MODIFIED CHANNEL ROUTING METHOD FOR SWAT MODEL

A DISSERTATION

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CANDIDATE'S DECLARATION

This is to certify that I have personally worked on the report entitled **"***Modified Channel Routing Method for SWAT model", a prerequisite towards fulfillment for the award of the Degree of Master of Technology in Hydrology submitted to the Department of Hydrology of the Indian Institute of Technology Roorkee, India, is an authentic record of my genuine work. This has been carried under the supervision of Dr. Sumit Sen, Asst. Professor and Dr. M. Perumal, Professor, Department of Hydrology, Indian Institute of Technology, Roorkee, India.

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This is to certify that the above mentioned statement made by the candidate is correct to the best of our knowledge.

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ABSTRACT

Soil Water Assessment Tool model is a watershed-scale model, widely used for various watershed management, land use-land cover scenario, and climate change studies. Due to its deterministic nature, stream flow is a key component in comparison to others. In any modeling study, a watershed is calibrated for stream flow first before modeling other processes, such as nutrient and sediment transport. There has been a significant development in the area of stream flow routing. SWAT model uses “Muskingum Routing Method” (MRM) and “Variable Storage Routing Method” (VSRM) for routing water from upstream of a reach to downstream. Being hydrologic model in nature, SWAT can yield appreciable result only when good amount of data are available. So, sensitivity analysis of parameters along with calibration is required for good model efficiency.

On the other hand, there are models like “Variable Parameter Muskingum Method” (VPMM, Perumal and Price 2013), which are physically-based and perform quite well when applied in its applicability range. The major advantage of this method is that it requires only inflow discharge data, channel parameter and geometry data in longitudinal as well as transverse direction. Due to less input data, this model can be handled more effectively.

To achieve our objective, SWAT and VPMM models is set-up to simulate streamflow on a watershed in the Vansadhara basin with upstream and downstream sites as Gunupur (Odisha) and Kashinagar (Odisha), respectively. Calibration and validation of both models are done for 2004-2006 and 2008-2012 respectively. Contribution of lateral flow into the routing reach is taken into account in the VPMM model and for this purpose, calibrated and validated SWAT model outflow is used. Test statistics like Nash-Sutcliffe efficiency (NSE), coefficient of determination (R^2) are evaluated for performance evaluation of both models. NSE for VPMM, SWAT (VSRM) for calibration and validation period are found out to be 0.904, 0.926 and 0.7, 0.632 respectively, and NSE for the VPMM, SWAT (MRM) for calibration and validation period are found out to be 0.902, 0.933 and 0.702, 0.684 respectively. R^2 for VPMM, SWAT (VSRM) for calibration and validation period are found out to be 0.905, 0.928 and 0.694, 0.635 respectively, and R^2 for the VPMM, SWAT (MRM) for calibration and validation period are found out to be 0.904, 0.934 and 0.695, 0.678 respectively. It can be seen that both

VPMM and SWAT (MRM) model are in good agreement with each other in terms of test statistics, whereas SWAT (VSRM) performance is lagging by 7% and 6% for NSE and R^2 respectively in validation period. If actual flow data corresponding to the intermediate catchment were available, then result of VPMM model could have been improved. This is the reason that VPMM performance is slightly lagging to SWAT model performance in calibration period. As the performance of VPMM model is at par with the SWAT model and has a sound physical basis than the SWAT model, it can be concluded that VPMM model can be incorporated into SWAT model for better model performance.

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Chapter 1 INTRODUCTION

Flood due to its devastating effect along the river reach and adjoining area is a challenging phenomenon to simulate. So, the study of stage and discharge hydrograph of flood event is required for proper depth and discharge estimation as the wave flows along the river. Chow (1959) states that: “in engineering hydrology, flood routing is an important technique necessary for the complete solution of flood control problem and for the satisfactory operation of a flood protection service. For such purposes, flood routing is recognized as a procedure required in order to determining the hydrograph at one point on a stream from the known hydrograph at an upstream point.” Flood routing in man-made channel and natural channels are an important tool in hydraulic engineering practices as it provides relevant information about the movement of flow along the channels at any particular time. This information helps to understand the temporal and spatial distributions of the flood wave and becomes useful for flood warning and protection policies implementation. In order to mitigate the devastating effect of flooding, engineers and hydrologists need to know the peak stages along the rivers and channels while the flood is propagating and these peak water levels can be estimated using flood routing methods.

Flood routing methods can be broadly classified as hydraulic and hydrologic. Hydraulic method employs the distributed continuity equation along with the equation of motion (momentum equation) of unsteady flow, both of which together known as Saint Venant’s equations. Hydrologic routing methods, on the other hand, employ the lumped continuity equation and a storage equation as a replacement of momentum equation. Ferrick (1985) pointed out that numerical instability may arise when the full Saint Venant’s equations are discretized without giving due importance to the magnitudes of different slope terms in momentum equation. This leads to the development of various simplified forms of the momentum equation for the development of simplified channel routing methods such as classical Muskingum method, Hayami’s diffusion analogy model (Hayami,1951), Kalinin-Milyukov method (Kalinin and Milyukov, 1958), Muskingum-Cunge method (Cunge, 1969), Muskingum-Dooge method (Dooge et al., 1982) etc. Generally linear routing structure is adopted for flood routing methods for computational and conceptual flexibility of linear models. Based on whether parameters of model are steady or unsteady, linear routing model can be classified as constant parameter routing method or variable parameter routing method. Depending on the basis of the formulation of governing routing equations, the model can be classified as semi-empirical or physically based. Due to the advantage of variable parameter routing methods to take into account the temporal variation of the model parameters ,various methods such as variable parameter Muskingum-Cunge method (VPMC) (Ponce and Yevjevich, 1978) and its variants (Chaganti, 1994), the parabolic and backwater model (Todini, Bossi, 1986), the variable parameter Muskingum discharge routing method (VPMD) (Perumal, 1994,a,b), the variable parameter Muskingum stage routing method (VPMS) (Perumal and Ranga Raju,1998), variable parameter Muskingum-Cunge-Todini method (MCT) (Todini,2007) , variable parameter Muskingum-Price method (VPMP) (Price, 2009) etc are developed to simulate the non-linear behavior of flood wave movement. Recently, Perumal and Price (2013) devised a scheme named as "Variable Parameter McCarthy Muskingum (VPMM)" method, which has verified the assumption of prism and wedge storages in the traditional Muskingum method and has deciphered that the diffusion in the flood wave as proposed by McCarthy (1938) was due to the effect of storage. The VPMM method is directly derived from the full Saint Venant's equations, without involving the use of the concept of matching the numerical diffusion with the physical diffusion as envisaged by Cunge (1969) and adopted in Variable Parameter Muskingum Cunge (VPMC) method (Ponce and Yevjevich, 1978) and its variants (Chaganti, 1994).

From the aforementioned models, Variable Parameter McCarthy Muskingum (VPMM) (Perumal and Price, 2013) is found out to be fully mass conservative with some constraint on absolute longitudinal water surface gradient at the inlet of the routing reach. This method is also particularly good at routing at flat slope reach with fine time scale resolution. So this model could be used in any integrated watershed model for modeling the channel flow dynamics. One such watershed model currently used extensively is Soil Water Assessment Tool (SWAT) model. Soil and Water Assessment Tool (Arnold et al., 1998) is a watershed model which is used to model the watershed as a system in which runoff, sediment and nutrient transport etc. are modeled taking into account the conservation of mass concept. Basically SWAT model is a hydrologic model. Various issues related to watershed and hydrology are studied by SWAT model by various researchers (Srinivasan et al., 1998; Abbaspour et al., 2004; 2007) to give the user flexibility to use different methods for a particular hydrologic component (such as stream flow, evapotranspiration etc.) simulation under different conditions as suitable for modeling purpose. SWAT is a hydrological model functioning on a time step of daily or monthly or annually depending on the purpose modeling and scale of watershed. Though calibration and validation is conducted on the model to accurately reproduce the observed field data, but uncertainty is always associated with the observed data and the processes that are virtually accounted in the model. Abbaspour et al. (2004, 2007) has discussed the issue of uncertainty in hydrological modeling and the procedure (SUFI-2 algorithm) of obtaining data from the inverse modeling technique for obtaining the unknown parameters of the watershed from the known output at a location. Authors also demonstrated the suitability of the algorithm on the Thur watershed for model calibration and uncertainty analysis. SWAT was developed for the watershed hydrological features, organization manipulation and storage of the related spatial and temporal data with an interface in Arc GIS. Arnold et al. (1998) defined that the HRU is a fundamental spatial unit and on which SWAT model simulates the water balance over the catchment. Spatial distribution of HRUs does not matter in the SWAT model as described in the SWAT manual. Lateral flow is calculated for each HRU separately based on its average slope and saturated hydraulic conductivity of the soil in the HRU. Only surface runoff is routed through tributary channels. After transmission loss through tributary channel is taken into account, the remaining water is added with lateral flow, base flow and cumulatively called as water yield of the HRU and added to the main reach for routing. The existing channel routing schemes used in the Soil Water Assessment Tool (SWAT) model are the variable storage routing method and the Muskingum method. Though the SWAT model is being used in various aspect of hydrology at a watershed scale, the channel routing analysis in the model do not take into account the non-linearity of the actual river flow channel dynamics.

