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Rainfall-Runoff Modelling using Mike11 Nam for SHER River Basin Model

Arpit Yadav, H.L. Tiwari, R.V. Galkate

Abstract: ***The runoff generation process is highly complex, nonlinear, dynamic in nature, and affected by many interrelated physical factors. Accurate runoff estimation is carried out for effective management and development of water resources. In present study, MIKE 11NAM rainfall runoff(R-R) model were used to develop R–R relationship. The model was developed using discharge data observed for 07 years at the Belkhedi G/d site, Narmada basin, Madhya Pradesh. The NAM model was calibrated for the period 2009 to 2012 and validated for the period 2013 to 2015. The input data required by the model was precipitation, potential evapotranspiration and observed discharge. The reliability of MIKE 11 NAM was evaluated based on coefficient of determination (R^2), Nash–Sutcliffe Efficiency Index (EI), sum of square error and root mean square error (RMSE). The coefficient of determination of model calibration and validation were observed to be 0.859 and 0.83 respectively. Efficiency Index during calibration and validation was found to be 73.7% and 67.5% respectively which is a good agreement. During sensitivity analysis model was found sensitive to the parameter like Lmax, CQOF, CKIF, CK_{12}, and TOF, out of which CQOF and CK_{12} was found highly sensitive modelling. The NAM model was found to be efficient in the runoff simulation and the model can be further employed for the deeper hydrological studies of the basin.***

Key words: ***MIKE11 NAM, Rainfall runoff modelling, Sher river basin, sensitivity analysis, calibration, validation.***

I. INTRODUCTION

For advancement and survival of society, water is an overwhelming inexhaustible asset. Evaluation and the operation of water assets with respect to quality and amount is basic for appropriate use of these assets. Around the globe there is an exceptional increment in water emergency brought about by floods, population rapid increment, urbanization, climatic changes, ground water contamination and misuse[2,3]. Due to increase in population water demand is going up day by day but the abundance of fresh water on earth remains same. Hence, to satisfy the prerequisite demand of fresh water there is a need of legitimate administration by utilizing the most recent innovation developed in the field of water resources.

In our present study we are developing the relation between rainfall and runoff using model. It is not easy to estimate the runoff flowing down the natural streams[5,7]. To know the amount of water flowing through the streams, indirect approaches are taken to estimate the runoff by assessing the amount of rainfall in the catchment area. Runoff is simulated using the input rainfall data and characteristics of the watershed by a suitable mathematical model. Thus rainfall runoff modelling[8]. Rainfall-runoff modelling therefore forms an essential component of many hydrological studies for water resource planning[6,9]. For the flood forecasting we need to develop rainfall runoff model so as to predict the flow for prolonged period.

II. STUDY AREA

Our study area is the Sher river basin which is the tributary of Narmada River, Madhya Pradesh. Sher joins the Narmada River from the left bank. The gauge-discharge site of Sher basin lies at 22.92° North latitude and 79.33° East longitude. The rainfall in this area is mainly because of southwest monsoon which starts from the mid of June and ends till last week of September. The climate condition of the study area, particularly in December and January, are extremely cold, whereas summer month of May is extremely hot. The mean annual rainfall of study area is about 1161.3 mm. The maximum mean temperature during the hottest months (May and June) is around 42 ^{0}C and minimum during the month (January) is 8.2 C. Norma daily mean maximum monthly is 33.2 C and daily mean minimum monthly is 18.1 C. The relative Humidity is high during the month of August which may exceed 90% sometime and lowest is 39% in April.

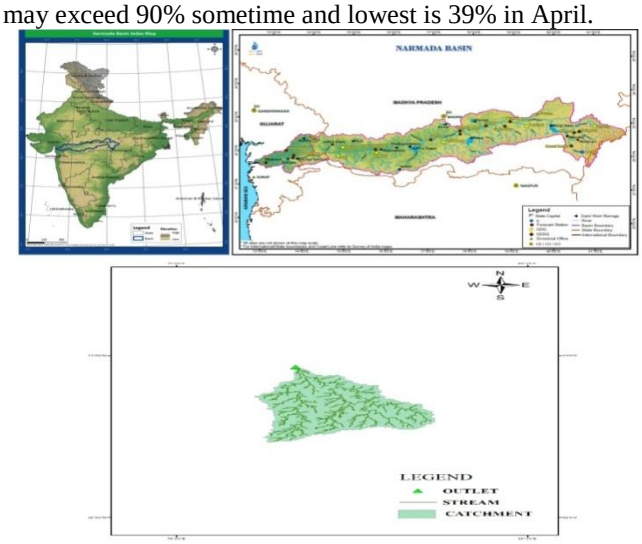

Figure 1: Index Map of Sher River Basin up to Balkheri g/d station (Source: india-wris central water commission website)

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III. MATERIAL AND METHODS

A. *MIKE 11 NAM model*

The NAM model is a deterministic, lumped and conceptual Rainfall-Runoff model. It consider river basin as one unit and based on considerations of the physical processes, these are highly relevant for this specific river basin under study and the simulation of the desired long-term flow. Furthermore, it is also as complete and efficient modelling program that allows flexibility for further research. MIKE 11 NAM is a software package developed by Danish Hydraulic Institute (DHI), Denmark. This is a one-dimensional modelling tool developed since 1972, particularly for water resource planning. The MIKE11 NAM software is specifically meant for simulation of irrigation channels, rivers and other water bodies. [1]

The hydrological model simulates at the catchment scale, the process of rainfall runoff .Within the same modelling framework; single catchment or a large river basin with numerous catchments and network of rivers can be treated as single unit. Four dissimilar and interconnected storages simulate the NAM model, these includes surface storage, ground water storage, root zone storage and snow storage. NAM model can therefore be prepared for the numbers of parameters of model, but considering the surface zone storage, root zone storage and ground water storage, model automatically accounts only 9 parameters as default.

