Kalaya station. This was done by specifying a particular storm event (23/10/2008) in order to produce a peak flow and comparing its heights of the cumulative rainfall distributions with the heights of the cumulative rainfall of the 4 SCS-storm distributions in a time step of 10 min [30] “The mean curve is to fit through the central points representing the average cumulative rainfall depth percentage at each five percent time increment” [29].

To generate the observed hydrograph for the kalaya watershed located to the South of Tangier city (figures 1and 9), the geographical and physical components of which are shown in table 6, the SCS Curve Number method was used for loss infiltration while the SCS Unit Hydrograph was used as a transform method. In this case, the hydrograph is scaled by the lag time to produce unit hydrograph.

Table 6: Geographical and Hydrologic features of Kalaya watershed.

Geographical components			**Loss Method (scs curve number)**		**Transfert (scs unit hydrograph)**
Area (Km2)	**Basin Slope (%)**	**Length (Km)**	**Initial Abstraction**	**Mean CN**	**Lag Time**
37	8.48	51.1	7.46	82.07	2.022

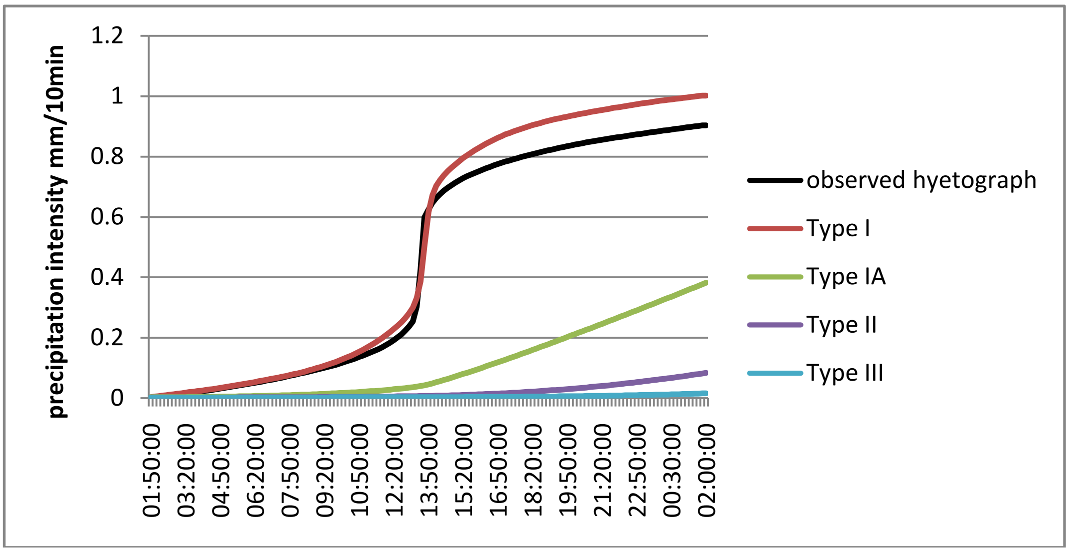

Figure 10: Comparison of observed hyetograph and synthetic rain on HEC-HMS included (SCS storm).

Figure 10 represents the comparison of cumulative depth curves of rainfall according to the SCS method for the 4 types of distributions with the observed distribution curve (hyetograph) and shows that the observed hyetograph corresponds almost perfectly with the type I SCS curve.

In the absence of appropriate measurements of rainfall, the SCS-24 hours rainfall, type I distribution (short duration, high intensity rainfall) was used to create rainfall hyetograph on the day of the event (156.4mm) by which storm runoff can be predicted accordingly.

The required factor for this method is the Lag time obtained from equation (6) [31] in hours, and converted to minutes by multiplying it by sixty:

Lag = basin lag time (hours)

L= hydraulic length of the watershed (longest flow path) (km)

S= potential maximum retention after runoff begins (mm)

Y = Basin slope (%)