A number of studies have been conducted on hydrologic channel routing schemes to make it physically-based from empirical-based by linking the storage equation to Saint Venant’s momentum equation. Though every channel routing method has its advantage and disadvantage, it seems that the VPMM method, because of its inherent ability to take care of the non-linearity of routing process, may serve as a useful channel routing method in SWAT model. Further this method is fully volume conservative (Perumal and Price, 2013). This method is suitable for routing in the natural river reach when there are surveyed channel cross-sections available only at few gauging stations. So, this method can be employed effectively in SWAT model for channel routing purposes.

So, the objective of the study is to compare the routing results of SWAT and VPMM model in the Vansadhara Basin between Gunupur and Kashinagar gauging stations.

Chapter 2 LITERATURE REVIEW

Perumal, (1994, a): Variable Parameter Muskingum Method was derived from the St. Venant's equations and widely appreciated for its ability to simultaneously compute the discharge and stage hydrograph at a selected downstream cross-section for the known upstream discharge hydrograph. The method was applicable to any type of prismatic channel with known cross-section data. The method was derived with no lateral flow assumption in routing reach.

Perumal, (1994, b): In this paper, performance of the VPMM method was verified based on the accuracy of the time to peak, and peak flow of the simulated hydrograph. The volume conservative aspect of the simulated hydrograph was also considered. Its performance was based on the approximation made on binomial expansion of the discharge, stage and slope equations and had a limitation on the basis of longitudinal water surface gradient value at the inlet of the routing reach. The variation of the weighing factor was found out to be not significant (nearly close to 0.5) for kinetic wave movement. The maximum error in conservation of mass of routed hydrograph with respect to the inflow hydrograph was found out to be 0.5% for all the cases considered in the study.

Perumal and Price, (2013): Though various variable parameter Muskingum methods had been derived to reestablish the heuristic assumption made by McCarthy (1938) on some physical basis, but there were some issues related to volume conservativeness of the model. So this method was devised to make the variable parameter Muskingum method fully mass conservative. The method was also compared with bench mark HEC-RAS solution and with other routing methods like MCT (Todini, 2007) to find out the suitability of the proposed method. For the routing purpose, hypothetical inflow hydrograph was applied in the inlet of the artificial prismatic channel. Different types of channel (rectangular, triangular, trapezoidal) cross-sections were used for analysis. Performance of the model with different models and bench mark solution was analyzed based on the Nash-Sutcliffe efficiency, time to peak estimation, simulated peak estimation, volume conservation.

Perumal et al., (2010): VPMS method, being a tool for rating curve development at a ungauged site, was affected by the channel cross-section of the routing reach. In this paper a methodology was developed for equivalent cross-section estimation for application in the routing method. The proposed method was applied between two cross-sections in Upper Tiber river of Italy and rating curve was developed at the downstream point of the routing reach, which was verified with respect to MIKE 11 result and was found out to be more suitable than the old approach.

Kim and Lee, (2010): A study was conducted on Mihocheon and Gyeongancheon basins in South Korea to describe the limitation of SWAT model to simulate the runoff in small basins and put forth a method (nonlinear storage routing method) as an alternative to the routing module operating on swat model. Continuity equation was combined with the manning's equation for the derivation of the proposed model. Mihocheon basin produced a lower flow value than the actual outflow at the outlet and the depth at the outlet was overestimated due to application of SWAT model. The inaccuracy in the result was due to inaccurate estimation of the travel time and residence time of water in the basin. Nonlinear storage routing method was then incorporated in SWAT model to find out the outflow, depth at the outlet points of both Mihocheon and Gyeongancheon basins. Performance of the model was studied by determination coefficient (R^2) between the observed and simulated data.

Perumal and Sahoo, (2008): In this paper, the volume conservative problem of "Variable Parameter Muskingum-Cunge method " was studied with unique set of manning's coefficient, bed slope, inflow hydrograph shape factor by conducting 6400 routing experiments by varying the channel cross-section between rectangle and trapezoid. The study result was compared with the solutions of full St. Venant's equations and variable parameter Muskingum discharge (VPMD) method. The result was found to be satisfactory for VPMD in comparison to VPMC method, which was attributed to the physically based nature of the VPMD method. Some insight into the negative weighted parameter and negative discharge at the outlet was also provided in this paper.

Williams, (1969): Williams devised two methods namely variable time and variable storage coefficient method for routing the flood. Routing interval was assumed to have same magnitude as that of travel time of flood wave through the reach. This assumption was bolstered by taking small routing reaches such that the inflow and outflow rates were approximately same. The methods were analyzed by taking a flood event in Brushy creek watershed and variable storage routing method was found out to be more efficient than the variable time method.

Arnold et al., (1994): In this study, routing command language was used to unite all three measure discretization schemes like grid cell, sub watershed, and representative hill slope in a single model.

Todini, (2007): This paper was about deriving a new method for flood routing as an alternative to the variable parameter Muskingum-Cunge method and its variants. As these methods were not fully mass conservative for flat surface, Todini tried to find out the loophole in those approaches. He held responsible the variation of parameters with time and the approach in which the parameters were estimated in the Muskingum-Cunge method as a possible cause for problem of mass loss in routing. He then assessed the proposed method with different slope, Manning’s coefficient and cross-sectional area. The results obtained were then verified with standard bench mark solution for their suitability.

Arnold et al., (1995): Routing output to the outlet (ROTO) model was developed to incorporate the land use management practices for simulation of stream flow and sediment so that it could be used in very large scale catchment. The proposed model was used to simulate discharge and sediment in small watershed scale (ARS station G, Texas), watershed scale (White rock lake, Dallas), river basin scale (Lower Colorado) and was verified with USGS data.

Haldar and Khosa, (2015): The impact of flood in Lhasi Nadi was studied in Chambal river basin, India. The study was concerned with the determination of flood levels along the course of Lhasi Nadi with respect to some extreme rainfall events with some specific return periods. Site specific preventive measures were suggested for the river in the study. MIKE and SWAT software were used for the analysis purpose.

Swain and Sahoo, (2015): Study was carried out to incorporate some additional features in to the VPMM method (Perumal et al., 2013) to enhance its applicability to simulate flood in dynamic catchment conditions. This model not only took in account the non-uniform lateral flow but also the catchment behavior in generation of lateral flow. The non-uniform lateral flow was determined by water balance approach accounting for catchment characteristics of normalized network area function, land use classes, soil texture classes and hydro-meteorological variables. This model was verified in Bolani-Gomlai reach of Baitarani river basin for 1980 to 1995.

Arnold et al., (1996): This study was carried out to establish the water balance in the central Illinois watershed with respect to various land use management practices and their effect on stream flow and water quality. The SWAT model was developed using watershed data (discharge, ET, precipitation etc.) of 1950s and model was calibrated and validated on monthly and annual basis.

Bingner, (1996): SWAT model was used for simulating Godwin Creek Watershed, Mississippi for 10 years. Relative trends of runoff produced from sub-basins on long run were established. The study concluded that simulations of individual storm events were less accurate than by aggregating the storms on an annual basis. The study also reported that the accuracy of SWAT could be increased if the sub-basins were further subdivided into multiple sub-basins, which would account for increased variability in soils and landuse.

Arnold et al., (1998): SWAT model was used to compute the sediment, runoff for the Trinity River basin, Texas. The input data for the SWAT was prepared from the GIS, such as land use map, soil map and DEM etc. In this paper, model assumptions, limitations and operations were also described.

Srinivasan et al., (1998): Results were analyzed for the model established in Arnold et al., (1998). Around 12 weather station data and two USGS stream gauge data for 1965 to 1984 were used for calibration and validation of the model for stream flow. The calibration and validation efficiency of stream flow data were observed to be around 84% and 65% respectively.

Arnold et al., (1999): Six sites of mid-west and western US were chosen for the study. Base flow separation technique was derived from the Rorabaugh hydrograph recession curve displacement method for the study. This technique was applied in the chosensites and the results obtained were compared with measured field data and a monthly coefficient of determination 0.86 was obtained. A coefficient of determination of 0.76 and a model prediction efficiency of 0.71 was established from the comparison of measured annual recharge with the computed.

King et al., (1999): SWAT was applied for evaluating SCS daily curve number method of simulating excess rainfall on a large basin with multiple rain gauges. It was modified to accept breakpoint rainfall data and route stream flow on sub daily time step for Green-Ampt method. For this study, 8 years of data from 32 gauging stations were used. The model efficiency was found out to be 0.84 for CN method and 0.69 for Green-Ampt method. It was reported that no significant advantage could be gained by using breakpoint rainfall and sub-daily time steps when simulating the large basin.

Tripathi et al., (2004): The study was conducted on small watershed in eastern India to evaluate stream flow and sediment yield using generated rainfall. Simulated and observed monthly average value of run off and sediment yield were compared for monsoon period for 1991 to 1998. It was concluded that SWAT could be used for multiple year management plans in critical erosion prone area.

