Rainfall and Runoff Estimation Using HEC HMS Models and RSGIS Techniques for Nekaroud Basin, North Iran

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Abstract

Estimation of rainfall-runoff by the use of hydrological models is applied for water basins without statistical data. This evaluation is used to check basin flood conditions and to manage them. It is also used to prepare map zoning of flood water. One of these models to estimate rainfall-runoff is HEC-HMS. In order to use this model better, we can also use GIS/RS technology to increase accuracy. For this purpose, in this study, landsat 8 and OLI sensor have been used to determine up-to-date land use which, in turn, is used to determine hydrological groups of the basin soil. In order to apply the model, the related layers have been extracted by the use of the basin DEM in ArcGIS and also extension HECGeo-HMS. By the use of SCS and CN, the levels of rainfall and runoff have been measured for the sub-basins. Then, data analysis was carried out by the use of HEC-HMS, and the level of runoff was measured for the whole Nekaroud basin (1446.3 m³). Results of this study can be used to manage floods of Nekaroud basin and also to plan development and expansion of the city of Neka located at the end of the basin.

***Keywords**: HEC-HMS, remote sensing, land use, flood, Nekaroud basin.*

Introduction

Nowadays, anticipation of risky geomorphological phenomena can decrease the potential risk of these phenomena; it can also minimize the physical injuries and financial losses of human as well as natural phenomena. One of these geomorphological risks is destructive runoff (flood) in the basin. For this purpose, hydrological simulation of basin could be very effective to deal with flood and to make adequate preparations for it. Nowadays, the use of these hydrological models and simulations have greatly increased. In applying these hydrological models, using modern technologies such as remote sensing and geographical information system has increased capabilities and practicalities of hydrological models. It has also made anticipation and assessment of models very much closer to natural realities.

One of these rainfall-runoff simulator models is HEC-HMS which nowadays is widely used. These models have been used in and out of the country in the studies related to water basins in the recent years. As an example, Kathol et al [9] can be mentioned who used the HEC-HMS model to determine debit and the runoff volume in two agricultural regions in the southeastern part of South Dakota where the curve had high sensitivity, whereas the initial loss had lesser sensitivity to the change of the target function quantity in HEC-HMS model. Yang Chen et al [5] used the experimental model of land use changes (CLUE-S) and the rainfall-runoff model (HEC-HMS) in order to quantify the effect of different scenarios of land use change on the created runoff in the Khitiavekhi basin in China. In this study, by calibration of HEC-HMS model and prediction of land use by the use of CLUES model for the year 2050, the results show increase of runoff as well as peak debit by changing land use for the future. Muhammad Ali et al [2] studied the effects of land use changes on the surface runoff in Lai Nullah basin in Islamabad, Pakistan by the use of HEC-HMS model. The results of this study show that for planning land use and management of the data useful information has been achieved, and the applied methods can offer services in the future as useful tools for studying the effects of land use. In Iran, Khosroshahi et al [12] have used HEC-HMS model in order to determine sensitivity of the effect of some influential factors on flooding in the sub-basins by the use of output hydrograph for Damavand basin. This study has shown that the hydrological behavior of the sub-basins towards the basin output is nonlinear; and also by the use of the influential factors of flooding, the sub-basins with high flooding potential are identifiable. Khodaparast et al [11] used HEC-HMS software and GIS data of Torogh Damn in Mashhad for evaluating HEC-HMS model. By comparing the initially calculated losses on the basis of supposing the initial losses to be 0.2 S, with the calculated value after calibration the curve number by the software, it was identified that the mentioned hypothesis was appropriate for this basin. Rahmani et al [18] evaluated the effect of land use change on the hydrological features of Kasilian basin by the use of HEC-HMS rainfall-runoff model; the HEC-HMS hydrological model was calibrated and validated by the use of the penetration of curve number (CN) and SCS hydrograph in the basin surface against the observed rainfall-runoff data. The results showed that during this 30-year period, 251.94 hectares of the forests in this region have undergone farming. Modeling of rainfall-runoff during this period showed that 11.2 m³ per second has been added to the peak debit and 98.81 m³ has been added to the volume of runoff, which shows the effect of decreasing forestry and increasing of meadow on the peak debit as well as on the runoff volume of the basin. In this study, HEC-HMS model has been used to stimulate rainfall-runoff processes in the Nekaroud basin by the use of GIS/RS.

