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# Hydrological Modeling of Upper OumErRabia Basin (Morocco), Comparative Study of the Event-Based and Continuous-Process HEC-HMS Model Methods

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## Abstract

Human population growth and land-use changes raise demand and competition for water resources. The Upper OumErRabia River Basin is experiencing high rangeland and matorral conversion to irrigated agricultural land expansion. Given Morocco's per capita water availability, River-basin hydrologic modelling could potentially bring together agricultural, water resources and conservation objectives. However, not everywhere have hydrological models considered events and continuous assessment of climatic data. In this study, HEC-HMS modelling approach is used to explore the event-based and continuous-process simulation of land-use and land cover change (LULCC) impact on water balance. The use of HEC-GeoHMS facilitated the digital data processing for coupling with the model. The basin's physical characteristics and the hydro-climatic data helped to generate a geospatial database for HEC-HMS model. We analyzed baseline and future scenario changes for the 1980-2016 period using the SCS Curve-Number and the Soil Moisture Accounting (SMA) loss methods. SMA was coupled with the Hargreaves evapotranspiration method. Model calibration focused on reproducing observed basin runoff hydrograph. To evaluate the model performance for both calibration and validation, the Coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE), Root Mean Square Error (RSR) and Percent Bias (PBIAS) criteria were exploited. The average calibration NSE values were 0.740 and 0.585 for event-based (daily) and continuous-process (annual) respectively. The $R^2$, RSR and PBIAS values were 0.624, 0.634 and +16.7 respectively. This is rated as good performance besides the validation simulations were satisfactory for subsequent hydrologic analyses. We conclude that the basin's hydrologic response to positive and negative LULCC scenarios is significant both positive and negative scenarios. The study findings provide useful information for key stakeholders/decision-makers in water resources.

**Keywords**

HEC-HMS Model, Land-Use and Land Cover Change, Soil Moisture Accounting (SMA), Upper OumErRabia Watershed

## 1. Introduction

Morocco like the most countries, experiences anthropogenic pressure and land-use dynamics particularly in and around mountainous basins [1] [2]. The interactions among land-uses, soil types, vegetation cover, climate variability and subsequent impact on hydrologic behaviors of watersheds have been studied by various researchers [3]-[9]. For the recent years, more people have settled around the OumErRabia (OER) due to favorable climate thus increasing the overall basin's population. This has consequently raised demand and competition for land, water and food resources [10] and thus leading to irrigated agriculture expansion. In the Upper OumErRabia River Basin (UOERRB), land-use and land cover change (LULCC) trends mainly involve the conversion of rangeland and matorral to irrigated agriculture and forestry. Land use and climate related studies done in Morocco for example [11]-[16] indicate a need for comprehensive mechanisms to conserve river waters and strategic planning to enable water availability for various competing uses. However, most recent land-use studies conducted in the OumErRabia (OER) basin are limited to water quality variation [17] and soil fertility impact [18].

The unsustainable land-use practice involving overgrazing, intense cultivation, over-exploitation of forests resources especially by the poor communities is pointedly shifting the hydrologic characteristics of the OUERRB. This has resulted in amplified runoff, erosion, sedimentation and degradation threatening the basin's water availability and reliability. The growing water demands, recurring and prolonged droughts associated with increasing climate variability and changing LULC are pointedly responsible for several water allocation challenges in the UOERRB [12]. Consequently, this has caused tension among water resources planning, developing and management authorities [19] towards allocation of the already scarce water resources among the increasing users [20] [21]. However, [22] noted limited or hardly any studies conducted to back up these insights.

The Morocco government and local authorities realize the disastrous impact of recurrent droughts on valued water resources. However, much of the government's effort has focused on sensitization of people about sustainable agricultural practices, water and related resources exploitation. The bearing of anthropogenic actions and climate variability studies is left less vibrant yet existing government policies are hardly implemented. According to an assessment study by [23], the distressing reduction in the basin's surface and ground water resources has been majorly linked to the regional climate variability in the previous decades. There is increased establishment of private wells within the watershed further adversely impacting the region's ground water resources. There is need for sustainable land-use and management plans and strategies especially at the moment when the OumErRabia Hydraulic Basin Agency locally known as *l'Agence du Bassin Hydraulique de l'Oum-Er-Rbia* (ABHOER) is extending irrigated area to fulfil the country's food demands and agricultural industries' raw materials needs. The ABHOER recognizes anticipated depletion of major available water resources owing to frequent droughts. However, the quantification of LULCC and impact-assessment of these processes on upstream river basin hydrology is still inadequate. The idea of hydrologic modelling [24] [25] [26] has been in use for quite time [24] [27] and is widely applied for instance in management of water resources [28], impact-assessment of LULCC and climate change on hydrology, water resource evaluation planning and allocation [16] [18] [29] [30] [31] [32] [33]. The HEC-HMS was selected for this study because it is a well-documented semi distributed hydrologic model flexible for both temporal and spatial scales and can be easily set-up and used with medium expertise [34]. Besides, the model usually requires less input calibration parameters.

In Morocco, HEC-HMS modeling approach has been used in recent studies such as [35]-[40]. Despite several national and regional studies evaluating hydrologic responses to LULCC and climate variability across the OER basin [9] [41], there is hardly any study that exclusively focuses on the UOERRB watershed accounting for local trends. Therefore, analyzing the impact of LULCC on hydrologic behavior of a watershed is vital for sustainable water resources management. Thus the objectives of the study were to: 1) explore and understand impact of land-use and land cover change (LULCC) on the water balance of the UOERRB using HEC-HMS-modelling approach; and 2) compare the performance of the event-based and continuous-process methods of the HEC-HMS model. We focus on the role of forests and agroforestry and the impacts of forest transition and forest degradation on the water availability in a case study area UOERRB.

## 2. Materials and Methods

### 2.1. Study Area Description

The OER River draining the middle Atlas and the north-western High Atlas [11] is a major source of hydroelectric power and irrigation for a significant population [42] and thus a key ecosystem to the Moroccan economy. The 550 km long main stream of the basin, covering 35,000 km$^2$ of the surface, is an agriculturally rich region containing 50 percent of Morocco's public irrigated agriculture [23] [43]. Nevertheless, the study focused on the 1049 km$^2$ UOERRB: a hydrological unit in the Middle Atlas with an equivalent length and perimeter of 119 km and 255 km respectively. The basin is located between latitude 33˚ and 33˚05' North and longitude 5˚01' and 5˚08' West, with basin outlet located at the Tarhat weather station. This basin contributes to the large watershed drained by the OER River whose source is at an altitude of 1800 m, 47 km of the Khénifra city (**Figure 1**). Geologically, the basin major soil substrates include limestone and dolomites, with the eastern boundary of Khénifra constituting Triassic formations. The Khénifra essentially comprises sandstones chists attributed to the ordovician with the limestone and dolomites located on flushing levels on the slopes. In the valleys, are the triassic red clays, constituting places of intense ravines mostly in the Middle Atlas margin slopes [44] [45]. At the Atlas mountain side, the basin experiences a Mediterranean climate characterized with high temperatures in the summer and warm autumn. There is an increasing rainfall distribution from downstream zones to upstream Atlas mountainous areas with significant spatial variation within the basin. The UOERRB's average annual temperature and rainfall are 16.1˚C and 600 mm respectively. The basin's mean minimum and maximum temperatures are 7˚C and 22˚C respectively. The minimum and maximum precipitation is 295 and 1300 mm respectively, with