Gosain et al., (2005): Palleru river basin of Andhra Pradesh was modeled using SWAT to quantify the amount of return flow contribution due to canal construction in the catchment. Virgin flow, which was prevailing before any man-made intervention in natural system, was assessed for the catchment. Return flow was found out to be around 50%, which was different from the usual assumption of 10-20%.

White et al., (2005): SWAT model was calibrated and validated on Beaver reservoir watershed of Northwest Arkansas. Three different sites were chosen for calibration and validation of variables like flow, sediment, phosphorous, nitrate, nitrite etc. The model was assessed based on multiple objective function results. Sensitivity analysis was performed on the parameters.

Moriasi et al., (2007): A guideline for model evaluation techniques on statistical ground was listed in the paper. Based on various literatures and model application, evaluation techniques, some ranges of statistical parameter like NSE, PBIAS, RSR were given for different variables like discharge, sediment etc. A value more than 0.5 for NSE and a value less than 0.7 for RSE were recommended for monthly analysis. Value of PBIAS around 15% was accepted as good result.

Schuol et al., (2007): As daily data are not so accurately available for field application, an algorithm was devised in this paper to develop daily precipitation and daily temperature from the monthly statistics available for SWAT modeling. The efficiency was verified by both direct comparison of observed and calculated weather parameters, and comparing the observed stream flow with the simulated stream flow using the calculated weather parameter in SWAT model at the catchment outlet

Abbaspour et al., (2007): Thur river basin was analyzed for all major processes related to water quality, sediment, nutrient etc. using SWAT model. Model calibration and uncertainty analysis was performed by SUFI-2 software. The performance of calibration was evaluated by P-factor and d-factor. Being iterative in nature, SUFI-2 was able to take care of any number of parameters simultaneously for calibration purpose. The results obtained for the watershed were quite satisfactory in terms of objective functions used.

Yang et al., (2008): Different optimization techniques such as GLUE, SUFI-2 and MCMC were studied for the Chaohe basin. Similar uncertainty band was produced by all the methods. Though SUFI-2 and GLUE were flexible in terms of choosing objective function, MCME was found out to be more appropriate because of its sound theoretical and statistical basis.

Babar and Ramesh, (2015): The effect of land use and land cover on stream flow was studied using SWAT and runoff coefficient routing model (RCRM) on Nethravati basin in India. RCRM model was devised to use only precipitation, LULC and stream flows for routing studies. Both the models were calibrated for 2001-2005 and validated for 2006-2009. The NSE for SWAT model calibration period and validation period was found out to be 0.81 and 0.62 respectively and NSE for RCRM model calibration period and validation period was found out to be 0.79 and 0.63 respectively. Effect of LULC change on hydrological parameters was studied in this paper by using both models.

Chapter 3 THEORY OF ROUTING IN SWAT AND VPMM MODEL

Chow (1959) stated that one of the easiest routing methods used for the study of flood wave propagation in natural channels is the classical Muskingum method, which is a hydrological method. Hydrological routing methods use the past observed inflow and corresponding outflow hydrographs for calibrating parameters of the model. But models which employ calibrated parameters fail to give accurate results when used outside the domain of flood range of the event used for the calibration of the method. The popularity of the classical Muskingum method prompted the development of different variations of Muskingum method, including the physically based one.

The routing schemes used in the SWAT model are the variable storage routing method and the Muskingum routing method. Both the methods use the Manning's equation for velocity estimation of flow.

3.1 Basic Channel Geometry Calculation Used in SWAT

SWAT model uses the width of water up to bankfull depth ($W_{bnkfull}$), depth of channel at the top of bank ($depth_{bnkfull}$), length of main channel(L_{ch}), slope of longitudinal channel (slp_{ch}), Manning's coefficient (n) as input data in the '.rte' file for the calculation of all the necessary geometric parameters and flow velocity in the channel (Neitsch et al., 2011).

SWAT model assumes the flow channel is described by a trapezoidal section. Side slope of the main channel and flood channel are assumed as 1:2 and 1:4 respectively in the model. The bottom width of flood plain are calculated as

$$W_{btm,fld} = 5 * W_{bnkfull} \quad (3.1.1)$$

In SWAT model, the bottom width of the main channel is calculated from the given top width and assumed channel side slope. So, sometimes there is a chance of negative bottom width. In that condition, the bottom width is assumed as

$$W_{btm} = 0.5 * W_{bnkfull} \quad (3.1.2)$$

and the new side slope of the main channel is calculated as

$$Z_{ch} = \frac{W_{bnkfull} - W_{btm}}{2 * depth_{bnkfull}} \tag{3.1.3}$$

For a given depth, top width can be calculated with the new Z_{ch} as

$$W = W_{btm} + (2 * Z_{ch} * depth) \tag{3.1.4}$$

Then subsequent calculation for area, hydraulic radius and wetted perimeter are done as follows.

$$A_{ch} = \left(W_{btm} + (Z_{ch} * depth)\right) * depth \tag{3.1.5}$$

$$R_{ch} = \frac{A_{ch}}{P_{ch}} \tag{3.1.6}$$

$$P_{ch} = W_{btm} + 2 * depth * \sqrt{1 + Z_{ch}{}^2} \tag{3.1.7}$$

The volume of water stored in the channel is calculated as

$$V_{ch} = 1000 * A_{ch} * L_{ch} \tag{3.1.8}$$

The units of V_{ch},A_{ch},$L_{ch}$are in m^3/sec,m^2, *Km*. respectively and units of P_{ch}, W_{btm}, W, $depth_{bnkfull}$, $depth$ are in meter.

When the volume of water in a reach exceeds the maximum amount of water that can be stored in main channel section, water distributes across the flood plain. The area and wetted perimeter for flooding condition are calculated as follows:

$$A_{ch} = \left(W_{btm} + \left(Z_{ch} * depth_{bnkfull}\right)\right) * depth_{bnkfull} + \left(W_{btm,fld} + \left(Z_{fld} * depth_{fld}\right)\right) * depth_{fld} \tag{3.1.9}$$

$$P_{ch} = W_{btm} + 2 * depth_{bnkfull} * \sqrt{1 + Z_{ch}{}^2} + 4 * W_{bnkfull} + 2 * depth_{fld} * \sqrt{1 + Z_{fld}{}^2} \tag{3.1.10}$$

3.2 Classical Muskingum Method

This method was formulated by McCarthy (1938) to study flood propagation in the Muskingum River of Ohio State, USA. The governing equations of the method are the lumped continuity equation and the reach storage equation, respectively, expressed as:

$$I - Q = \frac{dS}{dt} \qquad (3.2.1)$$

$$S = K(\theta I + (1-\theta)Q) \qquad (3.2.2)$$

where I =rate of inflow, Q=rate of outflow, S=storage, K=storage time factor, θ= weighing factor. The discharge $\theta I + (1-\theta)Q$ is known as the weighted discharge.

Discretizing equations (3.2.1) and (3.2.2) over the routing time interval, the governing equation for flood routing by Muskingum method can be obtained as

$$\frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} = \frac{K\big(\theta(I_2 - I_1) + (1-\theta)(Q_2 - Q_1)\big)}{\Delta t} \qquad (11)$$

Rearranging the terms in equation (3.2.3) and estimating the unknown Q_2 gives the classical Muskingum flood routing equation as:

$$Q_2 = C_1 I_2 + C_2 I_1 + C_3 Q_1 \qquad (12)$$

where the notation j denotes the time $j\Delta t$ and the coefficents C_1, C_2, C_3 are expressed as

$$C_1 = \frac{-2K\theta + \Delta t}{2K(1-\theta) + \Delta t} \qquad (13)$$

$$C_2 = \frac{2K\theta + \Delta t}{2K(1-\theta) + \Delta t} \qquad (14)$$

$$C_3 = \frac{2K(1-\theta) - \Delta t}{2K(1-\theta) + \Delta t} \qquad (15)$$

According to McCarthy, the routing parameters K and θ are estimated as follows:

- If the inflow and outflow hydrographs set is available for a given reach, values of S at various time intervals can be determined by the above technique. By choosing a trial value of θ, values of S at various instant of time t are plotted against the corresponding $[\theta I + (1-\theta)Q]$ values. If the value of θ is chosen correctly, a narrow loop relationship would develop, otherwise a wide loop curve would be formed.

- The inverse of the slope of this narrow loop will give the value of K.

Main disadvantage of the above procedure is that it considers the value of K and θ constant for the considered routing reach. But these parameters are inflow hydrograph dependent. So as the flood changes, these parameters also changes. Since the relationship between the weighted discharge and the reach storage is not linear for the entire time period of the event and therefore, using the classical Muskingum method may introduce considerable error.

