Water Resour Manage (2014) 28:351–371
DOI 10.1007/s11269-013-0486-x

Development of Geomorphology Based Regional Nash Model for Data Scares Central India Region

**R. K. Jaiswal · T. Thomas · R. V. Galkate · N. C. Ghosh ·
A. K. Lohani · Rakesh Kumar**

Received: 14 December 2012 / Accepted: 26 November 2013 /

Abstract The development of rainfall runoff relationship for ungauged watersheds using topography, geomorphology and other regional information remains the most active area of research in the field of hydrology. In the developing countries, some thumb rules and very old equations are in practice for designing water resources structures which sometimes provide erroneous results. In the proposed study, regional relationships have been developed for computation of peak velocity and scale parameters of Nash model using geomorphological and fluvial characteristics of 41 watersheds of varying characteristics in Central India region. The regional relationships developed to determine scale parameter (k) of Nash model from a morpho-fluvial factor, has facilitated derivation of at-site regional and regional only instantaneous unit hydrograph (IUH), unit hydrograph (UH) and direct surface runoff (DSRO). The performance of proposed regional model has been evaluated using spatial correlation coefficient, integral square error, relative mean absolute error, root mean square error, relative error in peak, coefficient of residual mass and model efficiency. The response of proposed regional model have been found comparable with the observed values as the Nash-Sutcliffe efficiency of proposed model during calibration varies from 69.7 % to 95.2 % for site specific approach, 60.6 % to 97.7 % for at-site regional and 67.1 % to 98.7 % for regional only approach. Similarly, the performance of proposed model have been found satisfactorily during validation as the efficiency varies from 81.3 % to 99.9 % for site specific approach, 83.5 % to 99.9 % for at-site regional and 82.7 % to 99.9 % for regional only approach. The simple regional relationships developed in the study can be used for event based rainfall-runoff modeling and estimation of design flood in ungauged catchments of central Indian region.

R. K. Jaiswal (✉) · T. Thomas · R. V. Galkate
GPSRC, National Institute of Hydrology, WALMI Complex, Bhopal, M.P., India
e-mail: rkjaiswal_sagar@yahoo.co.in

N. C. Ghosh · A. K. Lohani · R. Kumar
National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee, Uttarakhand, India

Keywords Nash model · Scale parameters · Shape parameter · Geomorphological instantaneous unit hydrograph (GIUH) · Direct surface runoff (DSRO)

1 Introduction

Regionalisation of conceptual rainfall-runoff models is a popular approach to estimate flows in ungauged catchments (Post et al. 1998; Sefton and Howarth 1998; Kokkonen et al. 2003). Numerous regionalisation methods have been proposed in the literature for predicting catchment model parameters (Bloschi 2005). Among the most widely used techniques are linear regression analysis between the model parameters and physiographic catchments atributes. Typically, linear multiple regression are used where each model parameter is estimated indepedently from the others (e.g. Post and Jackman 1996, 1999; Sefton and Howarth 1998). Often in regionalization studies, the predictive focus has been on a certain flow regime, in perticular, estimation of flood indices for ungauged catchments has received a great deal of attention (e.g., Farquharson et al. 1992; Mimikou and Gordios 1989, Zirnji and Burn 1994). Nathan and McMahon (1990) considered low flow characteristics, which may be of importance to ecological health of a river system.

The first major step in in the developemnt of relationship between rainfall and runoff was the theory of unit hydrograph proposed by Sherman (1932). Clark (1945) developed instantaneous unit hydrograph (IUH) model by assuming that the outflow hydrograph for any storm is characterized by the translation and storage effect of separable sub-areas of basin. Pure translation of the direct runoff to the outlet viz. the drainage network is described using the channel travel time, giving thereby an outflow hydrograph which ignores water storage effects. Nash (1957) proposed a conceptual model based on a cascade of equal linear reservoir for derivation of IUH for a natural watershed. Nash (1957) and Dooge (1959) suggested a two-parameter gama type model in which respons of instantaneous unit rainfall was represented by gama function of *n* numbers of identical linear reservoirs. Considering the importance of rainfall-runoff modelling for ungauged or partially gauged watersheds, Rodriguez-Iturbe and Valdes (1979) introduced geomorphological instantaneous unit hydrograph (GIUH) that used geomorhological parameters of the watershed for development of IUH which was further elaborated by Gupta et al. (1980). Rodriquez-Iturbe et al. (1982a and b) proposed geomorphoclimatic instantaneous hydrograph (GcIUH) as a link between climate, gemorphologic structures and hydrologic response of a basin. Koutsoyiannis and Xanthopoulos (1989) emphasized the advantages of parametric approaches for derivation of unit hydrograph in order to establish a relationship between the unit hydrograph (UH) and catchments characteristics.

Azward and Muzik (2000) developed spatially varied time area based GIUH that employed a cell structure and routes the spatially distributed excess rainfall from one cells to other following the maximum down slope deviation to the watershed outlet. Merz and Bloschi (2004) examined the performance of varoius methods of regionalising the parameters of a conceptual model in 308 Austrian catchments. Parajka et al. (2005) invetisgated the performance of a range of methods for transposing catchments model parameters to ungauged catchments using data of 320 Austrian catchments and found Kriging approach and similarity approaches are the best. Heuvelmans et al. (2006) investigated the use of neural nets for regionalisation. Bardosy (2007) discussed and analysed a different approach for transfer of entire parameter sets from one basin to another if the model performance (as defined by Nash-Sutuclife efficiency) on the doner catchment is acceptable. Ahmad et al. (2009) has proposed that time of concentration (T_c) and storage coefficient (R) of Clark's IUH can be determined using optimization based on downhill simplex optimization technique. The model resulted satisfactory efficiency of more than 95 % during validation and root mean square error less than 6 % during validation and sensitivity analysis indicated that surface runoff hydrograph is more sensitive to R compared to T_c. Jaiswal et al. (2010) developed regional relationships using geomorphological and fluvial characteristics of watersheds for determination of parameters of GIUH based Clark model.

Choi et al. (2011) proposed a new methodology to estimate Nash model parameters based on concept of geomorphologic dispersion stemming from spatial heterogeneity of flow path within a catchment. The characteristic velocity in the model was estimated using digital elevation model and statistical features of historical events. Ghumman et al. (2011) applied a downhill simplex optimization technique to optimize regional Nash model parameters (*n* & *k*) for computation of direct surface runoff. The performance of model was adjudged by model efficiency and concluded that direct runoff predicted with regional Nash model parameters in 57 events in six catchments has given model efficiency of 67 %. Sarkar and Rai (2011) used Soil Conservation Services-Curve Number (SCS-CN) method for computation of rainfall excess and Nakagami-m distribution for GIUH and then UH for a basin in Ganges river system. The generated UH has been routed with the help of kinematic wave approach at a gauged point on river Bhagirathi and ultimately a flood hydrograph was developed by adopting 100 year return period 1-h rainfall.

2 Nash Model

The Nash model is one of the most widely used models in applied hydrology. Nash (1957,1958, 1959, 1960) proposed a cascade of n number of identical linear reservoirs as a model on which to base the derivation of IUH's for natural watersheds. The linear reservoir assumed in Nash model are fictious reservoirs in which the storage is directly proportional to the outflow from it. Using the convolution equation and the impulse response function for linear reservoirs, the IUH corresponding to the Nash Model can be easily obtained as follows:

$$u(t) = \left(\frac{1}{k\Gamma(n)}\right)\left(\frac{t}{k}\right)^{n-1} e^{-t/k} \tag{1}$$

where u(t) is the ordinate of IUH at time t, n and k are the shape and scale parameters respectively. When the Eq. 1 is differentiated eith respect to time (t) and condition of $du(t)/dt$ is applied at $t = t_p$, the time to peak (t_p) can be obtained as:

$$t_p = (n-1)k \tag{2}$$

By putting the value of k from Eq. (2) to Eq. (1), $u(t)$ can be expressed as:

$$u(t) = \left(\frac{(n-1)^n}{t_p\Gamma(n)}\right)\left(\frac{t}{t_p}\right)e^{-t/t_p} \tag{3}$$

Rodríguez-Iturbe and Valdes (1979) suggested the following equation for computation of shape parameter (n) of Nash model with the help of geomorphologic parameters.

$$\frac{(n-1)}{n}e^{-(n-1)}(n-1)^{n-1}=0.58\left(\frac{R_B}{R_A}\right)^{0.55}{R_L}^{0.05} \tag{4}$$

Where R_B, R_L and R_A are the bifurcation ratio, length ratio and area ratio respectively. Rosso (1984) suggested finally the following equations for computation of n and k using the iterative computing scheme proposed by Croley (1977) :

$$n=3.29\left(\frac{R_B}{R_A}\right)^{0.78}{R_L}^{0.07} \tag{5}$$

$$k=\frac{0.44}{V(n-1)}\left(\frac{R_B}{R_A}\right)^{0.55}{R_L}^{-0.38} \tag{6}$$

For estimation of dynamic parameter velocity (V), Rodriguez-Iturbe et al. (1979) made an assumption of equilibrium state of basin. According to this assumption, the flow velocity and discharge at any moment during the storm can be considered as constant throughout the basin. This characteristic velocity for the basin as a whole changes throughout as the storm progresses and may be termed as equivalent velocity (V_e). Similarly, the discharge was considered as equilibrium discharge (Q_e). Using this principle, the peak velocity (V_p) which may be the equivalent velocity at the time of highest rainfall intensity (i_p) is estimated by developing a relationship between equilibrium velocity (V_e) and rainfall intensity (i) in the following form:

$$V_e=a*i^b \tag{7}$$

where, Ve is the equivalent velocity in m/sec, i is the intensity of rainfall excess in mm/hr and a and b are the watershed specific coefficient and exponent respectively.