Geographical location of the studied area

Nekaroud basin is composed of several large and small rivers whose main valley, unlike the valleys of most other rivers in the Mazandaran Province, flows east-to-west. This flow turns 90° near the city of Neka and becomes a north-south flow; it places Neka on alluvial fan. This permanent river is approximately 145 km long and is located within Gorgan and Mazandaran provinces. Its basin is located between longitudes of 53° and 17' and also 54° and 44' east; and latitudes of 36° and 26 north and also 36° and 44' north with an area of 1818 km². Basin altitude is minimum 27 and maximum 3400 meters high upside Shahkooh. This river's type of water supply is variable from snow-rain at the top, rain-snow in the middle, up to rain at the buttom.

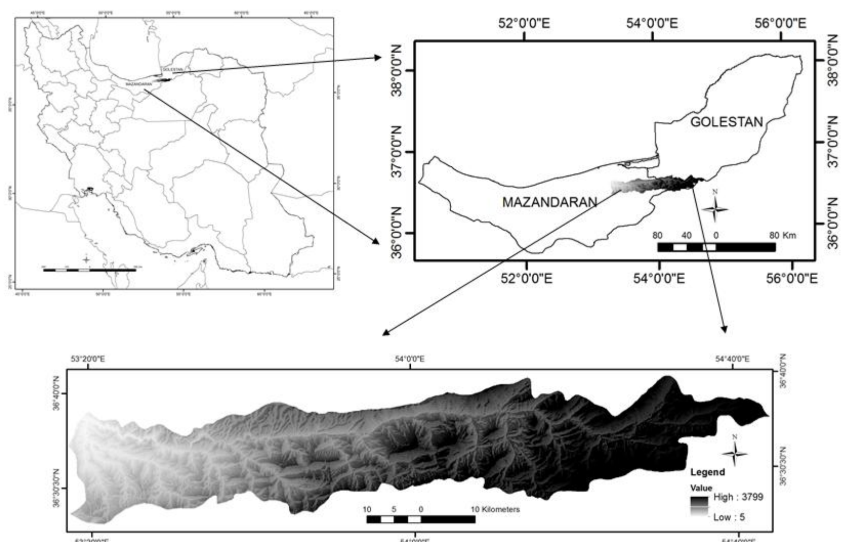

Figure 1: Nekaroud basin position in Iran, Mazandaran and Golestan Provinces.

Methods

HEC-HMS model

HEC-HMS model is one of the computer programs to analyze rainfall data and to convert rainfall into runoff in the regions where there is no hydrometric data. The program has been prepared by the Hydrologic Engineering Center in the U.S. Army Corps of Engineers. This program describes hydrographic flow for the basin hypothetically. In addition, it can be used to simulate detour paths. Generally, by the help of the basin's hydrological data, this application can be used to calculate hydrograph of basin's outlet section. HEM-HMS model can do the stimulation by the use of factors such as basin model, meteorological model and control specifications in the basins [21].

SCS Curve Number (CN) method

This method is used for estimating runoff in the basins where there are no measuring stations. SCS method is calculated using the following equation.

$$F = \frac{(P-0.2S)S}{(P+0.8S)} \quad [1]$$

wherein: F is the height of the current runoff in the basin at the time of t (m^3/s), P is level of 24-hour rainfall (mm), S is the maximum potential losses (mm). Measurements show that out of the total maximum surface storage, averagely 0.2 is lost as the initial loss before the flow of water starts, and the remaining 0.8 is absorbed as surface and deep soil absorption [16].