3.3 Routing Methods Adopted in SWAT Model

3.3.1 Variable Storage Routing Method (VSRM)

This method is proposed by Williams (1969). For a given reach, the continuity equation can be written as

$$V_{in} - V_{out} = \Delta V_{stored} \tag{3.3.1}$$

where V_{in} and V_{out} are the volume of water that entered and left in a reach in a given time step.

$$\left(\frac{q_{in,1} + q_{in,2}}{2}\right) * \Delta t - \left(\frac{q_{out,1} + q_{out,2}}{2}\right) * \Delta t = V_{stored,2} - V_{stored,1} \tag{3.3.2}$$

$$q_{in,ave} = \left(\frac{q_{in,1} + q_{in,2}}{2}\right) \tag{3.3.3}$$

$$TT = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,2}}{q_{out,2}} = \frac{V_{stored,1}}{q_{out,1}} \tag{3.3.4}$$

Here the travel time (TT) is in sec; q_{in} and q_{out} are the rate of flow with which water entered and left in a reach in a given time step Δt; $q_{in,ave}$ is the average inflow in a given time step; V_{stored} is the volume of water stored in a reach after a time step. This method assumes such a reach length that time step taken for routing is approximately equal to travel time through reach and inflow; outflow rates are equal in such reach.

To obtain relationship between travel time (*TT*) and storage coefficient (*SC*), equation (3.3.4) is substituted to equation (3.3.2) and the resulting equation obtained is

$$q_{out,2} = \left(\frac{2 * \Delta t}{2 * TT + \Delta t}\right) * q_{in,ave} + \left(1 - \frac{2 * \Delta t}{2 * TT + \Delta t}\right) * q_{out,1} \qquad (3.3.5)$$

Taking $SC = \frac{2*\Delta t}{2*TT+\Delta t}$ and multiplying the equation (3.2.12) with time step chosen for routing on both sides, volumetric form of the equation is written as

$$V_{out,2} = SC * (V_{in} + V_{stored,1}) \qquad (3.3.6)$$

3.3.2 Muskingum Routing Method (MRM)

In SWAT model, the Muskingum-Cunge method is implemented. The governing equations being same in the SWAT, there is some constraint on the time step to be chosen. To avoid numerical instability and negative outflow computation, the following condition is to be satisfied

$$2K\theta < \Delta t < 2K(1 - \theta) \qquad (3.3.7)$$

To cross check the values suitability, the equation to be checked is

$$C_1 + C_2 + C_3 = 1 \qquad (3.3.8)$$

Equation (3.3.8) signifies the mass conservation in the reach.

To calculate the storage constant K, the value of weighing factor θ is chosen by the user and are given as inputs on ".bsn" file for routing.

Following formula is used for K calculation

$$K = coef_1 K_{bnkfull} + coef_2 K_{0.1bnkfull} \qquad (3.3.9)$$

Here $coef_1$ and $coef_2$ are the user defined weighted quantities and for normal flow conditions and low flow conditions respectively. The value of the $K_{bnkfull}$ and $K_{0.1bnkfull}$ are calculated by the formula developed by Cunge (1969)

$$K = \frac{1000 * L_k}{C_k} \qquad (3.3.10)$$

Here L_k and C_k are channel length (km.) and celerity of the flood wave (m/s)

Here celerity is the velocity at which disturbance in a flow rate travels along the channel and is expressed as

$$C_k = \frac{\partial Q}{\partial A} = \frac{5}{3} V_c \qquad (3.3.11)$$

Where, V_c is the channel flow velocity (m/s).

The value of C_k is overestimated as compared to the equation (3.4.4.a) as perimeter is assumed to remain constant w.r.t. change in cross-sectional area and K value computed is dependent on some user defined coefficients. Apart from these errors in formulation, other disadvantage of the routing scheme of SWAT model is that any hydrologic response unit under a certain basin/sub basin has to route its contribution of water through the reach of the basin/sub basin irrespective of its location in the basin under consideration. Another disadvantage of the SWAT method is that to avoid negative outflow it used the condition $\Delta t > 2K\theta$. But Perumal (1992) pointed out that this is not needed for successful application of the method.

3.4 Variable Parameter McCarthy-Muskingum Method

During steady flow condition in a river reach, there is a unique relationship between the stage and discharge. The philosophy behind the development of this method is based on the linking of stage and discharge relationship during the unsteady flow condition. At any instant of time during unsteady flow, the steady flow relationship is applicable between the stage at the middle of the reach and the discharge passing somewhere downstream (Figure 3.1).

So this leads to some assumptions for basic building structure of the model, which are given below.

3.4.1 Assumptions

- Prismatic channel cross-section is assumed
- There is lateral flow into the reach and this lateral flow is not adding any momentum to the flow in the main channel reach.
- The slope of the water surface ($\frac{\partial y}{\partial x}$), the slope due to local acceleration ($\frac{1}{g}\frac{\partial v}{\partial t}$), and the slope due to convective acceleration ($\frac{v}{g}\frac{\partial v}{\partial x}$) are small in magnitude, but not negligible in comparison to bed slope (S_O).

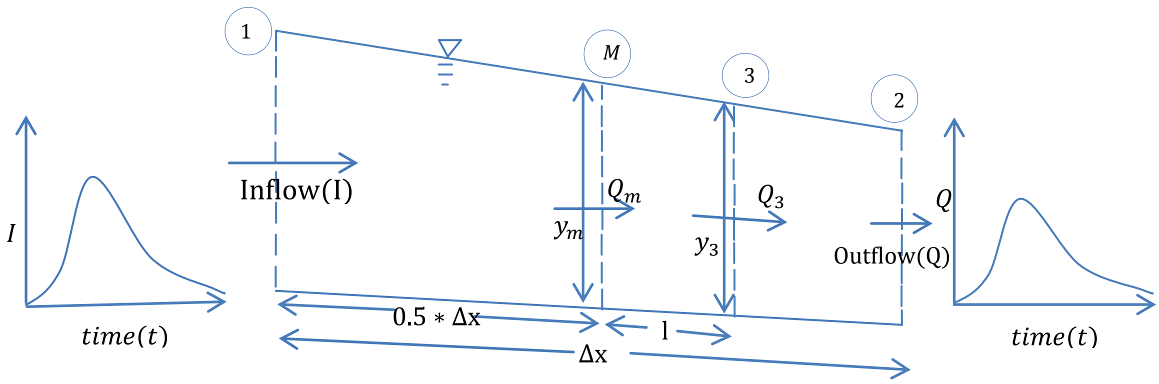


Figure 3.1: Definition sketch of the Muskingum reach

Where, Q_m represents the unsteady discharge at the middle of the reach, and Q_3 represents the steady discharge corresponding to the stage at the middle of the reach. 'l' represents the distance between the steady and unsteady sections from the middle of the Muskingum reach.

3.4.2 Basic Governing Equations of VPMM Method

Though no lateral flow condition is assumed in the Perumal and Price (2013), but lateral flow distribution is taken for the formulation of current study. Continuity and momentum equations, also known as St. Venant's equation are two main pillars on which the method is established and can be expressed as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = Q_l \qquad (3.4.1)$$

$$g\left(S_f - S_o + \frac{\partial y}{\partial x}\right) + v\frac{\partial v}{\partial x} + \frac{\partial v}{\partial t} = 0 \qquad (3.4.2)$$

where, Q_l is lateral flow per unit length; t= time; y, v, A and Q are flow depth, average cross-sectional velocity, cross-sectional area, discharge, respectively; g= acceleration due to gravity; S_f= frictional slope; S_o= bed slope. For same conveyance, unsteady and steady flow discharge are related as

$$\frac{Q_O}{{S_0}^{0.5}} = \frac{Q}{{S_f}^{0.5}} \qquad (3.4.3)$$

where, Q_O and Q are steady and unsteady discharge for the same stage. Using the third assumption, S_f can be taken as S_o approximately over the considered Muskingum reach at any instant of time

$$\frac{\partial Q}{\partial x} \approx BC\frac{\partial y}{\partial x} \tag{3.4.4}$$

where, $B = \frac{\partial A}{\partial y}$=top width at free surface level of the cross-section and C is known as wave celerity and $C = v\left[1 + \frac{2P}{3}\frac{\partial R/_{\partial y}}{\partial A/_{\partial y}}\right] = \left[\frac{5}{3} - \frac{2}{3}\frac{A}{P}\frac{\partial P/\partial y}{\partial A/\partial y}\right]v$ (3.4.4.a)

Using equations (3.4.1), (3.4.2), (3.4.3) and (3.4.3), a relationship for S_f is established as follows:

$$S_f \approx S_o\left[1 - \frac{1}{S_o}\frac{\partial y}{\partial x}\left(1 - \frac{4F^2}{9}\left(\frac{P\frac{\partial R}{\partial y}}{B}\right)^2\right)\right] \tag{3.4.5}$$

Here F is known as Froude's number and is expressed as $F^2 = \frac{Bv^2}{Ag}$. This equation (3.4.5) is used in the equation (3.4.3) to develop a relation between steady and unsteady flow discharge for same stage.

$$Q_o \approx Q\left[1 - \frac{1}{S_o}\frac{\partial y}{\partial x}\left(1 - \frac{4F^2}{9}\left(\frac{P\frac{\partial R}{\partial y}}{B}\right)^2\right)\right]^{-0.5} \tag{3.4.6}$$