In case of gauged catchments, where velocities and corresponding discharges passing through a gauging section are known from observations, assuming the equilibrium state of basin, the equilibrium discharge (Q_e) may be considered as the multiplication of rainfall intensity and contributing basin area (A). The intensity of rainfall excess (i) in mm/hr for an equilibrium discharge (Q_e) in m^3/sec can be computed with the help of the following equation

$$i=\frac{Q_e}{0.2778A} \tag{8}$$

Using different pairs of V_e and i, the coefficient a and exponent b can be computed using least square method. For an ungauged basin, bed slope, geometric properties of gauging section and Manning's roughness coefficient (N) are used to determine different pairs of V_e using Manning's equation and Q_e at different depths of gauging section. Graphs may be plotted between depth v/s area of cross-section and depth v/s discharge. The Q_e for a known value of rainfall excess is estimated using Eq. 8. The corresponding depth and area of cross-section may be obtained using graphs between depth v/s area of cross-section and depth v/s discharge. Knowing cross-sectional areas, the V_e for different values of i can be computed and a relation in the form of $V_e=a*i^b$ may be developed.

3 Study Area

The study area is the central part of India, administratively known as Madhya Pradesh (M.P.) state. This region is very rich in natural resources and many important tributaries of river Ganges and peninsular rivers originate from this part. The Narmada, Chambal, Parvati, Sindh, Son, Ken, Betwa, Bina, Dhasan, Bearma etc. are some of the important rivers that originate from this part of country. This region can be characterized by undulating topography, deciduas type of forest, small valley lands with productive soil and semi arid climate. The average rainfall in this region is about 1,100 mm, which is near to the national average. The base map showing the location of watersheds has been presented in Fig. 1. The geomorphological parameters of these watersheds (WS-1 to WS-41) have been depicted in Table 1. The catchment areas of watersheds vary from 0.77 sq. km to 518.67 sq. km. Similarly, bifurcation ratio and length ratio range from 2.00 to 5.48 and 1.11 to 5.98 respectively.

4 Methodology for Regional Approach

In the present paper an attempt has been made to develop the regional relationships for computation of peak velocity (V_p) at the time of peak rainfall intrensity (i_p) and scale parameter (k) of Nash model. The at-site, at-site regional and regional only approaches have been used for computation of ordinates of IUH and subsiquently the UH and direct surface runoff (DSRO) has been determined.

4.1 Estimation of Velocity

The development of V_e & i relationship is considered a difficult task for field engineers and water resoueces managers. In this study, regional relationships have been developed for computation of the coefficients a & b using basin characteristics of nine gauged and six ungauged watersheds. Separate regional relationships have been developed to compute coefficient a and exponent b of V_e-i relationship using catchment area (A) and average slope (S) of watersheds.

4.2 Estimation of Model Parameters

The shape parameter (n) of Nash model in can be computed easily with the help of geomorphologic parameters. For estimation of scale parameter (k), a regional relationship have been developed between the k and the geomorphologic and fluvial characteristics, 37 watersheds (WS-3 to WS-9 and WS-12 to WS-41) have been selected to derive the relationship during calibration, while remaining four watersheds (WS-1, WS-2, WS-10 and WS-11) have been chosen for validation. In the calibration, the scale parameter and ordinates of arbitrary GIUHs for all 37 watersheds have been determined for different rainfall excess ranging from 1 mm/hr to 40 mm/hr. Various combination of morphological and fluvial characteristics have been tried to develop regional relationship with scale parameter and in turn, a relation between a morpho-fluvial factor $L_\Omega/(R_L^{0.43} * V_p)$ and k has been derived to regionalize the scale parameter (k) of Nash model. The factor, $L_\Omega/(R_L^{0.43} * V_p)$, represents the combined effect of geomorphologic and fluvial characteristics of a watershed.

Employing the above method, at-site, at-site regional and regional only IUH and UH are determined for few known storms. In the site specific approach, the geomorphologic parameters and site specific relationship between V_e & i of the respective site are extended to derive the DSRO; while in the at-site regional approach, site specific relationship between V_e & i has

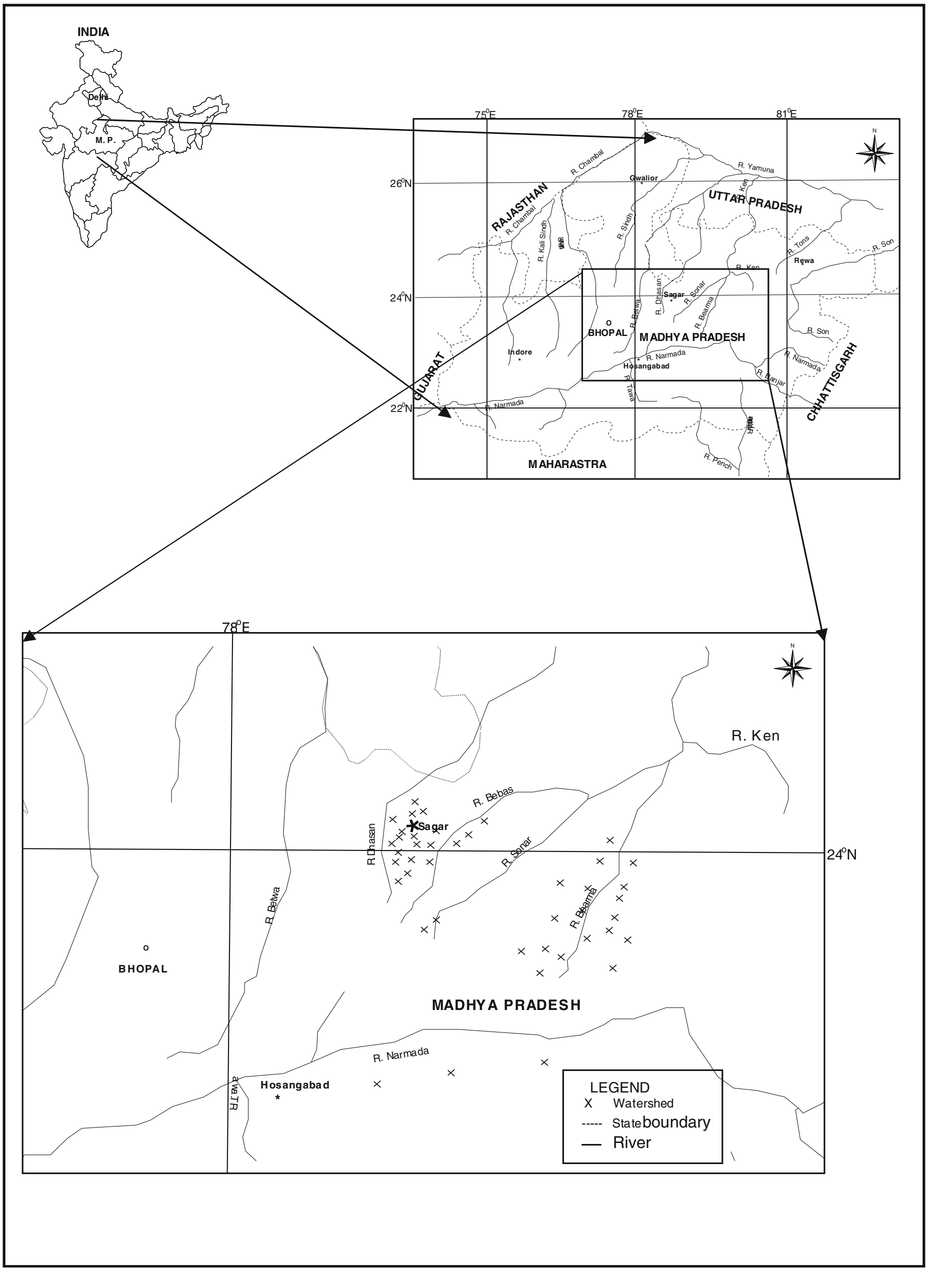

Fig. 1 Location map showing watersheds selected for the study

been used to compute peak velocity (V_p) and the regional relationship for computation of shape (n) and scale parameter (k) have been used to derive the IUH, UH and subsequently the DSRO. In case of regional only analysis, the regional relationships of V_e, n and k were used to