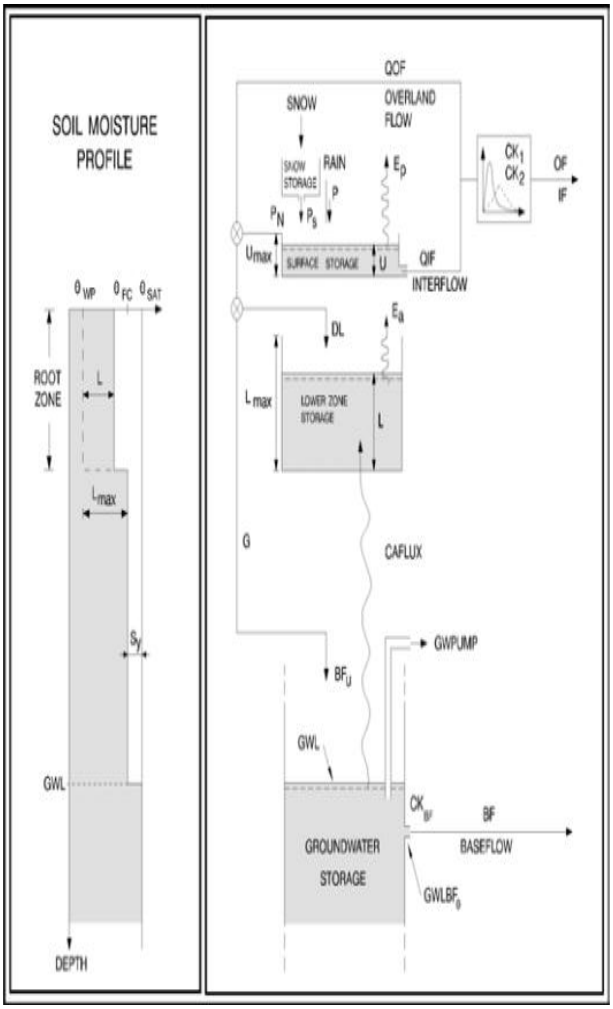

Figure 2: NAM Model Structure

B. *Model Setup*

The MIKE 11 NAM model was setup for Sher river basin to carry out R-R modelling. Catchment area of Sher river basin is 1484 $km^{2.}$ Daily data of rainfall, runoff and evapotranspiration for the period of 7 years from 2009 to 2015 was used for modelling. Daily timeseries dfs file of rainfall, runoff evaportranspiration is created using MIKE ZERO. Then the model was calibrated and validated.

C. Model Calibration

Model was calibrated using the daily rainfall data of 4 years i.e. from January 2009 to December 2012. In the process of calibration, model parameters are modified to reduce the error between the simulated stream flow and some portion of the observed flow record.

D. Model Validation

It tests the ability of model of estimated runoff. In the process of validation, the model parameters were kept as the parameters obtained during model calibration and runoff was simulated for the remaining period of 3 years i.e. from January 2013 to December 2015.

For rainfall runoff modelling of Sher river basin using MIKE11 Nam different data required i.e. rainfall, discharge and metrological data for the calculation of potential evapotranspiration and DEM(digital elevation model) for catchment delineation

E. ACCURACY OF THE MODEL

Coefficient of Determination (R^2) is the estimate of standard of calibration between the observed and simulated discharges data [4]. The equation of Coefficient of Determination (R2) is given by

$$R^2 = \frac{\sum_{i=0}^{n}\{(Q_{obs_i} - \overline{Q_{obs}})(Q_{sim_i} - \overline{Q_{sim}})\}}{\sqrt{\sum_{i=0}^{n}(Q_{obs_i} - \overline{Q_{obs}})^2\left(\sum_{i=0}^{n} Q_{sim_i} - \overline{Q_{sim}}\right)^2}}$$

Where; Q_{obs_i} =Observed discharge, $\overline{Q_{obs}}$ = Average observed discharge, Q_{sim_i} = Simulated discharge, $\overline{Q_{sim}}$ = Average simulated discharge.

Nash–Sutcliffe efficiency index (EI) is used to estimate the predictive power of rainfall-runoff models. The equation of Nash-Sutcliffe efficiency is given by

$$EI = 1 - \frac{\sum_{i=1}^{n}(Q_{obs_i} - Q_{sim_i})^2}{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q_{obs}})^2}$$

Where, Q_{obs_i} is the observed discharge, Q_{sim_i} is the simulated discharge, $\overline{Q_{obs}}$ is the Average observed discharge.