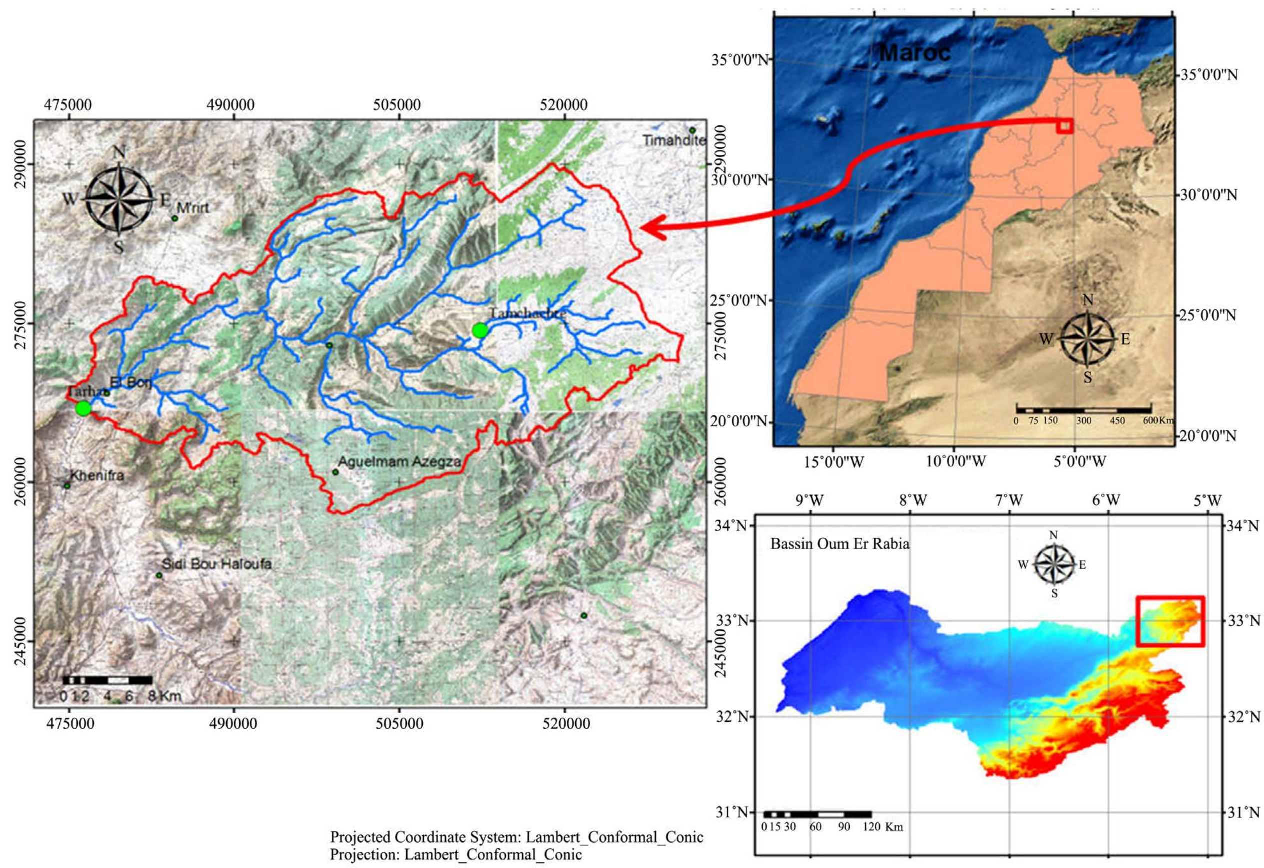


**Figure 1.** Location of upper oum er rabia river basin.

October to May being the wettest months contributing about 85% of the total annual rainfall. The basin's vegetation cover is characterized by the presence of matorrals with a predominance of olive, orange orchards and forests. The forest cover is mostly concentrated at the basin downstream. The basin's main economic activity is agriculture in the plains and irrigated fields. The basin's topography varies from 2400 m in the upstream south to 864 m in the downstream north.

## 2.2. Data, Collection and Analysis

### 2.2.1. HEC-HMS Model Inputs

Daily mean rainfall and hourly discharge data for the two gauging stations of Tarhat and Tamchachte (Figure 2) were collected from the ABHOER. The watershed has limited number of gauging and weather stations. Weather data was required for SMA continuous simulation of the watershed stream flow. However, due to lack of observed measurements, the weather data used for this study was estimated by interpolation on measured climate data from the 4 weather stations across the study area obtained from Global Weather Data for SWAT. The data was partitioned into sets for testing, calibration and for validation. Table 1 presents the model input data sources and processing.

### 2.2.2. Data Pre-Processing

The 2016 LULC map was derived from Lands at satellite imagery data (https://earthexplorer.usgs.gov/) with 2.5 m resolution. The image was classified into seven classes by using Arc-GIS 10.3 and photo-interpretation method [46]. The major LULC in UOERRB (Table 2 and Figure 3) is forest, matorral, arable

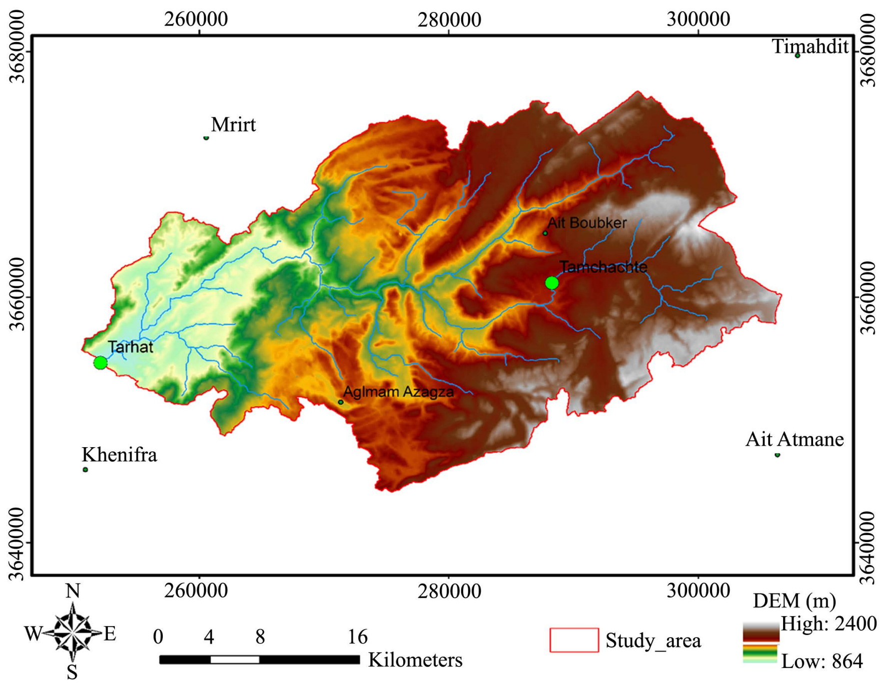


Figure 2. DEM of the UOERRB.

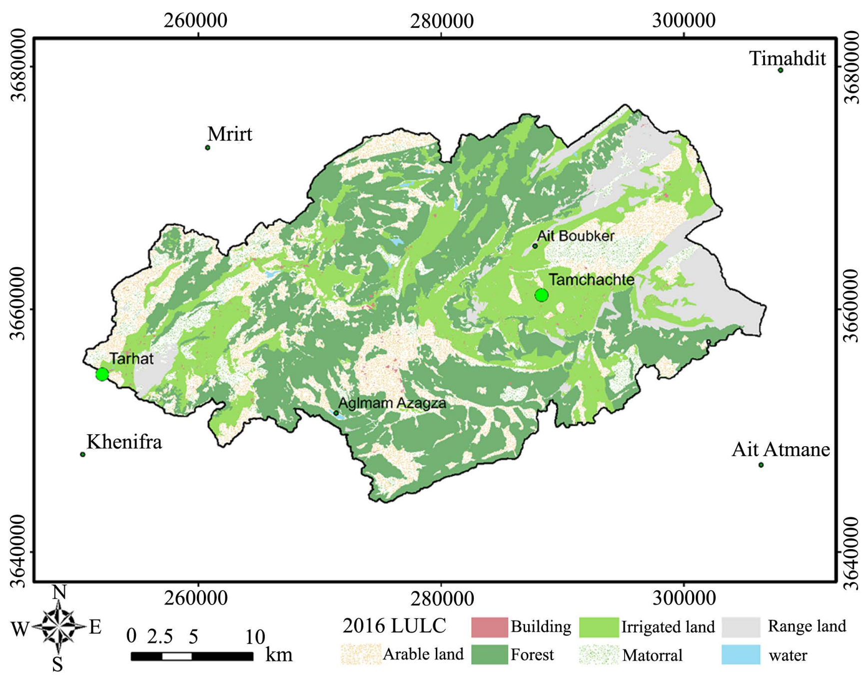


**Figure 3.** 2016 LULC map for the UOERRB.

**Table 1.** HEC-HMS model input data sources.

| Data type | Description (Source and Processing) |
|---|---|
| Climate | Rainfall intensity from ABHOER, Morocco. |
| Soils | Digital data from National Institute of Agronomic Research (Institut de La NationaleRecherrcheAgronomique), Pedology Regional Labaratory, Meknes (Labaratoire Region de Pedologie), Khenifra Rabat |
| Hydrologic (Stream flow) | Historical data sets from ABHOER, Morocco |
| Land use & Topography | Historical LU maps created/digitized from Lands at images (2002 and 2016) & DEM secured from USGS website. |
| Weather data | Interpolation on measured climate data from weather stations across the study area obtained from Global Weather Data for SWAT |

**Table 2.** Land-use classification in UOERRB.

| Land use | Surface Area (2016) | |
|---|---|---|
| | km² | Percentage |
| Arable land | 194.68 | 18.5 |
| Building | 4.05 | 0.4 |
| Forest | 419.97 | 39.9 |
| Irrigated land | 254.24 | 24.1 |
| Matorral | 84.72 | 8.0 |
| Range land | 92.88 | 8.8 |
| Water | 2.39 | 0.2 |
| Total | 1052.93 | 100 |

land and irrigated areas. The LULC and Hydrological Soil Group (HSG) maps were used to estimate the Curve Number (CN). The seven classes were later re-grouped into four classes for LULC change trend comparison and analysis with the 2002 LULC map. The basin area, river length, average slope value and CN were generated from HEC-GeoHMS.

