



## Lumped conceptual hydrological model for Purna river basin, India

V D LOLIYANA<sup>1</sup> and P L PATEL<sup>2,\*</sup>

<sup>1</sup>Department of Civil Engineering and Centre of Excellence (CoE) on ‘Water Resources and Flood Management’, SVNIT Surat, Surat 395 007, Gujarat, India

<sup>2</sup>Department of Civil Engineering, SVNIT Surat, Surat 395 007, Gujarat, India

e-mail: viraj\_nishi@yahoo.com; premlalpatel@yahoo.com;

premlalpatel1966@gmail.com

MS received 13 January 2015; revised 25 April 2015; accepted 23 May 2015

**Abstract.** In present study, a lumped conceptual hydrological model, NAM (MIKE11), is calibrated while optimizing the runoff simulations on the basis of minimization of percentage water balance (% WBL) and root mean square error (RMSE) using measured stream flow data of eight years from 1991 to 1998 for Yerli catchment (area = 15,701 km<sup>2</sup>) of upper Tapi basin, Maharashtra in Western India. The sensitivity of runoff volume and peak-runoff has been undertaken with reference to nine NAM parameters using the data of calibration period. The runoff volume and peak-runoff have been found to be highly sensitive with reference to maximum water content in root zone storage ( $L_{\max}$ ) and overland flow coefficient (CQOF) respectively. On the other hand, runoff volume is found to be moderately sensitive with maximum water content in surface storage ( $U_{\max}$ ). The calibrated model has been validated for independent stream flow data of Yerli gauging site for years 2001–2004, and Gopalkheda gauging site for years 1991–1998 and 2001–2004. The model performance has been assessed using statistical performance indices, and compared the same with their yardsticks suggested in published literature. The simulated results demonstrated that calibrated model is able to simulate hydrographs satisfactorily for Yerli (NSE = 0.86–0.88,  $r = 0.93$ – $0.96$ , EI = 1.05–1.12) as well as Gopalkheda sub-catchments (NSE = 0.76–0.92 and  $r = 0.88$ – $0.96$ , EI = 0.89–0.91) at monthly time scale. The model also performs reasonably well in simulating the annual hydrographs at daily time scale. The calibrated model may be useful in prediction of water yield and flooding conditions in the Purna catchment.

**Keywords.** Conceptual hydrological NAM model; calibration; sensitivity analysis; validation; Tapi basin; Purna catchment.

---

\*For correspondence

## 1. Introduction

In hydrological cycle, rainfall-runoff processes are highly dependent on topographic, soil and land use–land cover characteristics in the catchment. One of the prime objectives of hydrologic modelling is to understand the interactions between precipitation, evapotranspiration, stream flow and water balance at spatial and temporal scales in the catchment. The sophisticated geographical information system (GIS) based hydrological models are becoming increasingly useful in prediction of real time flood, and devising policies for management of storage reservoirs and mitigating extreme hydrological events, like flood and droughts. The distributed hydrological models are preferred over lumped conceptual models in prediction of runoff provided extensive data base related to topography, land use–land cover, soil types and hydrological inputs are available at finer scales in the catchment. Accessibility of observed hydrological data in the catchment with sparse ground based network is the key limitation of distributed hydrological modeling (Khan *et al* 2011). The lumped conceptual models are characterized by storage systems that include the catchment processes without considering the specific details of process interactions requiring detailed information of the catchment. Such models are based on spatially lumped method of continuity and linear storage-discharge equations of water for providing quantitative and qualitative effects of land use changes without demanding enormous quantities of spatial and temporal distributed data of the catchment (Merritt *et al* 2003).

MIKE 11 NAM is a well-proven hydrological model, applied in the past to a number of catchments while representing conceptually different hydrological regimes and climatic conditions in the world (Refsgaard & Knusden 1996). Schumann *et al* (2000) applied GIS technique in developing conceptual rainfall-runoff models of seven gauged catchments (area ranging 18–576 km<sup>2</sup>) within Pruem river basin (840 km<sup>2</sup>), Germany while using regional conceptual model parameters to describe spatial heterogeneity within the catchment. Madsen (2000) developed automatic calibration procedure for optimization of NAM parameters with multiple objectives using data base of Danish Tryggevælde catchment (130 km<sup>2</sup>). Prior to calibration, uncertainties in meteorological input data, recorded observations, use of non-optimal parameters and simplification in the models were quantified. Ahmed (2010) calibrated MIKE 11 NAM model for development of rainfall-runoff model of six regions of Rideau Valley watershed (4,257 km<sup>2</sup>), Ontario, Canada while dividing the watersheds into 34 sub-watersheds. The autocalibration procedure was adopted to calibrate the model parameters of the sub-watersheds. Total five years of stream flow data were used for calibration of model parameters while another five years data were used for satisfactory validation of the calibrated model. Rahman *et al* (2012) developed flood forecasting system for Jamuneswari River, Bangladesh using MIKE 11 rainfall-runoff (NAM model), hydrodynamic (HD) and flood forecasting (FF) modules. Rainfall-runoff NAM model was calibrated and, subsequently, used to predict runoff at upstream catchment outlets for using the same as upstream boundary conditions for the hydrodynamic model. The previous studies, as reported above, could not describe systematic variation of NAM output with variation in its model parameters. The knowledge on sensitivity of MIKE 11 NAM outputs (runoff volume and peak runoff) with reference to its surface and subsurface flow parameters is of utmost importance to the modellers in choosing their appropriate values to arrive precise runoff at the catchment outlets.

The Tapi basin is spanning over an area of 65,145 km<sup>2</sup>, and its lower part lies in western part of India. The Tapi river is amongst the largest rivers draining into the Arabian sea in western part of India, passes through Madhya Pradesh, Maharashtra and Gujarat states. The entire Tapi basin is delineated into three sub-basins, i.e. upper Tapi basin from origin to Hathnur dam (29,430 km<sup>2</sup>), middle Tapi basin from Hathnur to Gidhade (25,320 km<sup>2</sup>) and lower Tapi basin from

Gidhade. There are two major multipurpose reservoirs available to meet water availability in the catchment, i.e., Ukai reservoir and Hathnur reservoir (upstream of Ukai reservoir) along the Tapi river. Recent floods during monsoon in the years 1994, 1998, 2006, and 2013 had resulted severe direct and indirect damages to the Surat city, India, which is located in lower bank of Tapi river. For regulating the flow from upstream reservoirs of Tapi basin, it is necessary to predict accurate inflow into the reservoirs to mitigate the extremes (flood) in future. The Purna river is a major tributary of the Tapi river, which meets with latter at just upstream of Hathnur dam. The Hathnur reservoir is a water conservation project for meeting irrigation demands of the command area; and acts as first control structure upstream of Ukai reservoir with reference to management of flood in its downstream reaches. At present, there is no mechanism available for prediction of inflows into the Hathnur reservoir which may help in taking decision in regulating the releases in the command area and downstream reservoir, i.e. Ukai reservoir. Present study has been aimed with following objectives: (a) Assess the applicability of MIKE 11 NAM model in the large catchment with minimal information on physiographic and climatic data, (b) Examine the sensitivity of MIKE 11 NAM outputs with reference to its parameters, and derive optimal values of the parameters while minimizing % water balance and root mean square error (c) Evaluate the performance of calibrated NAM model for observed independent data in Yerli (2001–2004) and Gopalkheda (1991–1998 and 2001–2004) sub-catchments in terms of statistical performance indices.