This equation (3.4.6) can be used to derive relation between steady and unsteady case celerity as well as velocity. Using binomial expansion in the equation (3.4.6) with approximation of $\left|\frac{1}{S_o}\frac{\partial y}{\partial x}\right| \ll 1$ and using the approximated expression in equation (3.4.4), we obtained a relation as follows:

$$Q_o \approx Q + \frac{Q}{2S_oBC}\frac{\partial Q}{\partial x}\left(1 - \frac{4F^2}{9}\left(\frac{P\frac{\partial R}{\partial y}}{B}\right)^2\right) \tag{3.4.7}$$

Using this relation in continuity equation and then discretizing the resulting equation in spatial and temporal scale by finite difference method at the midpoint of the grid leads to the derivation of following equation as

$$\frac{\left(\frac{Q_i{}^{j+1}+Q_{i+1}{}^{j+1}}{2}\right)+\frac{a_{o,M}}{c_{O,M}}\Big|^{j+1}\left(\frac{Q_i{}^{j+1}-Q_{i+1}{}^{j+1}}{\Delta x}\right)}{v_{o,M}{}^{j+1}} \tag{3.4.8}$$

$$+\frac{\Delta t}{\Delta x}\left(\frac{Q_{i+1}{}^{j+1}+Q_{i+1}{}^{j}}{2}-\frac{Q_i{}^{j+1}+Q_i{}^{j}}{2}\right)-\frac{\left(\frac{Q_i{}^{j}+Q_{i+1}{}^{j}}{2}\right)+\frac{a_{o,M}}{c_{O,M}}\Big|^{j}\left(\frac{Q_i{}^{j}-Q_{i+1}{}^{j}}{\Delta x}\right)}{v_{o,M}{}^{j}}$$

$$\approx 0.5\frac{\Delta t}{\Delta x}(Q_l{}^{j+1}+Q_l{}^{j})$$

Where,

$$a_{0,M}=\frac{Q_{0,M}}{2S_oB_M}\left(1-\frac{4F_M{}^2}{9}\left(\frac{P\frac{\partial R}{\partial y}}{B}\right)_M^2\right) \tag{3.4.9}$$

and Q_l is the total lateral flow in the Δx grid scale of the routing reach.

Here, j and i represents temporal and spatial grid level. The suffix (0, M) associated with any variable represents the value of a variable corresponding to the normal depth (y_M)at the midsection of subreach and the suffix (M) associated with any variable represents the value of the variable corresponding to the flow depth (y_M).

By taking

$$K^{j+1}=\Delta x/v_{o,M}{}^{j+1} \quad and \quad \theta^{j+1}=0.5-\left[\frac{\frac{a_{o,M}}{c_{O,M}}\Big|^{j+1}}{\Delta x}\right] \tag{3.4.10}$$

$$K^{j}=\Delta x/v_{o,M}{}^{j} \quad and \quad \theta^{j}=0.5-\left[\frac{\frac{a_{o,M}}{c_{O,M}}\Big|^{j}}{\Delta x}\right] \tag{3.4.11}$$

$$\frac{\partial Q}{\partial x}_M\Big]^{j+\frac{1}{2}}=0.5\left(\frac{\partial Q}{\partial x}_M\Big]^{j}+\frac{\partial Q}{\partial x}_M\Big]^{j+1}\right) \tag{3.4.12}$$

$$\frac{\partial A}{\partial t}_M\Big]^{j+\frac{1}{2}}=\frac{1}{\Delta t}\left(\frac{Q_o}{v_0}_M\Big]^{j+1}-\frac{Q_o}{v_0}_M\Big]^{j}\right) \tag{3.4.13}$$

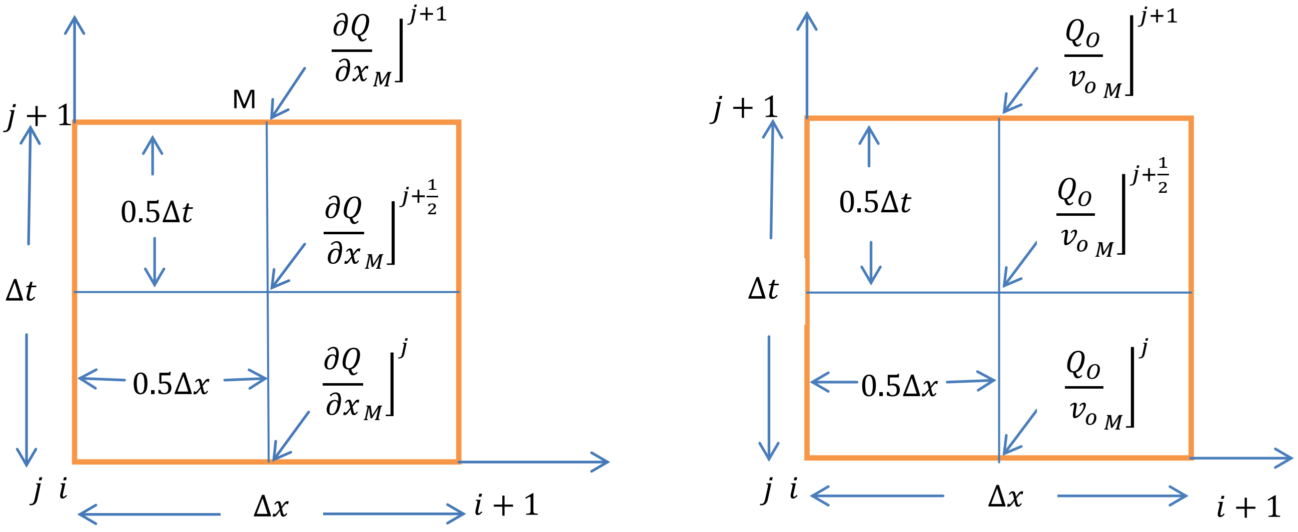


Figure 3.2: Spatial approximation of $\left.\frac{\partial Q}{\partial x}\right]_M^{j+\frac{1}{2}}$

By simplifying equation (3.4.8), we obtain

$$\begin{aligned} &K^{j+1}\left(\theta^{j+1}{Q_i}^{j+1}+\left(1-\theta^{j+1}\right){Q_{i+1}}^{j+1}\right) \\ &\quad -K^j\left(\theta^j {Q_i}^j+\left(1-\theta^j\right){Q_{i+1}}^j\right) \\ &\quad =\left(\frac{{Q_i}^{j+1}+{Q_i}^j}{2}-\frac{{Q_{i+1}}^{j+1}+{Q_{i+1}}^j}{2}\right)\Delta t \\ &\quad +\frac{\Delta t}{2}\left({Q_l}^{j+1}+{Q_l}^j\right) \end{aligned} \tag{3.4.14}$$

Equation (3.4.14) can be readjusted to form an equation same as that of classical Muskingum routing method, which is as follows:

$$\begin{aligned} {Q_{i+1}}^{j+1} &= \frac{(-2K^{j+1}\theta^{j+1}+\Delta t){Q_i}^{j+1}}{2K^{j+1}(1-\theta^{j+1})+\Delta t}+ \\ &\frac{\left(2K^j\theta^j+\Delta t\right){Q_i}^j}{2K^{j+1}(1-\theta^{j+1})+\Delta t}+\frac{\left(2K^j\left(1-\theta^j\right)-\Delta t\right){Q_{i-1}}^j}{2K^{j+1}(1-\theta^{j+1})+\Delta t} \\ &+\frac{\Delta t\left({Q_l}^{j+1}+{Q_l}^j\right)}{2K^{j+1}(1-\theta^{j+1})+\Delta t} \end{aligned} \tag{3.4.15}$$

3.4.3 Insight into Algorithm

The routing reach is subdivided into a number of subreaches by analyzing the field situation so that each subreach is approximately prismatic. Also the spatial step should be selected in such a manner that it is consistent with the linearly varying water surface assumption during the routing process. Inflow hydrograph is routed in a subreach and the outflow hydrograph at the outlet of this subreach becomes inflow hydrograph to the subsequent subbasin and so on. Routing using the VPMM method is carried out in following manner.

Denoting the time step as j and spatial step as i, we will get grid depending on the number of spatial and temporal divisions are made.