Different methods using physical and geomorphological techniques and statistics have been developed to determine the peak flow by a number of researchers [32-37]. The peak flow refers to the maximum flow for a particular stream during a storm event. This determination plays a crucial role in hydrology. It has a significant value in many hydrological applications such as the design of hydraulic structures (i.e. small dam, culverts, and bridges) and helps in understanding the available water resources for water resources management [6,7]. The present study sets to simulate the rainfall-runoff of corresponding hydrographs in the Boukhalef river for the storm event (23/10/2008) and to estimate the peak flow of 2-, 5-, 10-, 20-, 50-, 100- and 200-years return periods. The runoff volume, peak flow, and percent loss were determined from the results of the hydrographs. The peak flow was 121.1 m^3/s, the total precipitation was 156.40mm, the total loss was 60.29 mm, and the total rainfall excess was 96.11 mm. Therefore, the expected runoff volume is about $3877.2x10^3m^3$.The resulted runoff hydrographs for the Boukhalef watershed of the storm event is shown in (figure 11 and 12):

From the results of the simulation of this event, we can see that the percent of total loss constitutes 38.54% of the total precipitation against 61.46 % of the total excess. Designed precipitation for estimating the peak flow at various frequencies, based on the assumption of Gumbel distribution maximum likelihood, was computed with the help of the specialized statistical analysis software HYFRAN PLUS (figure 13). In this study, the maximum annual series of rainfall for a long series of observation (1965-2009), taken from the meteorological station of Boukhalef, were used to obtain long-term discharge series. The 2, 5, 10, 20, 50, 100, and 200 year 24 hours SCS storms were modeled and shown above in (Table 7):