## 2. Materials and methods

### 2.1 Study area and data source

Present study area includes Purna River catchment up to confluence of Tapi river, area 15,701 km<sup>2</sup>, draining through Maharashtra state in India. The Purna river, length 353 km, originates

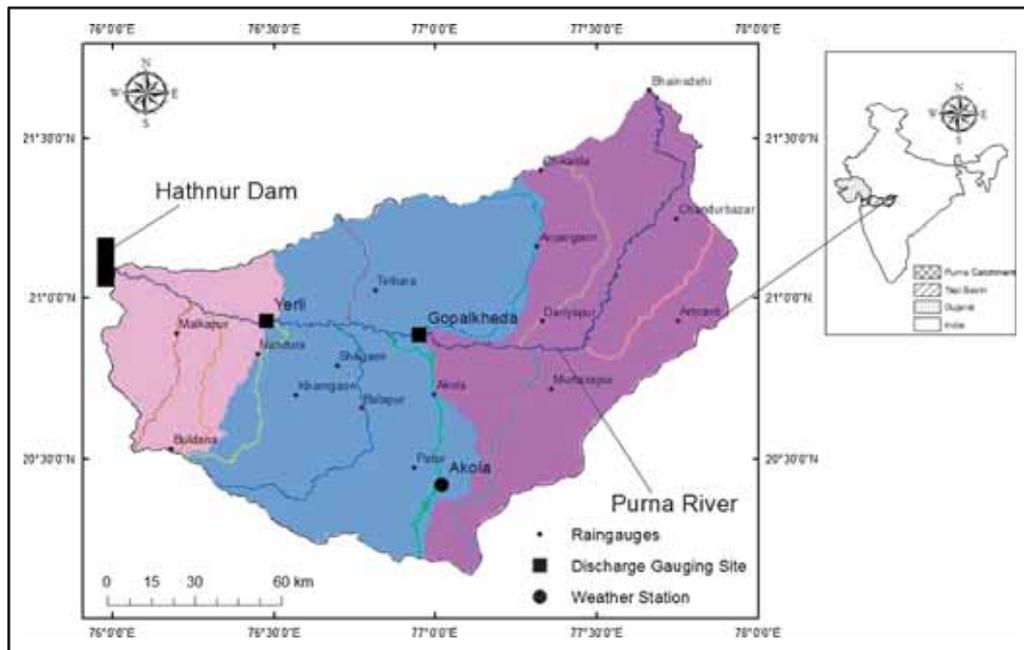


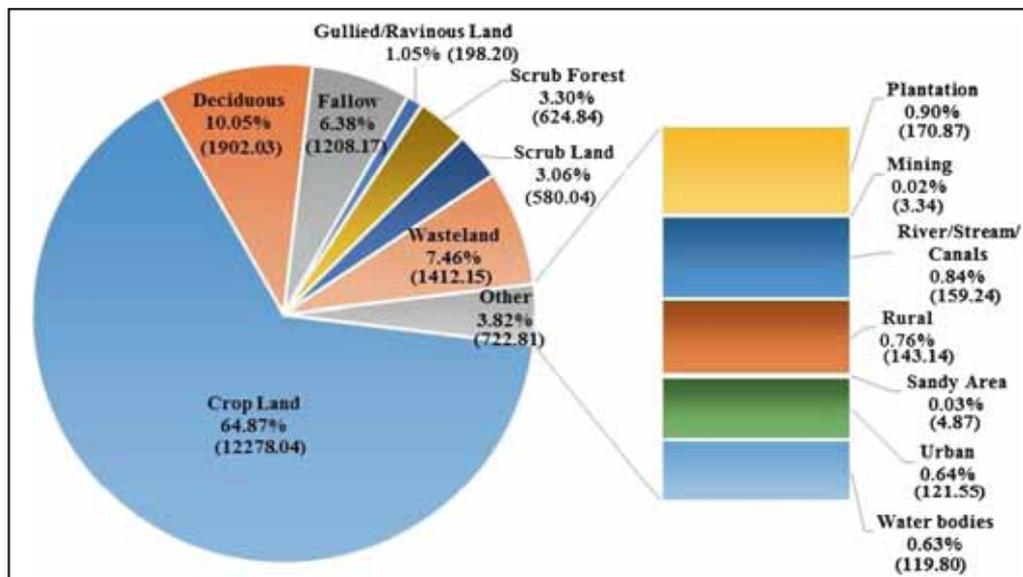
Figure 1. Index map of study area.

**Table 1.** Physiography of the study area.

Feature	Gopalkheda	Yerli	Purna*
Gauged/ungauged	Gauged	Gauged	Ungauged
Latitude	21°38' N	21°38' N	21°38' N
Longitude	77°36' E	77°36' E	77°36' E
Area (km <sup>2</sup> )	7,225	15,701	18,926
Perimeter (km)	514	901	975
Mean altitude (m)	394	382	372
Max. altitude (m)	1,162	1,162	1,162
Min. altitude (m)	240	227	211
Length of main river (km)	229	299	353

\*Lower part of Purna catchment.

from Gawilgarh steep mountains of eastern Satpura range (Betul district of Madhya Pradesh); and meets the Tapi river just upstream of Hathnur dam, see figure 1. There are 10 tributaries drain into the Purna river up to the confluence with Tapi river. The south-west monsoon sets in by the middle of June, and withdraws by mid-October, having an average rainfall of 750–800 mm in the catchment. The minimum and maximum temperatures vary from 10°C to 15°C and 38°C to 48°C respectively in the catchment (Jain *et al* 2007). There are two stream gauging stations, namely, Gopalkheda and Yerli gauging sites, located at 229 km and 299 km respectively from the origin of the Purna River. Main topographical features of the study area are included in table 1. Apart from above, there are 16 raingauge stations and one weather station are also available in the study area, as shown in figure 1. In present study, land use–land cover of the study area were classified into 14 classes using supervised classification of IRS LISS-III imageries in ERDAS Imagine 10, and validated the same from available details on India-WRIS web portal (<http://india-wris.nrs.gov.in/>).

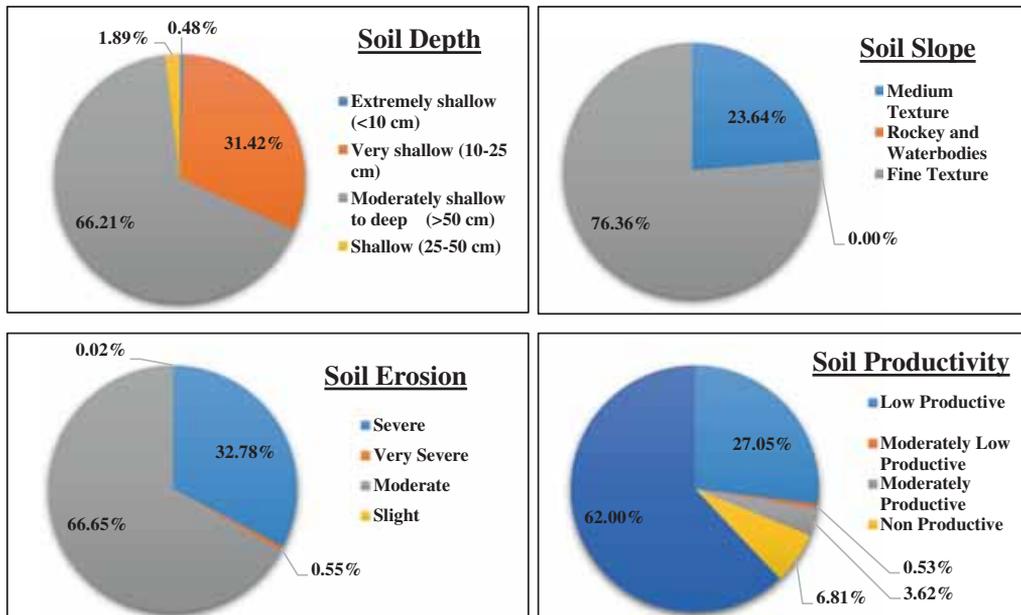


All values in bracket are areas in km<sup>2</sup> of land use in the study area.

