Hydrological Modeling of the Potential Impact of a Forest Fire on Runoff in a Mediterranean Catchment

Shital DHAKAL, Nepal and Dennis M. FOX, France

Key words:

Forest fires, Hydrological Modeling, HEC-HMS, GIS

SUMMARY

Forest fires are a recurrent phenomenon in Mediterranean environments around the world. Each year, hundreds of thousands of hectares are burned, leaving the soil bare and unprotected against rainfall. Runoff and soil erosion risks are therefore greatly increased during the first year after a fire. This study used a partially distributed hydrological model to examine the potential effect of forest fire on runoff in a Mediterranean Catchment in SE France. The Hydrological Engineering Center's Hydrological Modeling System (HEC-HMS) was used for this purpose. Daily discharge and rainfall data from 1975 to 1991 were available. Different short events were selected and two representative storms were modelled with and without a fire scar. The model was calibrated and validated with the observed data and was employed to simulate the after fire scenario. The model revealed that, after forest fire, the peak discharge in the stream can rise from 10% to 50 % while the general pattern of discharge does not change much. A better result was obtained when the antecedent rainfall before the storm event was fed in the system.

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1.INTRODUCTION:

Hydrological Phenomena are governed by many elements in nature. Runoff and erosion rates are known to increase substantially after a major forest fire (Shakesby and Doerr, 2006; Shakesby, 2011). Forest favors infiltration, helps to slow runoff, and reduces peak flow. Therefore, forest fire and its aftermath is a concern from hydrological point of view.

Modern hydrologic models have large input data requirement and require substantial computing power, but they have the ability to model processes occurring within the watershed as well as the outlet (Kilgore, 1997). Most hydrologic models are now linked to Geographic Information Systems (GIS). GIS, with the advantage of modern day computing abilities, can be used to process the vegetation, hydrological, land-use, fire and weather data to create the hydrological model. Remote sensing (RS) imagery is also very valuable as it provides a quick evaluation of the vegetation status, as well as a survey of the effects of fire upon the environment (Chuvecio and Russel, 1989). The study is centered upon the use of GIS and RS for modeling of hydrological phenomenon.

The main objective of this study was to investigate the potential changes in hydrological response of a catchment following a forest fire and develop a methodological framework that can support the prediction of future behavior based on hydrological model and parameters in Mediterranean Catchments using appropriate techniques of GIS and Remote Sensing.

2.THEORETICAL BACKGROUND:

2.1) Hydrology:

The hydrological cycle is the central focus of hydrology which has no beginning or end (Chow et al, 1988). Water evaporates from ocean and land surfaces, condenses in the atmosphere and precipitates on the land or the ocean. The precipitation can be rain, snow or hail. The precipitated water may be intercepted by vegetation, become overland flow over ground surface, infiltrate into the ground, flow through the soil as subsurface flow, and discharge into streams as surface runoff. The infiltrated water may percolate deeper, later emerging as surface runoff, and finally flowing out to the sea or evaporating into the atmosphere. In this paper, we are more concerned with the stream flow process. The process can be better understood by Figure 1.

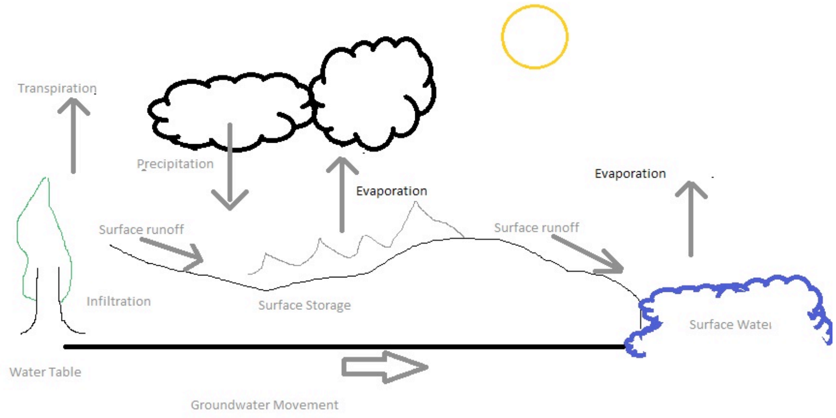

Figure 1: Hydrological Cycle

2.1.1) Factors Affecting Runoff:

The factors affecting Runoff can be listed as the following:

Rainfall extent and distribution: A storm is often described by the length of time over which precipitation occurs, the total amount of precipitation occurring and how often this same storm might be expected to occur i.e. frequency.

Surface Coverage: Forested or grass land generates less runoff than bare soil for given soil type and bare soil generates less runoff than paved surface. Also, the foliage and its litter maintain the soil's infiltration potential by preventing the sealing of the soil surface by the impact of raindrop.

Soil type: Soil texture and structre both influence infiltration. Silty soils form surface seals easily and generate high runoff rates. Well-structured loam maintain high infiltration rates even after much rain.

Antecedent Moisture Content: The runoff from a given storm is affected by the existing soil moisture content resulting from the precipitation preceding the event of interest. Antecedent moistures lowers the matric suction gradient and final infiltration capacity is reached more quickly.

Time of Concentration: Time of Concentration is the travel time from the hydraulically furthermost point in the watershed to the outlet. It affects peak discharge and shape of the hydrograph.

2.1.2) Watershed:

The topographically delineated area drained by a stream system is waterhsed or in other word- the total land area above some point on a stream or river that drains past that point is a watershed or catchment. During precipitation, the short term storage in the soil begins to fill and water begins to flow as unsaturated flow, ground water flow, overland flow and channel flow. Channel flow is the main form of surface flow and all other surface flow processes contribute to it. Determining flow rates in a stream channel is a central task of surface water hydrology (Chow et al, 1988).

When the flow rate of a particular drainage basin is graphed as a function of time, it is called a discharge hydrograph. An annual hydrograph is a plot of stream flow vs. time over a year that reflects the long-term balance of precipitation, evaporation, and stream flow in a watershed. A storm hydrograph, on other hand, displays the discharge of a river over the duration of an event.