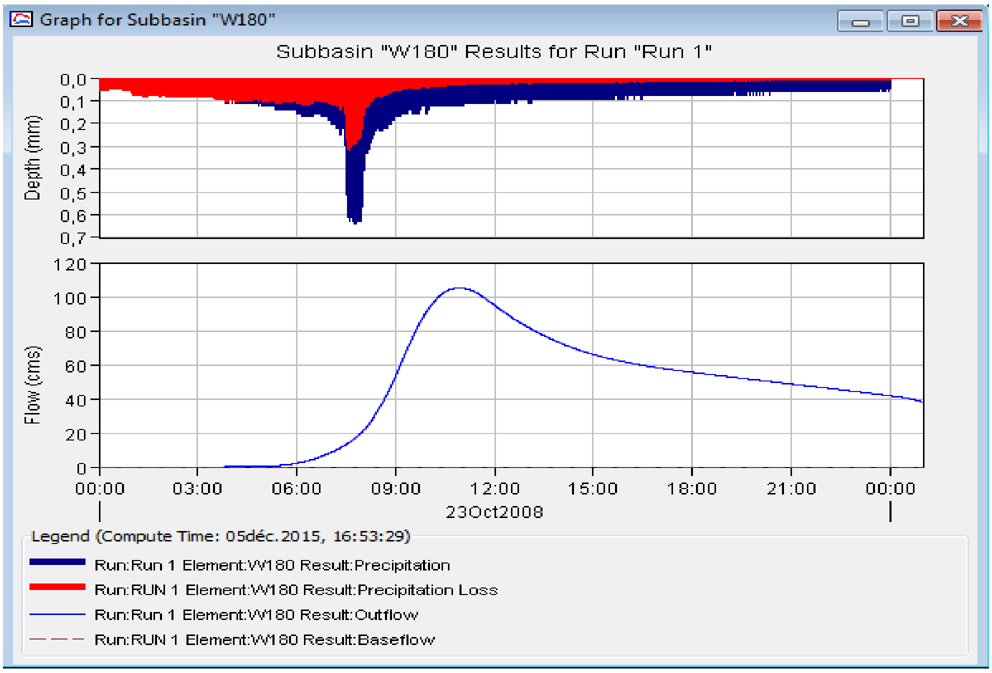

Figure 11: The simulated hydrograph for the event of 23/10/2008

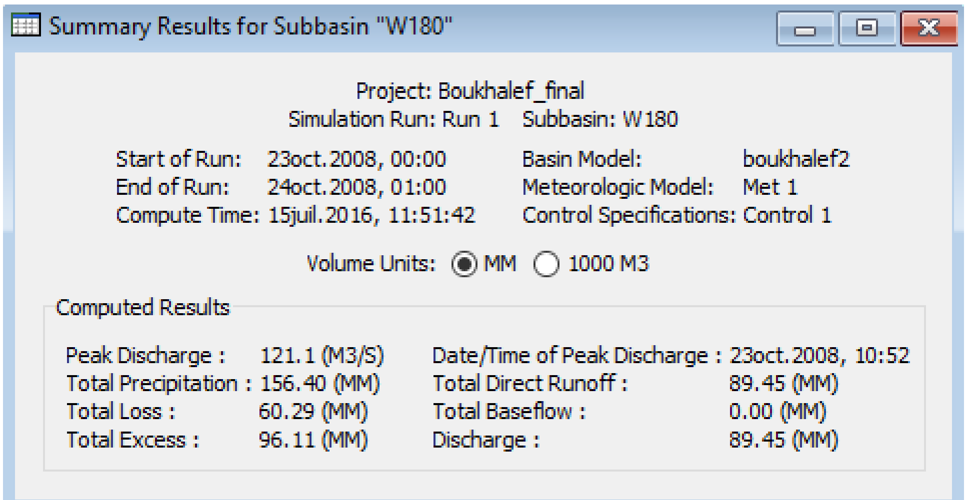

Figure 12: Results extracted from the simulation of the event of 23/10/2008.

Table 7: Peak flow for each return period.

Return interval (years)	Rainfall depth (mm)	Peak flow (m^3/s)
1	19.3	0.2
2	61.7	16.5
5	81.8	34.3
10	95.1	48.1
20	108	62.4
50	124	81.1
100	137	96.9
200	149	111.8

The peak flow of the 200 year-return-period flash-flood is 111.8 m^3/s, while the value for the 100 year-return-period flash-flood is 97 m^3/s. The peak flow for the 50 year-return-period reaches 81 m^3/s, while the 10 year-return-period peak flow is 48 m^3/s. The runoff in the Boukhalef watershed predicted by the SCS-CN model increases gradually with Rainfall increase. However, the runoff shows a rapid increase when the rainfall exceeded 61.7mm.

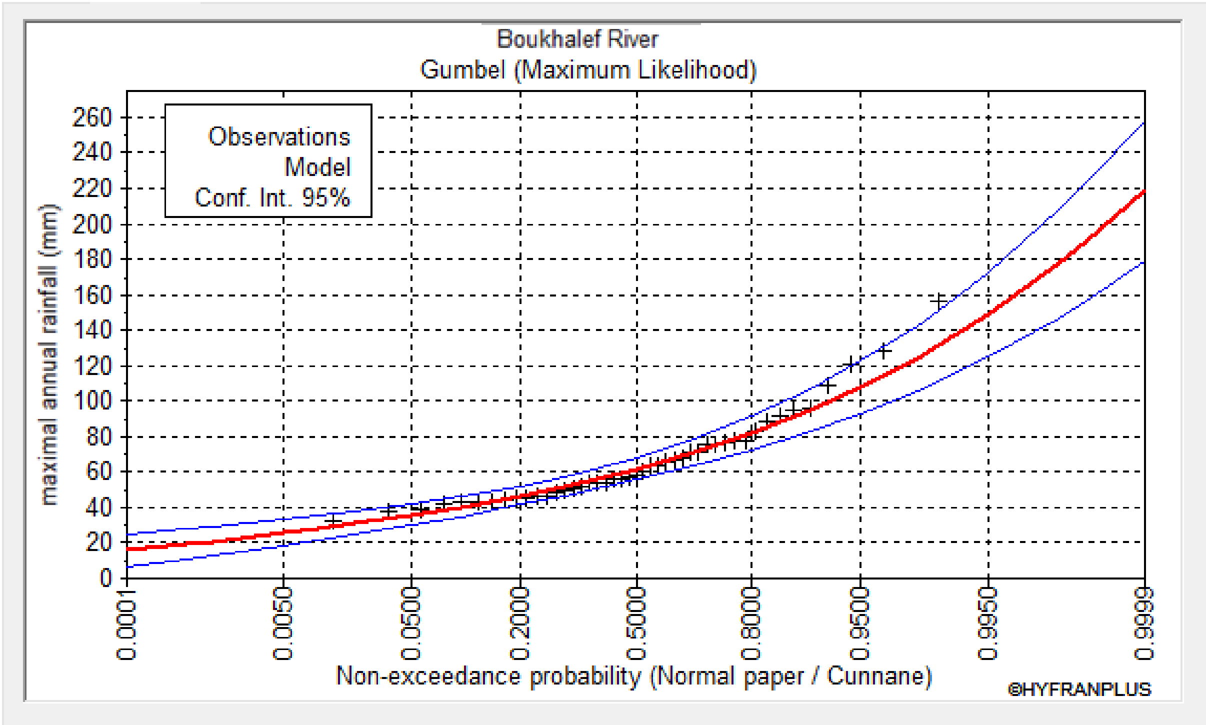

Figure 13: The Gumbel distribution fitting the Tangier maximum Probable Precipitation Data.