The HSG map comprising of numerous soil textures was generated by digitizing from the pedological map of Khenifra region (Figure 4). From the two gauging stations of Tarhat and Tamchachte (Table 3), the daily rainfall and hourly streamflow data for periods of 1980-2015 and 1975-2011 respectively were collected. Weather data was obtained from the Global Weather Data for SWAT. The analysis of the hydro-climatic series involved checking, analysis and testing of the rainfall and hydrometric data. The precipitation and flow datasets are from Tamchachte (Upstream) and Tarhat (downstream). We consider a 35 hydrologic year precipitation records of 1980-2015. The analyses aimed at determining the hydro-climatic trends, extracting rainfall variability, and identifying the extreme rains expectedly resulting in the basin floods. From Figure 5, Tarhat and Tamchachte records, the wettest and driest months are November-February

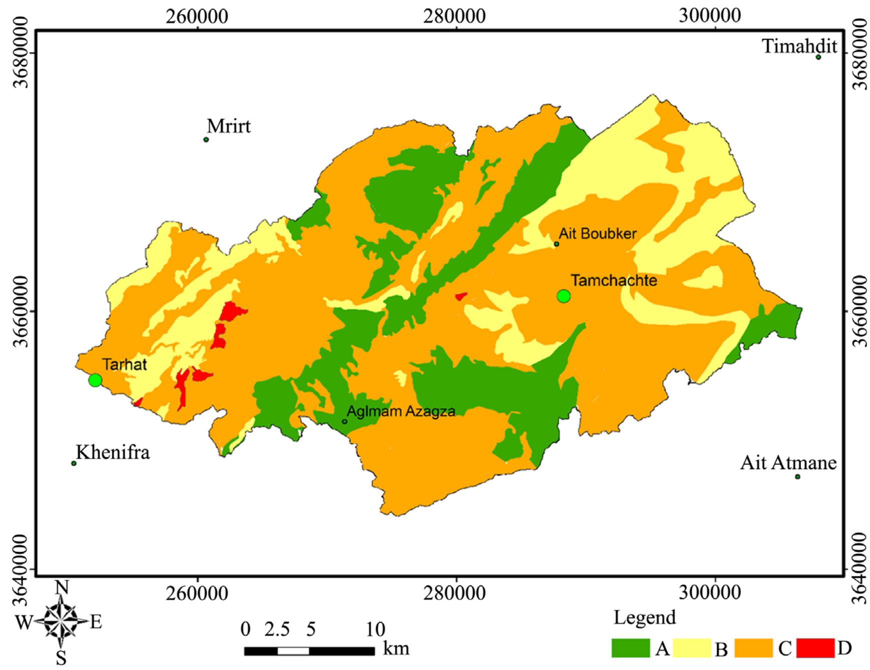


Figure 4. SCS-CN HSGs for UOERRB.

Table 3. Tarhat and Tamchachte locations.

| Stations | Station Reference | Coordinates (m) | | | Measurement period | |
|---|---|---|---|---|---|---|
| | | X | Y | Z | Precipitation | Flow |
| Tarhat | 4875 | 476,400 | 267,500 | 1036 | 1980-2015 | 1975-2011 |
| Tamchachte | 7708 | 512,330 | 274,340 | 1685 | 1980-2015 | 1975-2011 |

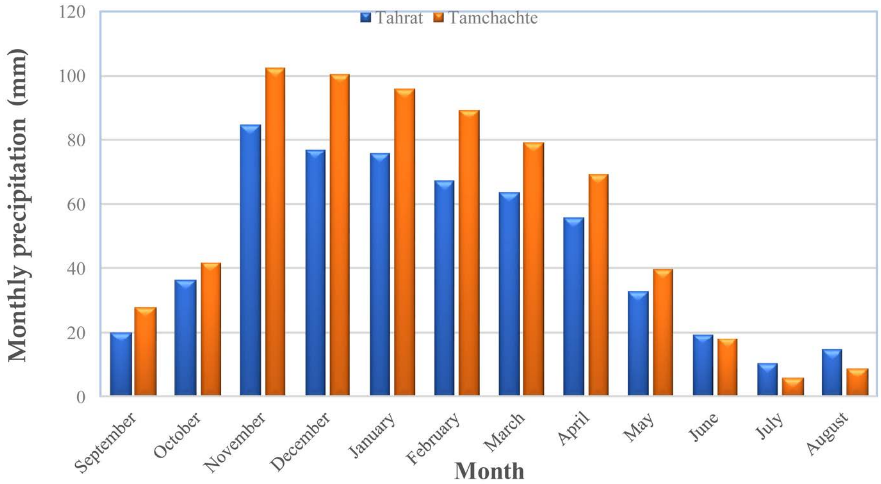


**Figure 5.** Tarhat and Tamchachte mean monthly precipitation, 1980-81 to 2014-15.

and June-August respectively. From both stations' records, significant rainfall amounts are recorded during the winter period. Precipitation distribution is determined by various factors with the Atlas mountain experiencing a cold sub-humid climate where some precipitation amounts are transformed into snow. The average annual rainfall was 679 mm and 557 mm for Tamchachte and Tarhat respectively.

## 2.3. Methods

The study is based on analysis of climate and stream flow data used for HEC-HMS model calibration and validation. Field visits were done to ascertain the current land use in the basin for the model setup. The major inputs for the HEC-HMS model included the DEM, soil data, land use and land management. The model was first calibrated and validated before simulating hydrologic processes scenarios. Multiple parameters were individually and manually adjusted (maximum-minimum) and the model was executed with identified reasonable ranges of the most sensitive parameters. **Figure 6** illustrates detailed research study methodology. Land-use mapping aimed at better understanding the vegetation trends and evolution for the period 1980-2016. We conducted on-screen digitization of the 2016 Lands at satellite to generate the 2016 LULC map. To study the detailed LULC change in UOERRB, the 2016 LULC was then reclassified for assessment and comparison with the existing 2002 LULC map. We aimed at linking and comparing the trends of vegetation cover and flood hydrographs. GIS software was utilized for digitization, integration, overlay and presentation of the spatial and non-spatial data of LULC change. Limited field inspections were performed using Global Positioning System (GPS) to ascertain accurate location data points for specific LULC classes. The 2002 LULC map [47] was developed by the maximum likelihood supervised classification (MLC) method for time series of Lands at bands and vegetation-soil–water (VSW) index detailed in [48].

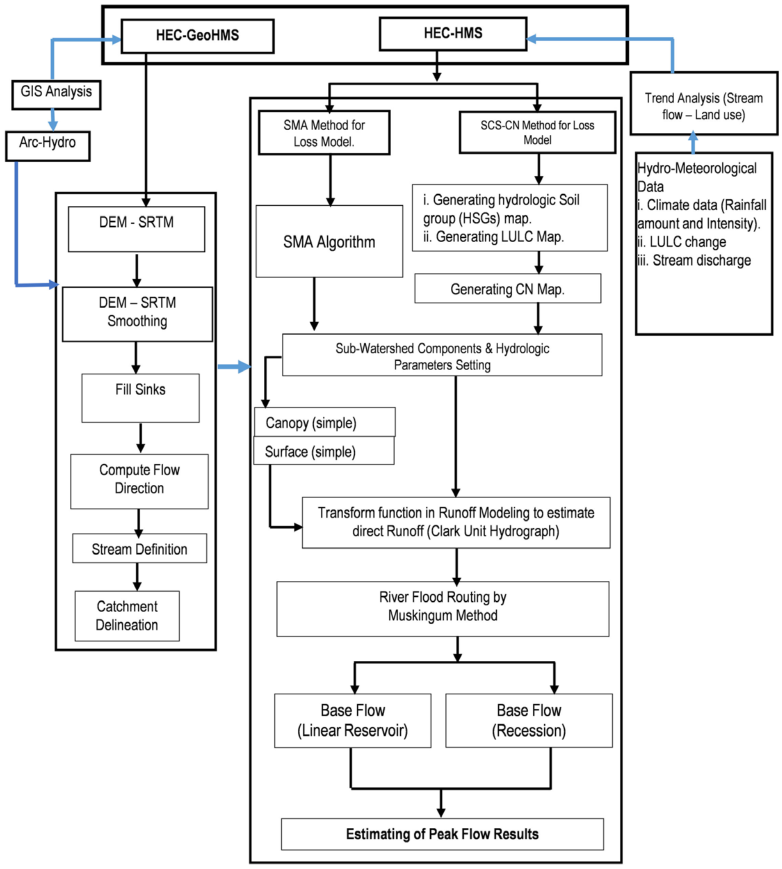


**Figure 6.** Study methodology.

### 2.3.1. The Modules of the HEC-HMS Model

The basin model (structural module of the basin) involves schematizing the catchment area in basic elements connected in form of a branched tree. HEC-HMS also known as Hydraulic Engineering Center-Hydrologic Modelling System is a development of the United States Army Corps of Engineers, designed to simulate the precipitation-runoff processes of watershed systems belonging to the famous HEC (HEC-RAS, HEC-GeoRAS, HEC-GeoHMS) [49] [50] [51]. The HEC-HMS offers the opportunity to represent all natural or artificial entities installed in a basin [50]. These elements influence the rainfall-flow transformation from sub-basins, outfalls to rivers and diversion water channels. The meteorological model's objective is to distribute the rainfall seized over whole study area. The HEC-HMS has seven different precipitation methods [52] for describing meteorology.