2.2) Impacts of a forest fire on hydrology

On average, from 2000 to 2005, about 95,000 fires occurred annually in 23 European countries, burning almost 600,000 ha of forest land every year (Barbosa et al, 2008). Of these, about two-thirds or 65,000 fires occurred in 5 European Union Mediterranean countries (France, Greece, Italy, Portugal, and Spain). Climate change in combination with human intervention and increment of forest biomass due to the abandonment of agricultural lands and lack of forest management significantly increases forest fire risks. In recent years, due to the increase in forest fire frequency and intensity, a new awareness has increased of the impacts of forest fire not only on vegetation but also on hydrological regime (Konstantinos et al, 2010).

Fire is the most important natural threat to forests and wooded areas in the Mediterranean basin (Alexandrian et al, 1998). The impacts of a forest fire on hydrology can be both direct and indirect. The destruction of forest decreases the water holding capacity of the soil; infiltration rate is reduced and surface flow and velocity increase (Prosser and William 1998, Robichaud 2000, 2005). This happens mainly because of the destruction of the vegetation and litter layer and its consequent direct impact on interception, evapo-transpiration and overland flow velocity (Prosser and William 1998, Pierson et al, 2001, 2002, 2008).

Forest fires can also affect hydrological processes indirectly, especially altering the hydraulic properties of the soil. Fire destroys the top soil organic matter thereby affecting soil structure, and the combustion of the organic litter layer can form soluble ash and/or give rise to water repellency (Cerda and Doerr, 2005, Konstantinos et al, 2010).

The direct and indirect effects of forest fire ultimately lead to increased surface runoff. Other consequences are the decrease in ground water recharge, increase in soil erosion rates and greater peak discharge. Increases in the flood frequency and alteration in the shape of the flood hydrographs have also been reported (Imeson et al,1992, Inbar et al, 1998). These peak discharge and floods can cause loss of life and property damage.

2.3) Hydrological model

The rainfall in a catchment can be monitored using different models. Hydrologic models are usually mathematical representations of an idealized situation that has the important structural properties of the real system (Woolhiser and Brakensiek,1982).

2.3.1) Selection of suitable Models:

Spatially variable hydrologic systems require the use of distributed models rather than lumped models to describe the system. However, because the boundary between lumped and distributed models is not clearly defined, there have been attempts to account for spatially distributed terrain attributes based on lumped models (Olivera and Maidment, 1999). The Hydrologic Engineering Center (HEC) Hydrological Modeling System (HMS), for example, allows users to subdivide the watershed into smaller sub basins to route flow to the watershed outlet. Hence, HEC-HMS was chosen to study the potential changes in runoff after a forest fire.

2.3.2) HEC-HMS Model:

HEC-HMS is the US Army Corps of Engineers' Hydrologic Modeling System computer program developed by the Hydrologic Engineering Center. The program simulates precipitation-runoff and routing processes, both natural and controlled. HEC-HMS can be used in various geogrpahical domains to solve broad range of problems (USACE-HEC, 2000, 2008).

HEC-HMS uses separate sub-models to represent each component of the runoff process. Each model run combines the Basin Model, the Precipitation Model, and the Control Model. The Basin Model contains the basin and routing parameters of the model, as well as connectivity data for the basin. The Meteorological Model contains the rainfall data for the model. The Control Model contains all the timing information for the model. The user may specify different data sets for each model (USACE-HEC, 2000, 2008).

3. METHODOLOGY:

The Giscle watershed is a Mediterranean watershed with natural forest and moderate mountains. The watershed is 234 km^2 and is located in SE France near the Gulf of St. Tropez. The hilly upper part of the catchment is made up of metamorphic rocks and the lower part is a gently sloping alluvial plain (Fox et al, 2012). *Quercus suber* (cork oak), *Pinus pinaster*(pine), and *Quercus pubescens* are the dominant trees; cork oak is fire resistant with low fire mortality rate whereas the pines have high mortality rates .

Data needed for the parameters were the following: rainfall, discharge, land cover, hydrological soil group, digital elevation model (DEM), evapotranspiration and the stream network. These data further provided the foundation for additional files needed to delineate river network, estimate Curve Number, and determine other watershed characteristics like watershed boundary, slope, longest flow length etc. Remote Sensing techniques were applied to determine the curve number.

Mean daily discharge was measured automatically about 3.5 km upstream of the outlet. The evapotranspiration was calculated by the Thornthwaite method (Thornthwaite, 1948). The stream network was derived from a 25 m Digital Elevation Model (IGN, 2003). Total daily rainfall was measured in the plain about 2 km West of the stream gauge. Daily data for both rainfall and discharge were available for a 31 year period, 1975-2005. But, since the Verne dam was completed in 1991 and it may have altered the hydrological behavior significantly, only data before 1991 were used for modeling. Peak rainy season is from October to January and summers are hot and dry. The rainfall-runoff relationship shows a strong seasonal trend where the first heavy rains of September and October generate little channel flow. In contrast, later equivalent winter rains create more runoff since antecedent soil moisture is greater (Fox et al, 2012).

3.1) Process Involved:

The methodology for evaluating the hydrological phenomenon after the forest fire can be integrated using remote sensing, GIS and hydrological models created through HEC HMS. After terrain pre-processing using Arc hydro, the DEM of Giscle watershed was processed in GeoHMS, an extension of ArcGIS.

The Geospatial hydrological Modeling Extension (HEC-GeoHMS) of ArcGIS was used for extracting necessary information from spatial data and developing the hydrological modeling inputs for HEC-HMS.

The basins characteristics in the HEC-GeoHMS Project view were used to extract characteristics like River Length, River Slope, Longest Flow Path, Basin Centroid (Center of Gravity Method) and Basin Centroid Elevation.

3.2) HEC-HMS Model Description:

HEC-HMS is a public domain software developed by the US Army Corps of Engineers (USACE; http://www.hec.usace.army.mil/software/hec-hms/). It has a wide range of methods to set up and control variables for simulating rainfall-runoff relationships (HEC, 2000). The delineated watershed is imported in HEC-HMS to make a semi-distributed model. The sub basins, junctions and reach are defined in the watershed and the downstream flow are allotted accordingly (Figure 2).