Table 1 Geomorphological characteristics of the watersheds selected for study

WS No.	A	L_Ω	R_B	R_L	R_A	WS No.	A	L_Ω	R_B	R_L	R_A
WS-1	1.01	1.06	4.00	2.46	6.97	WS-22	5.16	3.14	5.00	3.75	6.92
WS-2	4.08	1.52	3.46	1.64	4.26	WS-23	8.12	4.17	4.69	5.98	9.55
WS-3	1.87	1.73	3.95	2.91	7.40	WS-24	5.88	2.28	4.48	2.29	5.88
WS-4	5.41	2.22	3.16	1.94	4.08	WS-25	17.76	1.66	3.39	1.43	3.98
WS-5	23.91	9.33	3.30	0.64	3.24	WS-26	11.05	3.93	4.80	2.59	6.46
WS-6	0.77	0.61	2.00	1.18	3.61	WS-27	3.44	3.16	4.36	2.27	6.17
WS-7	28.06	3.34	2.90	1.89	4.40	WS-28	2.68	0.53	2.65	1.82	3.89
WS-8	518.67	24.75	4.17	3.89	5.81	WS-29	6.31	0.48	2.98	1.11	3.47
WS-9	226.27	30.00	4.04	2.56	4.76	WS-30	25.54	0.13	3.03	1.57	3.55
WS-10	114.22	35.42	4.08	2.75	4.58	WS-31	2.51	0.09	3.00	1.54	3.98
WS-11	2.68	0.90	3.50	1.30	4.33	WS-32	5.27	0.45	2.42	1.49	3.16
WS-12	18.65	6.20	3.12	2.19	3.73	WS-33	4.64	1.99	3.87	1.95	5.13
WS-13	4.13	1.24	2.99	1.82	5.04	WS-34	12.34	6.26	5.48	3.06	7.41
WS-14	27.54	4.62	3.80	2.16	5.02	WS-35	10.91	1.86	4.25	1.75	5.37
WS-15	2.39	0.81	2.65	1.37	3.71	WS-36	48.63	11.78	4.49	2.56	5.62
WS-16	2.51	1.00	2.83	1.22	3.95	WS-37	32.53	5.82	4.21	1.82	5.01
WS-17	3.66	1.16	2.98	1.36	4.06	WS-38	11.18	0.45	3.11	2.81	4.68
WS-18	9.07	2.17	2.56	1.77	3.74	WS-39	16.42	3.76	4.90	2.11	4.09
WS-19	8.67	1.47	3.16	1.47	4.15	WS-40	26.43	4.47	3.87	2.08	5.01
WS-20	8.53	2.69	3.61	2.34	6.12	WS-41	43.94	1.77	3.40	1.91	4.27
WS-21	15.82	5.04	5.20	3.46	7.59						

WS No. watershed number, A catchment area (km^2), L_Ω length of highest order stream (km), R_B bifurcation ratio, R_L length ratio, R_A area ratio

compute the IUH, UH and DSRO. The relationships derived from analysis of watersheds used in calibration were extended to WS-1, WS-2, WS-10 and WS-11 for validation. The flow chart showing various steps in regionalization of parameters for development of model has been given in Fig. 2.

The performance of at-site, at-site regional and regional only approaches are evaluated in comparison to the observed runoff data using spatial correlation coefficient (*SC*), integral square error (*ISE*), relative mean absolute error (*RMAE*), root mean square error (*RMSE*), relative error in peak (*REP*), Nash & Sutcliffe efficiency (Nash and Sutcliffe 1970) and coefficient of residual mass (*CRM*). The *SC* gives the measure of the degree to which two variables are linearly related and varies between −1 and 1. The high value of *SC* indicates strong correlation. The *ISE* is a measure of system performance formed by integrating the square of the system error over a fixed interval of time; smaller the ISE value closer is the match. The *RMAE* is a measure indicating how close forecasts or predictions are to the eventual outcomes and the *RMSE* is the square root of the mean-squared-error. The *RMAE* and *RMSE* ranges from 0 to infinity, with 0 corresponding to the ideal. The *REP* is the measure of deviation in two peaks. Nash-Sutcliffe efficiency is widely used statistics in hydrology and reaching toward 100 % indicative of closer match in most of the observations. The *CRM* is a measure of the tendency of the model to overestimate or underestimate the measurements (Bhadra et al. 2008). Positive values for *CRM* indicate that the model

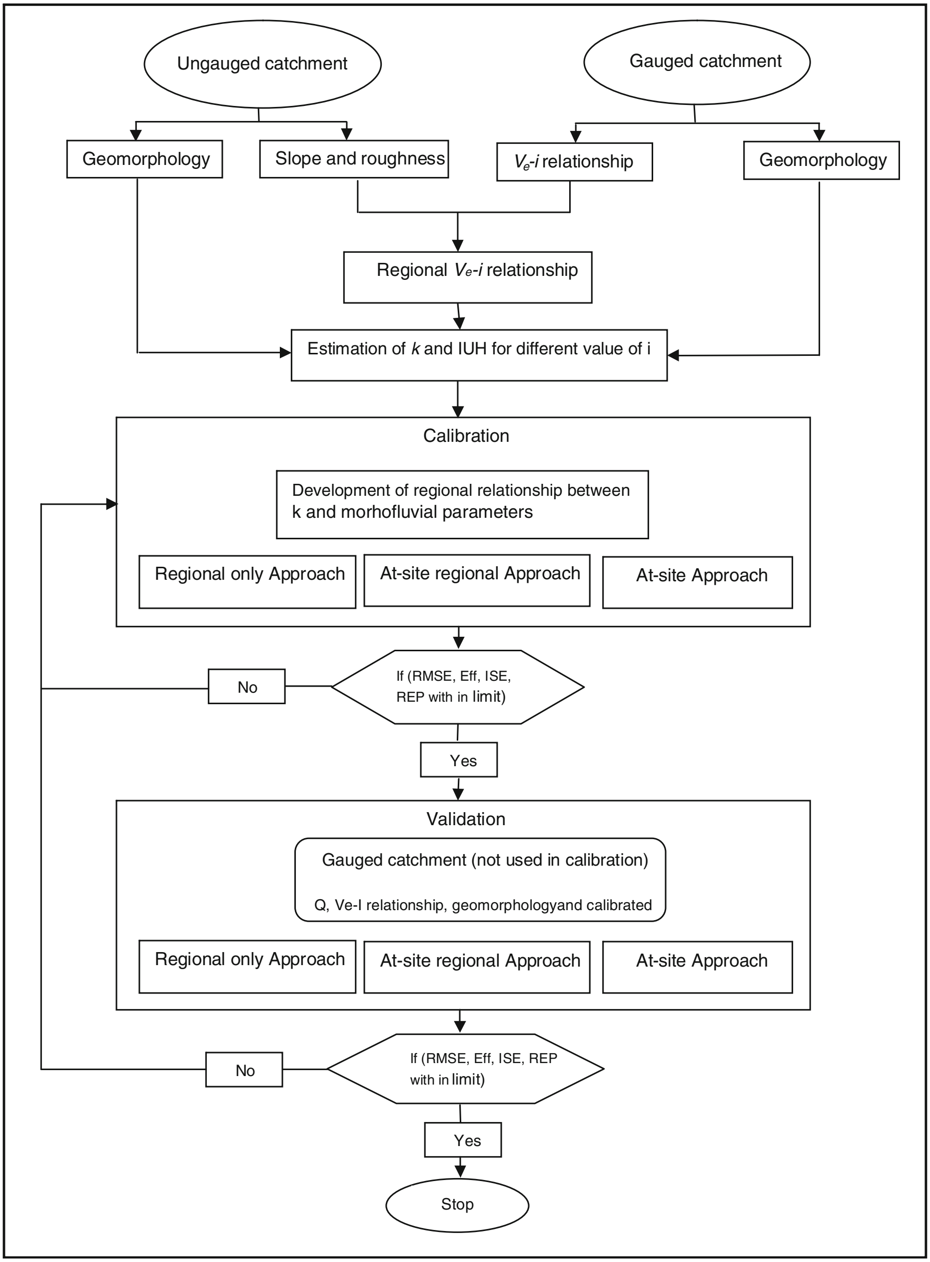

Fig. 2 Flow chart for development of regional Nash model

underestimates the measurements while negative values for *CRM* indicate a tendency to overestimate. For a perfect fit between observed and simulated data, the values of *CRM* should be equal to 0.0. Formulae for various goodness of fitness parameters used in the study are given below.