Using the data presented in Table 7, a second order polynomial regression relationship has been carried out to minimize the statistical error in the model equation. In order to estimate the peak flow for each return period, an equation was derived and a very good correlation between runoff and rainfall was observed with value of 0.998 (figure 14).

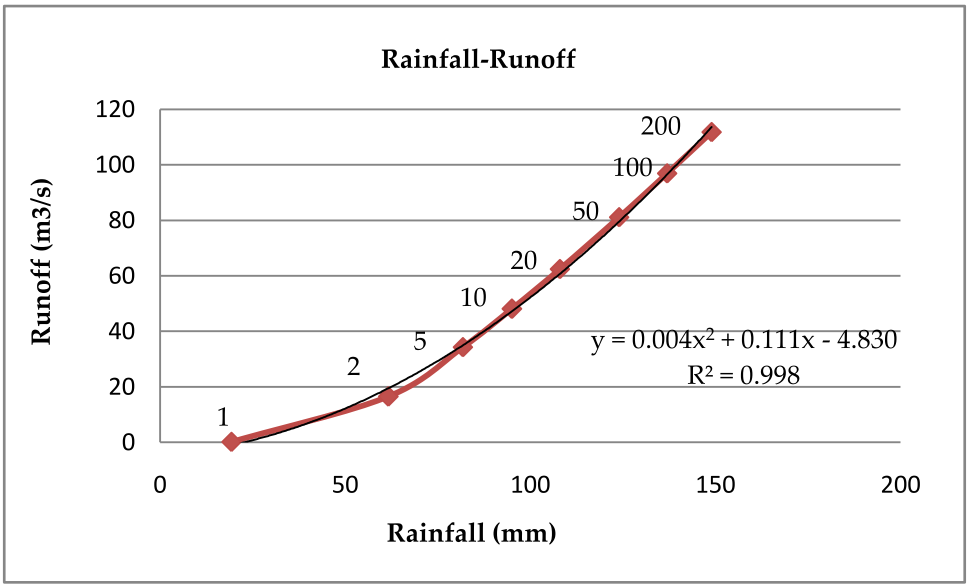

Figure 14: The peak flow for various return periods predicted in the Boukhalef watershed.

Conclusion

The Rainfall-Runoff simulation applied to semi-rural ungauged basins of boukhalef was based on the Hydrologic model. The results obtained from this simulation provide exploitable information for protection against floods and for the design of hydraulic structures along the boukhalef watershed. In this study, the SCS-24 hours rainfall distribution was used to create rainfall hyetograph on the day of the event. The results show that the SCS-24 storm type I represents the best distribution to simulate the rainfall-runoff event for various return interval, because it is the most similar to the observed instantaneous rainfall during the storm event.

On the other hand, the objective of this study is therefore to adapt the real conditions of the basin to the problems exposed during extreme events and analyze the risk of flooding in the major Boukhalef watershed in order to predict flood hydrograph for the 200-, 100-, 50-, 20-, 10-, and 5-years return periods in an "ungauged" basin. The results deduced that the peak flow was lower in the Atlantic side of Tangier city (represented by Boukhalef watershed) compared to the Mediterranean side. It's doesn't have the same intensity in the Mediterranean side (486.7 m^3/s) because of land development, typically associated with increasing urbanization and impervious surface. Therefore, we presented in this study methodologies which have never been applied before in this area, and which leads to a reduction in the uncertainty of the estimation of surface runoff.

Acknowledgments-The authors sincerely thank the Hydraulic Basin Agency of Loukkos (ABHL-Morocco) for the rainfall data. A special thanks to Benjbara Abdelkader (ABHL), for his help and suggested improvements concerning the hydrologic methodology.

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