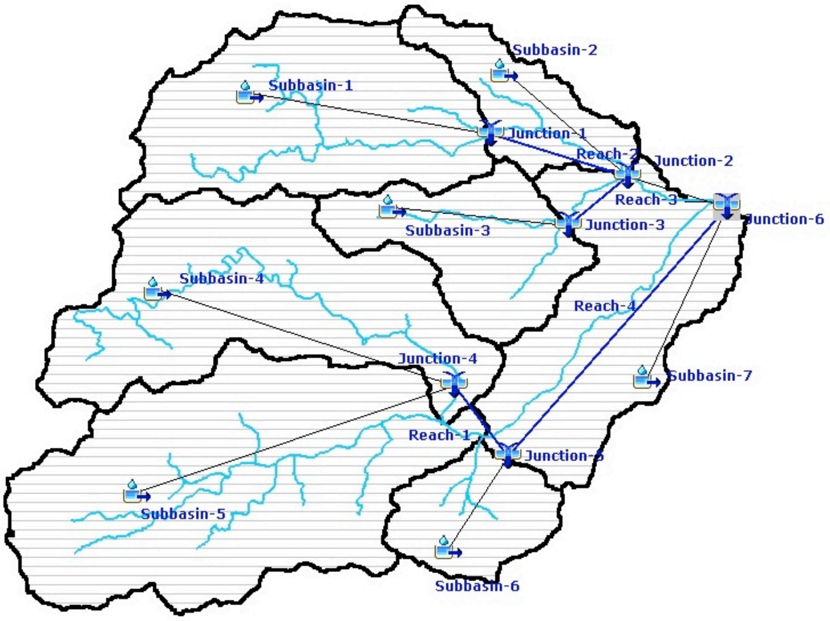

Figure 2 HEC HMS Model Set up

The Basin Model in HEC HMS includes these models for representation of runoff process:

a- Runoff Volume Model
b- Direct Runoff Model
c- Base flow Model
d- Channel Routing Model

The Models, Methods and Parameters adopted in this study are listed in Table 1.

Table 1: Models, Methods and Parameters

Model	Method	Estimated Parameters
Runoff Volume Model (Loss)	SCS Curve Number	Initial Abstraction, Curve Number, Impervious rate
Direct Runoff Model (Transform)	Clark Unit Hydrograph	Time of Concentration, Storage Coefficient
Base flow Model	Recession	Initial Discharge, Recession Constant, Threshold Flow
Channel Flow Model	Muskingum Routing	Muskingum K and X

3.2) Calibration and Parameter Estimation:

For the loss model, SCS Curve Number (CN) Method was used as it involves the use of simple empirical formula and readily available tables and curves. It can incorporate land use for computation of runoff and rainfall. The CN and initial abstraction were computed using the empirical formula as explained in the earlier sections and the impervious rate was kept to 0 as it was already included in the CN number.

For the direct runoff model, the Clark unit hydrograph was used. Time of concentration used in the Clark unit hydrograph is the travel time from the hydraulically furthermost point in the watershed to the outlet. For each sub watershed, the initial value of concentration time was calculated using Kirpich's equation (Kirpich, 1940)

Kirpich's equation:

$$\mathbf{T_c=0.0195L^{0.77}/S^{0.385}}$$

where T_c= Time of Concentration (min)
L= Flow Length (m)
S= Average Slope along the Flow Path

The flow length and average slope along the flow path were calculated using the HEC-GeoHMS extension in ArcGIS. The storage coefficient value was estimated for each subbasin as shown in table 2. For the base flow model, the recession method was used. As initial flow is an initial condition, the starting discharge of the selected event was taken into consideration. Pilgrims and Cordery (1992) suggest a recession constant of 0.95 for ground water flow component, 0.8-0.9 for interflow and 0.3-0.8 for surface runoff. We estimated the value of 0.9 as the recession constant and 0.1 was used as an approximation of the threshold ratio from the graph of observed discharge versus time. The flow at which the recession limb is approximated well by a straight line defines the threshold value.

For the channel flow model, Muskingum routing was used. It involves two parameters: K which is the travel time of the flood wave through the routing reach; and X which is the dimensionless weight and is between 0 and 0.5.

For the calibration process, a separate basin model was created and the new estimated parameters were applied. Empirical corrections are common in modeling, and it is understood that every hydrological model should be tested against observed data, preferably from the watershed under study, to understand the level of reliability of the model (Linsley 1982, Melching 1995). After calibration, the parameters were slightly changed which are listed below (Table 2):

Table 2: Methods and their parameters involved for normal antecedent moisture condition (SB1, SB2... refer to sub-basins shown in Figure 2)

CN LOSS	**SB1**	**SB2**	**SB3**	**SB4**	**SB5**	**SB6**	**SB7**
Initial Abstraction	58.5	48	51.5	58.5	57	57	45
SCS CN	40.7	40.3	36	40.7	37.6	33	36.3
Impervious	0	0	0	0	0	0	0
CLARK UNIT HYDROGRAPH							
Time of	46.77	37.9	33.21	66.19	52.51	21.33	50.94

Concnt.(Hr)							
Storage Coff (Hr)	4.6	3.7	3.3	6.6	5.2	2.1	5.0
RECESSION *							
Initial Discharge(m^3/s)	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Recession Constant	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Threshold Ratio	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MUSKINGUM	REACH1	REACH2	REACH3	REACH4			
K(hr)	1.05	4.22	2.23	8.83			
X(hr)	0.1	0.1	0.1	0.1			

Note: * The Recession parameters were changed as per the storm data

But for the wet condition, the curve number and initial abstraction were changed as shown in Tables 3-5:

Table 3: Curve Number (CN) and Initial Abstraction (IA) parameters for wet antecedent moisture condition before forest fire

Sub Basin	CN	IA
1	61.02	74.63
2	60.32	76.83
3	56.29	90.70
4	60.42	76.51
5	58.08	84.30
6	53.00	103.60
7	56.61	89.53

Table 4: Curve Number (CN) and Initial Abstraction (IA) parameters for normal antecedent moisture condition after forest fire

Sub Basin	CN	IA
1	56.2	39.6
2	45.8	60.1
3	44.5	63.4
4	39.9	76.5
5	37.6	84.2
6	32.9	103.7
7	36.2	89.4

Table 5: Revised Curve Number (CN) for normal antecedent moisture condition after forest fire

Sub Basin	CN
1	74.69
2	65.48
3	64.84
4	60.42
5	58.08
6	53.00
7	56.61

4. RESULTS AND DISCUSSION:

This project compares the results obtained from the hydrological model of the storm event before and after forest fire. Of the different storm events that were modeled, two best fit storms were selected for discussion and analysis here.

4.1) Storm I

4.1.1) Before Forest Fire (calibration of model)

The first event was selected for an event between 4th of November 1984 and 29th of November 1984. It had two rainfall and corresponding discharge peaks on 9th and 15th of November, forming a connection of two storm events, which was one of the reasons it was of interest to us.