F. ESTIMATION OF EVAPORTRANSPIRATION

In our study Penman-Monteith equation was applied for the given data from January 2009 to December 2015 using CROPWAT 8.0 model, which evaluates the ETo using Penmann method. The below formula is developed by Penmann is[10]

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,(e_S - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where,

ETo (mm/day)	=	Reference evapo-transpiration
Rn (MJm^2/ day)	=	Net radiation at the crop surface
G m2/ day)	=	Soil heat flux density (MJ
T	=	Mean daily air temperature at 2 m height (°C)
u_2	=	Wind speed at 2 m height (m/sec)
eS	=	Saturation vapour pressure (kpa)
ea	=	Actual vapour pressure (kpa)
eS-ea (kpa)	=	Saturation vapour pressure deficit
Δ (kpa/°C)	=	Slope vapour pressure curve
γ	=	Pyschrometric constant (kpa/°C)

IV. RESULTS AND DISCUSSIONS

A. Catchment delineation using ArcGis

The DEM file of our study area is downloaded from the website earthexplorer.usgs.gov. DEM-file is of ASRTM 30m elevation. Area of interest was downloaded from website using google earth and output point is selected and catchment was delineated using ArcGis 10.3. In ArcGis drainage, flow direction, flow accumulations, sub-catchments, fill, digital elevation is done to delineate the final catchment area, and output shape file obtained is our required final catchment area. Study area DEM is shown in figure 3.

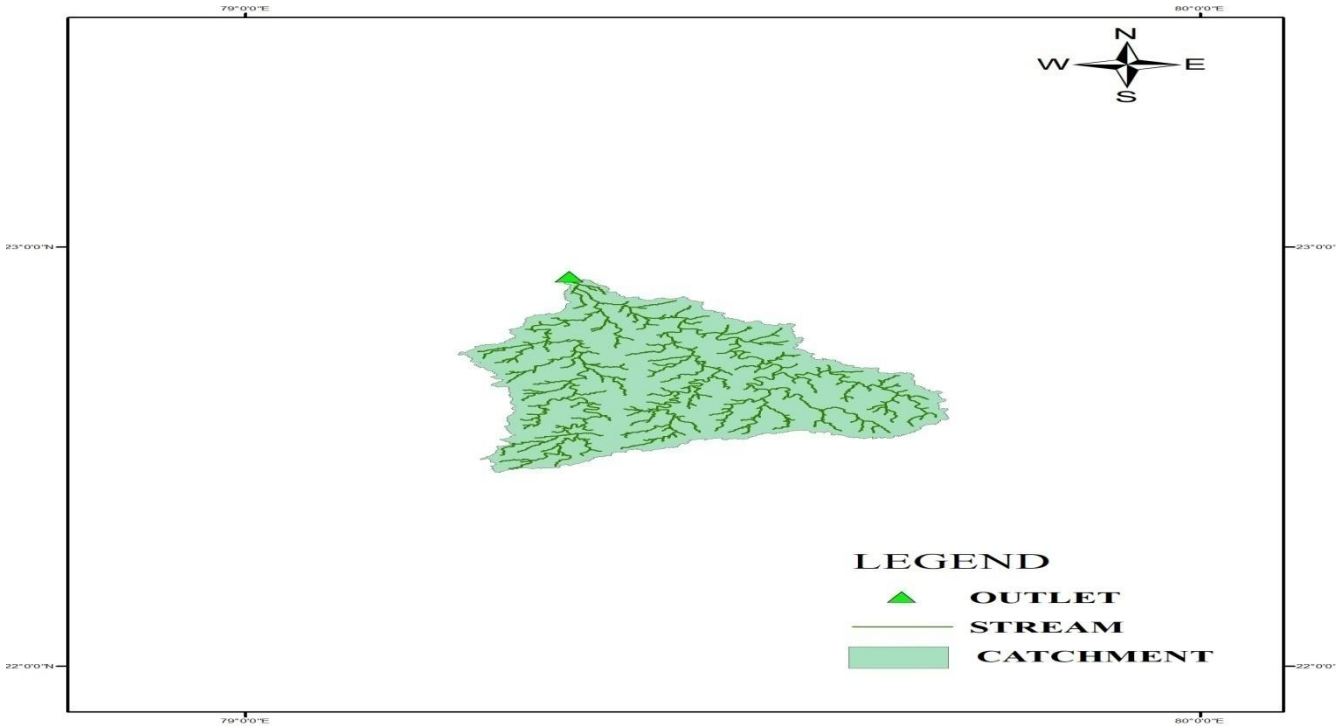

Figure 3: Delineated Catchment Area

B. DEVELOPMENT OF THIESSEN POLYGON MAP USING Arc-GIS

The weighted average rainfall of Sher river basin was estimated using Thiessen polygon method. The river basin consists of four raingauge stations whose weights play a main role in calculating weighted average of the basin. Total area of catchment was calculated using ArcMap.

Table 1: Thiessen weights of the raingauge stations

S.No	Rainfall Station	Percentage Weight (%) of station	Individual Weights
1	NARSINGHPUR	10	.1
2	HARRAI	20	.2
3	PATAN	28	.28
4	LAKHNADON	42	.42