The amount of total losses or S gets related to a dimensionless factor called curve through a relation.

$$S = \frac{25400}{CN} - 254 \quad [2]$$

wherein: S= storage maximum (mm), CN=runoff curve number. By determining the value of CN, the S value is determined and by considering the rainfall, height of runoff is calculated. The CN value is variable between zero and 100. In CN equal to zero, no runoff is achieved from rain; and in CN equal to one hundred, all precipitation flows on the ground and runoff height will be equal to the rainfall height [16]. In turn, the curve number is determined from the soil features, the type of land use, and the previous moisture conditions.

One of the most important factors in reducing the level of penetration and consequently increase of runoff is previous soil humidity. Soil's acceptability of penetration is highest when the soil is dry [16]. In SCS method, soil humidity is considered in three types. First, when the S value is maximum and the level of soil humidity is low and the potential of runoff production is weak. In the second case, the soil humidity is moderate; and in the third case, the soil is almost saturated and S is in its lowest level. Previous conditions of soil humidity are achieved based on the following table from the total rainfall over a period of five days before the target day.

Table 1: Conditions of the previous soil moisture [16]

Previous soil humidity	Rain five days ago (growth season)	Rain five days ago (dormant season)
I	Less than 36 degrees	Less than 13mm
II	26-53 mm	13-28mm
III	More than 53mm	More than 28mm

First the curve number has to be determined for the humidity type II and then using the mentioned eqns, $CN_{(II)}$ is turned into humidity conditions type I and III [16].

$$CN_{(I)} = \frac{4.2CN(II)}{10-0.058CN(II)} \quad [3]$$

$$CN_{(III)} = \frac{23CN(II)}{10+0.13CN(II)} \quad [4]$$

Specification of runoff curve number

This number is a dimensionless parameter used in SCS method to determine the initial loss and latency parameters of the basin. It is used to determine the basin CN and to overlap different layers such as land use and soil hydrological groups. They are done in the ArcGIS environment.
In the large basins where the soil usually has a variety of uses and types, it is required that the number of weight curve is calculated in the basin by the use of the following equation:

$$CN = \frac{\Sigma AiCNi}{\Sigma Ai} \quad [5]$$

Calculating direct runoff

The flood peak debit can be obtained using different dimensionless methods. In this study, in order to simulate the process of converting excess rainfall into surface current in the basin, hydrograph model of the SCS unit has been used. SCS calculates the peak debit of hydrograph unit and time up to the peak by the use of the following equation:

$$\frac{2/83A.Q}{Tp} \; Q_{Max=} \quad [6]$$

Wherein A is the basin area; C is the runoff height in square centimeters and T_c is the time starting from the rising hydrograph until it reaches the climax according to the hours. It can be obtained from the following equation.

$$Tp = \sqrt{C} + 0/6t_c \quad [7]$$

When the delay time was determined, HEC-HMS calculates the time up to the hydrograph peak by the use of the relation (6); and the peak debit of hydrograph unit is calculated using the eqn (7). SCS states the delay time based on time concentration.

Tlag= .0.6Tc [8]

The time concentration of basin (TC) is calculated as minutes which is known as Korpich relation.

$$Tc = 0.0195L^{0.77}S^{-0.385} \quad [9]$$

Wherein TC=time of concentration in minute, L= water way length in meter, and S= slope of water path in meter /meter.

The meteorological basin model

To analyze meteorological data by the use of meteorological model, factors such as evaporation, rainfall, and snowmelt are used. To study the local effects of rainfall in the HEC-HMC model, the distance gage weighting method was used with inverse distance. In this method, the rainfall hyetograph for points in each sub-basin is calculated as a node with the determined geographical longitude and latitude. The weight of each station is calculated with the square inverse relationship between the nodes and requires no manual calculation. The use of this method is suggested in the basins where in some stations some data are missing. This is because the data of the nearest station is used for reconstruction and completion of the data.