a) Spatial correlation Coefficient (*SC*)

$$SC = \frac{2\sum_{t=1}^{n} Q_o(t)\ Q_c(t) \ -\sum_{t=1}^{n} [Q_c(t)]^{\ 2}}{\sum_{t=1}^{n} Q_o(t)} \tag{9}$$

b) Integral Square Error (*ISE*)

$$ISE = \frac{\left[\sum_{t=1}^{n} \{ Q_o(t) - Q_c(t)\}^{\ 2}\right]^{0.5}}{\sum_{t=1}^{n} Q_o(t)} \tag{10}$$

c) Relative Mean Absolute Error (*RMAE*)

$$RMA = \frac{\frac{1}{n}\sum_{t=1}^{n} [\ Q_o(t) \ -Q_c(t)\ ]}{Q_{op}} \tag{11}$$

d) Relative Mean Square Error (*RMSE*)

$$RMS = \frac{\left[\sum_{t=1}^{n} \{ Q_o(t) - Q_c(t)\}^{2}\right]^{0.5}}{n} \tag{12}$$

e) Relative Error in Peak (*REP*)

$$REP = \frac{Q_{op}-Q_{cp}}{Q_{op}} \tag{13}$$

f) Nash-Sutcliffe Efficiency (η)

$$\eta = \frac{IV-RV}{IV} * 100 \tag{14}$$

where $Q_o(t)$ = observed discharge at time t; $Q_c(t)$ = computed discharge at time t; Q_{op} = observed peak discharge; Q_{cp} = computed peak discharge; n = no. of observation, IV = initial variance, RV = remaining variance. If $\overline{Q}_o$ is the mean observed discharge, the IV and RV can be expressed as:

$$IV = \sum_{t=1}^{n} \left[Q_o(t) - \overline{Q}_o\right]^2 \tag{15}$$

$$RV = \sum_{t=1}^{n} \left[Q_o(t) - Q_C(t)\right]^2 \tag{16}$$

g) Coefficient of residual mass (*CRM*)

$$CRM = \frac{\sum_{i=1}^{n} \left[Q_o(t) - Q_c(t)\right]}{n * \overline{Q}_o} \tag{17}$$

5 Results and Discussion

Using the methodology explained above, an attempt has been made to develop a regional relationship for determination of scale parameter (k) of Nash model in data scarce central India region using geomorphologic and fluvial characteristics of the basins. In the analysis, regional relationships for computation of coefficients (a & b) of V_e and i relationship have been developed. Using at-site, at-site regional and regional only approaches, the IUH, UH and the DSRO for different events have been computed in these watersheds. The results obtained from the analysis have been compared with the observed results using different performance evaluation parameters.

5.1 Regional Relationship for Estimation of Equilibrium Velocity (V_e)

The estimation of peak velocity requires the gauge discharge data or information of section and Manning coefficient (N) of the watershed. In this study, an attempt has been made to develop a regional relationship between fluvial characteristics with basin characteristics. From the analysis, it has been observed that slope and catachment area play an important role in deciding the coefficients a & b of V_e-i relationship. The following equations have been developed for estimation of a & b.

If $A\sqrt{S}$ is less than 3.5

$$a = 0.239A\sqrt{S} + 0.351 \tag{18}$$

$$b = 0.127A\sqrt{S} + 0.195 \tag{19}$$

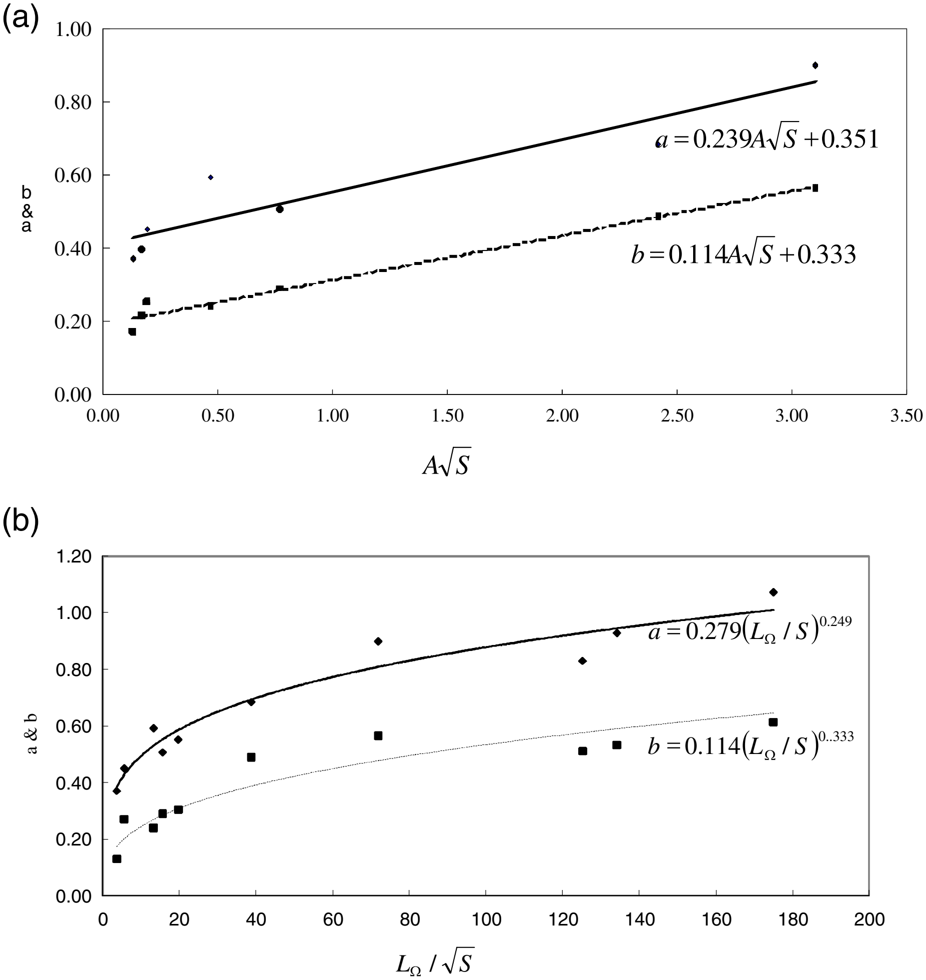

Fig. 3 Regional relationship for computation of a & b of equilibrium velocity (*Ve*). **a** Relationship for computation of a & b if $A\sqrt{S}$ is < 3.5. **b** Relationship for computation of a & b if$A\sqrt{S}$ is ≥ 3.5

If $A\sqrt{S}$ is equal to or greater then 3.5

$$a = 0.279\left(\frac{L\Omega}{\sqrt{S}}\right)^{0.249} \tag{20}$$

$$b = 0.114\left(\frac{L\Omega}{\sqrt{S}}\right)^{0.333} \tag{21}$$

The graphical representation for computation of *a & b* are given in Fig. 3.

5.2 Development of Regional Parameters of Nash Model

For development of regional relationship, the geomorphological parameters of 37 watersheds (WS-3 to WS-9 and Ws-12 to Ws-41) and *Ve-i* relationship of gauged watersheds have been

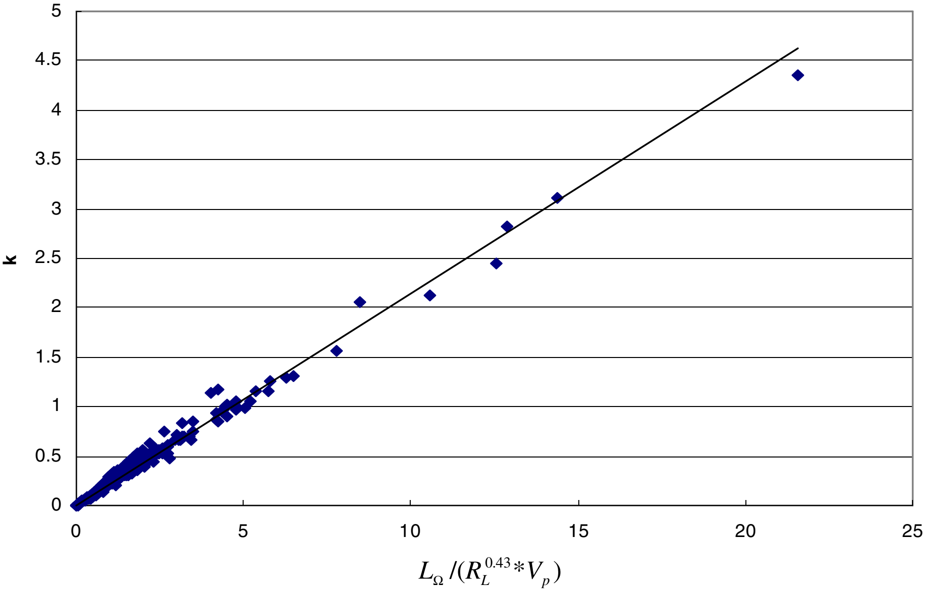

Fig. 4 Regional relationship betwen $L_\Omega/(R_L^{0.43}*V_p)$ and scale parameter (k)

used as inputs. In case of ungauged watersheds, peak velocity (V_p) has been computed using regional Eqs. (7) and (18) to (21). The scale parameter k and ordinates of IUH's for different arbitrary excess rainfall intensity ranging from 1 mm/hr to 40 mm/hr for all the watersheds have been computed. Various combination of morphologic and fluvial characteristics have been tried to define relationship with k for the region. Finally, the following mathematical relationship between a morpho-fluvial factor $[L_\Omega/(R_L^{0.43}*V_p)]$ and k has been found the most appropriate for estimation of scale parameter for ungauged watersheds.