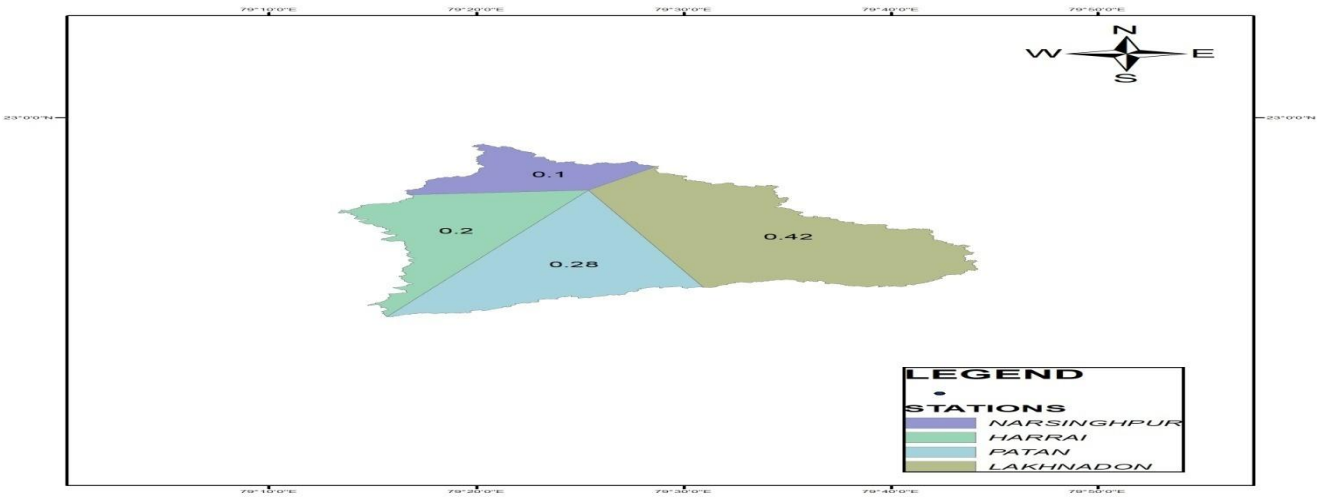

Figure 4. Thiessen polygon of study area

C. *Rainfall Analysis*

Our study area is the Sher river basin, rainfall stations which influence the runoff of the catchment are Narsinghpur, Harrai, Patan, and Lakhnadon. The mean annual precipitation of study area is about 1161.3 mm.

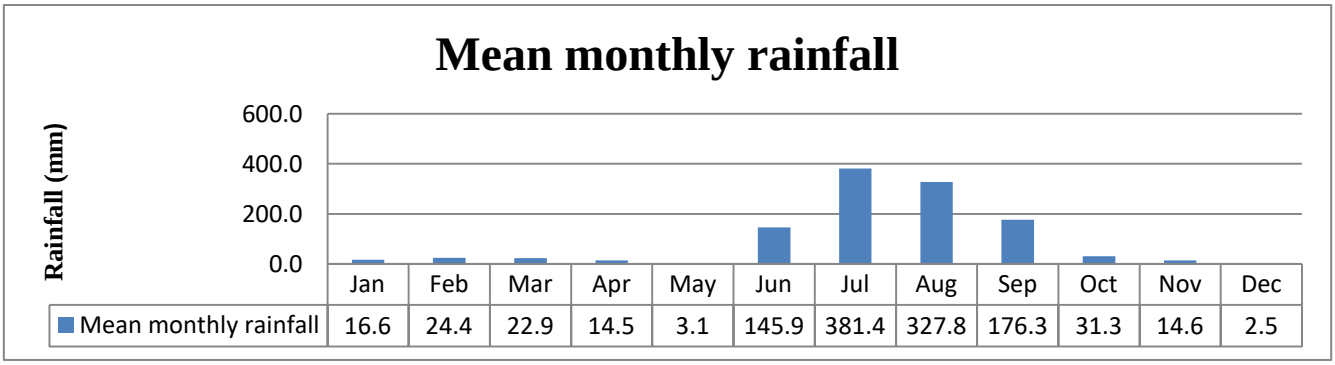

Figure 5: Mean monthly rainfall of study area

D. *POTENTIAL EVAPOTRANSPIRATION*

In the present study the potential evapotranspiration (ETo) has been calculted using the software CROPWAT 8.0 which make use of Penman-Monteith method. The ETo (mm/day), on daily basis was calculated based on long term meteorological data such as temperature, wind speed, relative humidity, sunshine hours. Mean monthly ET distribution is shown in Figure 6. the total annual ETo of the study area is 2270 mm and the ETo during monsoon and non-monsoon seasons were 864.2 mm and 1406 mm respectively. Highest ET was observed in the month of May and lowest in November.