The methods include: Specified Hyetograph, the user is responsible for specifying time series data for sub-basins hyetograph at his disposal; Frequency Storm, is utilized in developing an event precipitation where the heights for different durations in the downpour have a coherent probability; Gages weights, weighted stations, uses a weighting coefficient for each precipitation measurement station; Inverse distance, applies the square inverse method of distances to compute the mean precipitation by assigning each station a weighting coefficient; Gridded precipitations method, introduces the precipitation in form of a grid and is designed to work with Modclark gridded transform; Standard Project Storm-distributes height of precipitation over a definite time interval; SCS Storm-applies to the daily precipitation depth one of project downpour distributions defined by the SCS; and HMR 52 storm-uses specified storm area and area duration precipitation curves to compute total precipitation depth.

The choice of best method depends on: modeler's objectives (determination of the project flow, hydrologic study of the watershed among others) and data availability that is the quantity (number of stations, measurement period, etc.); the quality (rain gauges, measure, etc.) of precipitation data; and the type of modeling envisaged. However, almost all methods have the specificity of homogeneous spatial and temporal rainfall depth distribution [53]. For this study, the Specified Hyetograph was adopted.

#### 2.3.2. Application of the HEC-HMS

We analyzed LULC change and climate variability relationship with hydrologic processes in the UOERRB. The HEC-HMS model was selected for the study as it is: widely used to assess hydrology and water availability in agricultural catchments around the world [54] [55] [56] [57]; open source and user-friendly in relations to handling input data [58]. HEC-HMS is a semi-distributed conceptual hydrological model potentially capable of spatio-temporal simulations of rainfall-runoff relations within a basin [59] [60]. The model can be used for computation of other downstream processes for instance channel routing and reservoir routing. Globally, HEC-HMS has fruitfully been applied in catchment modeling of several river basins [51] [61] [62]. In Morocco, there are several studies on the HEC-HMS application for instance [40] [63] [64] [65] [66]. Most of the studies assessed the impact of climate and land-use on hydrology at watershed level. Reference [22] established water availability of the OER basin using different models. *However*, *failure by most findings to account for LULCC and climatic variability effects sparked this research*.

#### 2.3.3. LULC Change Scenarios

We considered LULC maps of 2002 and 2016 for impact analysis. *Scenario* 1 is about a negative effect of deforestation and urbanization on peak flows. The CN values were estimated by increasing the surface of the urbanized/built up area, and assuming low forest density vegetation cover. For *Scenario* 2, we assumed that the pressure exerted on the forest cover with parallel actions to reforest the bare soils would result in clear dense forests. The percent conversion of arable land and rangeland to forest cover was assumed to be 80 and 20 respectively.

## 3. Results and Discussion

### 3.1. Event-Based and Continuous-Process Calibration and Validation of the HEC-HMS Model

The calibration was done for the event-based and the continuous-process methods and some of the results have been selectively presented. The event-based model calibration results for the 10 events between 1991-1996 and 2001-2006 are presented in **Table 4**. Out of the 10 events, the resultant hydrographs of six sampled events are presented in **Figure 7** and **Figure 8**.