To check the rainfall in the studied basin, the data from the stations in the region were used. By visiting rain gauge and hydrometeric stations, selection of statistical data from1982 to 2012, determining various stations baragraph for thirty years, removal of deficiencies of incomplete statistics using correlation method between the stations where the correlation equation can be generally written as Y=a + b X, after determining the values of the coefficients (a) and (b), the values of (Y) can be calculated by the use of (X) values. Statistics and information needed for the project is taken from the Iranian Water Resources Management Organization and also from Mazandaran Regional Water Organization.

Table 2: weather stations of Nekaroud basin

Row	Station	Longitude	latitude	Elevation	Average rainfall Annual (mm)	Maximum rainfall 24 H
1	Pajim	54^{0}44'00"	36^{0}36'00"	1797	810	48
2	Sefidchah	53^{0}52'58"	36^{0}35'55"	1036	422	35
3	Barkola	54^{0}04'00"	36^{0}38'00"	570	471	41
4	Evard	53^{0}40'00"	36^{0}37'00"	1200	515	37.6
5	Ablo	53^{0}17'41"	36^{0}38'54"	69	710	53

Control specifications

Another one of the factors in HEC-HMS model for hydrological simulation of the basin is control specification. Control specifications represent the date and time of start and completion of a project as well as the time step of the calculations [21]. Finally after a thorough introduction of basin modes, meteorology and also control specifications to HEC-HMS model of hydrological calculations is accomplished by this model.

Results and discussion

Whereas soil properties affect the evolution and appearance of runoff, it is required to determine the hydrological soil group to check the status of CN and the curve number. In order to determine hydrological group, it is required to determine land use. Land use is required to be closer to the current situation so that determination of soil hydrological groups could be done more precisely. It is because different applications have different hydrological groups; and since the land use will change with the time lapse, consequently, the soil hydrological group, too, changes. So in order to get good results in this zoning, it is necessary to update the land use map. For this purpose, in order to prepare land use maps, the 2016 data of Landsat 8 satellite on OLI-TIRS sensor have been used.

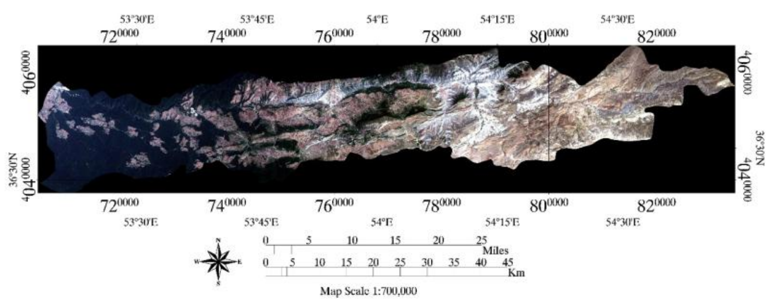

Figure 2: image of Landsat 8 satellite map from Nekaroud basin.

Since the satellite data have already been Geo-referenced, they do not need to be pre-processed nor do they need geometric corrections. Topographic maps of 1:25000 have been used for satellite data classification; and the region’s land use map has been used to match the geometric correspondence and overlapping of vector layers. By land navigation, picking up and collecting of training samples have been carried out in a number larger than a hundred. In the next step, classification of the classes was done in the ENVI software; and to check the accuracy, Jeffries–Matusita method was used. In order to select the bands for classification, OLI sensor bands were used and the best were chosen according to the Kappa coefficient and the overall accuracy. The prepared maps have been used to check the map precision as well as accuracy of the applications.
For accuracy and precision of classification, the Kappa coefficient value and also the overall accuracy of classification have been calculated as mentioned in the table below. Then the applied classification has been inserted into ArcGIS environment and areas of different land uses were calculated; and the necessary output has been prepared from them.