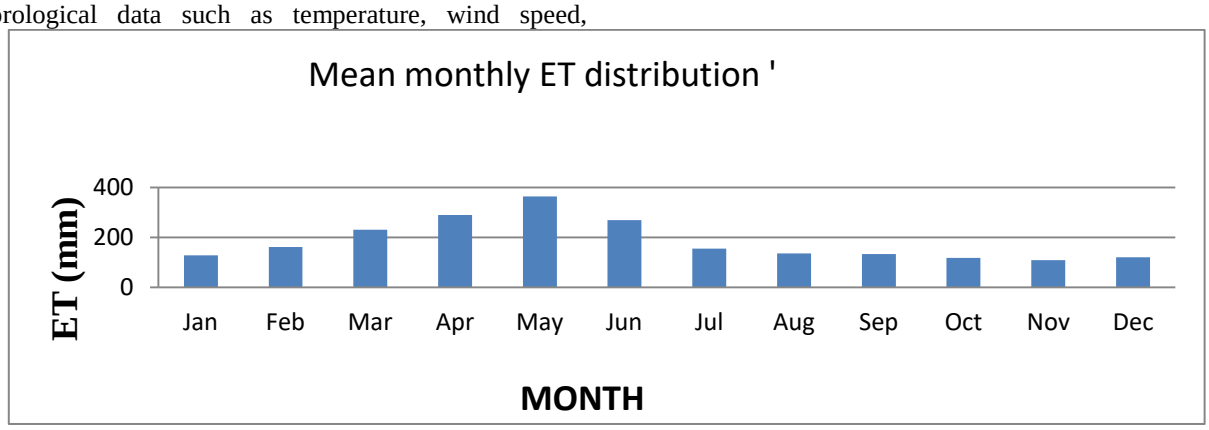

Figure 6: Mean Monthly ET distribution in Sher river basin

E. Model Calibration

Calibration is the process of modifying model parameters to reduce the error between the simulated stream flow and some portion of the observed flow record. The MIKE11 NAM Model was setup by using weighted daily rainfall, daily potential evapotranspiration and daily observed runoff time series for the periods of 7 years from 2009 to 2015 was created using MIKE ZERO. The set of model parameters were obtained during the model calibration were found initially for period of 4 year from 2009 to 2012 as shown in Table 2. The model output simulation results performance are analysed based up on the coefficient of determination and Nash-Sutcliffe coefficient ,during the calibration it is found to be 0.859 and 0.737 respectively and the total water balance error during calibration is 0%. Figure 7 illustrates the comparison of observed and simulated discharge during calibration period. Peak and low flows between observed and simulated hydrograph were found matching well.

Table 2. NAM calibrated parameter

Sr. No.	Parameter	Unit	Model Parameter Final Values	Parameter Range
1	U_{max}	mm	18.5	10 – 20
2	L_{max}	mm	216	100 – 300
3	C_{QOF}		0.481	0.1- 1
4	C_{KIF}	hrs	202.3	200 – 1000
5	C_{K12}	hrs	17.7	10 – 50
6	T_{OF}		0.00645	0 - 0.99
7	T_{IF}		0.0694	0 - 0.99
8	T_G		0.579	0 - 0.99
9	C_{KBF}	hrs	1497	1000 – 4000

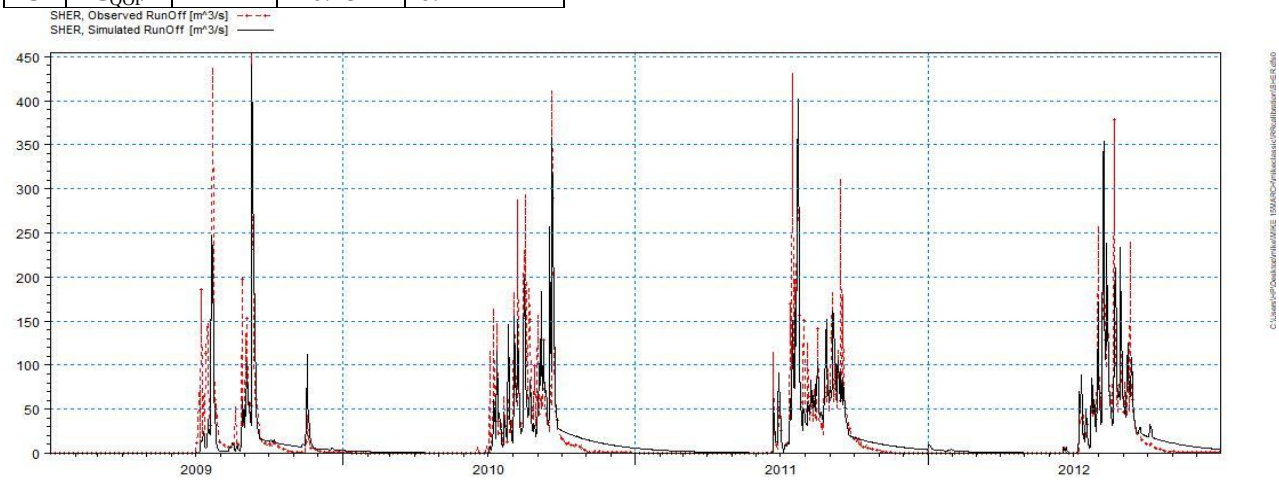

Figure 7: Comparison between observed and simulated runoff hydrograph during calibration period (x axis time period in year , y axis discharge in cumec)

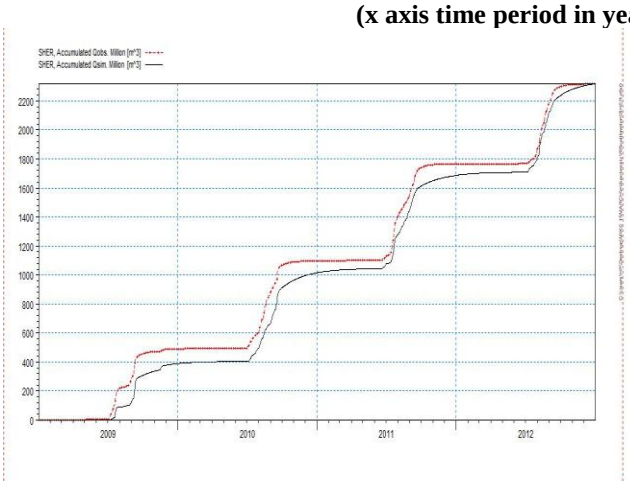

Figure 8: Double mass curve during calibration period (x axis time period in year , y axis discharge in cumec)

Table 3. Model calibration results

Year	Q-Obs	Q-Sim	% Diff	RF	PET	AET	GWR	OF	IF	BF
2009	330.6	262.4	20.6	930.8	2270.1	590.8	77.8	138.6	60.3	63.5
2010	408.7	422	-3.3	1145.5	2259.4	735.4	143.1	178.2	110.2	133.5
2011	449.6	451.7	-0.5	1159.8	2145	710	137.4	175.3	132.8	143.6
2012	373	426.4	-14.3	1141.1	2286	729.3	141.5	177.8	108.4	140.2
Total	1561.9	1562.4	0	4377.1	8960.5	2765	496.4	669.9	411.7	480.8