**Figure 2.** Land use patterns in the study area (Source: India-WRIS.gov.in).

**Table 2.** Soil characteristics in the study area.

Class type	Area (%)	Soil type	Characteristics	Drainage	Deep	Erosion
B	63.0	Loamy	Moderate infiltration rate (0.13–0.78 cm/h) when thoroughly wetted and consists chiefly loamy soils with well drained soils	Excessively drained	Extremely shallow	Moderate with stoniness
C	30.0	Clayey, loamy	Low infiltration rates (0.13-0.38 cm/h) when thoroughly wetted and consist chiefly of soils with a layer that impedes downward movement of water and soils	Well drained	Shallow	Severe/ Moderate
D	7.0	Fine, clayey, calcareous	Highest runoff potential and having very low infiltration (<0.13 cm/h) rates when thoroughly wetted and consist chiefly of clayey soils with a high swelling potential, soils with a permanent high water table, soils with a clay layer at or near the surface and shallow near soil over nearly impervious bed rock	Moderately/ imperfectly drained	Deep	Moderate



**Figure 3.** Area (%) of soil depth, slope, erosion and productivity in the study area (Source: India-WRIS.gov.in).

**Table 3.** Data inputs for development of NAM model.

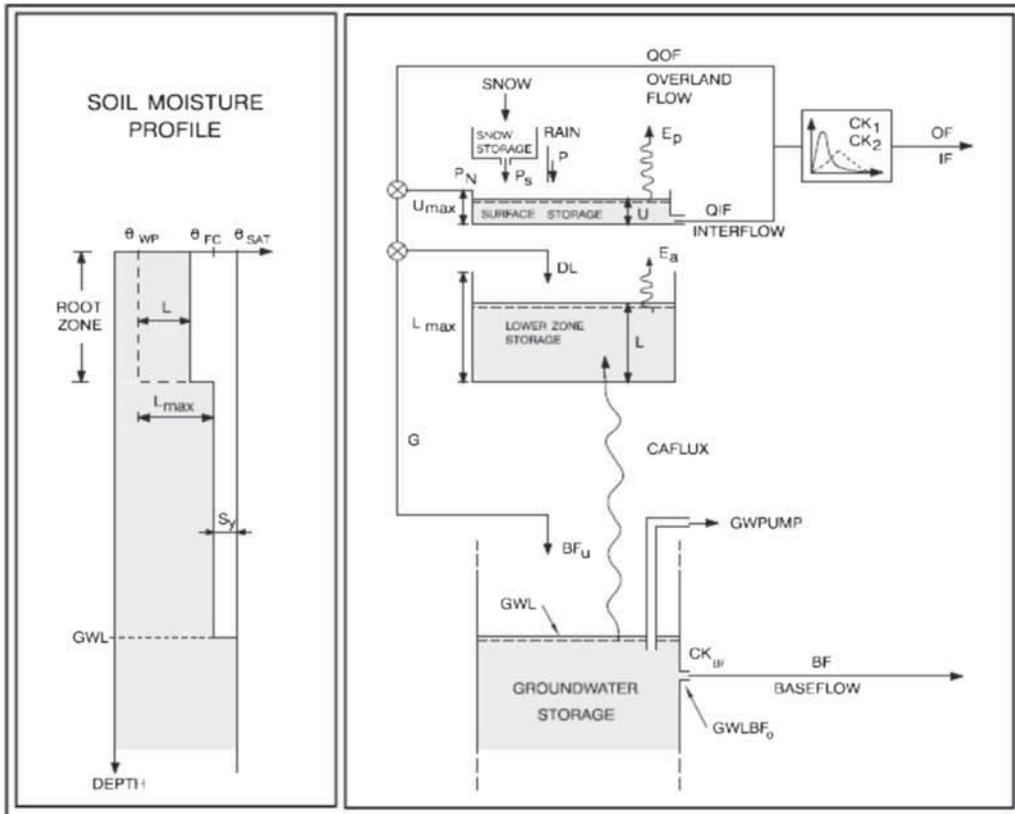
Sr. no.	Types of data	Description of data	Sources	Purpose
1.	Satellite data	(1) SRTM DEM (90 m × 90 m) (2) IRS P6 LISS III – Imagery (2009)	(1) U. S. Geological Survey (USGS) (2) Indian Remote Sensing Centre	<ul style="list-style-type: none"> <li>● Catchment delineation</li> <li>● Land use/cover classification</li> </ul>
2.	Topographic data	(1) Topographic sheets (2) Soil maps	(1) Survey of India (2) National Bureau of Soil Survey & Land use Planning	<ul style="list-style-type: none"> <li>● Digitizing river network</li> <li>● Soil characteristics</li> </ul>
3.	Hydrologic data	(1) Rainfall data (2) Evapotraspiration data (3) Discharge data	(1) India Meteorological Department (IMD) (2) India Meteorological Department (IMD) (3) Central Water Commission (CWC)	<ul style="list-style-type: none"> <li>● Calibration: 1991–1998</li> <li>● Validation: 2001–2004</li> </ul>

The fourteen classes of land use–land cover, and their percentage area, are shown in figure 2. The crop land (64.87%) being dominant in the Purna river catchment indicates higher productivity of the soil in the region (62%) in the study area. The Purna river basin is having three classes of soils, i.e., B, C, and D types. The predominant soil in the catchment is loamy soil (B class, around 63% of the total catchment area), in which the water is well drained with moderate erosion and runoff potential, see table 2 and figure 3. The characteristics of soils, such as soil depth, texture, erosion and productivity, for the Purna river catchment are shown in figure 3. The input data required for development of conceptual rainfall-runoff model of the study area are described in table 3.

## 2.2 Analytical tool

The MIKE 11 GIS-NAM (Nedbor-Afstromnings-Model), developed by the Danish Hydrologic Institute (DHI), Denmark, is a 1D deterministic lumped conceptual rainfall-runoff model. The NAM simulates the rainfall-runoff process by constantly accounting for the water content in four dissimilar and reciprocally interrelated storages, representing different physical elements of the basin for instance, surface storage, root zone storage, ground water storage and snow storage. As the study area is not affected by snow, therefore, snow storage criterion has not been considered in the present study. Apart from calibrated lumped parameters, rainfall and evapotranspiration are the major inputs into the NAM model. After giving appropriate inputs to the model, it can generate outputs like catchment runoff, actual evapotranspiration, temporal variation of soil moisture content and ground water recharge. The consequential catchment runoff is composed of overland flow, interflow and base flow components. The NAM model has ability to operate on number of time scales from single storm events to multistorm events (DHI 2000). The structure of the model parameters of MIKE 11 GIS-NAM is shown in figure 4.

In NAM model,  $U_{\max}$  gives maximum water content in the surface storage in mm;  $L_{\max}$  (mm) gives maximum water content in the lower or root zone storage in mm; CQOF denotes for overland flow runoff coefficient, a vital parameter for determining amount of excess rainfall available as overland flow; CKIF indicates as time constant for interflow for determining, the amount of interflow in hours;  $CK_{1,2}$  is a time constant for routing interflow and overland flow in hours, and determines the shape of hydrograph peaks; CKBF represents the time constant for base flow in hours and determines the shape of the simulated hydrograph in dry periods; TOF



**Figure 4.** Hydrological processes in MIKE 11 NAM model (Source: DHI 2008).

denotes root zone threshold value for overland flow, means no overland flow would result, if the relative moisture content is less than this in the lower zone storage; TIF is root zone threshold value for interflow; TG specifies root zone threshold value for groundwater recharge which has the same effect on recharge as TOF on overland flow in simulating rainfall-runoff process in MIKE 11 NAM model (DHI 2008).

Madsen (2000) recommended upper and lower bounds of aforesaid NAM parameters to calibrate the model in estimation of their optimal values for the chosen study area.