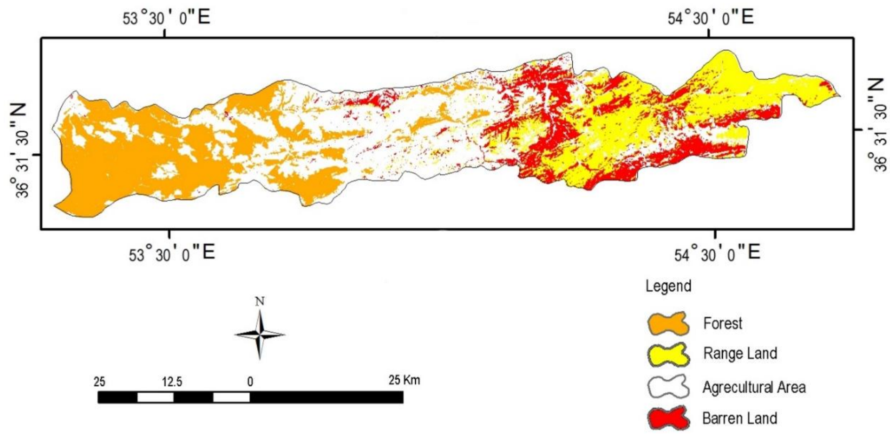

Figure 3: The map of the land use classification of Landsat 8 in Nekaroud basin.

Table 3: the classified overall outcome and ultimate accuracy and kappa. coefficient

Row	Satellite data	Graduation Year	Overall Accuracy	The kappa	Data Source
1	Landsat	2016	96.53%	0.9322	USGS

.Table 4: Results area classified types of users

Row	User	Area (km)	Percent
1	Agriculture	348	19.14
2	Jungle	715	39.32
3	Grassland	445	24.47
4	Arid	310	17.05

According to the conducted studies and evaluations acquired from basin agrology maps, land use map, vegetation status and the slope of the basin, on the basis of classification of the hydrological groups of soil [16], the soil hydrological groups (according to land use) have been determined in the form of map no. 4 and by the use of ArcGIS software, output was obtained from it.

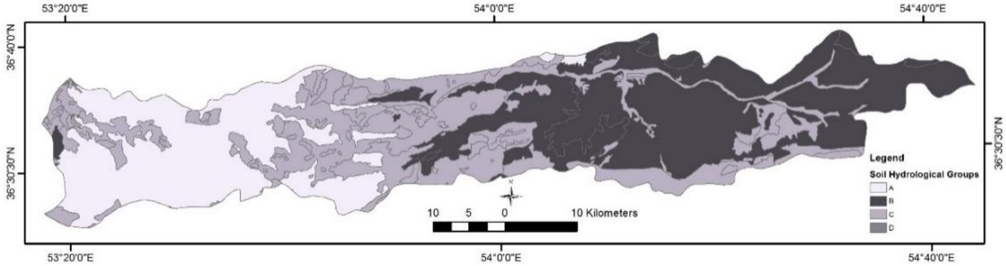

Figure 4: Map of basin soil and water groups, Nekaroud.

Table 5: The area of the basin hydrologic soil groups, Nekaroud.

Soil hydrological groups / Sub-basin	Total area (km^2)	A		B		C		Total Percent
		Percent	Area (km^2)	Percent	Area (km^2)	Percent	Area (km^2)	
1	45.4	*	*	1.8	33.4	0.66	12.1	2.49
2	89	*	*	4.35	79.1	0.54	9.9	4.89
3	50.99	*	*	2.13	38.8	0.67	12.19	2.8
4	64.2	0.34	6.2	1.82	33.1	1.37	25	3.53
5	52.7	*	*	2.5	45.6	0.39	7.5	2.89
6	61.3	*	*	0.94	17.1	2.43	44.2	3.37
7	46.2	*	*	1.77	32.2	0.77	14	2.54
8	68.6	*	*	3.63	66	0.14	2.6	3.77
9	56.4	*	*	2.49	45.4	0.60	11	3.10
10	74.5	3.19	58	*	*	0.90	16.5	4.09
11	60.5	*	*	3.11	56.7	0.20	3.8	3.32
12	32.3	*	*	1.22	22.3	0.55	10	1.77
13	56.3	0.12	2.2	0.64	11.8	2.32	42.33	3.09
14	21.9	*	*	0.45	8.3	0.74	13.6	1.20
15	36.7	0.84	15.4	*	*	1.17	21.3	2.01
16	77.9	0.15	2.9	0.97	17.8	3.14	57.2	4.28
17	57.9	*	*	1.77	32.2	1.41	25.7	3.18
18	72.7	*	*	2.55	46.5	1.44	26.2	3.99
19	71.7	1.81	33	*	*	2.12	38.7	3.88
20	37.4	0.73	13.3	*	*	1.32	24.1	2.05
21	60.9	2.37	43.1	0.36	6.7	0.61	11.1	3.34
22	10.9	0.02	0.4	*	*	0.57	10.5	0.59
23	53.5	*	*	1.77	32.3	1.16	21.2	2.94
24	45.26	*	*	1.92	35	0.56	10.26	2.48
25	114.8	0.94	17.2	0.93	17	4.43	80.6	6.31
26	80.3	3.04	55.3	*	*	1.37	25	4.41
27	126.9	5.14	93.5	*	*	1.83	33.43	6.98
28	93.2	*	*	1.32	24	3.80	69.21	5.12
29	47.73	1.75	31.83	*	*	0.87	15.9	2.62
30	49.93	*	*	2.48	45.1	0.26	4.83	2.74
The entire basin	1818	20.44	372.03	40.92	743.8	38.64	702.55	100