Q=Discharge, RF=Rainfall, PET=Potential Evapotranspiration, AET=Actual Evapotranspiration, GWR=Ground Water Recharge, IF=Inter Flow, BF=Base Flow, OF=Overland Flow)

F. MODEL VALIDATION

Model output simulation results performance are analysed based up on the coefficient of determination and Nash-Sutcliffe coefficient, during calibration it is found to be 0.83 and 0.675 respectively and during validation the total water balance error during validation is 7.5%. Figure 9 illustrate the comparison between observed and simulated runoff hydrograph during calibration period. Auto-calibration was done during calibration, NAM model parameters were obtained and then the simulated discharge was compared with observed discharge.

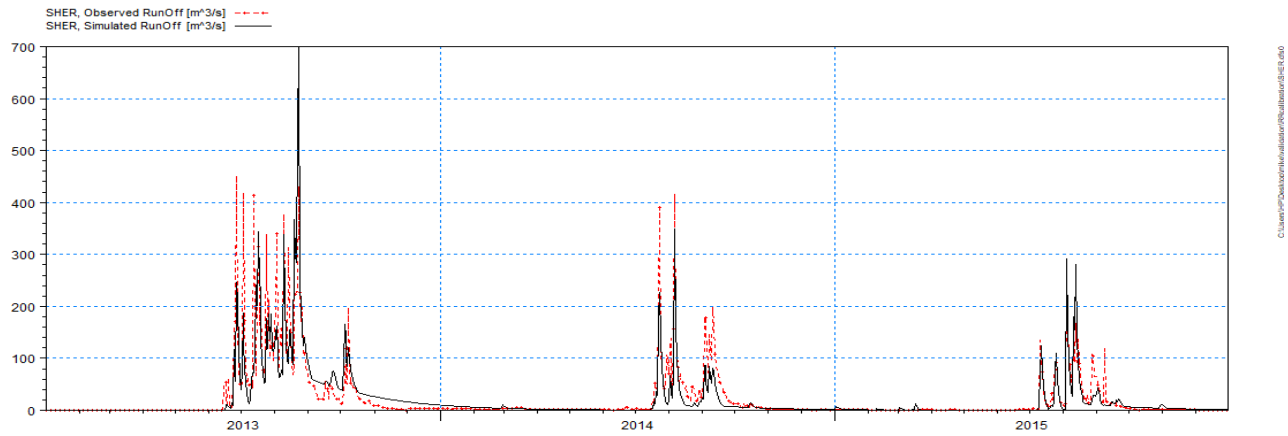

Figure 9: Comparison between observed and simulated runoff hydrograph for validation period (x axis time period , y axis discharge in cumec)

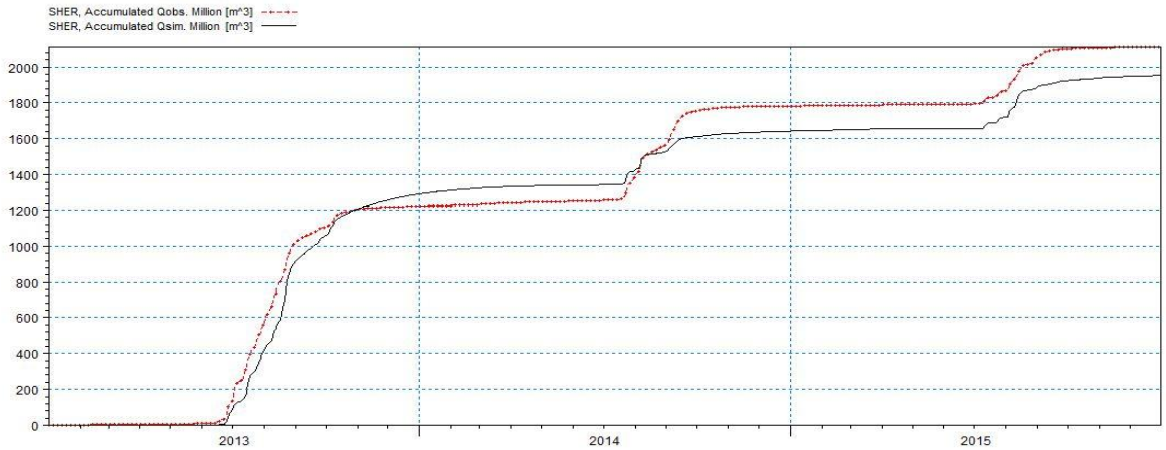

Figure 10: Comparison between observed and simulated runoff hydrograph for validation period

(x axis time period in year , y axis discharge in cumec)

Table 4. Model validation results

Year	Q-Obs	Q-Sim	% Diff	RF	PET	AET	GWR	OF	IF	BF
2013	823.7	871.6	-5.8	1758.2	2103.7	800.5	360.2	387.7	158.5	325.4
2014	377.4	234.9	37.8	951.4	2250.6	753.4	50.2	93.6	61.5	79.78
2015	222.2	209.7	5.6	1042.5	2183.7	855.7	54.1	98.6	56.9	54.2
Total	1423.3	1316.1	7.5	3752.1	6538	2409.7	464.5	579.9	276.9	459.3

Q=Discharge, RF=Rainfall, PET=Potential Evapotranspiration, AET=Actual Evapotranspiration, GWR=Ground Water Recharge, BF=Base Flow, OF=Overland Flow, IF=Inter Flow)

G. SENSITIVITY ANALYSIS

Sensitivity analysis is essential in deciding how model is sensitive to some of the parameters. Sensitivity analysis is helpful for a range of uses; this includes evaluating the robustness of the results of a model or system. In the analysis of sensitivity of the MIKE 11 NAM model, all nine parameters were selected and the value of each parameter is changed by 20% on both side of the value obtained from the calibration. Sensitivity of the each parameter is depends on the accuracy determiners of the model.