### 2.3 Methodology

The methodology adopted in present study including preparation of data base, calibration/sensitivity analysis of NAM parameters, and validation of calibrated model, is depicted through a flow chart (see figure 5). Brief description of each step is described in succeeding paragraphs:

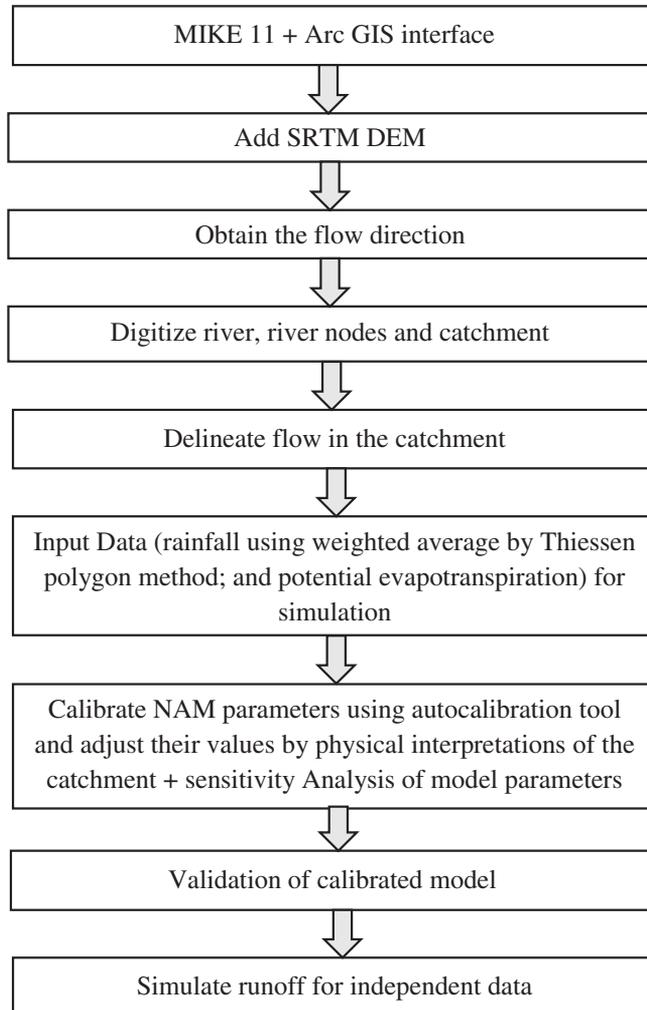
**2.3a Preparation of data base:** The SRTM DEM (raster data) data was used to get flow direction in the catchment using MIKE 11 GIS module with ArcGIS 10.0 interface. The Purna River (up to confluence at Tapi River) including river nodes and catchment area were digitized to delineate the sub-catchments using GIS. Rainfall and estimated potential evapotranspiration data for 12 years (1991–1998 and 2001–2004) were taken as inputs to simulate the runoff at the

catchment outlet The missing data analysis was undertaken for estimation of missing rainfall data at raingauge stations using inverse squared distance method (Eq. 1).

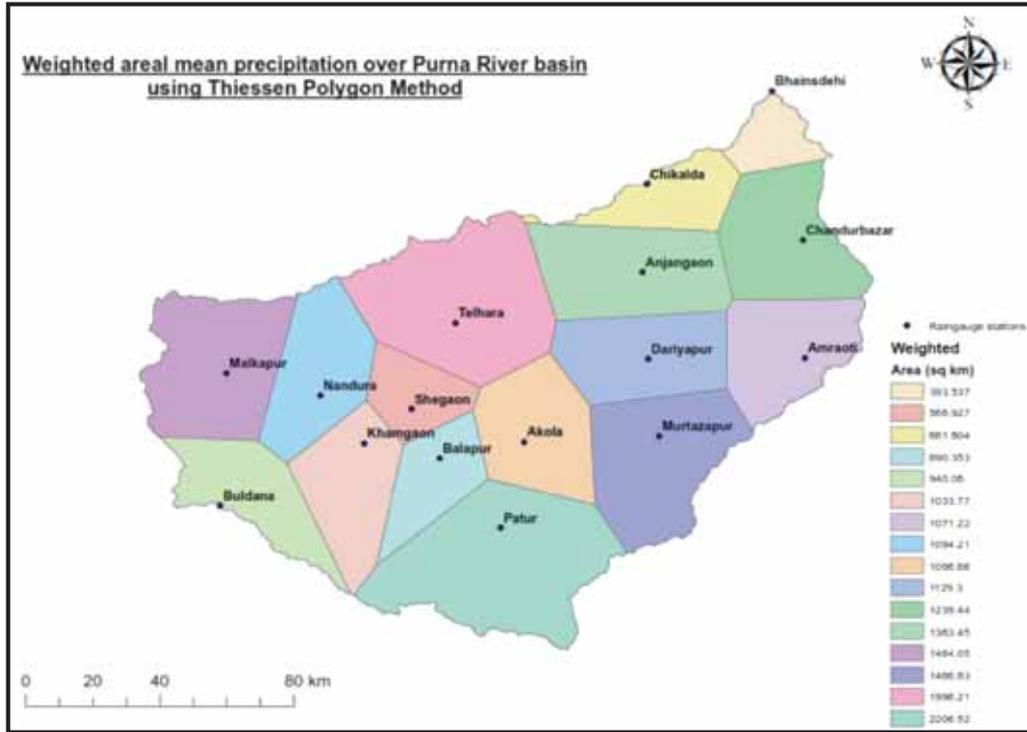
$$P_i = \frac{\sum_{i=1}^n \frac{R_i}{d_i^2}}{\sum_{i=1}^n \frac{1}{d_i^2}}, \quad (1)$$

where  $P_i$  = rainfall value at missing raingauge station,  $R_i$  = known rainfall value at  $i^{\text{th}}$  surrounding raingauge station, and  $d_i$  = distance between missing raingauge station and  $i^{\text{th}}$  surrounding raingauge station.

Proposed rainfall-runoff model, being lumped type, the Thiessen polygon method was used to obtain weighted mean precipitation over Gopalkheda, Yerli sub-catchments and sub-catchment lying between Yerli and confluence with Tapi river while using data of nine, fifteen and sixteen



**Figure 5.** Methodology for simulation of runoff in MIKE 11 NAM.



**Figure 6.** Weighted rainfall distribution over Purna River catchment.

rain gauge stations respectively. The rainfall distribution over the Purna catchment prepared using GIS is shown in figure 6.

The daily potential evapotranspiration in the study area was estimated using Penman's equation (Subramanya 2011), (Eq. 2).

$$PET = \frac{AH_n + E_a\gamma}{A + \gamma}, \quad (2)$$

where  $A$  = slope of the saturation vapour pressure vs temperature curve at the mean air temperature, in mm of mercury per °C;  $H_n$  = net radiation in mm of evaporable water per day;  $E_a$  = parameter including wind velocity and saturation deficit;  $\gamma$  = psychrometric constant = 0.49 mm of mercury/°C.

**2.3b Calibration of model parameters:** For calibration of NAM model, values of model parameters are selected such that hydrological processes of the catchment are simulated as closely as possible. The autocalibration procedure, based on Shuffle complex evaluation algorithm, has been used to obtain the optimal values of nine NAM model parameters. Few NAM parameters related with ground water flow like  $C_{r,low}$  (recharge to lower ground storage),  $CK_{low}$  (time constant for routing lower baseflow), Specific yield ( $S_y$ ),  $GWL_{BF0}$  (maximum groundwater depth causing baseflow), and  $KO_{inf}$  (Infiltration factor) could not be included in calibration due to paucity of ground water data, and their default values were used in present study. The autocalibration procedure, in present study, has been accomplished by optimizing two objective functions, i.e., (i) agreement between average simulated and observed runoff volume from the

catchment (i.e. minimizing the water balance error, % WBL) and (ii) overall agreement of the shape of the hydrograph (minimizing the overall root mean square, RMSE). The calibrated values of all nine NAM model parameters are included in table 4. The parameters percentage water balance and RMSE are described in Appendix – A.

While selecting several trial values of initial condition parameters (see table 4), the performance of the model in simulating the runoff was assessed in terms of % water balance and peak runoff. The final optimized values of initial parameters are included in table 4. The flow data of December 1990 was used as ‘hot start run’ in the model for simulating the flows for years 1991–1998. Therefore, initial condition parameters QOF and QIF are taken 0.0, which indicate no overland flow and interflow in December 1990. The performance of the model, using ‘initial parameters’ as described in table 4, and ‘hot start run’ as described above, for optimized model parameters, was found to be of same order.