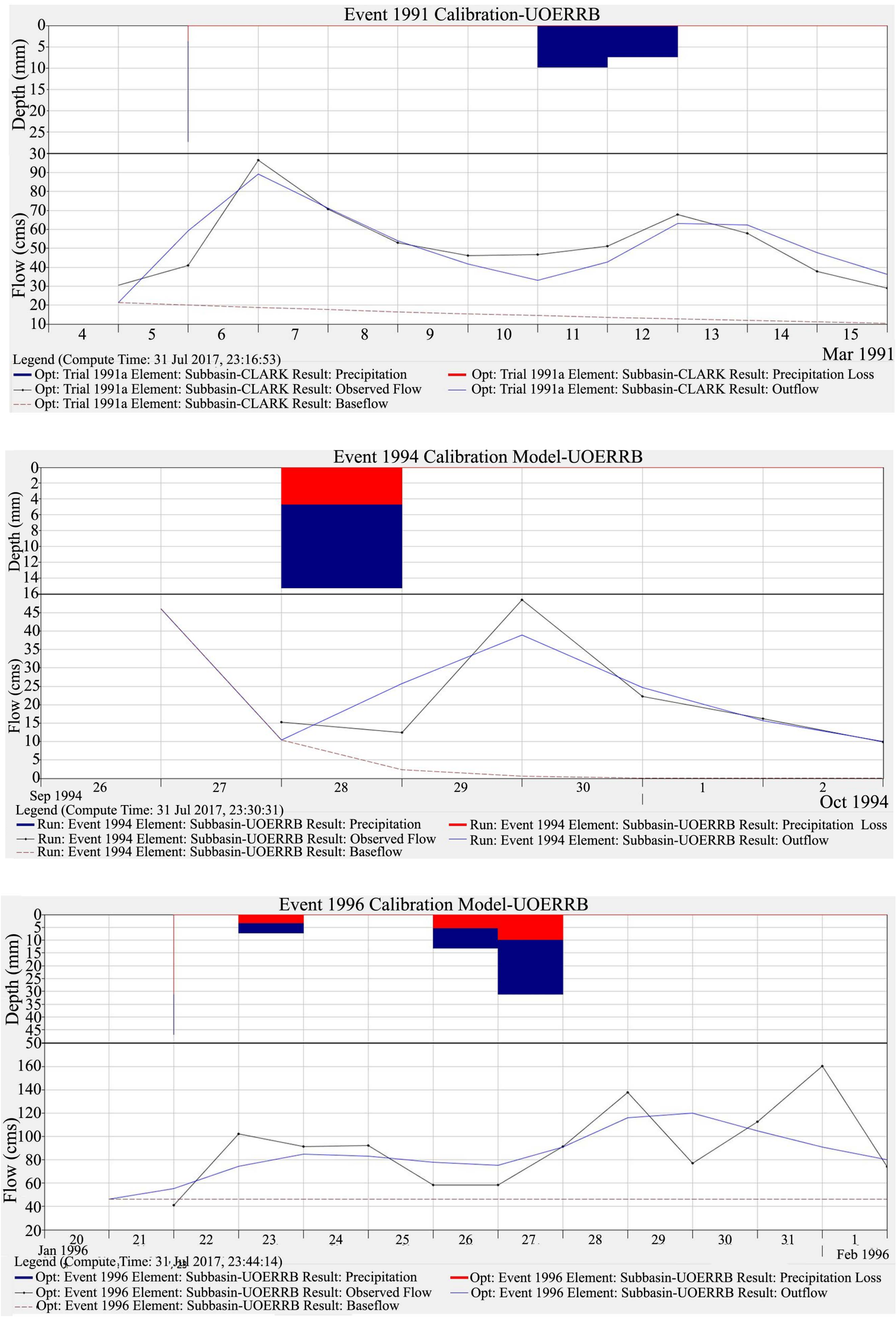


**Figure 7.** 1991-1996 events for model calibration.

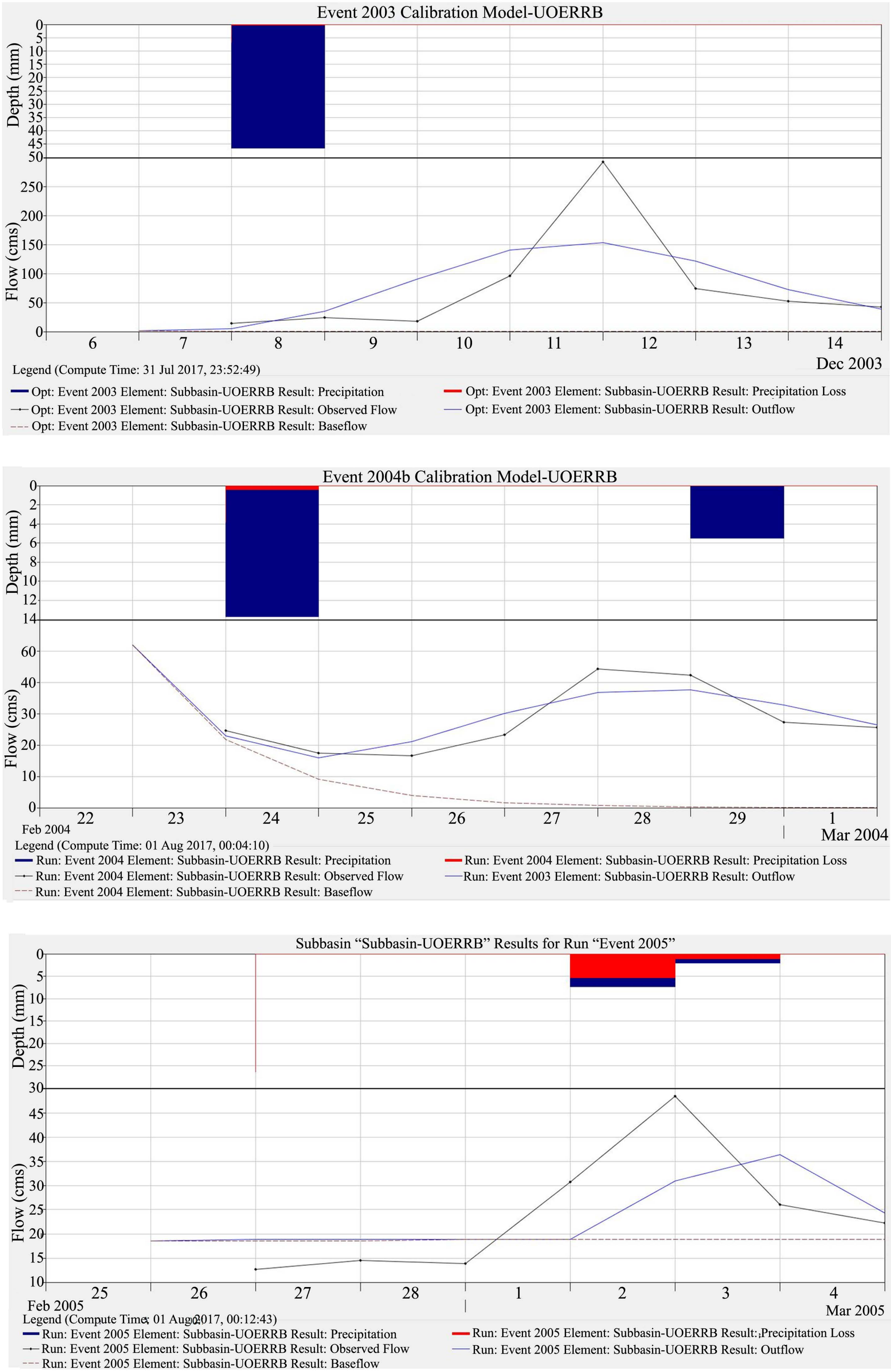


**Figure 8.** 2001-2006 events for model calibration.

Table 4. HEC-HMS event-based calibration models.

| Event | Date | | Volume (mm) | | Peak flow ($m^3/s$) | | difference | | Percent difference | | RMS Error ($m^3/s$) | Volume Residual (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End | Sim. | Obs. | Sim. | Obs. | Volume | Flow | Volume | Flow | | |
| 1 | 5-Mar-1991 | 16-Mar-1991 | 49.040 | 49.3 | 87.0 | 96.6 | −0.2 | −9.6 | −0.5 | −9.9 | 8.5 | −0.23 |
| 2 | 2-Apr-1992 | 10-Apr 1992 | 31.770 | 26.5 | 63.1 | 72.9 | 5.3 | −9.8 | 20.1 | −13.4 | 14.0 | −0.98 |
| 3 | 29-Jul-1993 | 2-Aug-1993 | 9.500 | 7.7 | 44.1 | 38.0 | 1.8 | 6.1 | 22.9 | 16.1 | 4.1 | −0.06 |
| 4 | 27-09-1994 | 3-Oct-1994 | 11.820 | 9.8 | 46.1 | 48.4 | 2.0 | −2.3 | 20.2 | −4.8 | 6.5 | 0.09 |
| 5 | 28-Dec-1995 | 1-Jan-1995 | 38.750 | 25.1 | 86.6 | 123.7 | 13.6 | −37.1 | 54.2 | −30.0 | 21.8 | 0.54 |
| 6 | 26-Jan-1996 | 30-Jan-1996 | 71.340 | 67.2 | 103.3 | 102.1 | 4.1 | 1.2 | 6.1 | 1.2 | 8.4 | 0.19 |
| 7 | 13-Nov-2002 | 18-Nov-2002 | 3.510 | 3.2 | 8.8 | 8.6 | 0.3 | 0.2 | 10.0 | 2.3 | 0.1 | 0.00 |
| 8 | 7-Dec-2003 | 15-Dec-2003 | 51.420 | 48.8 | 150.2 | 293.3 | 2.6 | −143.1 | 5.3 | −48.8 | 57.4 | 2.42 |
| 9 | 23-Feb-2004 | 2-Mar-2004 | 0.760 | 0.6 | 0.8 | 1.3 | 0.2 | −0.5 | 31.0 | −38.5 | 0.2 | 0.00 |
| 10 | 26-Feb-2005 | 5-Mar-2005 | 13.630 | 13.0 | 36.8 | 48.4 | 0.7 | −11.6 | 5.2 | −24.0 | 8.9 | −0.09 |
| | Average | | 28.154 | 25.1 | 62.7 | 83.3 | 3.0 | −20.7 | 17.5 | −15.0 | 13.0 | 0.19 |

During model calibration, ranges of parameters were adopted. Table 5 summarizes the range of event-based parameters used during event-based model calibration.

Event-based validation was based on precipitation and flow data of 2006-2011 and a sample of the resultant hydrographs is presented in Figure 9. Table 6 summarizes the volume and peak flow for the 3 selected validation events. The 1991-2001 continuous-process calibration hydrograph is shown in Figure 10.

The model validation results with the 2001-2011 precipitation and stream flow data are presented in Table 7. A comparison of observed and simulated output from the SMA continuous validation modelling of daily flow series for the UOERRB is presented in Figure 10.

#### 3.1.1. Model Performance Evaluation

The calibration and validation performance results of the HEC-HMS at the Tarhat gauging station, the UOERRB outlet indicate good predictability of both the event-based and continuous-process model. Table 8 summarizes the performance of the 10 calibration events considered for the study. The average NSE, $R^2$, RSR and PBIAS were 0.697, 0.474, 0.828, and −8.128 respectively.

The performance rating of the three validation events is depicted in Table 9 with average NSE, $R^2$, RSR and PBIAS values of 0.581, 0.692, 0.596, and 3.213 respectively.

For the continuous-process, the NSE, $R^2$, RSR and PBIAS for bothcalibration and validation models are presented in Table 10.

#### 3.1.2. Simulation of Future Land-Use and Land Cover Scenarios

A simple future LULC distribution pattern in *Scenario* 1, used as a direct input to the calibrated event No. 6 generated various CNs that resulted in numerous volumes and peak flows (Table 11). Similarly, *Scenario* 2 simulation (increase in forest cover) resulted in volume and peak flow values presented in Table 12.