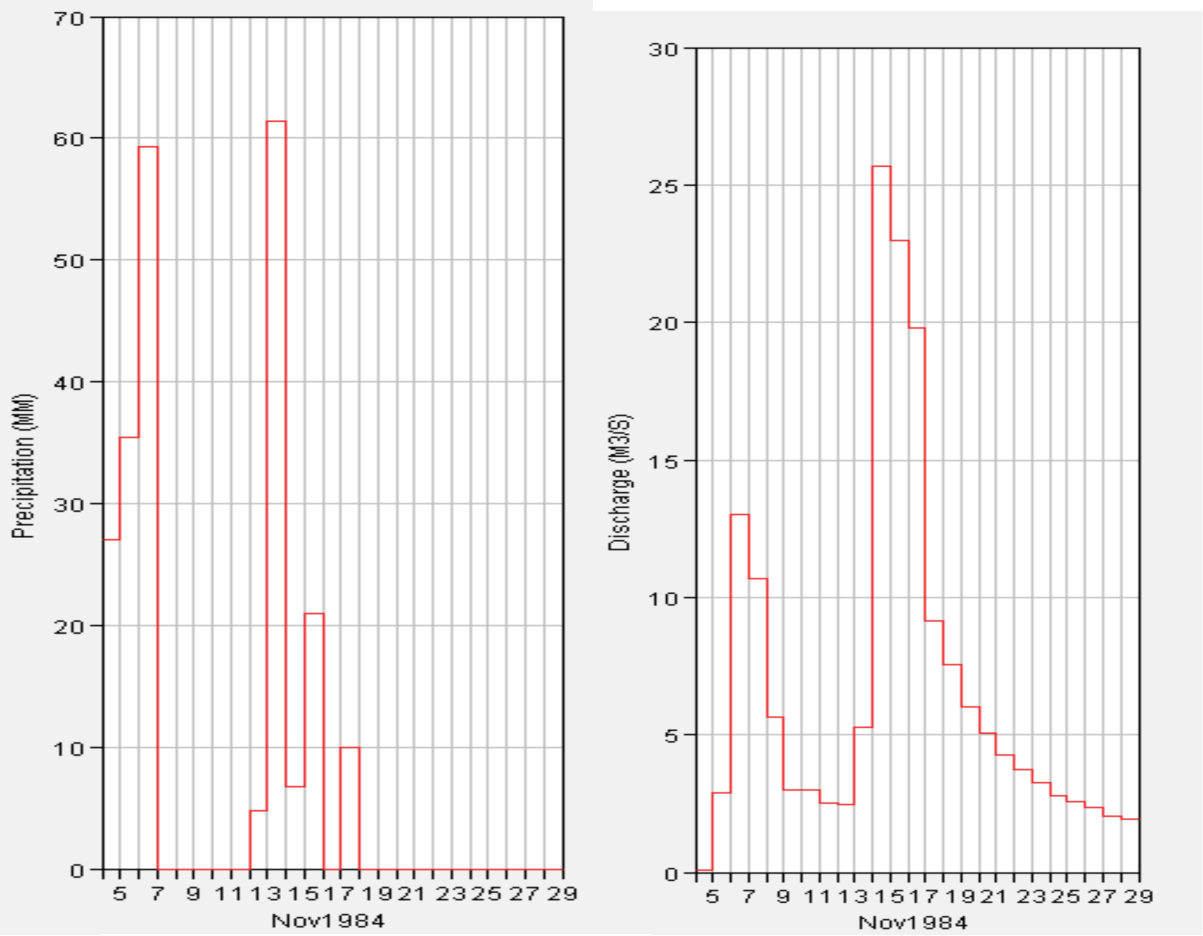

Figure 3 Precipitation and discharge plotted against time for storm I

It is quite interesting to notice that though peak precipitation is almost the same on two days, the corresponding graph for discharge does not reach the same height during the first event (Figure 3). Before November 5, precipitation was not significant, so a large portion of rainfall was lost in initial abstraction and in increasing the soil moisture condition. But for the November 13 event, since the soil was already wet, more of the precipitation was changed directly into runoff. The antecedent soil moisture condition and initial abstraction play a prominent role in catchment response.

Upon modeling the storm event in HEC-HMS using the initial parameters and methods described above, and plotting a graph against the observed discharge, we obtained the following result (Figure 4):