In table 4, the value of  $U_{\max} = 19.50$  mm indicates that a maximum 19.50 mm water would be retained in the surface storage including interception storage (on vegetation), surface depression storages and uppermost part of the ground surface;  $L_{\max} = 234.10$  mm denotes the maximum water available in the root zone to meet the vegetative-transpiration requirement. The lower calibrated values of  $U/U_{\max} = 0.50$  indicates low surface storage due to existence of thin forest cover in the catchment. On the other hand, higher values of  $L/L_{\max} = 0.8$  signify significant root zone storage in the catchment due to availability of major crop land in the catchment. Slightly high values of CQOF may be ascribed due to presence of certain low permeable soil like clay and bare rocks in the upper part of Purna catchment;  $L/L_{\max}$  being greater than TOF suggests that overland flow is generated during the wet periods.

The sensitivity of the model outputs with reference to relative change in the NAM parameters was investigated. In present study, the sensitivity analysis has been undertaken by varying the optimum values (obtained through autocalibration) of the model parameters up to  $\pm 20\%$  to ascertain the sensitivity of the simulated model results with reference to the simulated outputs corresponding to optimal model parameters for the data of years 1991–1998 of Yerli sub-catchment. The variation in runoff volume (% water balance) and peak runoff has been used to assess their sensitivity with respect to percentage variation in the model parameters. The estimated variations in percentage volume runoff and peak runoff with reference to runoff volume and peak runoff corresponding to optimal model parameters are included in table 5.

From table 5 and figure 7, it is inferred that  $L_{\max}$  parameter has significant influence on % water balance (runoff volume) and moderate influence on the peak runoff. While changing the value of  $L_{\max}$  in the range of  $\pm 20\%$  with reference to its calibrated value, the corresponding

**Table 4.** NAM calibrated parameters with initial condition parameters.

NAM model parameters	Calibrated values	Initial condition parameters	Calibrated values
$U_{\max}$ (mm)	19.50	$U/U_{\max}$	0.50
$L_{\max}$ (mm)	234.1	$L/L_{\max}$	0.80
CQOF	0.585	QOF	0.00
CQIF (h)	502.9	QIF	0.00
$CK_{1,2}$ (h)	37.70	BF	0.20
$CK_{BF}$ (h)	500.2		
TOF	0.204		
TIF	0.963		
TG	0.990		

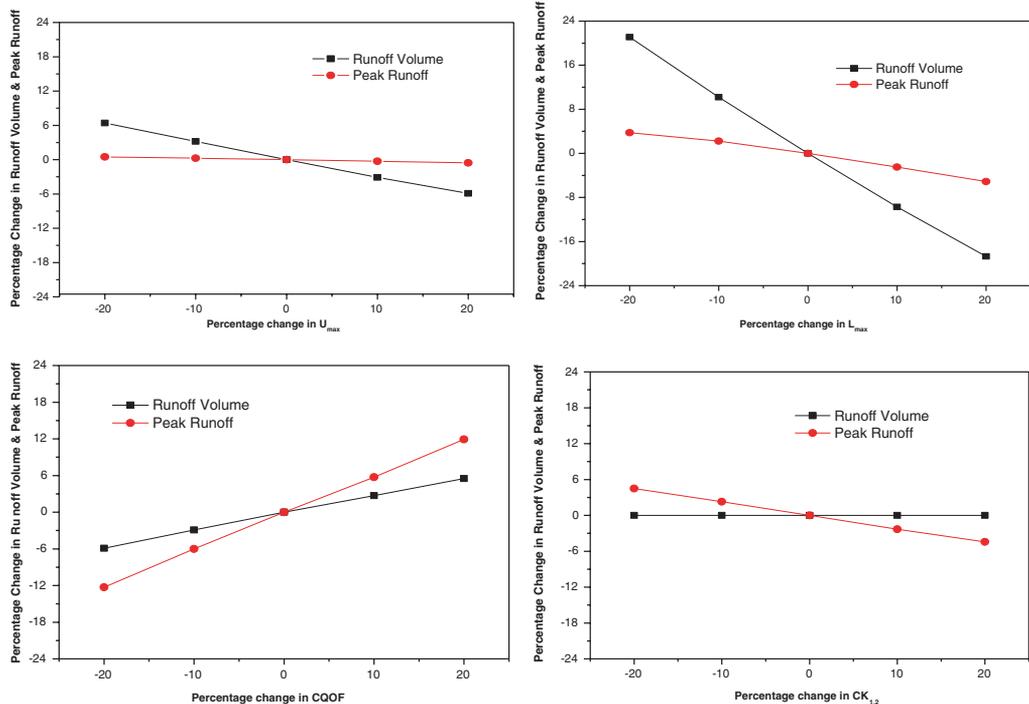
**Table 5.** Sensitivity analysis of NAM parameters.

NAM parameters	% Variation in model outputs with variation in model parameters								Level of significance <sup>#</sup>
	Runoff volume				Peak runoff				
	+20%*	+10%*	-10%*	-20%*	+20%*	+10%*	-10%*	-20%*	
U <sub>max</sub> (mm)	-5.90	-3.10	3.20	6.40	-0.56	-0.27	0.26	0.49	Moderate
L <sub>max</sub> (mm)	-18.70	-9.70	10.20	21.10	-5.11	-2.49	2.22	3.75	High
CQOF	5.50	2.70	-2.90	-5.90	11.92	5.72	-6.01	-12.27	High
CKIF (h)	-0.10	0.00	0.00	0.10	0.00	0.00	0.00	0.00	None
CK <sub>1,2</sub> (h)	0.00	0.00	0.00	0.00	-4.43	-2.32	2.29	4.49	Less
TOF	-1.90	-0.90	0.90	1.80	0.38	0.19	-0.19	-0.40	Less
TIF	0.30	0.10	-0.10	-0.50	0.30	0.10	-0.10	-0.40	None
TG	-	-	2.20	4.40	-	-	-1.40	-2.50	None
CKBF(h)	-0.40	-0.20	-	-	-1.40	-0.80	-	-	None

\*The variation in model parameters w.r.t. autocalibration values.

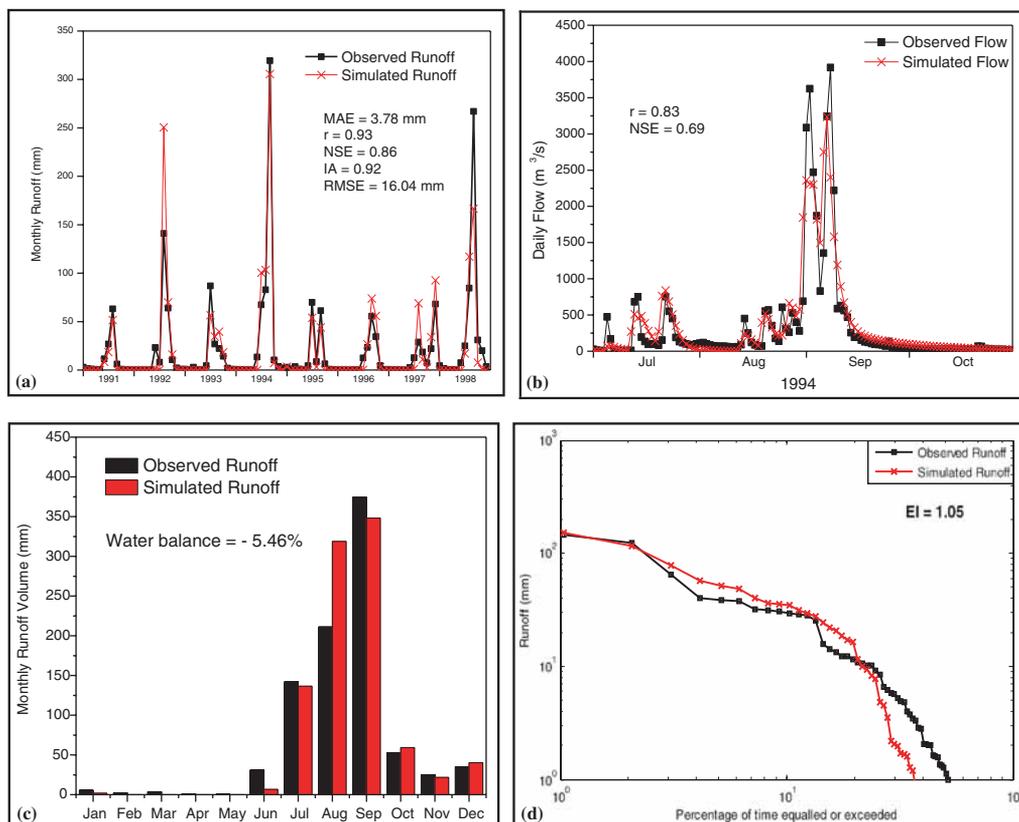
#The level of sensitivity has been categorised as high for variation in model result greater than 10%; moderate, for variation between 5 and 10%; less, for variation in model output 0.5 and 5%; insensitive, for no change.