One of the important parameters of model HEC-HMS is the curve number parameter. This parameter analyses runoff production in the basin. The curve number varies between 0 and 100. It becomes 100 when all rainfall is converted to runoff, and it becomes zero when all rainfall gets stored on surface of the basin [19].

In big basins where there are several groups of soil, the position of each one of the groups has to be considered; and groups whose areas are less than three percent of the total area of the basin can be deleted. However, impervious surfaces should always be considered.

After determining the hydrological groups of the basin soil, in order to determine the basin CN, by the use of a numerical height model, the land use map is updated. By the use of Landsat satellite data where land use is clarified and the area of every one of them is obtained, the data is updated. Then, they are inserted into ArcGIS environment along with the soil map of the basin and layers are made of them. The overlapping of these layers is estimated in the environment of that curve number for the soil groups and vegetation by the use of the related table [16]. The previous average curve number of mode II is estimated which is shown in tables 6.

Considering the fact that for determination of the curve number for the hydrological collection of soil-vegetation, mode II of the previous humidity has been used, in case of necessity, to determine and convert curve number, this mode is turned into modes III, I of previous humidity; and the S value as well as minimum rainfall which are for the mode II are determined from other tables with regard to curve II, curve number III and I [16].

Table 6: CN for a hydrologic soil [16].

Land use	Hydrological status	Soil hydrological groups			
		A	B	C	D
Jungle	Average	36	60	73	79
Grassland	Natural or cultured average	39	61	74	80
Agriculture	Crops, poor and good	63	73	81	84
Bare land	-	77	86	91	94

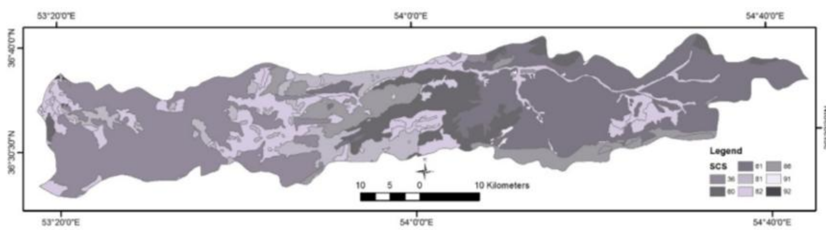

Figure 5: Curve number map of Nekaroud basin.

Using satellite data, land use map, and 1:25000 topographic map of Nekaroud basin numeral altitudinal model, the area, and by the use of the GIS/RS softwares and the extension of Hec-GeoHMS, ArcHydro, the required parameters for the HEC-HMS model are provided. They consist of the hydrological data of basin, basin slope, rainfall, the river flow and route, sub-basins, soil hydrological groups, curve number, land use, etc.