$$k = 0.2143\frac{L_\Omega}{R_L^{0.43}\quad V_p} \tag{22}$$

The graphical representation of regional relationship between $L_\Omega/(R_L^{0.43}*V_p)$ and k has been presented in Fig. 4.

5.2.1 Calibration of Regional Model

The regional relationship for computation of k has been developed using geomorphologic parameters of 37 watersheds. For calibration, few storms of seven watersheds (WS-3 to WS-9) which were used in developing the regional relationship have been analyzed. These watersheds have been selected for performance evaluation due to availability of observed discharge data. The ordinates of excess rainfall for selected storms have been computed using $\varphi-index$ method. In this method, a uniform value of loss rate ($\varphi-index$) has been computed by trial and error method to make the volume of excess rainfall equal to the volume of (DSRO). The at-site, at-site regional and regional only IUH, UH and corresponding DSRO for these storms have been computed. From the observed point observations, smoothened flood hydrograph has been prepared and straight line base flow separation technique was used to compute DSRO from the flood hydrograph. The at-site, at-site regional and regional only DSRO for few

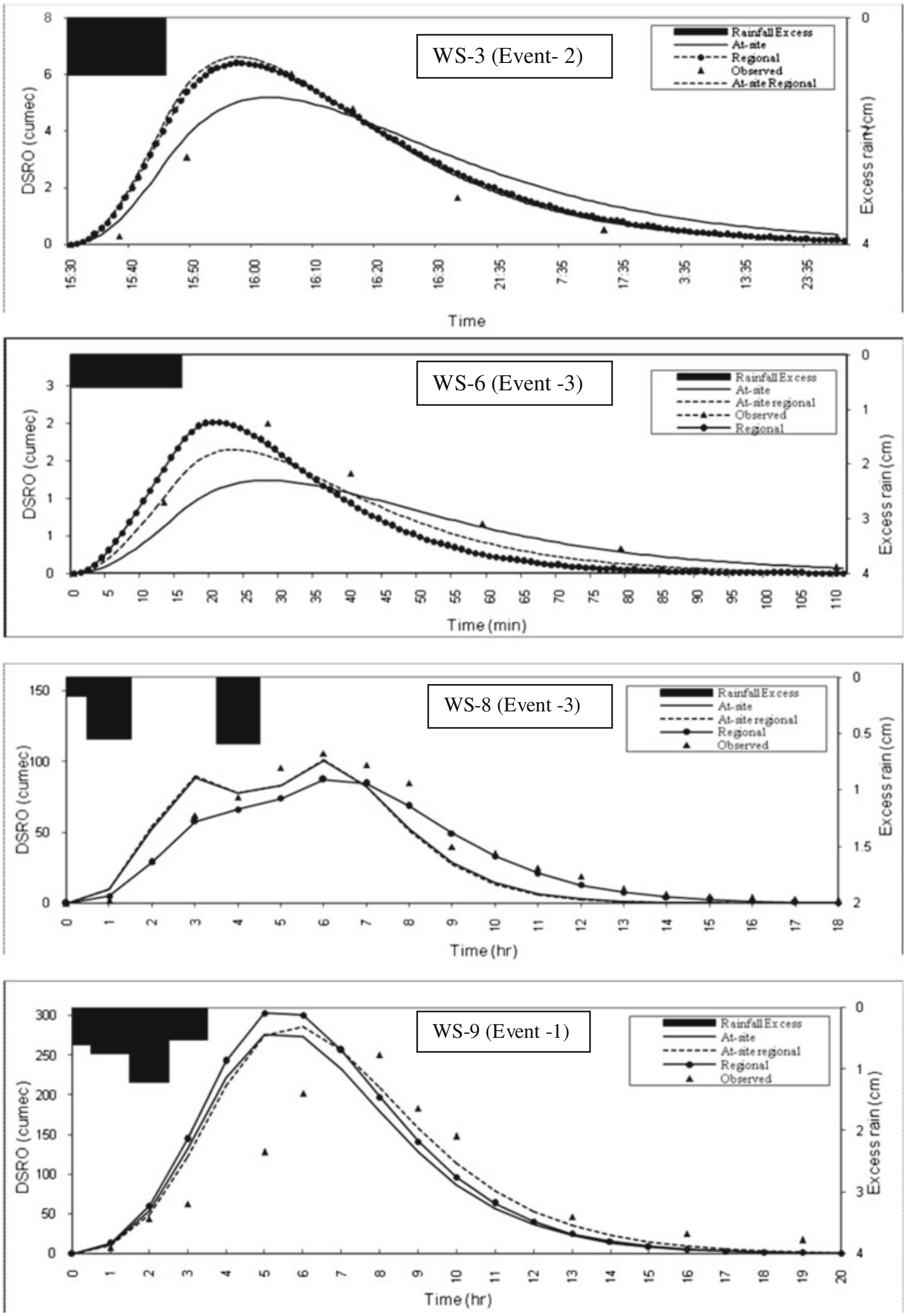

Fig. 5 Comparison of site specific and regional model during calibration

known storms are presented in Fig. 5. It can be observed from Fig. 5 that site specific, at-site regional and the regional only approach exhibit a close resemblance with the observed data.

Table 2 Parameters of Nash model during calibration

Watershed	Date/s of event	Event	i_p	n	At-site approach				At-site regional approach				Regional only approach			
					V_p	k	Q_p	t_p	V_p	k	Q_p	t_p	V_p	k	Q_p	t_p
WS-3	14-08-03	Event-1	7	2.194	0.61	0.493	3.569	35	0.61	0.382	4.594	25	0.60	0.393	4.468	30
	15-09-03	Event-2	40	2.194	0.90	0.336	1.909	17	0.90	0.260	6.752	20	0.87	0.269	6.527	19
	24-09-03	Event-3	24	2.194	0.80	0.376	4.681	27	0.80	0.291	6.052	21	0.78	0.301	5.844	22
WS-4	14-08-03	Event-1	7	2.823	0.90	0.404	10.504	45	0.90	0.399	10.617	45	0.94	0.379	11.172	40
	15-09-03	Event-2	40	2.823	1.49	0.243	17.357	25	1.49	0.241	17.573	25	1.57	0.228	18.62	25
	24-09-03	Event-3	24	2.823	1.28	0.282	15.009	30	1.28	0.279	15.186	30	1.35	0.264	16.017	30
WS-5	05-09-06	Event-1	7	3.235	2.73	0.806	21.157	110	2.73	0.888	19.208	120	3.17	0.765	22.281	100
	07-07-07	Event-2	40	3.235	7.37	0.298	57.16	40	7.37	0.329	51.852	45	8.51	0.285	59.396	35
	29-07-07	Event-3	20	3.235	4.96	0.493	38.502	59	4.96	0.488	34.944	65	2.928	0.422	40.424	57
	01-08-07	Event-4	8	3.235	2.94	0.747	22.787	105	2.94	0.823	20.728	110	3.42	0.702	24.048	95
WS-6	14-08-03	Event-1	7	2.10	0.48	0.348	2.175	23	0.48	0.255	2.959	17	0.55	0.223	3.391	16
	15-09-03	Event-2	40	2.10	0.60	0.277	2.728	18	0.60	0.203	3.709	13	0.78	0.156	4.893	10
	24-09-03	Event-3	24	2.10	0.56	0.296	2.552	20	0.56	0.218	3.472	14	0.70	0.133	4.356	11
WS-7	14-08-03	Event-1	7	2.485	0.87	0.706	34.149	65	0.87	0.622	38.784	55	0.93	0.587	41.075	50
	15-09-03	Event-2	40	2.485	2.28	0.271	89.05	25	2.28	0.239	100.88	20	1.54	0.354	85.107	40
	24-09-03	Event-3	24	2.485	1.72	0.359	67.109	30	1.72	0.316	76.147	1.33	0.417	0.411	58.664	44
WS-8	23-07-62	Event-1	3.9	2.793	2.47	1.22	303.87	180	2.47	1.19	340.58	120	1.76	1.682	243.60	180
	05-09-62 to 06-09-62	Event-2	5.9	2.793	3.18	0.949	421.36	120	3.18	0.93	427.21	120	3.18	0.93	427.21	120
	20-07-64 to 21-07-64	Event-3	7.6	2.793	3.72	0.813	456.33	87.4	3.72	0.795	465.37	85.7	2.49	1.223	331.29	120
	14-08-64 to 15-08-64	Event-4	4.6	2.793	2.73	1.105	370.74	151	2.73	1.083	378.25	116.5	1.92	1.544	263.92	166.1
WS-9	22-06-71 to 23-06-71	Event-1	12	3.092	2.78	1.449	114.99	181.8	2.78	1.591	103.55	199.8	2.96	1.451	114.78	182.2
	02-08-71 to 03-08-71	Event-2	5.8	3.092	2.02	1.998	83.221	250.8	2.02	2.126	77.506	266.8	2.08	2.061	80.375	258.7
	15-08-72	Event-3	6.6	3.092	2.14	1.887	88.274	236.9	2.14	2.007	82.794	252	2.22	1.931	86.022	243.1
	15-08-72 to 16-08-72	Event-4	4.65	3.092	1.83	2.203	75.086	276.5	1.83	2.344	71.06	294.2	1.87	2.292	72.531	287.8