variation in % runoff volume and peak runoff has been estimated to be -18.70% to 21.10% and -5.11% to 3.75%, respectively. The significant influence of L<sub>max</sub> on runoff volume and peak runoff is due to existence of major crop land and, hence, major root zone storage in the catchment. On the other hand, CQOF has significant influence on peak runoff wherein by varying its values in the range of ±20% with reference to its autocalibrated value, % variation in peak



**Figure 7.** Sensitivity of significant NAM model parameters.

runoff has been observed to be in the range of 11.29 to  $-12.27\%$ , see table 5. Similar variation in the CQOF causes a moderate variations in the runoff volume in the range of 5.50 to  $-5.90\%$ , see figure 7. The parameters,  $U_{\max}$  by varying its value by  $\pm 20\%$  with reference to its calibrated value, cause a moderate percentage variation in the runoff volume in the range of  $-5.90\%$  to 6.40% due to the presence of thin forest cover and depression storage in the catchment. The parameter has low influence on the peak runoff wherein by changing its value by  $\pm 20\%$  with respect to its autocalibrated value, causes an insignificant variation in the peak runoff, i.e.  $-0.56$  to 0.49%. The variation of model outputs, i.e., runoff volume and peak runoff, with reference to autocalibrated values for other model parameters, like CKIF,  $CK_{1,2}$ , TOF, TIF, TG and CKBF, are negligible except  $CK_{1,2}$  which has noticeable effect on the peak runoff (see table 5 and figure 7). The parameters TG and CKBF are varied, respectively, in their lower and upper ranges only with reference to their calibrated values as the values are already close to their respective maximum and minimum values. Keeping in view the significant variations in model outputs with reference to  $U_{\max}$ ,  $L_{\max}$ , CQOF, and  $CK_{1,2}$  (on peak runoff), selection of their values are crucial in developing rainfall-runoff model of catchments wherein sufficient data for calibration of the lumped conceptual model are not available, particularly ungauged catchment.



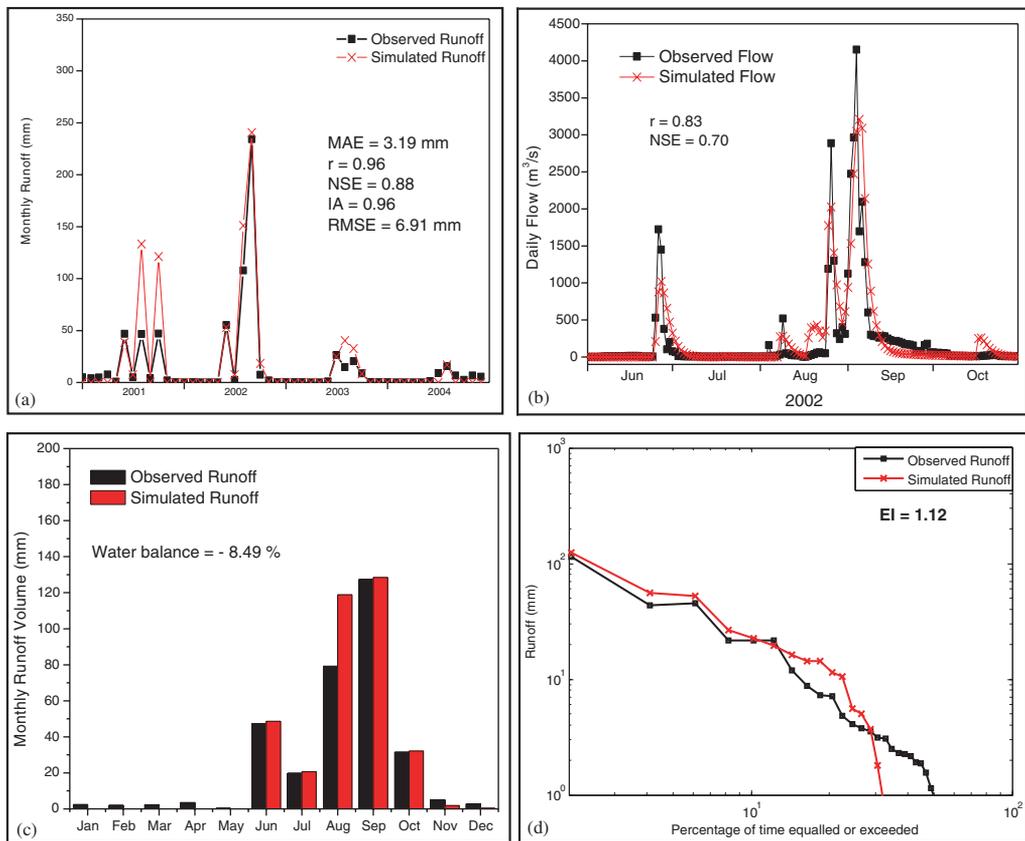
**Figure 8.** Comparison of observed and simulated (a) hydrograph for 1991–1998 monthly scale; (b) hydrograph for 1994 at daily time scale; (c) runoff volume for 1991–1998 at monthly time scale; (d) flow duration curve at monthly time scale; under calibration stage for Yerli sub-catchment.

### 3. Results and discussions

#### 3.1 Yerli sub-catchment

The performance of the NAM model under calibration stage for years 1991–1998 is shown in figure 8 for Yerli sub-catchment. The statistical performance indices, like Mean absolute error (MAE), correlation coefficient ( $r$ ), Nash Sutcliffe efficiency (NSE), Index agreement (IA) and flow duration curve index (EI), used in quantitative evaluation of NAM model, are included in Appendix – A. In table A of Appendix – A,  $Q_{sim,i}$  and  $Q_{ob,j}$  respectively represent observed and simulated values of  $j^{th}$  observation;  $n$  = number of observed data points; and  $\bar{Q}_{obs}$  and  $\bar{Q}_{sim}$ , respectively, represent mean observed and mean simulated values of runoff. The hydrological models can be considered satisfactory for % water balance (%WBL) <10%, NSE >0.80,  $r$  >0.75 and EI >0.70 (Refsgaard & Knusden 1996; Lorup *et al* 1998; Ahmed 2012; Wang *et al* 2012).