In order to obtain curve number for the sub-basins and all basins, average weight method was used. For this purpose, initially, the soil and land use maps should be obtained and be overlapped in the ArcGis environment so that convergent units could be identified. Then the curve number in every unit and in every sub-basin is identified and multiplied by the area under its cover. If we divide the overall products by the overall area of the basin, the number of the basins' average curve is achieved [16]. By the use of HEC-HMS V4.2 software, the achieved parameters by it are calculated in the average humid conditions, calibrated conditions and for the HEC-HMS model.

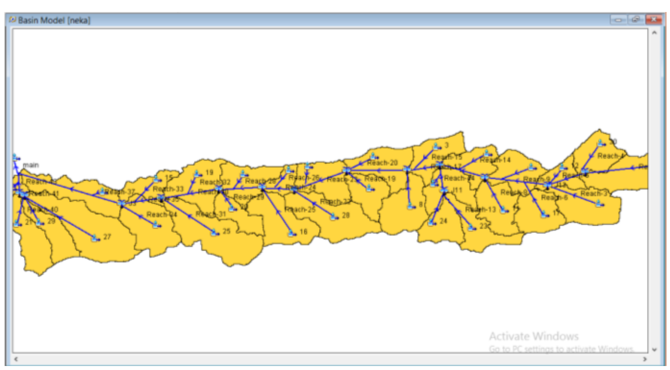

Figure 6: Schematic view of the Sub-basin and stream in the HEC-HMS environment.

After the above points, the required data are placed in HEC-HMS model in the software, and after calculation, the result of model evaluation is mentioned in table no 7.

Table 7: Specifications runoff and evaluation of peak discharge and runoff volume calculated using computational models HEC-HMS on sub-basin, Nekaroud basin.

Sub-Basin	Area	T_l (min)	T_C (min)	S (m/m)	CN	L(m)	Runoff 1000 m^3	Peak m^3/s
1	45.4	70	118	0.018	70.83	11053	36.1	816541.8
2	89	76	127	0.021	63.07	14953	70.8	1596837.2
3	50.99	63	106	0.011	65.32	7472	40.6	915558.5
4	64.2	90	150	0.016	66.26	12735	51.1	1153101.6
5	52.7	52	86	0.015	64.2	6707	41.9	945910.6
6	61.3	91	153	0.011	78.6	12017	48.8	1104663.6
7	46.2	17	29	0.083	65.49	3843	36.8	829596.9
8	68.6	43	72	0.023	60.5	6556	54.6	1229667.1
9	56.4	65	109	0.023	64.35	11270	44.9	1012372.9
10	74.5	155	259	0.013	46.2	25867	59.3	1326115.1
11	60.5	17	29	0.044	65.59	2771	48.1	1086412.1
12	32.3	48	80	0.020	65.2	7074	25.7	579944.7
13	56.3	74	124	0.010	76.5	8900	44.8	1014065.1
14	21.9	29	49	0.065	71.19	6659	17.4	393921.4
15	36.7	71	118	0.021	50.29	11716	29.2	654796.7
16	77.9	48	81	0.035	76	9390	62	1402951.6
17	57.9	10	16	0.054	70.6	1566	46.1	1041293.7
18	72.7	48	81	0.033	67.9	9158	57.8	1306434.8
19	71.7	86	143	0.016	59.29	13372	57	1284632.2
20	37.4	15	26	0.046	67.7	2493	29.8	672045.3
21	60.9	61	102	0.023	45.42	10333	48.4	1083371.1
22	10.9	41	69	0.010	76.6	4183	8.7	196333.5
23	53.5	43	72	0.047	71.12	9461	42.6	962301.7
24	45.26	33	55	0.034	68.58	5644	36	813497.7
25	114.8	53	89	0.078	62.36	15830	91.3	2059222.8
26	80.3	49	82	0.024	51.14	79.16	63.9	1433358.3
27	126.9	106	176	0.018	48	18524	100.9	2261162.7
28	93.2	53	88	0.047	76.3	12364	74.1	1678620.6
29	47.7	53	89	0.019	51	7888	38	851919.1
30	49.93	38	63	0.017	61.78	4805	39.7	895430.7
The entire basin	1818	541	901	0.016	64.16	145270	1446.3	32630780.2