i_p peak rainfall intensity (mm/hr), n shape parameter, V_p Peak velocity (m/sec), k scale parameter (hrs^{-1}), Q_p peak runoff (m^3/sec), t_p time to peak (min)

Table 3 Evalution of performance of at-site, at-site regional and regional Nash model during calibration

WS	Event	At-site approach							At-site regional approach							Regional approach						
		SC	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*CRM*	*SC*	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*CRM*	*SC*	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*CRM*
WS-3	Event -1	0.69	0.24	0.24	0.07	0.15	95.2	0.24	0.37	0.35	0.33	0.09	−0.2	85.8	0.25	0.42	0.33	0.32	0.09	−0.2	78.9	0.24
	Event -2	0.91	0.15	0.11	0.36	0.27	84.3	0.01	0.92	0.15	0.11	0.36	0.15	83.7	−0.07	0.92	0.14	0.11	0.34	0.17	91.5	−0.06
	Event -3	0.92	0.13	0.13	0.26	0.33	75.8	0.08	0.90	0.15	0.15	0.29	0.12	69.8	0.004	0.91	0.14	0.14	0.27	0.14	72.9	0.01
WS-6	Event -1	0.95	0.09	0.13	0.03	0.21	78.9	0.22	0.91	0.13	0.17	0.03	−0.07	61.8	0.09	0.82	0.18	0.23	0.05	−0.19	67.1	0.04
	Event -2	0.97	0.07	0.06	0.09	0.18	93.4	−0.05	0.89	0.14	0.12	0.19	−0.10	72.9	−0.12	0.19	0.19	0.19	0.25	−0.14	69.9	−0.03
	Event -3	0.89	0.16	0.11	0.15	0.38	74.9	0.25	0.95	0.11	0.09	0.10	0.21	87.9	−0.19	0.90	0.15	0.14	0.14	0.14	76.9	0.12
WS-7	Event -1	0.96	0.10	0.09	0.30	0.21	90.5	0.05	0.99	0.05	0.04	0.15	0.12	97.7	0.00	0.99	0.04	0.03	0.11	0.07	98.7	−0.03
	Event -2	0.96	0.11	0.08	3.7	0.08	89.9	0.00	0.91	0.15	0.12	5.21	0.01	79.9	0.00	0.97	0.09	0.08	3.03	0.07	93.2	−0.11
	Event -3	0.79	0.24	0.16	2.26	−0.01	69.7	−0.08	0.69	0.29	0.19	2.75	−0.09	60.6	−0.10	0.87	0.19	0.13	1.80	0.09	74.6	−0.05
WS-8	Event -1	0.43	0.25	0.32	17.5	0.25	89.2	−0.05	0.42	0.29	0.32	17.7	0.23	81.5	−0.05	0.59	0.24	0.26	14.83	0.45	84.6	0.05
	Event -2	0.60	0.19	0.26	8.86	0.25	88.5	0.18	0.59	0.19	0.26	8.98	0.24	86.2	0.17	0.76	0.15	0.21	6.24	0.35	83.4	0.16
	Event -3	0.57	0.21	0.21	16.5	−0.13	73.3	0.13	0.54	0.22	0.21	16.9	−0.15	78.7	0.10	0.72	0.17	0.14	13.22	−0.34	84.4	0.10
	Event -4	0.48	0.31	0.39	18.02	−0.52	69.1	0.30	0.43	0.31	0.40	18.4	−0.54	68.7	0.31	0.44	0.34	0.42	19.88	−0.44	69.4	0.28
WS-9	Event -1	0.98	0.06	0.07	5.6	−0.01	94.5	−0.12	0.98	0.06	0.07	5.62	−0.01	94.4	0.10	0.85	0.15	0.15	13.82	0.06	86.2	−0.11
	Event -2	0.74	0.18	0.16	7.41	0.10	74.3	0.07	0.79	0.16	0.17	7.07	0.15	81.7	0.06	0.77	0.17	0.17	7.04	0.13	78.8	0.06
	Event -3	0.32	0.32	0.31	11.9	0.08	69.2	0.09	0.43	0.29	0.28	10.9	0.11	75.4	0.06	0.36	0.31	0.30	11.54	0.09	73.1	0.08
	Event -4	0.57	0.29	0.30	14.34	0.28	71.8	0.05	0.51	0.32	0.32	15.3	0.29	65.7	0.08	0.53	0.31	0.31	14.97	0.28	68.6	0.07

SC spatial correlation coefficient, *ISE* integral square error, *RMAE* relative mean absolute error, *RMSE* root mean square error, *REP* relative error in peak, *EFF* efficiency, *CRM* Coefficient of residual mass