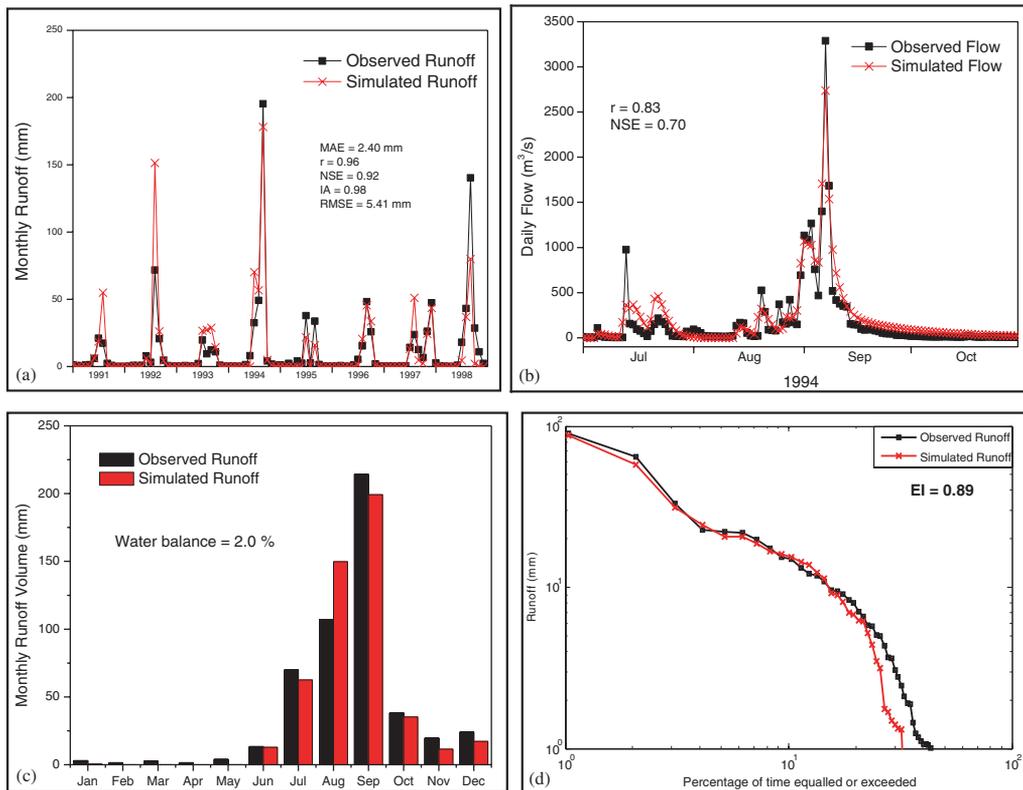
Figure 8 and statistical performance indices, enumerated on the figure, indicate that NAM model is able to simulate water balance (figure 8c) and peak (figure 8a) reasonably well in the calibration stage. The model is not able to simulated well ‘high dependable lean period flows’ (figure 8d), may be due to using default values of groundwater flow parameters due to paucity



**Figure 9.** Comparison of observed and simulated (a) hydrograph for 2001–2004 monthly scale; (b) hydrograph for 2002 at daily time scale; (c) runoff volume for 2001–2004 at monthly time scale; (d) flow duration curve at monthly time scale; under validation stage for Yerli sub-catchment.

of data for calibrating the same. The performance of NAM model under calibration stage is also assessed by simulating the hydrographs at daily time scale for year 1994 (figure 8b). Invariably, the model simulates reasonably well; however, the performance is not as good as hydrograph for monthly time scale due to non-consideration of storage effects in the NAM model on account of minor hydraulics structures present across the river. Furthermore, the calibrated model has been validated using independent data for four years at Yerli gauging station, from January 01, 2001 to December 31, 2004, see figure 9.

The calibrated NAM model simulates annual hydrograph reasonably well (figure 9a), however, daily peak discharges are, invariably, underestimated for year 2002 (figure 9b). The divergence of observed and simulated water balances is due to heterogeneity in the catchment, in terms of land use and land cover pattern, and consideration of the same calibrated lumped parameters for the whole catchment. As indicated earlier, high dependable flows during the lean period (figure 9d) are not well simulated due to non-consideration of calibrated ground water parameters in the calibrated model. While consideration of annual hydrographs for the entire period (2001–2004), the statistical performance indices, i.e.,  $r = 0.96$ ,  $NSE = 0.88$ ,  $EI = 1.27$ ,  $IA = 0.96$  are within acceptable ranges (Refsgaard & Knusden 1996; Lorup *et al* 1998; Ahmed 2012; Wang *et al* 2012). The calibrated model, for independent data, is able to simulate the hydrographs, at daily time scale, reasonably well for year 2002 (figure 8b). Being satisfactory



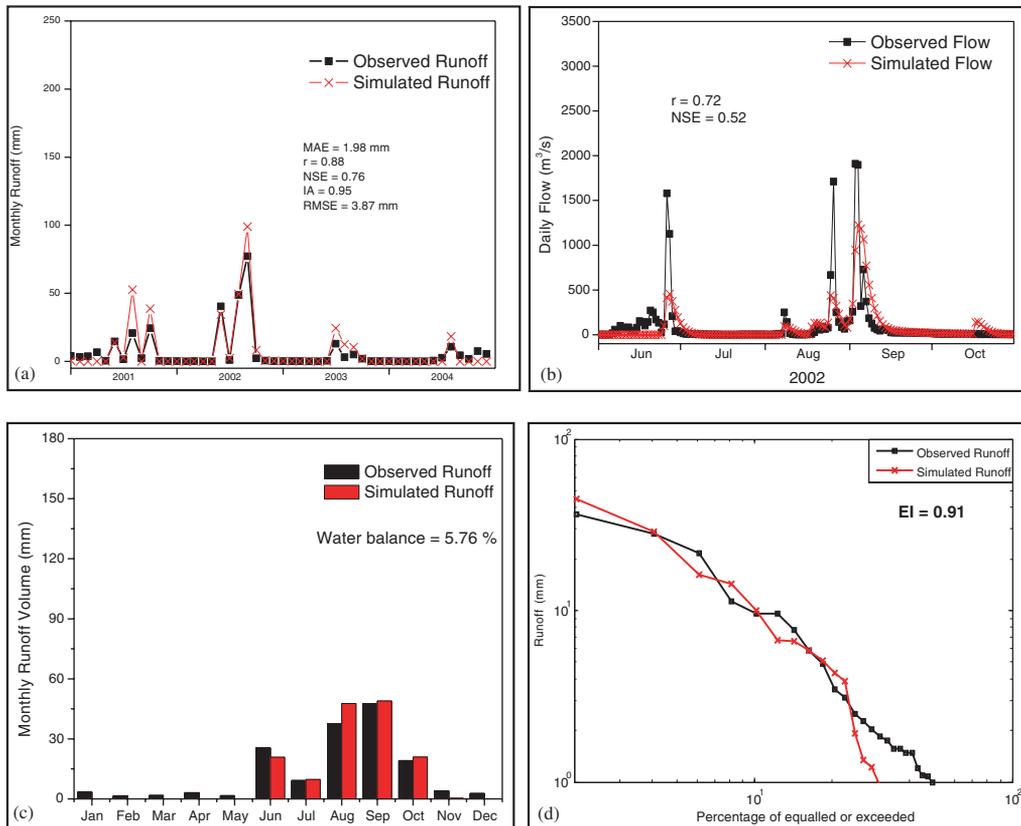
**Figure 10.** Comparison of observed and simulated (a) hydrograph for 1991–1998 monthly scale; (b) hydrograph for 1994 at daily time scale; (c) runoff volume for 1991–1998 at monthly time scale; (d) flow duration curve at monthly time scale; under validation stage for Gopalkhedha sub-catchment.

performance in simulating the hydrograph at daily time scale, the calibrated NAM model may be useful in forecasting the floods for Hathnur reservoir. However, the performance of the model requires improvement in simulating the flood hydrograph, particularly for capturing higher peaks by considering the minor storage structures across the Purna river, while using combination of hydrodynamic and NAM models.

### 3.2 Gopalkheda sub-catchment

To ascertain the applicability of calibrated model in simulating the flood within the catchment, the calibrating model at Yerli gauging station (downstream station) has been validated at Gopalkheda gauging station (upstream of Yerli gauging station) for data of years 1991–1998 and 2001–2004, see figures 10 and 11 respectively. The statistical performance indices are also indicated on respective figures for assessing the quantitative performance of the model.