Sensitivity analysis is done based up on the statistical performance indices i.e. coefficient of determination, Nash-Sutcliff Efficiency Index, root mean square error and sum of square error. Results of various parameters value are plotted against R^2, EI, RSME, and SSE for sensitivity analysis.

From figure 11 and figure 12 we can conclude that the model parameters CQOF, CK_{12} were found most sensitive, Lmax and TOF were found moderate sensitive and CKIF is low sensitive parameter for modelling .

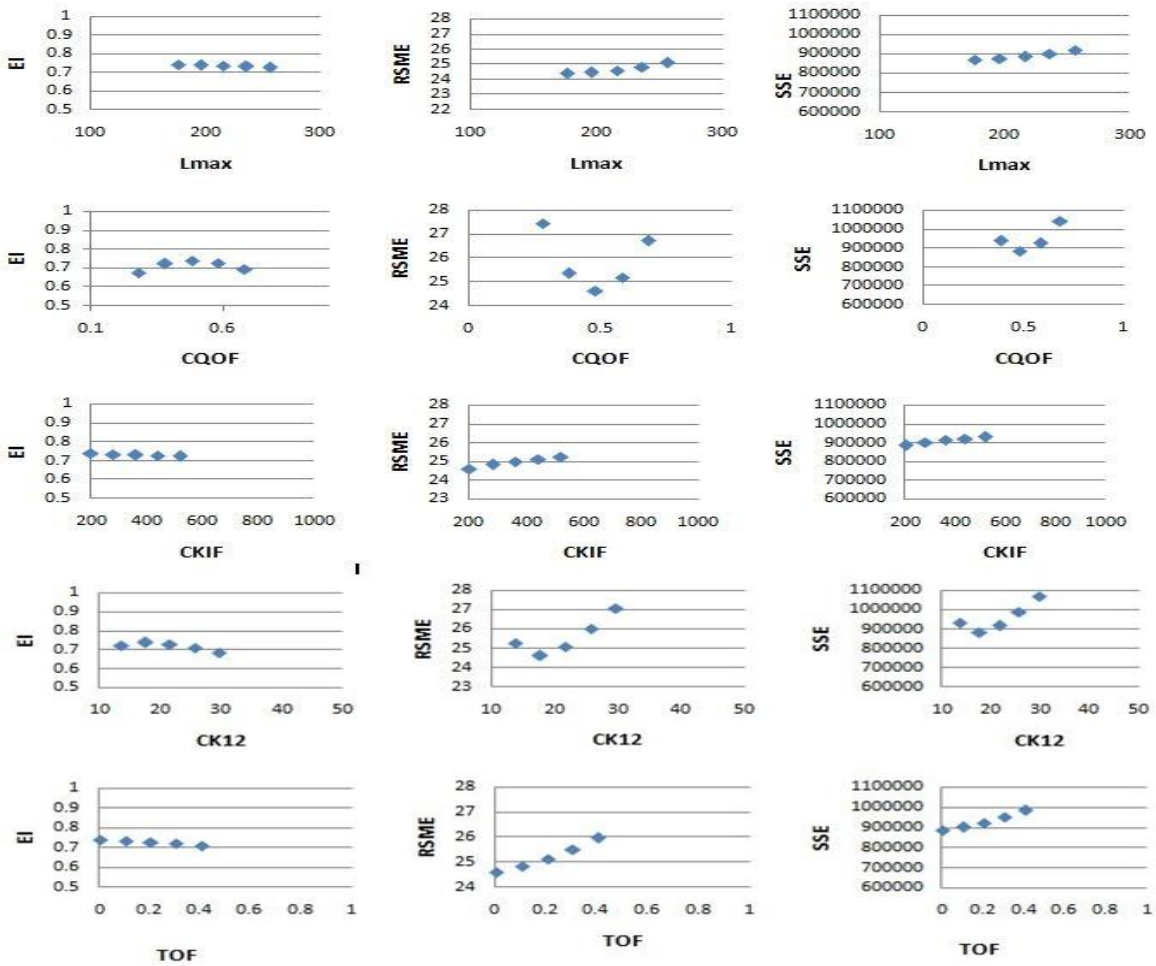

Figure 11: Graph between EI, RSME and SSE against the sensitive model parameters

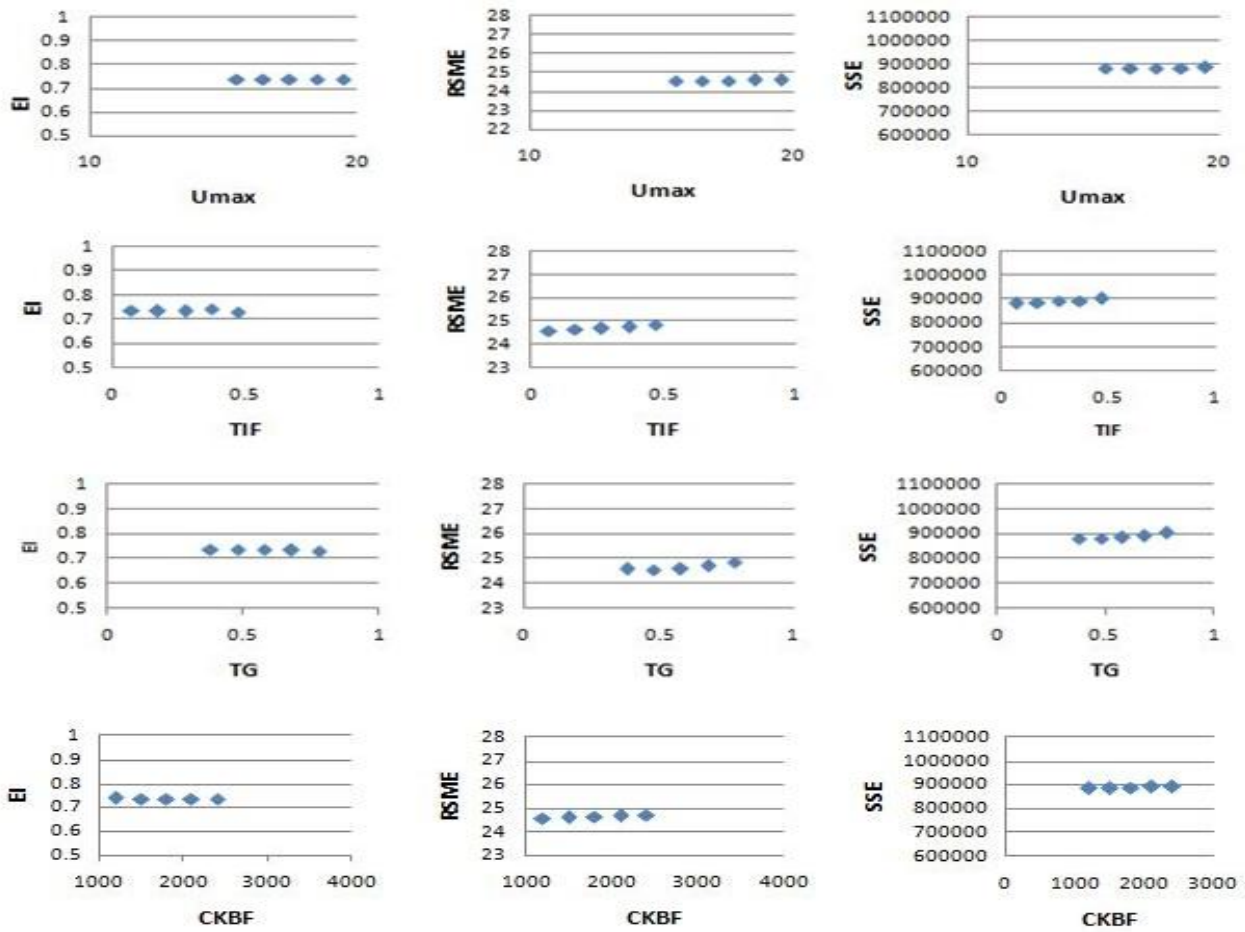

Figure 12: Graph between EI, RSME and SSE against the non-sensitive model parameters

Table 5: NAM Parameter and their level of sensitivity**.**

NAM PARAMETERS	LEVEL OF SENSTIVITY
Maximum water content in surface storage (U_{max})	None
Maximum water content in root zone storage (L_{max})	Moderate
Overland flow runoff coefficient (CQ_{OF})	High
Time constant for interflow (CK_{IF})	Low
Time constants for routing overland flow (CK_{12})	High
Root zone threshold value for overland flow (T_{OF})	Moderate
Root zone threshold value for inter flow (T_{IF})	None
Root zone threshold value for ground water recharge (T_g)	None
Time constant for routing baseflow (CK_{BF})	None

V. CONCLUSIONS