- Estimation of K_0 , θ_0, c_0, F_0 is done by using the following equations for initial condition

$$K_0 = \Delta x / v_{o,M} \tag{3.4.16}$$

$$\theta_0 = 0.5 - \frac{Q_0[1 - \frac{4}{9}{F_0}^2 \left[\frac{\left(\frac{P\partial R}{\partial Y}\right)}{\left(\frac{\partial A}{\partial Y}\right)}\right]^2_0]}{2S_0 \frac{\partial A}{\partial Y}_M C_{0,M}\Delta x} \tag{3.4.17}$$

$$C_{0,M} = \left[1 + \frac{2}{3}\left\{\frac{\frac{P\partial R}{\partial Y}}{\frac{\partial A}{\partial Y}}\right\}_{0,M}\right] v_{0,M} \tag{3.4.18}$$

$$F_0 = \{[v^2 \frac{\frac{\partial A}{\partial Y}}{gA}]_0\}^{0.5} \tag{3.4.19}$$

- So, initially we have the discharge data at (i, j), (i, j+1), (i+1,j) points and to find out the discharge of the location (i+1,j+1), we have to get the values of C_1,C_2,C_3,C_4at the subreach between i and i+1. So, we need to have the values of K_{j+1} , θ_{j+1}. But, we don't have that value at this moment of routing. So, K_{j+1} , θ_{j+1} values are taken as K_j , θ_j approximately. And values of C_1,C_2,C_3,$C_4$are calculated as below:

$$C_1 = \frac{-2K^{j+1}\theta^{j+1} + \Delta t}{2K^{j+1}(1-\theta^{j+1}) + \Delta t} \tag{3.4.20}$$

$$C_2 = \frac{2K^j\theta^j + \Delta t}{2K^{j+1}(1-\theta^{j+1}) + \Delta t} \qquad (3.4.21)$$

$$C_3 = \frac{2K^j\left(1-\theta^j\right) - \Delta t}{2K^{j+1}(1-\theta^{j+1}) + \Delta t} \qquad (3.4.22)$$

$$C_4 = \frac{\Delta t}{2K^{j+1}(1-\theta^{j+1}) + \Delta t} \qquad (3.4.23)$$

- $Q_l$values at various time level is required for ${Q_{i+1}}^{j+1}$ calculation. So, the approximate discharge at (i+1, j+1) is calculated by

$${Q_{i+1}}^{j+1} = C_1 {Q^{j+1}}_i + C_2 {Q^j}_i + C_3 {Q^j}_{i-1} + C_4\left({Q_l}^{j+1} + {Q_l}^j\right) \qquad (3.4.24)$$

- Then steady state discharge at section (3) is found out by

$$Q_3 = Q_{0,M} = \theta^{j+1}{Q^{j+1}}_i + (1-\theta^{j+1}){Q^{j+1}}_{i+1} \qquad (3.4.25)$$

Which is the steady discharge corresponding the stage of the middle of the subreach during unsteady discharge (Q_M).

- After gettingQ_3, the stage(${y^{j+1}}_M$) at the mid-section for this discharge is calculated by any friction law, i.e. Manning’s or Chezy’s formula in any numerical method and the corresponding normal velocity(${v^{j+1}}_{0,M}$) is also calculated.
- Then, the discharge (Q_M) at the midsection of the reach corresponding to the stage just found out, is calculated as

$${Q_M}^{j+1} = \frac{{Q_{i+1}}^{j+1} + {Q_i}^{j+1}}{2} \qquad (3.4.26)$$

- After knowing the value of $Q_M{}^{j+1}$ and $y_M{}^{j+1}$, the channel dimensions are calculated and then, celerity and Froude's number at the mid-section are calculated as

$$C_M = \left[1 + \frac{2}{3}\left\{\frac{\frac{P\partial R}{\partial Y}}{\frac{\partial A}{\partial Y}}\right\}_M\right] v_M \qquad (3.4.27)$$

$$F_M = \{[v_M{}^2 \frac{\frac{\partial A}{\partial Y}}{gA}]_M\}^{0.5} \qquad (3.4.28)$$

- Then with new C_M and F_M value at mid-section of subreach, the refined value of K and θ is calculated at the (i+1, j+1) grid point. Later, the refined value of $Q_{i+1}{}^{j+1}$ is calculated. After that the refined values of $y^{j+1}{}_M$ and $Q_M{}^{j+1}$ are found out. Then the flow depth $y_{i+1}{}^{j+1}$corresponding to the discharge $Q_{i+1}{}^{j+1}$ is found out by

$$y_{i+1}{}^{j+1} = y_M{}^{j+1} + \frac{Q_{i+1}{}^{j+1} - Q_M{}^{j+1}}{\frac{\partial A}{\partial Y}_M \left[1 + \frac{2}{3}\left\{\frac{\frac{P\partial R}{\partial Y}}{\frac{\partial A}{\partial Y}}\right\}_M\right] v^{j+1}{}_M} \qquad (3.4.29)$$

- The above steps are followed for each grid point (i+1, j+1) to get the final discharge and stage hydrograph.
- If any contribution from tributary as a point source is there into the main channel, then routing in the main channel should be done up to that point and the lateral tributary contribution should be added to the routing outflow. Then the combined flow can be routed to the downstream up to the desired point as described above.

3.4.4 Limitation of VPMM Method

The VPMM method performs well when basically three conditions are satisfied well.

- The reach length should be such that the linear variation of discharge along the reach is satisfied.
- There may be error due to the truncation of higher order terms in the development of the method. The scaled longitudinal water surface gradient must be sufficiently less than “x”, for good accuracy of the approximation of binomial expansion. Where “x” is a value less than 1. Based on theoretical considerations Perumal and Price, (2013) pointed out that $x<=0.5$.
- Back water effect should not be there in the reach.

Chapter 4 STUDY AREA

4.1 Overview of Area

The area under study is located at the border of Odisha and Andhra Pradesh. The reach is in the "East flowing river Mahanadi-Pennar" basin and on the "Vansadhara" river (Figure 4.1). In the upstream of the reach, Gunupur station (lat-19.08 m, long-83.80 m) and in the downstream of the reach, Kashinagar station (lat-18.85 m, long-83.87 m) is located. Altitudes of upstream and downstream points are 80.25 m and 51 m, respectively. The distance between upstream and downstream location is 32 km. The slope of the reach is calculated to be approximately 0.0009.

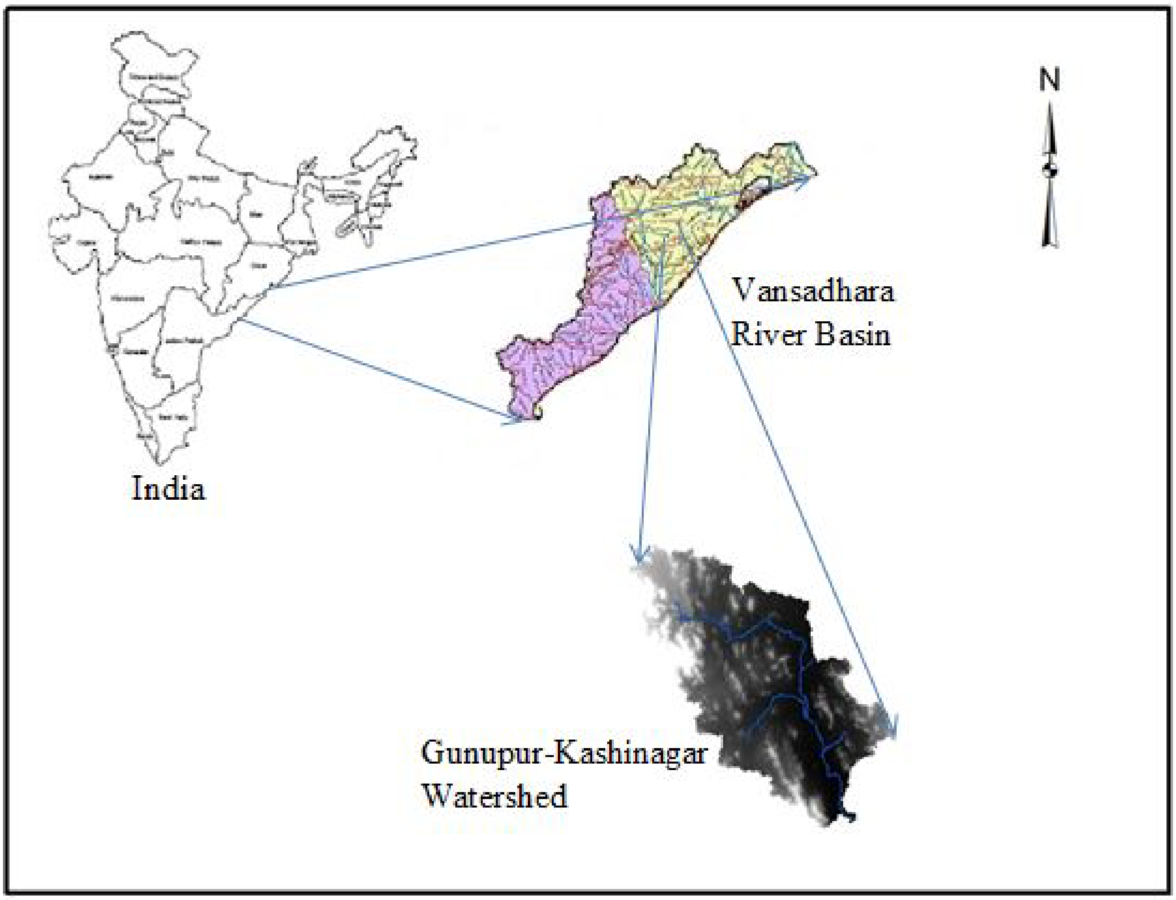


Figure 4.1: Location of Gunupur-Kashinagar watershed

4.2 Climate Conditions

Weather condition is classified in three parts; cool, hot and raining. From the middle of October to middle of February there is very low rainfall in the EFR Mahanadi Pennar basin, which leads to cool weather. From middle February to middle of June, practically dry and hot weather is experienced in the basin. From middle of June to middle of October good amount of rainfall takes place due to South West monsoon. Moderate rainfall is observed in small parts of basin due to North West monsoon during October to December.