**Table 5.** Range of calibration parameter values, 1991-1996 and 2001-2006.

| Parameter | Units | Range | Average |
|---|---|---|---|
| Clark Unit Hydrograph - Storage Coefficient | Hr. | 4.0 - 82.0 | 42.0 |
| Clark Unit Hydrograph - Time of Concentration | Hr. | 13.3 - 138.0 | 131.5 |
| Recession - Initial Discharge | $m^3/s$ | 4.0 - 52.0 | 10.9 |
| Recession - Recession Constant | | 0.2 - 1.0 | 0.9 |
| Recession - Threshold Discharge | $m^3/s$ | 0.4 - 39.5 | 0.1 |
| SCS Curve Number - Curve Number | | 36.0 - 99.0 | 48.5 |
| SCS Curve Number - Initial Abstraction | Mm | 0.00 - 2.25 | 1.0 |

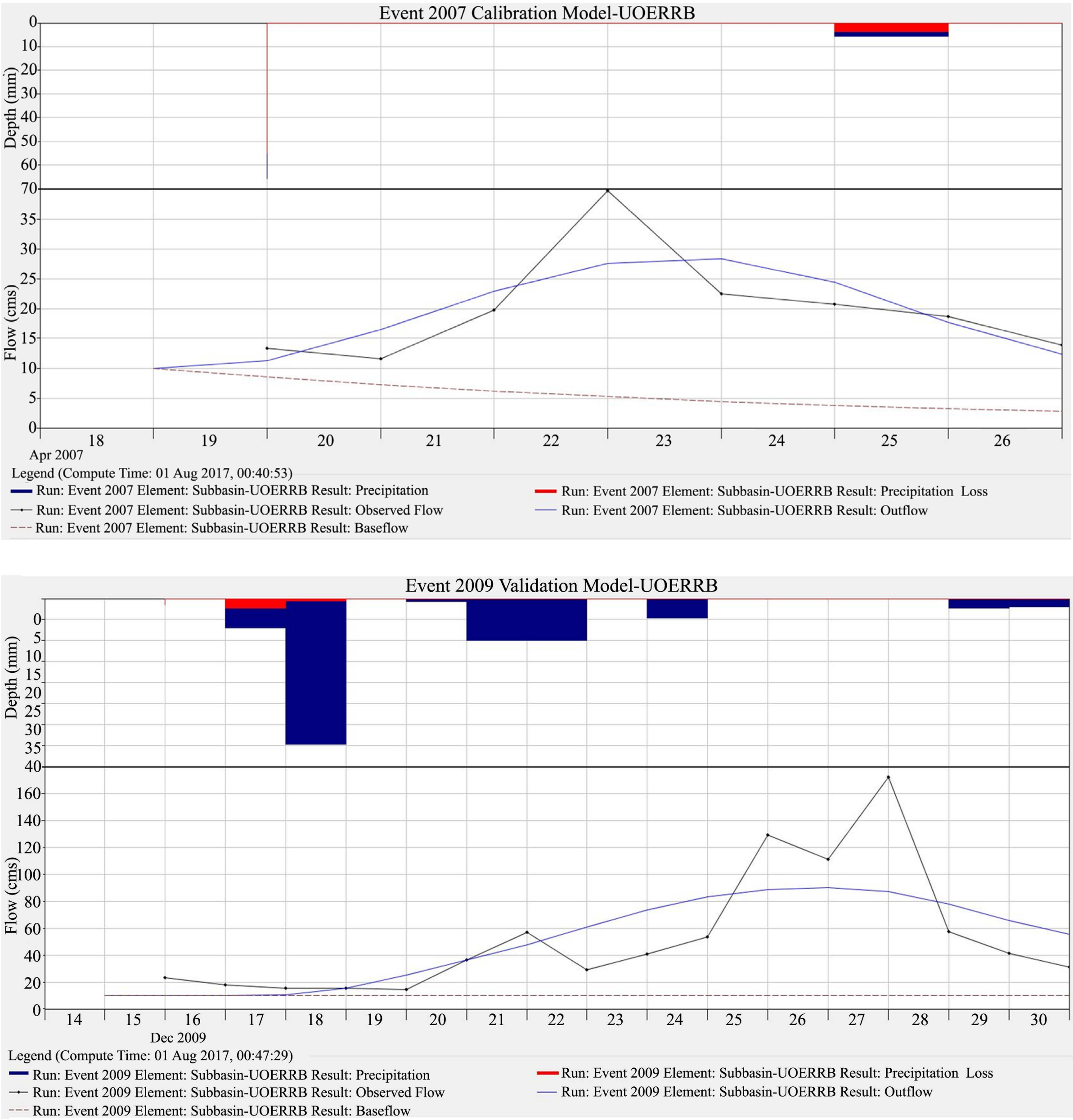


**Figure 9.** 2006-2011: Events for model validation.

**Table 6.** Validation model event results for Tarhat, 2006-2011.

| Event | Date | | Volume (mm) | | Peak flow ($m^3/s$) | | Difference | | Percent difference | | RMS Error ($m^3/s$) | Volume Residual (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End | Sim. | Obs. | Sim. | Obs. | Vol. | Qmax | Volume | Flow | | |
| 1 | 23-Jan-06 | 31-Jan-06 | 13.7 | 12.8 | 37.7 | 40.4 | 0.8 | −2.7 | 6.5 | −6.7 | 6.7 | −0.5 |
| 2 | 19-Apr-07 | 27-Apr-07 | 13.2 | 12.6 | 28.4 | 39.7 | 0.6 | −11.3 | 4.5 | −28.5 | 5.1 | 0.2 |
| 3 | 15-Dec-09 | 31-Dec-09 | 67.7 | 68.5 | 90.5 | 172.6 | −0.8 | −82.1 | −1.1 | −47.6 | 29.1 | −1.2 |
| Avg. | | | 31.5 | 31.3 | 52.2 | 84.2 | 0.2 | −32 | 3.3 | −27.6 | 13.6 | −0.5 |

**Table 7.** Continuous-process calibration and validation.

| Continuous-process | Date | | Volume (mm) | | Peak flow ($m^3/s$) | | Difference | | Percent difference | | RMS Error ($m^3/s$) | Volume Residual (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Start | End | Sim. | Obs. | Sim. | Obs. | Volume | Qmax | Volume | Flow | | |
| Calibration | 1-Sep-91 | 31-Aug-01 | 3672.5 | 4421.3 | 130.8 | 160.4 | −748.8 | −29.6 | −16.9 | −18.5 | 8.0 | −748.8 |
| Validation | 1-Sep-01 | 31-Aug-11 | 4094.2 | 4775.4 | 75.8 | 293.3 | −681.2 | −217.5 | −14.3 | −74.2 | 13.4 | −700.7 |

**Table 8.** Event-based calibration performance rating.

| Event | Start date | End date | NSE | $R^2$ | RSR | PBIAS |
|---|---|---|---|---|---|---|
| 1 | 5-Mar-91 | 16-Mar-91 | 0.783 | 0.784 | 0.465 | 0.414 |
| 2 | 2-Apr-92 | 10-Apr-92 | 0.525 | 0.394 | 0.790 | −9.963 |
| 3 | 29-Jul-93 | 2-Aug-93 | 0.826 | 0.014 | 1.177 | −37.114 |
| 4 | 27-09-1994 | 3-Oct-94 | 0.718 | 0.155 | 1.099 | −28.455 |
| 5 | 28-Dec-95 | 1-Jan-95 | 0.561 | 0.606 | 0.400 | 0.285 |
| 6 | 26-Jan-96 | 30-Jan-96 | 0.895 | 0.708 | 0.648 | 7.297 |
| 7 | 13-Nov-02 | 18-Nov-02 | 0.996 | 0.899 | 1.173 | 0.781 |
| 8 | 7-Dec-03 | 15-Dec-03 | 0.506 | 0.517 | 0.700 | −0.701 |
| 9 | 23-Feb-04 | 2-Mar-04 | 0.775 | 0.282 | 1.034 | −11.003 |
| 10 | 26-Feb-05 | 5-Mar-05 | 0.381 | 0.384 | 0.789 | −2.824 |
| Average | | | 0.697 | 0.474 | 0.828 | −8.128 |

**Table 9.** Event-based Validation performance rating.

| Event | Start date | End date | NSE | $R^2$ | RSR | PBIAS |
|---|---|---|---|---|---|---|
| 1 | 23-Jan-06 | 31-Jan-06 | 0.600 | 0.906 | 0.497 | 7.598 |
| 2 | 19-Apr-07 | 27-Apr-07 | 0.598 | 0.608 | 0.628 | 0.349 |
| 3 | 15-Dec-09 | 31-Dec-09 | 0.546 | 0.563 | 0.663 | 1.691 |
| Average | | | 0.581 | 0.692 | 0.596 | 3.213 |

**Table 10.** Continuous-process model performance for Tarhat station.

| Continuous-process | Start date | End date | NSE | R2 | RSR | PBIAS |
|---|---|---|---|---|---|---|
| Calibration | 1-Sep-91 | 31-Aug-01 | 0.598 | 0.637 | 0.622 | 16.946 |
| Validation | 1-Sep-01 | 31-Aug-11 | 0.341 | 0.361 | 0.800 | 14.683 |

**Table 11.** Predicted CN, max flow and discharge volume for *Scenario* 1.

| Percent forest reduction | CN | Peak flow ($m^3/s$) | | Runoff Volume (mm) | |
|---|---|---|---|---|---|
| | | Simulated | Observed | simulated | observed |
| 10 | 71 | 80.4 | 137.7 | 20.09 | 29.24 |
| 20 | 72 | 81.3 | 137.7 | 20.22 | 29.24 |
| 50 | 74.9 | 84.3 | 137.7 | 20.64 | 29.24 |