During our study our objective was to develop MIKE11 NAM model for Sher river basin to provide a realistic hydrological modelling. Model was found appropriate for simulation of discharge in Sher river basin. The coefficient of determination and Nash-Sutcliffe coefficient, during the calibration and is found to be 0.859 and 0.737 respectively, during validation it is 0.83 and 0.675 respectively. The total water balance error during calibration is 0% which indicates and during calibration the total water balance error is 7.5% which indicates good match of results. During sensitivity analysis model was found sensitive to the parameter like Lmax, CQOF, CKIF, CK_{12}, and TOF, out of which CQOF and CK_{12} was found highly sensitive modelling.

APPENDIX A

Performance Indices [4]

1. Nash Sutcliffe Efficeiency Index (EI)

$$= 1 - \frac{\sum_{\square=1}^{\square}(Q_{obs_i} - Q_{\square\square\square_i})^2}{\sum_{i=1}^{n}(Q_{obs_i} - \overline{Q_{obs}})^2}$$

2. Root Mean Square Error (RMSE)

$$= \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{obs_i} - Q_{sim_i})^2}$$

3. Sum of Square Error (SSE) $= \sum_{i=1}^{n}(Q_{obs_i} - Q_{sim_i})^2$

Where, Q_{obs_i} is the observed discharge,

Q_{sim_i} is the simulated discharge,

$\overline{Q_{obs}}$ is the Average observed discharge.

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