More than 90% of rainfall in the basin occurs during the monsoon between June to October. Average annual rainfall in the basin is around 1200 to 1400 mm. Being subjected to tropical climate, the basin has annual maximum and minimum temperature of about 33.28° C and 23.33°C, respectively (source: East Flowing Rivers Between Mahanadi and Pennar Basin, Version 2).

Chapter 5 MODEL SET-UP AND CALIBRATION

5.1 SWAT Model Setup

5.1.1 Software Used in SWAT Model

In the present study, mainly ARCGIS-10.1, ARCSWAT-12.101.15 and ERDAS IMAGINE-15 are used for model set up. Land use/land cover (LULC) and digital elevation model (DEM) is prepared using ERDAS IMAGINE-15 and ARCGIS-10.1 software, respectively. ARCGIS Spatial Analyst-10.1, ARCGIS Development kit are also used for arranging the input raster and vector dataset so that they can be used in SWAT model.

5.1.2 Input Required for SWAT Model

SWAT requires various types of spatially and temporally varied dataset. The spatially varied data include DEM, LULC and soil map, which can be used as raster or vector layer type as per the suitability. Some database files are also required to merge with layer data to give meaning to the modeling catchment. Those database files are precipitation, relative humidity, wind data, solar radiation data, temperature data, weather generator table, location files containing the gauging station data, runoff data, soil database, soil lookup table, and LULC lookup table.

5.1.3 Description of Data

Table 5.1: Data Description

Data Type	Scale	Source	Data Description
Topography	30 meter	Cartosat1,version3R1 (http://bhuvan.nrsc.gov.in/data/download/index.php)	Digital Elevation Model(DEM)
Land use land cover	15 meter	Landsat L7 ETM+SLC off (http://earthexplorer.usgs.gov/)	Land Use and Land Cover map
Soil	1:50000	National Bureau of Soil Survey and Land use Planning(NBSS)	Soil map
Meteorology	daily	NASA data (http://power.larc.nasa.gov/) and SWAT Global weather data (http://globalweather.tamu.ed)	Rainfall, Max-Min temperature, Relative humidity, wind data, solar radiation data
Hydrology data and Cross-section data	daily	WRIS data (http://www.india-wris.nrsc.gov.in/)	Daily discharge and cross-section data at gauging stations

5.1.4 SWAT Setup Details

5.1.4.1 Digital Elevation Model Preparation

The digital elevation model (DEM) of the catchment is downloaded from the Bhuwan site (Cartosat-1, version 3R-1). Two layers of UTM 44N are taken from the Bhuwan site as per the catchment location Then those two layers are merged together and projected to WGS 1984 UTM 44N. Then the whole layer is masked and 'ArcSwat' procedure is followed to get the desired watershed.

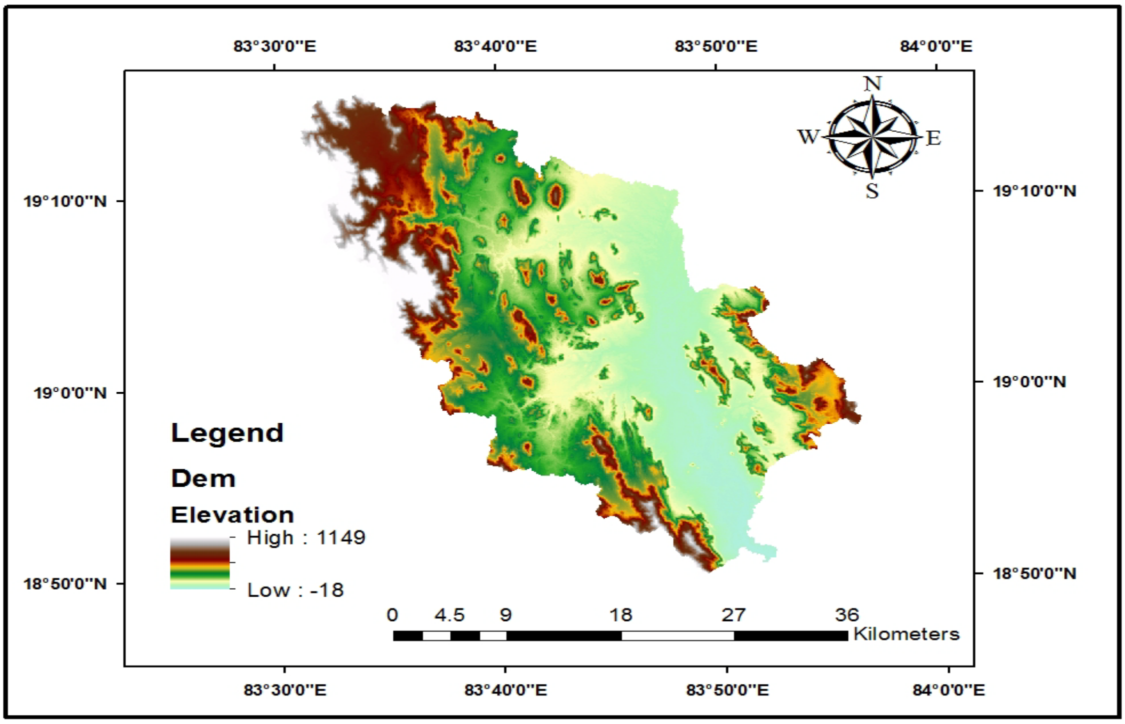


Figure 5.1: Digital Elevation Model of Gunupur-Kashinagar watershed

5.1.4.2 Land Use and Land Cover

The land use land cover data is prepared using 'classification' option in "ERDAS Imagine" software. To get the land use data, the 'Earth explorer' site is used, from which the L7 ETM sensor is used to obtain the maps of different wavelength response of different features of earth surface captured by the satellite. Then the satellite data are layer stacked and projected to the WGS 1984 UTM 44N. Then unsupervised classification procedure is followed to create the map with suitable number of land use land cover classes. The map is added in the ARCGIS software and only the area covering desired watershed is extracted. The various land use classes are summarized in Table 5.2.

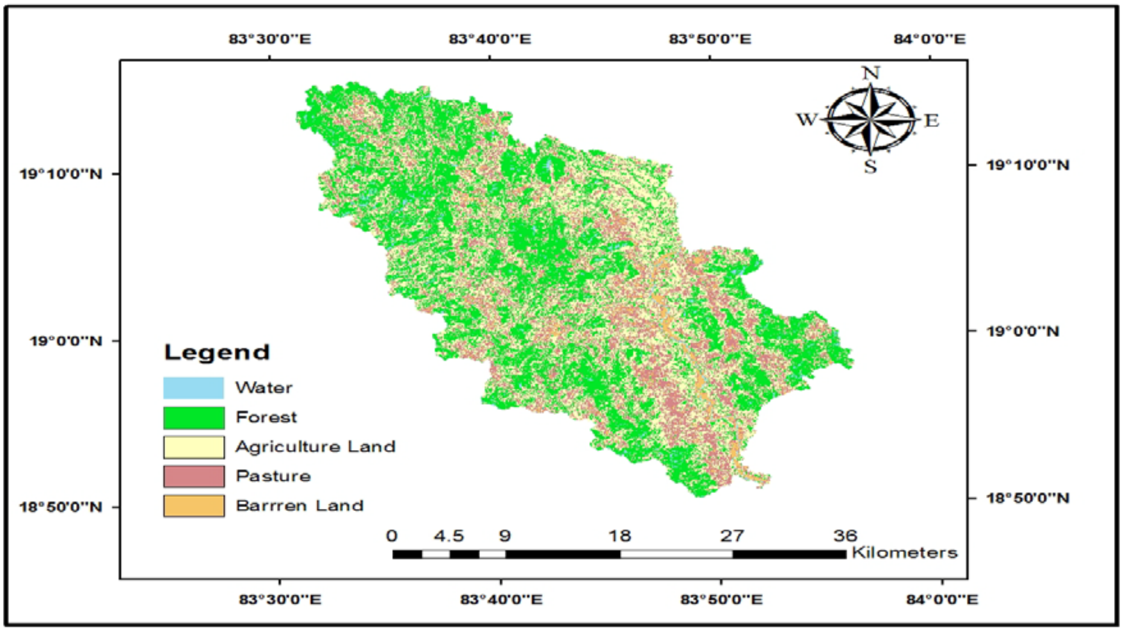


Figure 5.2: Land use and Land Cover of Gunupur-Kashinagar watershed

Table 5.2: Area under Different Land Use Land Cover Type

LULC TYPE	Area (KM^2)	% Watershed Area
WATER	16.47	1.67
FOREST COVER	404.02	40.98
AGRICULTURE LAND	362.15	36.73
PASTURE LAND	169.57	17.20
BARREN LAND	33.72	3.42
Total	985.94	100

5.1.4.3 Soil Data

Soil map is obtained from National Bureau of Soil Survey and Land Use Planning. The soil map is prepared so that it can be used in ArcSWAT format. The watershed is subdivided into 7 soil types as shown in Table 5.3. To effectively use the soil map, soil database in SWAT 2012.mdb file is edited suitably. Various unknown data required are

A. Soil Component Parameters are Soil name(SNAM), soil hydrologic group (HYDGRP), Maximum rooting depth of soil profile(SOL_ZMX), Fraction of Porosity(Void Space) from which anions are excluded(ANION_EXCL), Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume(SOL_CRK), texture of the soil layer(TEXTURE).