From figures 10 and 11, it is evident that the calibrated NAM model is able to simulate annual hydrographs (figures 10a and 11a), water balance (figures 10c–11c) and dependable flows reasonably well. Such recommended model can be used for computation of water yield, which may be useful in planning water conservation schemes within the catchment. As stated earlier,



**Figure 11.** Comparison of observed and simulated (a) hydrograph for 2001–2004 monthly scale; (b) hydrograph for 2002 at daily time scale; (c) runoff volume for 2001–2004 at monthly time scale; (d) flow duration curve at monthly time scale; under validation stage for Gopalkheda sub-catchment.

performance of calibrated models can be improved in simulating high dependable low flows while considering ground water parameters more rigorously under the calibration stage. The calibrated model is able to simulate flood hydrograph, at daily time scale, reasonably well (figures 10b and 11b), and, hence the same can be used for predicting the flooding conditions within the catchment.

The performance of the model at Gopalkheda gauging station is relatively better than Yerli gauging station in terms of its performance prediction of daily, monthly flows and flow duration curve due to existence of better homogeneity in the smaller catchment (Gopalkheda) and, hence, better applicability of lumped hydrological model. The performance of calibrated NAM model for independent data at Yerli and Gopalkheda gauging stations indicates that the model can be used for prediction of water yield while planning water conservation scheme within the catchment, and prediction of flooding conditions in the catchment.

The performance of the model can be improved, particularly at daily time scale, by using distributed hydrological modelling approach, wherein spatial and temporal heterogeneity within the catchment can be quantified in terms of input to the hydrological model.

#### 4. Conclusions

The principal objective of the present study was to develop a conceptually realistic and less data intensive hydrological model, to predict the water yield and flood hydrographs within the catchment. The following conclusions have been arrived from the foregoing study:

- (1) The sensitivity analysis of MIKE 11 NAM hydrological model parameters is extensively investigated using observed data at Yerli stream gauging station for period 1991–1998. The parameters  $L_{\max}$  plays dominant role in affecting the runoff volume while CQOF governs the peak flow. The parameter  $U_{\max}$ , representing surface water storage, affects the water balance moderately within the catchment. On the other hand, routing parameter  $CK_{1,2}$  for interflow and overland flow affects the peak of flood hydrograph at the outlet of catchment.
- (2) The NAM model parameters, including their initial values, are optimized for the catchment while minimizing % water balance and root mean square error of observed and simulated runoff.
- (3) The calibrated model with optimal model parameters has been validated for its performance with multisite (Yerli and Gopalkheda) and multiperiod (2001–2004 for Yerli, and 1991–1998 and 2001–2004 for Gopalkheda) data in the catchment in both monthly and daily time scales. The simulated hydrographs are compared with observed hydrographs using statistical performance indices, and found to be within their acceptable limits as suggested in the published literature.
- (4) The lean period flows, being contributed due to ground water flows, are not simulated satisfactory due to adoption of default values of ground water flow parameters. The calibrated values of ground water parameters could have improved the performance of NAM model.
- (5) The performance of NAM model in prediction of flood at daily time scale requires improvement while considering the combination of hydrograph and NAM model in the catchment.

#### Acknowledgements

Authors are thankful to MHRD-NPIU-TEQIP-II for providing the funding through *Centre of Excellence (CoE)* Project on ‘Water Resources and Flood Management Centre at SVNIT’ under which present investigation has been undertaken.

**Appendix A**

*Statistical performance indices*

The statistical performance indicators enable to assess the performance of model from different viewpoints, and would provide a broader appraisal of the developed model. Performance indices

**Table A.** Statistical performance indicators used in present study.

Sr. no.	Statistical indices	Description	Equation	Theoretical value
1	Mean absolute error (MAE)	Measure of average deviation of flow	$MAE = \frac{\sum_{i=1}^n  (Q_{sim_i} - Q_{obs_i}) }{n}$	0
2	Root mean square error (RMSE)	Measure of scatter of residuals (flow)	$RMSE = \left[ \frac{\sum_{i=1}^n (Q_{sim_i} - Q_{obs_i})^2}{n} \right]^{1/2}$	0
3	Correlation coefficient (r)	Measure of correlation between observed and simulated flows	$r = \sqrt{\frac{\sum_i (Q_{sim,i} - \bar{Q}_o)^2}{\sum_i (Q_{obs,i} - \bar{Q}_o)^2}}$	1
4	Nash-Sutcliffe efficiency (NSE)	Ratio of mean square error to the variance of observed flow subtracted from unity	$NSE = 1 - \frac{\sum_{i=1}^n (Q_{sim_i} - Q_{obs_i})^2}{\sum_{i=1}^n (Q_{obs_i} - \bar{Q}_{obs})^2}$	1
5	Flow duration curve error index (EI)	Difference between the flow duration curves of simulated and observed daily flows	$EI = 1 - \frac{\sum_{i=1}^n (Q_{sim_i} - Q_{obs_i})}{\sum_{i=1}^n (Q_{obs_i})}$	1
6	Index agreement (IA)	Measure of insensitivity of correlation-based measures to differences in observed and simulated means and variances	$IA = 1 - \frac{\sum_{i=1}^n (Q_{obs_i} - Q_{sim_i})^2}{\sum_{i=1}^n ( Q_{sim_i} - \bar{Q}_{obs}  +  Q_{obs_i} - \bar{Q}_{obs} )^2}$	1
7	Water balance (%)	Ratio of difference in observed and simulated runoff volume (R.V.) to the observed runoff volume	$\%WBL = \frac{\sum_{i=1}^n (RV_{sim_i} - RV_{obs_i})}{\sum_{i=1}^n (RV_{obs_i})}$	0

$Q_{sim}$  = simulate discharge,  $Q_{ob}$  = observed discharge,  $\bar{Q}_{obs}$  = mean observed discharge,  $\bar{Q}_{sim}$  = mean simulated discharge, RV = runoff volume.

(Refsgaard & Knusden 1996; Lorup *et al* 1998; Ahmed 2010; Wang *et al* 2012) being used to evaluate the performance of the developed model in present study are described in table A.

## References

- Ahmed F 2010 Numerical modeling of the Rideau valley watershed. *Nat. Hazards* 55: 53–64
- Ahmed F 2012 A hydraulic model of Kemptonville basin – calibration and extended validation. *Water Resources. Manag.* 26: 2583–2604
- DHI 2008 *MIKE 11 Rainfall Runoff reference manual*, MIKE by DHI, Denmark
- Jain S K, Agarwal P K and Singh V P 2007 *Hydrology and water resources of India*. Springer, ISBN: 1-4020-5179-4
- Khan S I, Adhikari P, Hong Y, Vergara H, Adler R F, Policelli F, Irwin D, Korme T and Okello L 2011 Hydroclimatology of Lake Victoria region using hydrologic model and satellite remote sensing data. *Hydrol. Earth Syst. Sci* 15: 107–117
- Lorup J K, Christian R J and Mazvimavi D 1998 Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modeling: Case study from Zimbabwe. *J. Hydrol.* 205: 147–163
- Madsen H 2000 Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. *J. Hydrol.* 235: 276–288
- Merritt W S, Letcher R A and Jakeman A J 2003 A review of erosion and sediment transport models. *Environ. Model. Softw.* 18: 761–799
- Rahman Md M, Goel N K and Arya D S 2012 Development of the Jamuneswari flood forecasting system: A case study in Bangladesh. *J. Hydrol. Eng.* 17(10): 1123–1140
- Refsgaard J C and Knusden J 1996 Operational, validation and intercomparison of different types of hydrological models. *Water Resources. Res.* 32: 2189–2202
- Schumann A H, Funke R and Schultz G A 2000 Application of a geographic information system for conceptual rainfall-runoff modeling. *J. Hydrol.* 240: 45–61
- Subramanya K 2011 *Engineering hydrology*. New Delhi: Tata McGraw-Hill Publishing Company Limited
- Timbadiya P V, Mirajkar A B, Patel P L and Porey P D 2013 Identification of trend and probability distribution for time series of annual peak flow in Tapi Basin, India. *ISH J. Hydraulic Eng.* 19(1): 11–20
- Wang S, Zhang Z, Sun G, Strauss P, Guo J, Tang Y and Yao A 2012 Multi-site calibration, validation, and sensitivity analysis of the MIKE SHE model for a large watershed in northern China. *Hydrol. Earth Syst. Sci.* 16: 4621–4632