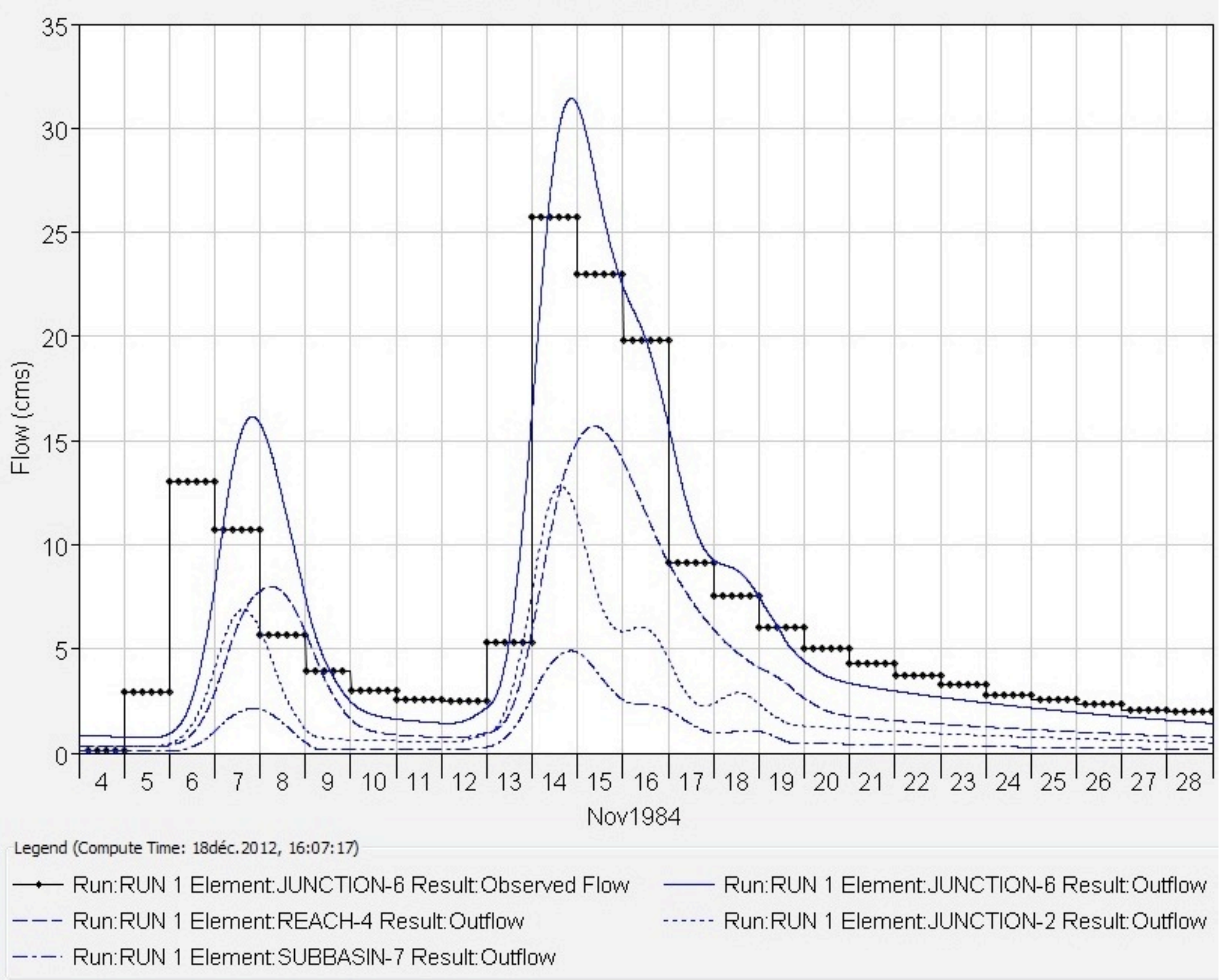

Figure 4 Obtained result without calibration

The simulation results were satisfactory for this event (Fig 4), but in simulating other storm events, the initial parameters were not satisfactory. After calibration of the model, we obtained parameters which fit best for all storm events. Appling the final parameters, and running the model once again, we obtained a different result (Figure

5).

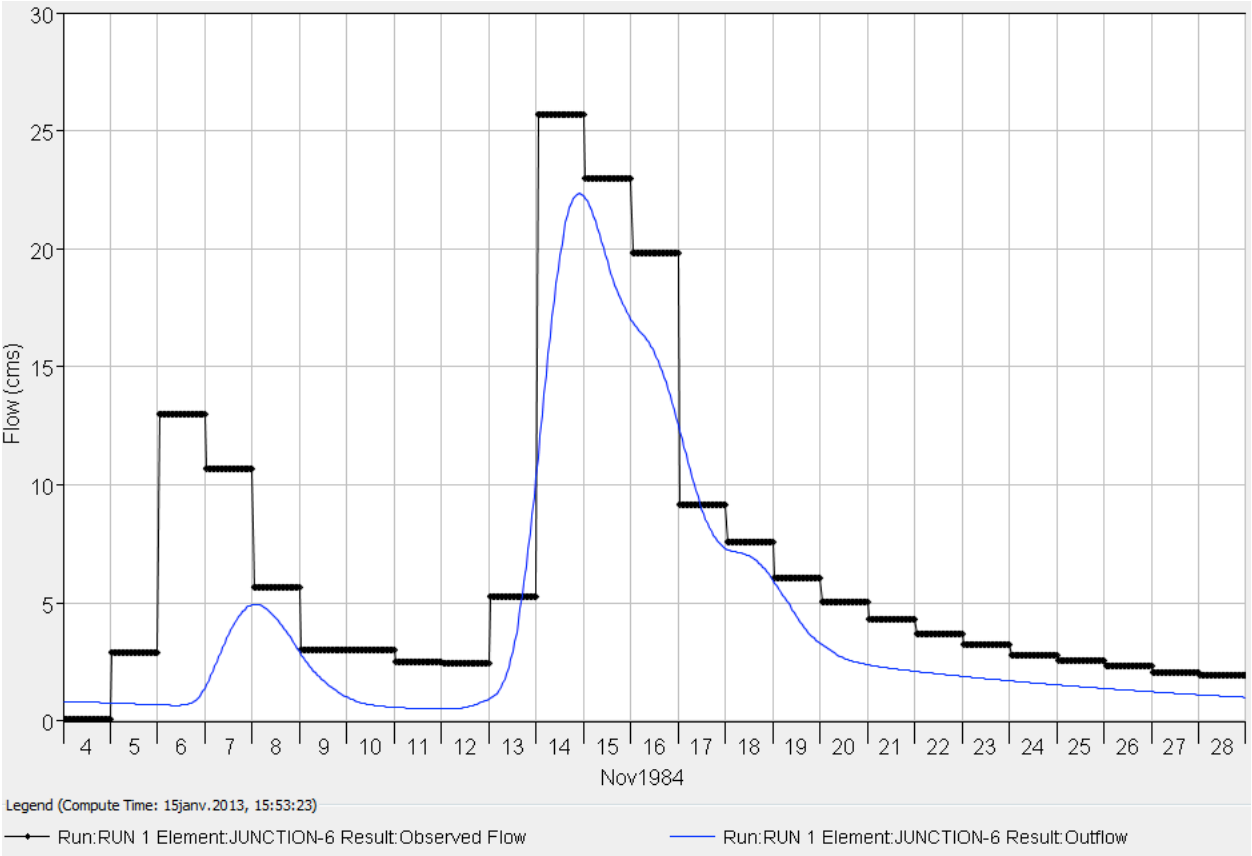

Figure 5 Obtained result after calibration

In figure 5, the overall shape of the curve shows the under-estimation of the discharge (5%-25%) in most of the instances. It should be noted that the simulation fails to match the first peak discharge because of the initial abstraction loss after precipitation. Hence, both the higher peaks curves sought for in the result. To improve the model, another storm was also taken into consideration, with only one peak discharge and a better result was achieved. This is the case for ‘Storm II’.

4.1.2) After Forest Fire:

Alonistioti et al. (2011) explain the effect of forest fire on CN, IA and lag time. Taking the fire scar into consideration, new CN and IA for the sub basins were calculated. Upon simulating the model and plotting the graph against the earlier observed discharge, the following result was obtained (Figure 6).