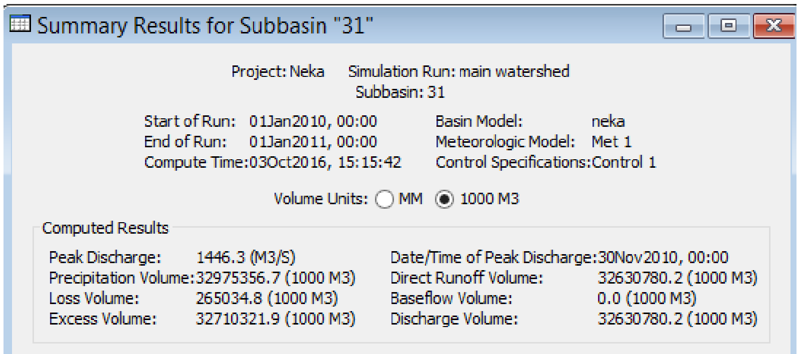

Figure 7: Runoff volume and peak flow rate calculation.

To search for model calibration data of rainfall and runoff, the period 2010- 2011 has been used.

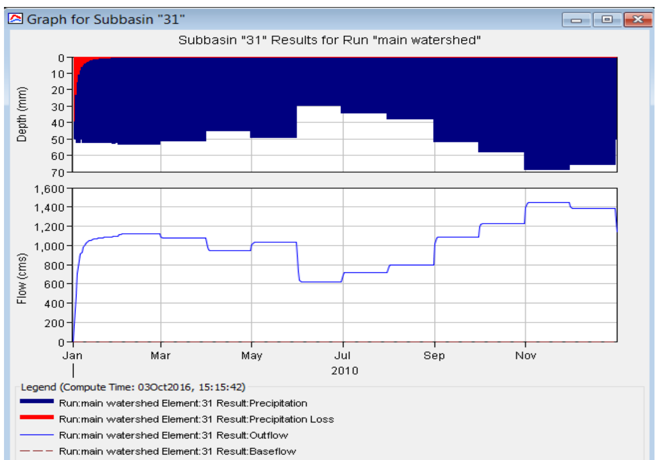

Figure 8: Graph of the carried out computational evaluation in model HEC-HMS.

Conclusion

This study shows that the HEC-HMS model has appropriate capability to simulate hydrological behavior of Nekaroud basin. with regard to the fact that the parameters of the model were prepared in ArcGIS environment, using this environment in order to enhance the accuracy and speed and to modulate it with the model shows high performance of this compound.

In this study, Landsat 8 satellite data have been used. As a result, they have had a lot of impacts on provision of up-to-date land use layer with high accuracy. It has also been very effective on provision of up-to-date curve number as well as other analyses and evaluations for the HEC-HMS model. This is because the time of collecting land data should be in accordance with the time of measuring satellite data; otherwise, rapid occurrence of events creates changes in reflections of the spectrum. After entering the necessary data into HEC-HMS model applying it, the report has shown high rate of calculated runoff. The results show that in the sub-basins located in the B and C hydrological groups, the level of runoff is approximately high, and they have higher potentials of flood because the height of runoff is more in these regions. In the sub-basins formed of the soil A hydrological group, the level of flood reaches its minimum point; therefore, the lower height of runoff has been calculated. In the regions where the level of runoff is high, the result is destruction of forests, formations of agricultural farms and appearance of lands without vegetation. It leads to intensive erosion in those regions and the potential of flood formation grows up. In the basins with denser forests, the height of runoff is comparatively lower and the level of water penetration in soil is higher.

In the hot seasons of the year, the level of rainfall-runoff goes down. Therefore, considering the fact that the geomorphology of the basin in terms of topography and slope doesn't experience much change in different seasons, increase of the runoff is due to the deforestation and the changes made to it by human beings.

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