**Table 12.** Predicted CN, max flow and discharge volume for *Scenario* 2.

| Percent forest increase | CN | Peak flow ($m^3/s$) | | Runoff Volume (mm) | |
|---|---|---|---|---|---|
| | | Simulated | Observed | Simulated | Observed |
| 10 | 69.3 | 78.8 | 137.7 | 19.87 | 29.24 |
| 20 | 68.5 | 78.2 | 137.7 | 19.78 | 29.24 |
| 50 | 66.3 | 76.4 | 137.7 | 19.53 | 29.24 |

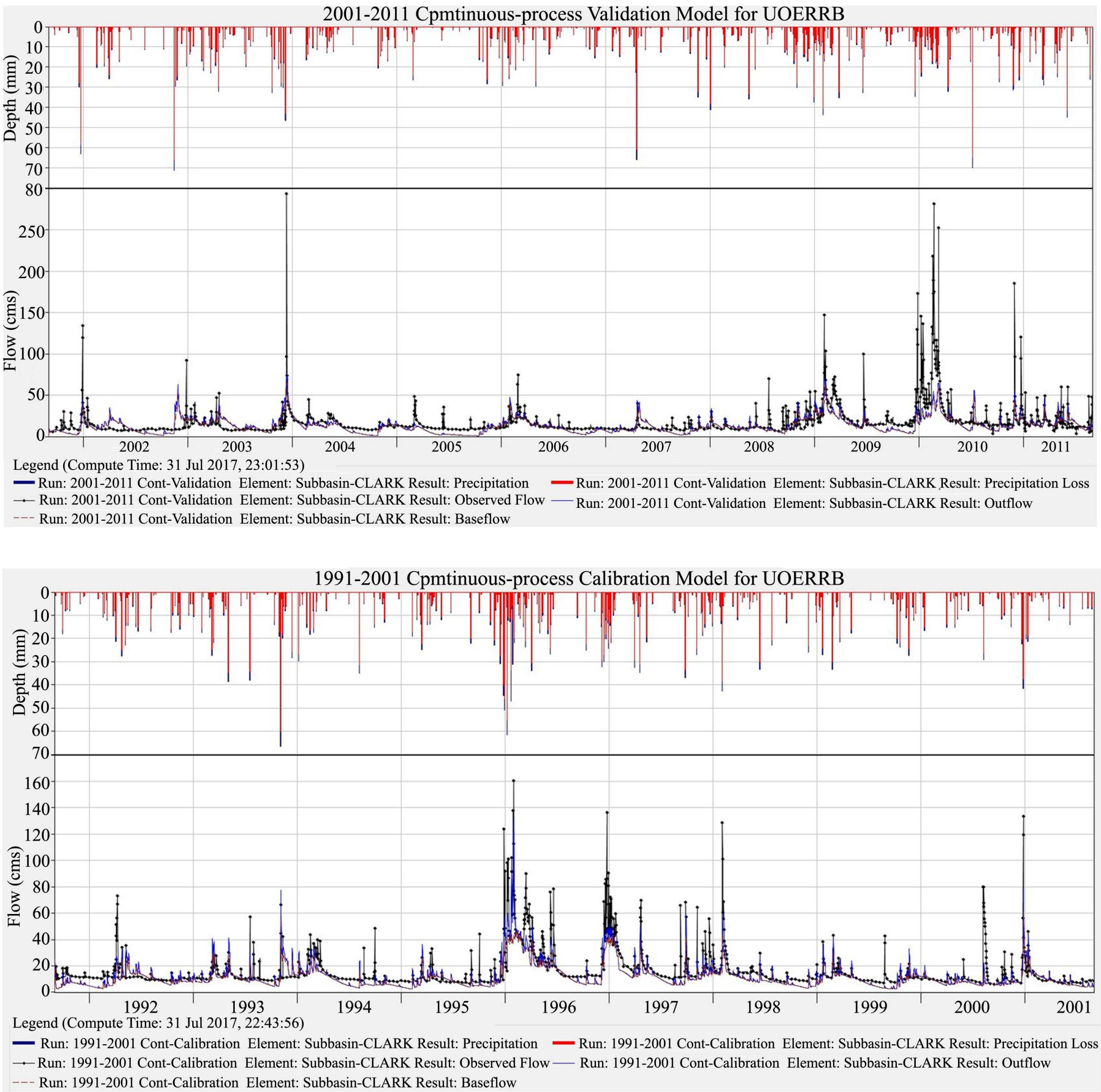


**Figure 10.** Continuous-process calibration (1991-2001) and validation (2001-2011).

### 3.1.3. Typical Peak Streamflow Trends and Duration

Vegetation plays an attenuating and important role during flood periods. An increase in vegetation results in a corresponding delay in the surface runoff thus the flood point is attenuated. From Table 13 and Figure 11, a decrease in vegetation cover reflected in CN increase directly resulted in peak flow increase.

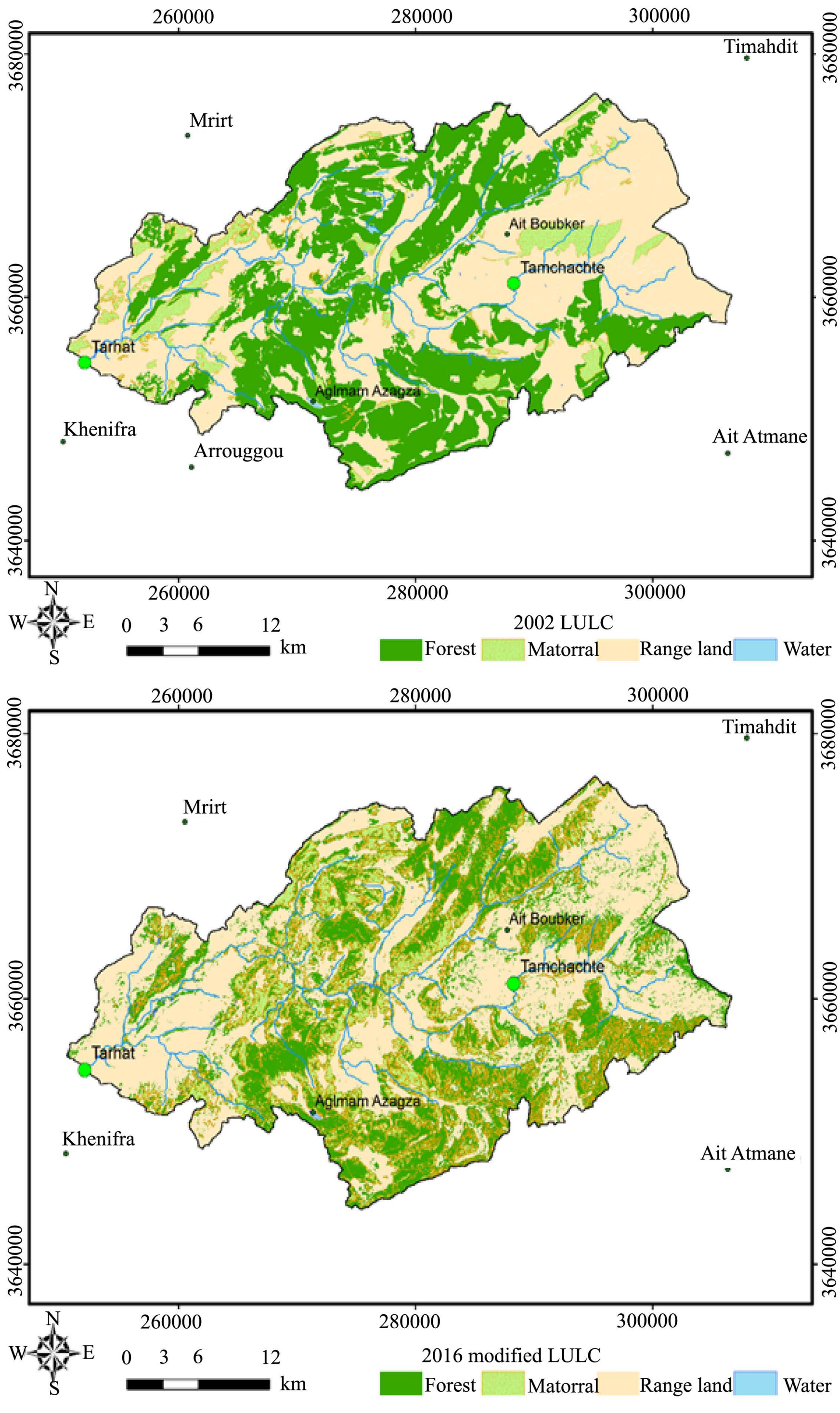


Figure 11. 2002 and 2016 LULC comparison maps for UOERRB.