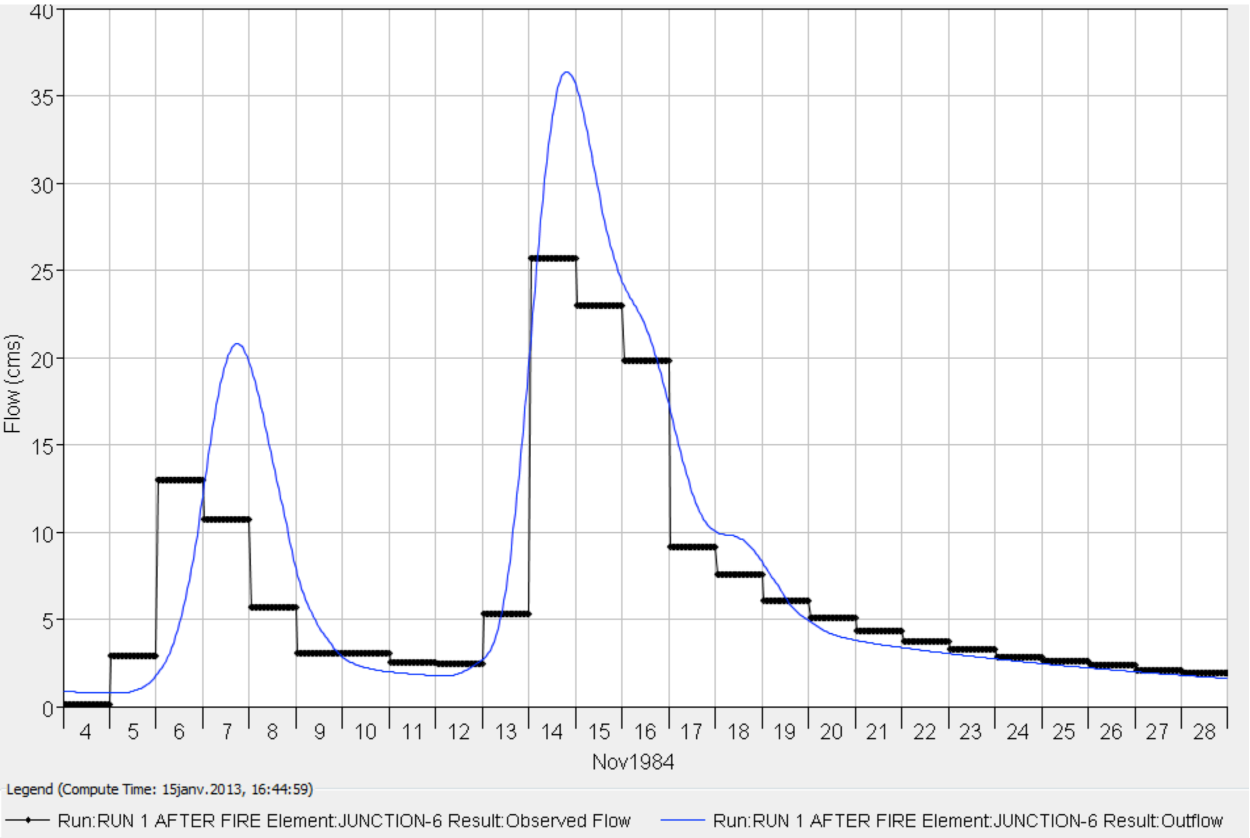

Figure 6 First storm after forest fire

The analysis of runoff response before and after forest fire can be performed by concentrating in three areas: the peak discharge, concentration time and overall shape of the curve. After forest fire, it has been observed that the graph of peak flow has increased. From around 22 cms the peak discharge has gone up to 36 cms which illustrates about 50% increase in discharge. The concentration time of the watershed can be determined by observing the time to reach the peak, which in this case has not changed much. The shape of the curve also remains quite constant after the forest fire scenario. Only the overall increment in discharge is depicted throughout the graph. The total observed outflow before forest fire was 73.8 mm while the total computed outflow after forest fire is 85.6 mm.

4.2) Storm II:

4.2.1) Before Forest Fire (validation of model):

For the second event, the time period selected was from 13th April 1976 to 22nd April 1976. This storm was selected for analysis as it represents a different season and the storm has only one peak discharge (Figure 7).