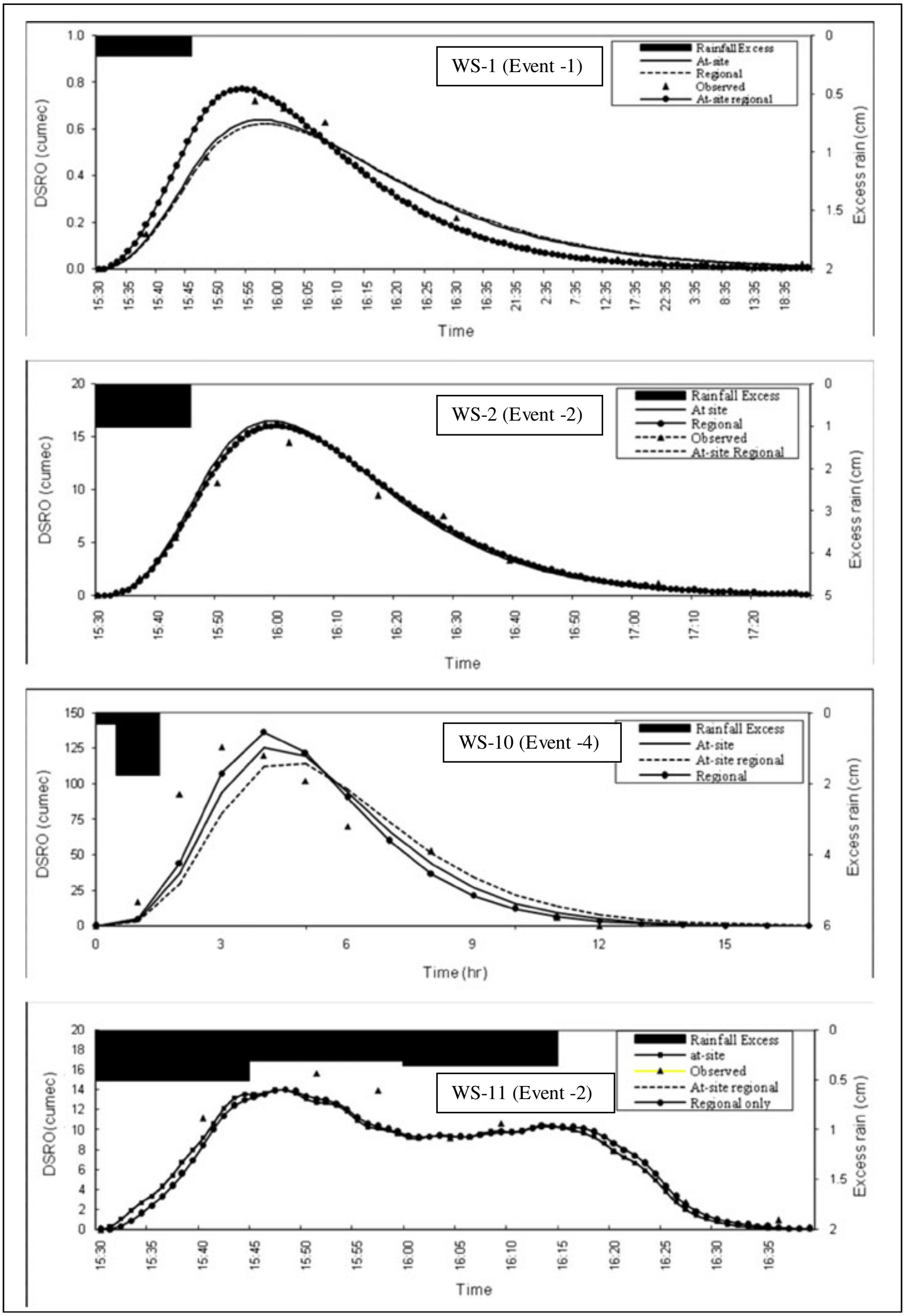

Fig. 6 Comparison of site specific and regional model during validation

The model results for at-site, at-site regional and regional only approach including i_p, V_p, $n,,k$, peak runoff (Q_p) and time to peak (T_p) for few storm events during calibration were given in Table 2.

Table 4 Parameters of Nash model during validation

Watershed	Date/s of event	Event	i_p	n	At-site approach				At-site regional approach				Regional only approach			
					V_p	k	Q_p	t_p	V_p	k	Q_p	t_p	V_p	k	Q_p	t_p
WS-1	14-08-03	Event-1	7	2.272	0.78	0.247	3.76	18.84	0.78	0.198	4.677	15.15	0.61	0.26	3.556	19.92
	15-09-03	Event-2	40	2.272	1.25	0.153	6.049	11.71	1.25	0.123	7.51	9.41	0.89	0.173	5.353	13.23
	24-09-03	Event-3	24	2.272	1.09	0.176	5.26	13.46	1.09	0.142	6.547	10.82	0.80	0.194	4.787	14.08
WS-2	14-08-03	Event-1	7	2.896	0.94	0.277	11.346	31.51	0.94	0.280	11.236	31.82	0.76	0.347	9.058	39.47
	15-09-03	Event-2	40	2.896	1.43	0.182	17.24	20.74	1.43	0.184	17.072	20.95	1.18	0.223	14.109	25.34
	24-09-03	Event-3	24	2.896	1.27	0.206	15.248	23.44	1.27	0.208	15.1	23.68	1.04	0.253	12.392	28.68
WS-10	31-07-67	Event-1	19	3.227	3.73	1.20	66.965	160.3	3.73	1.319	61.862	176.2	4.44	1.107	70.410	147.9
	13-08-70	Event-2	7	3.227	2.24	1.997	40.38	266.8	2.24	2.194	37.173	293.2	2.64	1.86	43.817	248.5
	16-08-70	Event-3	13	3.227	3.07	1.456	55.674	194.6	3.07	1.6	50.22	213.8	3.64	1.349	60.51	180.2
	04-09-73 to 05-09-73	Event-4	17.5	3.227	3.57	1.251	64.813	167.2	3.57	1.375	59.324	183.7	4.25	1.156	68.698	154.4
WS-11	07-07-07	Event-1	40	2.841	7.23	0.024	85.881	2.65	7.23	0.024	86.263	2.63	3.49	0.049	62.087	5.45
	29-07-07	Event-2	20	2.841	4.88	0.035	58.899	3.92	4.88	0.035	59.235	3.90	2.62	0.066	41.844	7.26
	03-08-07	Event-3	8	2.841	2.91	0.059	34.982	6.58	2.91	0.059	35.165	6.54	1.80	0.096	31.768	10.59
	05-09-07	Event-4	15	2.841	4.15	0.042	49.774	4.61	4.15	0.041	50.020	4.58	2.33	0.074	38.246	8.17

i_p peak rainfall intensity (mm/hr), n shape parameter, V_p Peak velocity (m/sec), k scale parameter (hrs^{-1}), Q_p peak runoff (m^3/sec), t_p time to peak (min)

Table 5 Evalution of performance of at-site, at-site regional and regional Nash model during validation

WS	Event	At-site approach							At-site regional approach						Regional only approach						
		SC	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*CRM*	*SC*	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*SC*	*ISE*	*RMAE*	*RMS*	*REP*	*EFF*	*CRM*
WS-1	Event -1	0.81	0.13	0.11	0.05	0.11	99.7	−0.12	0.85	0.17	0.16	0.06	−0.05	99.9	0.91	0.13	0.11	0.05	0.14	99.6	−0.11
	Event -2	0.82	0.18	0.15	0.44	0.09	99.9	0.07	0.72	0.22	0.19	0.55	0.06	99.7	0.87	0.16	0.13	0.38	0.21	99.8	0.06
	Event -3	0.87	0.17	0.14	0.19	0.01	99.8	0.09	0.72	0.25	0.20	0.28	−0.17	99.7	0.92	0.13	0.11	0.02	0.10	99.9	0.08
WS-2	Event -1	0.74	0.23	0.21	0.22	0.08	99.5	0.05	0.78	0.21	0.19	0.20	0.13	99.6	0.82	0.19	0.17	0.19	0.17	99.3	0.07
	Event -2	0.97	0.07	0.07	0.45	−0.21	99.8	0.02	0.98	0.06	0.06	0.38	−0.18	99.9	0.97	0.07	0.07	0.45	−0.21	99.8	0.02
	Event -3	0.40	0.35	0.32	1.05	−0.04	99.7	0.003	0.42	0.35	0.31	1.04	−0.09	99.7	0.73	0.24	0.22	0.71	0.17	99.5	0.007
WS-10	Event -1	0.88	0.13	0.15	8.96	−0.12	99.7	−0.004	0.86	0.14	0.16	9.89	−0.06	99.6	0.86	0.14	0.16	9.89	−0.07	99.6	0.00
	Event -2	0.82	0.18	0.15	7.16	0.51	99.7	−0.02	0.77	0.19	0.16	7.97	0.55	99.4	0.84	0.17	0.14	6.66	0.48	99.8	−0.01
	Event -3	0.97	0.06	0.08	2.19	0.25	99.9	−0.01	0.95	0.08	0.09	2.76	0.29	99.8	0.97	0.06	0.07	1.99	0.19	99.9	−0.01
	Event -4	0.91	0.13	0.13	7.33	0.01	99.9	0.02	0.87	0.15	0.15	8.60	0.09	99.8	0.93	0.11	0.12	6.49	−0.08	99.9	0.02
WS-11	Event -1	0.76	0.27	0.18	2.57	−0.07	99.9	0.01	0.78	0.28	0.17	2.58	−0.06	99.7	0.99	0.05	0.04	0.49	0.03	99.6	0.01
	Event -2	0.97	0.08	0.08	0.61	0.19	99.7	−0.01	0.97	0.07	0.08	0.60	0.18	99.7	0.97	0.07	0.08	0.60	0.16	99.7	0.01
	Event -3	0.93	0.14	0.11	0.32	0.14	81.3	0.001	0.93	0.14	0.10	0.31	0.14	83.5	0.94	0.13	0.11	0.31	0.13	82.7	0.00
	Event -4	0.69	0.29	0.22	1.16	0.04	99.2	0.00	0.68	0.28	0.21	1.17	0.04	99.2	0.91	0.15	0.16	0.61	0.37	99.0	0.003

SC spatial correlation coefficient, *ISE* integral square error, *RMAE* relative mean absolute error, *RMSE* root mean square error, *REP* relative error in peak, *EFF* efficiency, *CRM* Coefficient of residual mass

The statistical correlations between the observed and the computed values of the DSRO's representing, *SC*, *ISE*, *RMAE*, *RMSE*, *REP* and *CRM* are given in Table 3. Bhadra et al. 2008 has used coefficient of residual mass (CRM) for evaluating the performance of GIUH models and in the present study, *CRM* varies between −0.12 and 0.25 for the site specific approach, −0.12 to 0.31 for at-site regional approach and -0.11 and 0.24 for regional only approach. It has been observed that model efficiency varied from 59.7 % to 92.2 % for the site specific approach, 40.6 % to 94.4 % for at-site regional and 68.6 % to 98.7 % for the regional only approach; while RMAE varied between 0.06 and 0.39 for the site specific approach, 0.04 to 0.40 for at-site regional and 0.03 to 0.42 for the regional only approach.