**Table 13.** 2002 and 2016 land use volume and peak flows comparison.

| Land use | CN | Peak flow ($m^3/s$) | | Run off Volume (mm) | |
|---|---|---|---|---|---|
| | | Simulated | Observed | simulated | Observed |
| 2002 | 67.8 | 77.6 | 137.7 | 19.7 | 29.24 |
| 2016 (Digitized) | 70 | 79.5 | 137.7 | 19.96 | 29.24 |
| 2016 (Modified) | 68.8 | 78.4 | 137.7 | 19.81 | 29.24 |

Climate variability was assessed as the difference between the flow rates of 1980 and 2011. The stream flow rates increased by 1261 $Mm^3$ within this period. The total flow difference between 1981 and 2011 hydrologic years was 202 $Mm^3$. Temporally, although climate variability has accelerated an increase in the basin flows, there was a clearly observed decreasing trend of flows in 2001. The decrease was a result of a lower rainfall in the basin. From 1975-2011, the average water flow was approximately 684 $Mm^3$/year with a maximum of 5692 $Mm^3$/year and a minimum of 265 $Mm^3$/year.

## 3.2. Discussion

The basin characteristics such as the elongated shape delays the flow of water to the outlet during a flood period and thus justify the results of the HEC-HMS model. We observed strong annual streamflow variation and the average inter-annual monthly flow was 21 $m^3/s$. Variation in basin precipitation was found influential to streamflow trends thus the positive correlation between precipitation and peak flows. The changes in precipitation are directly reflected in surface runoff pattern (magnitude and frequency) of peak flows for the study period.

### 3.2.1. Land-Use and Land Cover Change Impact Analysis

We focused on determining the major LULCC based on the 2002 and 2016 LULC maps. The forest cover increased by 22.4 percent between 2002 and 2016 indicating a remarkable increase in the basin's vegetation cover. This increase can be explained by the significant annual average rainfall increase from 690 to 714.1 mm over the period 2002-2016. Besides, the increased basin's re/afforestation rate in the recent decades has also arguably offset land degradation. On a contrary, there is a remarkable decrease in area covered by matorral between the two years. However, this study is strictly limited to changes in LULC pattern (**Figure 11**) rather than LULC analyses. From the results of *Scenario* 2, considering a proposed 50 percent increase in forest cover, the simulated peak flow decreased by 9 percent. From the results of the two scenarios of vegetation cover trends, there is positive and negative CN effect and thus hydrologic response of the basin. Considering the proposed LULC change *Scenario* 1, the increase in simulated peak flows reflects high vegetation cover degradation. The results are sensitive to the CN parameter with the same rainfall data. However, flooding is not very sensitive to the variation of this parameter. CN value analysis is physically expressed by the modification of dense vegetation into less dense (thin) vegetation. This partly explains the increased surface runoff generation from continued felling of trees in the basin.

From the LULC maps, forest cover accounts for 32.6 percent of total watershed area in 2002 compared to the 39.9 percent in 2016. The expansion rate of forest land attributed to reforestation directly affects the magnitudes of runoff volume and peak flows as presented in scenarios. The information on LULC change serves as a vital tool in decisions making and policy formulation by the local authority (ABHOER). From the 2016 LULC map, we categorize the UOERRB as an agricultural basin and propose irrigated land expansion to be sustainably balanced with re/afforestation to offset the likely tremendous impact on the basin's available water resources.

Considering the 10 calibration events, the performance evaluation ratings were generally good. However, events 3 and 4 produced relatively poor results. This is reflected in better average validation performance rating values compared to the calibrated ones. Out of the 10 calibration events, only one had an NSE value less than 0.5 indicating a very good performance accordingly. The calibration results indicate an adequately done process where average and maximum NSE values are 0.697 and 0.996 respectively. In general, most of the RSR and PBIAS values are considered good according to performance ratings. Despite achieving relatively less acceptable RSR values, the overall performance is considered satisfactory. Generally considering average performance values, the calibration model was accurate.

The ratings indicate a strong correlation between simulated and observed runoff volumes and peak discharges for all chosen events. From the event-based validated model (2006-2011), the simulated daily hydrograph matched with observed stream flow with an underestimation of peak flows. The event-based validation performance results obtained were satisfactory and acceptable to simulate the basin runoff for future LULC pattern projection.

#### 3.2.2. Continuous-Process Simulation Analysis and Scenario

The 1991-2001 continuous process calibration model comparisons between the observed and simulated flow rates hydrographs at the Tarhat station are presented in **Figure 10**. The calibration results indicate a good generated hydrograph thus an adequately done process. The performance rating values indicate a strong relationship between observed and simulated values achieved during calibration. However, there was a multitude of spikes during the calibration period. The simulated model timing of the peak matches well, but the peak flow is underestimated by 18.5%. Besides, there is under prediction of low flows for the simulated model. Considering the continuous-process simulation, the model fairly reproduced the observed hydrographs for 1991-2001. However, there are some scatters in peak flows. One can conclude that the calibrated HEC-HMS model simulates the runoff and it can be used to evaluate the effects of LULC change on runoff generation in the UOERRB.

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Similarly, comparison of the simulated and observed runoff hydrographs with the continuous-process method based on the same performance criteria, indicate good model results. Relative to calibration, the event-based model validation performance during validation is generally reduced. However, the results remain adequately acceptable with average NSE, $R^2$, RSR and PBIAS values of 0.581, 0.692, 0.596, and 3.213 respectively. For 2001-2011 continuous-process validation, the simulated flow values fairly correlate with the observed values. However, out of the 4-performance rating, the model satisfactorily fulfilled only the RSR and PBIAS. Besides, the NSE and $R^2$ of 0.341 and 0.361 respectively are close to 0.400 considered satisfactory. Therefore, the prediction of the validation model can be considered acceptable.

#### 3.2.3. Sensitivity Analysis of SCS-CN and SMA Parameters

From the model results, imperviousness; simple canopy-max storage; SMA's soil storage, tension storage, and maximum infiltration were the most sensitive parameters for estimating runoff by continuous-process simulation. During the non-winter months, the basin follows a wetting and drying sequence. However, this study assumed only dry periods during SMA continuous-process modelling. The calibrated GW-1 storage depth varied between 1.45 and 4.5 mm, while the GW-2 storage depth values ranged between 22.5 to 36 mm. The GW-1 storage coefficient varied between 18 and 85 hours. The GW-2 storage coefficient values ranged from 36 to 1485 hours. This variability clearly indicates a non-uniformity behavior between the interflow and groundwater flow throughout the water years [67]. Overall, the model is reliable to reproduce stream flows in the basin and the abnormalities in the results can be explained by the impact of precipitation uncertainties.

Considering the UOERRB, the measured precipitation of Tarhat and Tamchachte stations are considered non-representative due to high spatial variability in the basin rainfall. The HEC-HMS results obtained are similar to those of [40] [64] [65] [68] [68]. The mean NSE values for calibration and validation were 0.65 and 0.62 [64] and 0.74 and 0.73 [40]. The average NSE values were 0.99 for studies by [65] [69]. However, all these studies were carried out from other basins rather than UOERRB and most of the research studies were event-based.

In SCS-CN event-based model, initial soil moisture is normally classified into dry, moderate and wet conditions that may lead to increased simulation error. However, the initial soil moisture content was not measured in field. The study was based on AMC-II conditions and [70] notes difficult in correct selection of CN values from available handbook tables. Development of SMA continuous-process model requires several parameters for quality model outputs. However, most of these parameters were not readily available and were thus deduced from published research. The Lands at images used in this study were taken during different weather seasons and thus separate analysis of these images could yield precise representative LULC and better SMA validation model results.

## 4. Conclusion

In this study, the HEC-HMS modelling approach is used to explore the event-based (SCS-CN) and the continuous-process (SMA) simulation of land-use and land cover change (LULCC) impact on water balance. The HEC-HMS performance results were good with average calibration NSE values of 0.740 and 0.585 for event-based and continuous-process respectively. We argue that the basin's hydrologic response to positive and negative LULCC scenarios is significant. The HEC-HMS model simulation of the daily stream flow at basin outlet was considered satisfactorily good and acceptable. However, there is a slight under and over prediction of the high flows. Like with hydrologic research, the results of the study should be carefully interpreted with some measure of uncertainty. The results of the model indicated that an increase in forest cover and irrigated agricultural land expansion negatively impacted the peak flow and river stream discharge volumes. This hydrological modeling could also be used to facilitate subsequent hydrological studies within the region. The outcomes of this study can be vital in the future flood prediction and warning. For further development of this study, we recommend: detailed LULC survey within the basin to verify the HEC-HMS; adopting field-based data approaches to establish the SMA parameters; localized PET measurements to give more representative results; and evaluating significance of snow effect on stream flows.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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