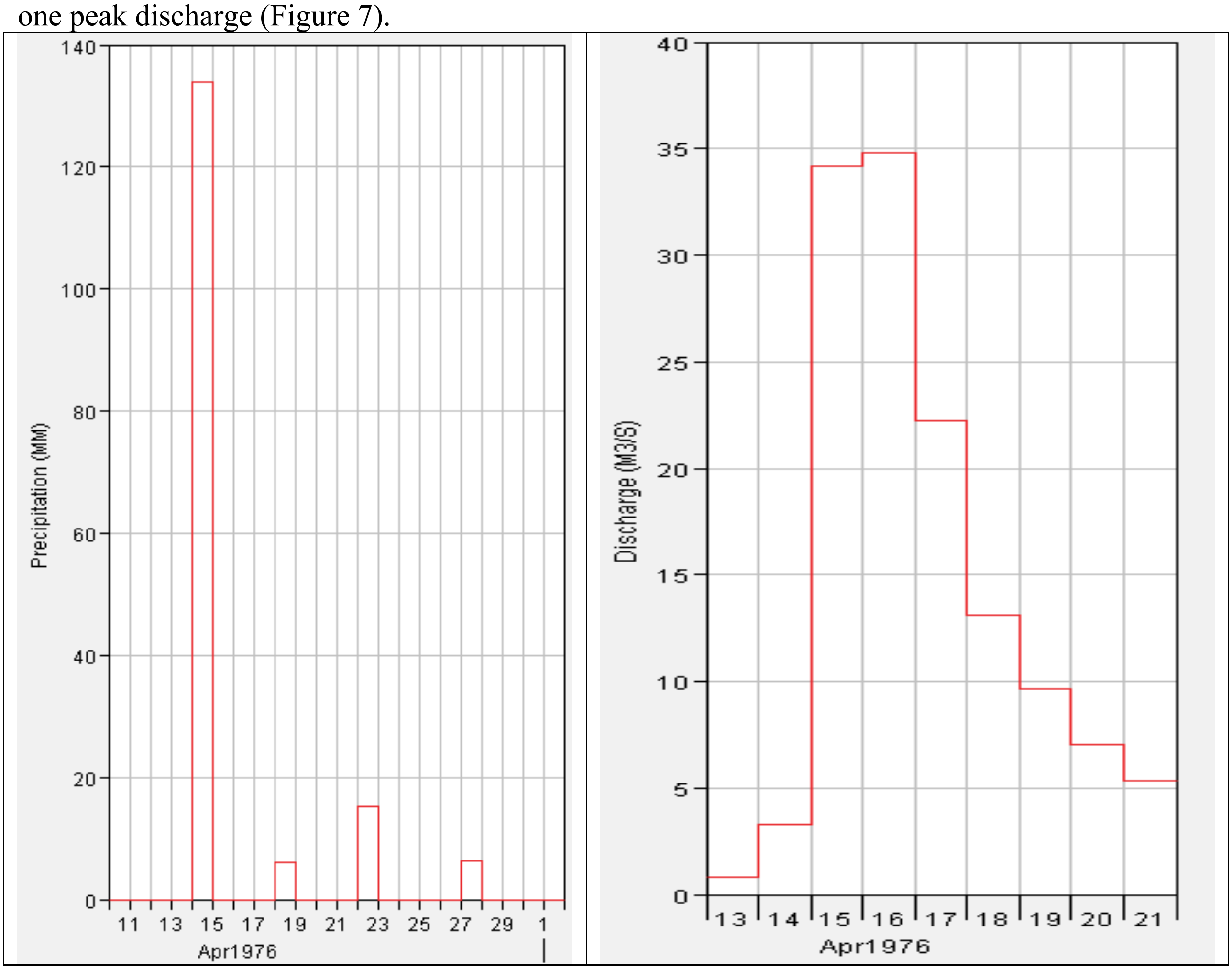

Figure 7: Precipitation and discharge plotted against time for Storm II

Unlike the case in storm I, storm II is inferred to be a wet environment. This is because of two reasons: the first is season - April-May is the second rainiest time of year, and the second is the antecedent rainfall 2 weeks before the event, which is more significant than in November. Hence, a correction was applied for the CN, as mentioned earlier.

Upon modeling the event in HEC HMS with a new CN number and plotting the graph with the observed discharge, we get the following result (Figure

8).

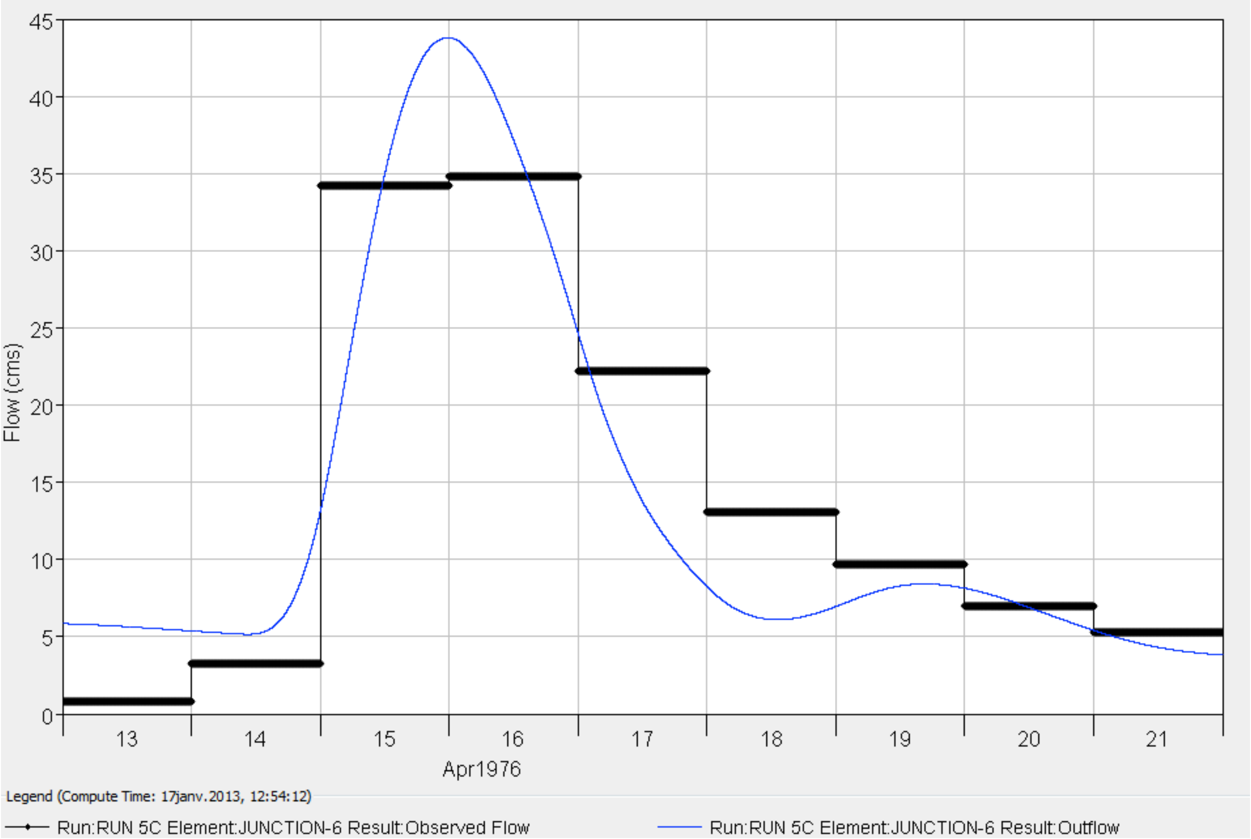

Figure 8 Second Storm before forest fire

The resulting peak outflow is slightly more than the observed outflow, unlike in the first case, and this is probably because the soil was already wet before this particular event, for which case HEC-HMS seems to have a good modeling capacity. For the overall shape of the curve, the real flow is slightly underestimated.

4.2.2) After Forest Fire:

Appling the required treatment for the parameters after forest fire, and plotting the result with the observed outflow, we get the following result (Figure 9).