5.2.2 Validation of the Regional Model

The developed model has been validated with WS-1, WS-2, WS-10 and WS-11 which were not included in the development of the regional relationship during calibration. The at-site, at-site regional and regional only DSRO for few storms have been computed (Fig. 6). In the at-site approach, parameters of Nash model (n, k) and peak velocity (V_p) have been computed using site specific fluvial and morphologic information. The at-site regional approach used site specific relationship for computation of k, while V_p was computed with the help of regional relationship developed during calibration. In regional only approach, all parameters of Nash model and V_p were derived from regional relationships developed for the study area. The model parameters, peak discharge and time to peak for all three approaches during validation are given in Table 4.

The parameters showing the performance of regional model during validation are presented in Table 5. It can be seen from Table 5 that the *REP* varied from −0.21 to 0.51 for site specific, −0.18 to 0.55 for at-site regional and −0.21 to 0.48 for regional only approach. Similarly, *RMSE* varied from 0.05 to 8.96 for site specific, 0.06 to 8.60 for at-site regional and 0.05 to 9.89 for regional only approach, which imply a close match. And thus, it validates the approach for application in the region of Central India. As the model results during calibration where changes have been made to develop relationships and validation with independent data indicate satisfactory results in terms of model evaluation, the relationship developed for computation of peak velocity and model parameters of Nash model can be used in other watersheds of Central India region where water resources planning is difficult due to non-availability of gauge discharge data.

6 Conclusions

The Nash model is the most widely used rainfall-runoff model in the field of hydrology and proposed regional approach for computation of model parameter and peak velocity have been found successful to derive the flood hydrograph for ungauged watersheds. The regional relationships developed for computation of peak velocity suggested that the basin characteristics may be very useful for computation of peak velocity for geomorphology based rainfall-runoff models. The scale parameter can reasonably be estimated using morpho-flluvial characteristics of watershed linking to equilibrium peak velocity, rainfall intensity, bifurcation ratio, length ratio and area ratio. The regional relationships developed using geomorphic and fluvial characteristics of 37 watershed and verified on four watersheds (not used in calibration) indicated that relative error in peak (*REP*) varies from −0.58 to 0.38 for site specific approach, −0.15 to 0.54 for at-site regional and −0.18

to 0.55 for regional only approach which is fairly accurate in regional approach in comparison to site specific approach.

The results of the regional approach have been found in close match with the observed data. The regional model developed based on the analysis of watersheds in the Central India region of India can successfully be used in other ungauged small and medium watersheds in the region for rainfall-runoff modeling and designe flood estimation knowing geomorphologic characteristics of the watersheds. The proposed analysis could provide a wide range of application in the field of rainfall-runoff modeling, derivation of flood hydrograph and design flood estimation particularly in ungauged catchments and catchments with limited data.

References

Ahmad MM, Ghumman AR, Ahmad S (2009) Estimation of Clark's instantaneous unit hydrograph parameters and development of direct surface runoff hydrograph. Int J Water Resour Manag 23:2417–2435. doi:10.1007/s11269-008-9388-8

Azward MH, Muzik I (2000) A spatially varied unit hydrograph model. J Environ Hyd 8:1–8

Bardosy A (2007) Calibration of Hydrological model parameters for ungauged catchments. J Hydrol Earth Syst Sci 11:703–710

Bhadra A, Panigrahy N, Singh R, Raghuwanshi NS, Mal BC, Tripathi MP (2008) Development of a geomorphological instantaneous unit hydrograph model for scantily gauged watersheds. Environ Model Softw 23(8):1013–1025. doi:10.1016/j.envsoft.2007.08.008

Bloschi G (2005) Rainfall-runoff modeling of ungauged catchments, Encyclopedia of Hydrolgical Sciences. John Wiley & Sons, New York

Choi YJ, Lee G, Kim J (2011) Estimation of the Nash model parameter based on concept of geomorphologic dispersion. J Hydrol Eng 16(10):806–817. doi:10.1061/(ASCE)HE.1943-5584.0000371

Clark CO (1945) Storage and the unit hydrograph. Trans Am Soc Civil Eng 110:1419–1446

Croley TE (1977) Hydrologic & hydraulic computation on small programmable calculator. Iowa Institute of Hydraulic Research University of Iowa

Dooge JCI (1959) A general theory of the unit hydrograph. J Geophys Res 64(2):241–256

Farquharson FAK, Meigh JR, Sutcliffe JV (1992) Regional flood frequency analysis in arid and semi-arid areas. J Hydrol 139:487–501

Ghumman AR, Ahmed MM, Hasmi HN, Kamal MA (2011) Regionalization of hydrologic parameters of Nash model. J Water Resour 38(6):735–744

Gupta VK, Waymire E, Wang CT (1980) A representation of an instantaneous unit hydrograph from geomorphology. Water Resour Res 16(5):863–870

Heuvelmans G, Muigs B, Feyon J (2006) Regionalisation of the parameters of a hydrological model: comparison of linear regression models with artificial neural nets. J Hydrol 319:245–265

Jaiswal RK, Thomas T, Ghosh NC, Galkate RV, Singh S (2010) GIUH based regional rainfall-runoff model for ungauged watersheds in Bundelkhand region of Madhya Pradesh, India. I J Water Resour Environ Manag 1(2):135–148

Kokkonen TS, Jackman AS, Young PC, Koivusale HJ (2003) Predicting daily flows in ungauged catchments: Model regionalisation from catchment descriptors at the Coweeta Hydrologic Labratory, North California. Hydrol Process 17:2219–2230

Koutsoyiannis D, Xanthopoulos (1989) On the parametric approach of unit hydrograph identification. Water Resour Manag 3:107–128

Merz R, Bloschi G (2004) Regionalisation of catchments and model parameters. J Hydrol 287:95–123. doi:10.1016/jhydrol.2003.09.028.2004

Mimikou M, Gordios J (1989) Predicting the mean annual floods and flood quantiles for ungauged catchments in Greace. Hydrol Sci 34:169–184

Nash JE (1957) The form of instantaneous unit hydrograph. J Int Assoc Hydrol Sci 45(3):114–121

Nash JE (1958) Determining runoff from rainfall. Proc Inst Civ Eng 10:163–184

Nash JE (1959) Systematic determination of unit hydrograph parameters. J Geophys Res 64(1):111–115

Nash JE (1960) A unit hydrograph study with particular reference to British catchments. Proc Inst Civ Eng 17:249–282

Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models, part I: a discussion of principles. J Hydrol 10(3):282–290

Nathan RJ, McMahon TA (1990) Identification of homogemeous regime for the purpose of regionalisation. J Hydrol 121:217–238

Parajka J, Merz R, Bloschi G (2005) A comparison of regionalisation methods for catchments model parameters. J Hydrol Earth Syst Sci 9:157–171

Post DA, Jackman (1996) Relationship between physical descriptors and hydrologic response characteristics on small Australian mountain catchments. Hydrol Process 10:872–892

Post DA, Jackman (1999) Predicting the daily stream flows of ungauged catchments in SE Australia by regionalisation parameters of a lumped conceptual rainfall-runoff model. Ecol Model 123:91–104

Post DA, Jones JA, Grant GE (1998) An improved methodology for predicting the daily hydrologic response of ungauged catchments. Environ Model Softw 13:395–403

Rodriguez-Iturbe I, Valdes JB (1979) The geomorphologic structure of hydrologic response. Water Resour Res 20(7):914–920

Rodriguez-Iturbe I, Devoto G, Valdes JB (1979) Discharge response analysis and hydrologic similarity: the interrelation between the GIUH and the storm characteristics. Water Resour Res 16(6):1435–1444

Rodriguez-Iturbe I, Gonzalez-Sanabria, Brass RL (1982a) A geomorphoclimatic theory of instantenous unit hydrograph. Water Resour Res 18(4):877–886

Rodriguez-Iturbe I, Gonzalez-Sanabria, Brass RL (1982b) On the climatic dependence of the IUH: a rainfall-runoff analysis of the Nash model and the geomorphoclimatic theory. Water Resour Res 18(4):887–903

Rosso R (1984) Nash model relation to Horton order ratio. Water Resour Res 20(7):914–920

Sarkar S, Rai RK (2011) Flood inundation modeling using Nakagami-m distribution based GIUH for a partially gauged catchment. Int J Water Resour Manag 25(14):3805–3835

Sefton CEM, Howarth SM (1998) Relationship between dynamic response characteristics and physical descriptors of catchments in Englan & Wales. J Hydrol 211:1–16

Sherman L (1932) Stream flow from rainfall by unit-graph method. Eng News Rec 108(14):501–505

Zirnji Z, Burn DH (1994) Flood frequency analysis for ungauged sites using a region of influence approach. J Hydrol 153:1–21