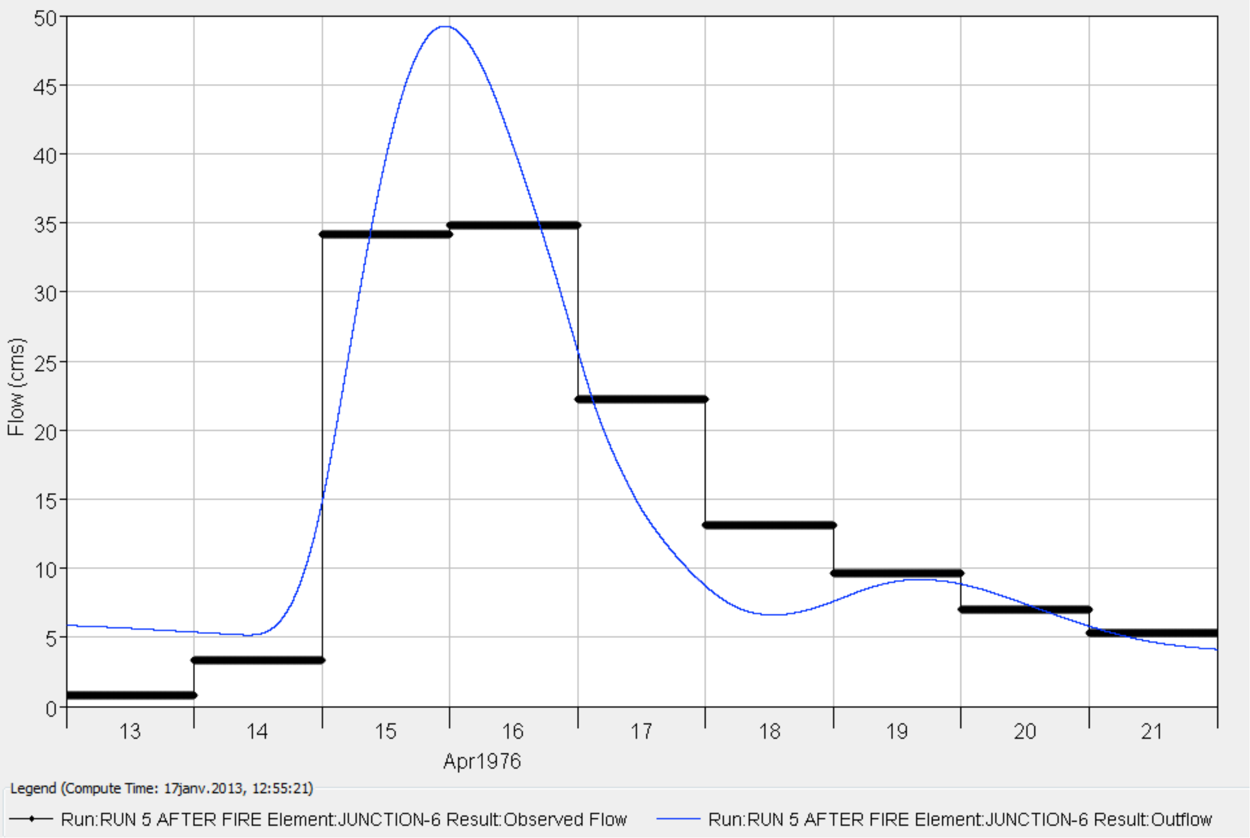

Figure 9 Second Event after forest fire

On comparing the curve of before and after fire, it is easy to comprehend that peak discharge has certainly risen up. From 44 cms, the discharge has risen to 49 cms depicting a rise of around 10 %. Apart from the rise in peak discharge and a slight increase in overall discharge, the nature of the result remains almost the same. The total observed outflow before forest fire was 57.3 mm while the total computed outflow after forest fire was 58.0 mm.

5.CONCLUSION:

This project focused on studying the runoff phenomenon of Giscle watershed before and after a forest fire. After GIS treatment in ArcGIS, a semi distributed hydrological model was set up for this purpose using HEC-HMS. Required parameters were either calculated or estimated and later calibrated for best fit in all situations. Precipitation and discharge data were available from 1975 to 2005 of which many instances were modeled and calibrated. Only two events were selected for analysis in this paper, representing heterogeneous conditions and their corresponding future scenarios were predicted before and after a forest fire. Remote sensing was also used for estimating parameters for forest fire scenarios.

We found that after forest fire, the peak discharge increases by 10 % to 50% although the time of concentration and other overall patterns of flow did not vary much. The soil moisture conditions, amongst other factors, were looked upon as a possible cause of discharge response. HEC-HMS was found to be sensitive to antecedent precipitation of event. There was a need to alter the Curve Number for wet and normal conditions, even after calibrating it.

The project has valuable implications in predicting runoff respons to forest fires. Correct estimations of parameters for achieving a curve close to the observed data can be done. However, storm modeling can be improved further by acknowledging the effect of antecedent soil moisture conditions.

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Acknowledgement:

The work for this publication was carried out thanks to an Erasmus Mundus Program (Erasmus Mundus Mobility with Asia) scholarship, and the authors express their gratitude to the European Commission and the EMMA consortium of the University of Nice Sophia Antipolis.

BIOGRAPHICAL NOTES

Shital Dhakal is a Geomatics Engineer from Kathmandu University, Nepal. He also went to University of Nice Sophia Antipolis, France for research in GIS and remote sensing as an Erasmus student under Prof. Dennis M. Fox. This article is result of the same study. At present he is a Graduate Research Assistant in Boise Center Aerospcae Laboratory. He is pursuing his Msc in Hydrological Sciences under Prof. Nancy Glenn in Geoscience department of Boise State University, Idaho, USA. He has obtained different honors and scholarships like Mahatma Gandhi scholarship and Erasmus Mundus among others for his excellent academic and research performance. He has successfully completed research projects in prestigious institution of Nepal, France and the US that includes Hydrological Modeling of Watersheds, Satellite Remote Sensing and GIS analysis, Land Cover assessment and change detection, Time series mapping, Establishment of Mapservers and Spatial tool development using object oriented Programming language. He has authored University Geo informatics Journal and is comfortable with four languages: English, Nepali, Hindi and French and is a registered Geomatics Engineer in Nepal.

Dennis M. Fox is a Geography Professor at the University of Nice Sophia Antipolis and member of the UMR 7300 CNRS laboratory. His research interests are in the fields of soil erosion, runoff, forest fire risks and land cover modeling.

CONTACTS

Shital Dhakal
Graduate Research Assistant
Department of Geosciences
Boise State University
1910 University Drive, Boise, ID
USA
Tel. +1- 9165968562
Email: ctaldigital@gmail.com
shitaldhakal@u.boisestate.edu