B. Soil Layer Parameters are SOL_Z (layer#) Depth from soil surface to bottom of layer(mm), SOL_BD (layer#) Moist bulk density (g/cm3), SOL_AWC (layer#) Available water capacity of the soil layer(mm H_2O/mm of soil), SOL_K(layer#) Saturated Hydraulic Conductivity(mm/hour), SOL_CBN (layer#) Organic Carbon Content (% soil weight), SOL_CLAY (layer#) Clay Content (% soil weight), SOL_SILT (Layer#) Silt Content (% soil Weight), SOL_SAND (layer#) Sand Content (% soil Weight), SOL_ROCK (layer#) Rock Fragment Content (% total weight), SOL_ALB(top Layer). Moist soil albedo, USLE_K (top Layer) USLE equation soil erodibility (K), SOL_EC (layer#) Electrical conductivity (dS/m), SOL_CAL (layer#) Soil CaCo3 (%), SOL_PH (layer#) Soil ph.

Here “#” represents layer number. To obtain most of these data, Soil Series of Odisha (Sarkar et al., 2005) paper is followed and SPAW software is used for obtaining data like SOL_AWC, SOL_K, SOL_BD from known SOL_SILT, SOL_SAND, SOL_CLAY data for a particular soil group.

Table 5.3: Area under Different Soil Types

Soil name	Area (KM^2)	% Watershed Area
TypicRhodustalfs	284.32	28.84
AericEndoaquepts	0.345	0.035
TypicEndoaquepts	56.984	5.78
TypicHaplustepts	194.514	19.73
TypicPaleustalfs	192.64	19.54
TypicArgiustolls	219.26	22.24
RhodicPaleustalfs	37.80	3.83
Total	985.88	100

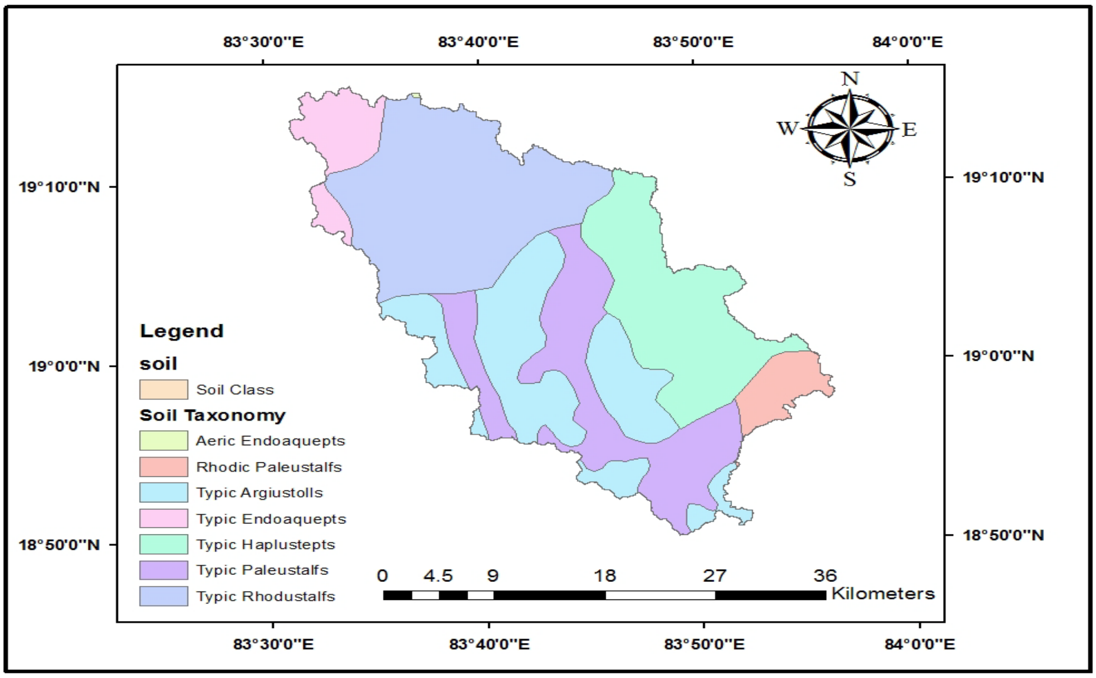


Figure 5.3: Soil Map of Gunupur-Kashinagar watershed

5.1.4.4 Weather Data

The weather data is taken from "SWAT global weather data" and "NASA data" for 1989 to 2012. There is only one station available in the whole catchment, with latitude, longitude as 18.88 m, 83.75 m, respectively. Rainfall, wind, solar radiation, relative humidity and maximum and minimum temperature are prepared in the required format as required in ARC SWAT software. For the project, ".txt" format is used instead of ".dbf" format.

To take into account the missing data and long term prediction, the weather generated data is prepared (Table 5.4).

5.1.5 ARC SWAT Analysis Details

By watershed delineation procedure, catchment is divided into 11 sub basins (Table 5.5). Number of stream generated in the watershed can be adjusted by manually changing the "area of cell" option in the "stream definition section." The watershed has an inflow to one of its sub-basin, whose coordinate point of the inlet is provided in ".dbf" file.

Table 5.4: Weather Generated Data for SWAT Model

Month	1	2	3	4	5	6	7	8	9	10	11	12
TMPMX	30.2	33.8	39.5	42.4	43.1	37.4	32.4	31.22	31.57	30.57	29.6	29.1
TMPMN	11.3	13.4	17.3	20.3	23.4	25.2	24.1	23.53	22.86	20.57	16.8	12
TMPSTDMX	5.4	6.11	4.06	3.71	4.43	5.51	3.22	2.504	2.27	2.46	2.5	2.44
TMPSTDMN	3.57	3.6	3.02	2.41	2.4	1.47	0.98	0.748	0.798	1.87	2.91	3.05
PCPMM	12.7	18.4	12.8	15.8	49.4	230	373	412.1	262.5	146.6	46.7	6.93
PCPSTD	1.42	3.52	3.35	2.46	8.04	16.6	15.6	15.08	9.39	9.43	6.99	2.01
PCPSKW	5.87	16.5	21.7	8.83	8.8	6.22	4.17	3.33	2.651	5.30	8.37	17.3
PR_W1	0.1	0.11	0.08	0.15	0.21	0.45	0.69	0.5	0.365	0.28	0.11	0.04
PR_W2	0.63	0.65	0.69	0.64	0.65	0.88	0.94	0.957	0.936	0.85	0.73	0.66
PCPD	7.25	7.21	7	9.38	12.3	24.5	29.9	30.33	27.83	22.3	10.8	3.71
RAINHHMX	5.33	26	28.2	12.5	38.7	72	64.1	42.7	29.27	40.47	29.1	15.2
SOLARAV	17.3	19.1	20.7	19.8	18.9	17.3	18.5	18.6	19.9	18.6	17.3	17
DEWPT	13.6	15.2	19.7	22.4	23.5	23.6	23.8	24.05	24.14	22.21	18.7	15.7
WNDAV	1.64	1.83	2.05	2.28	2.23	2.03	1.77	1.716	1.526	1.49	1.62	1.58

Table 5.5: Area-Elevation Detail of Catchment

Sub Basin Number	Maximum Elevation (Meter)	Minimum Elevation (Meter)	Mean Elevation (Meter)	Area(Km2)	Watershed Area (%)
1	1149	103	512.18	124.93	12.66
2	681	103	264.09	78.57	7.96
3	326	70	115.42	3.75	0.380
4	1147	69	323.50	111.75	11.33
5	561	9	99.45	147.93	15.0
6	566	9	104.34	19.11	1.93
7	573	0	91.907	65.89	6.68
8	721	1	172.275	223.99	22.7
9	439	-8	46.59	25.30	2.56
10	710	-2	183.16	77.87	7.89
11	739	-18	103.55	107.00	10.85

5.1.5.1 Hydrologic Response Unit Details

Hydrologic response units (HRUs) are unique combination of land use, soil, slope, which constitutes the basic building block of SWAT model. After adding land use, soil layers on the watershed DEM with proper projection, multiple slope characterization are used to subdivide the whole terrain into various slope classes. In the current study, five slope classes are created with boundary values as 2%, 6%, 12%, 20%, and >20%. The areal distribution of the slope classes are given in Table 5.6. The added layers are then readjusted by "threshold value" option in HRU definition section to simplify the catchment classes into fewer classes as per suitability of model analysis. For the current study, land use, soil, slope class threshold values are 5%, 0%, 0% respectively. After the threshold specification, the layers are reclassified into new layers and 542 hydrologic response units (HRUs) are created and analyzed.

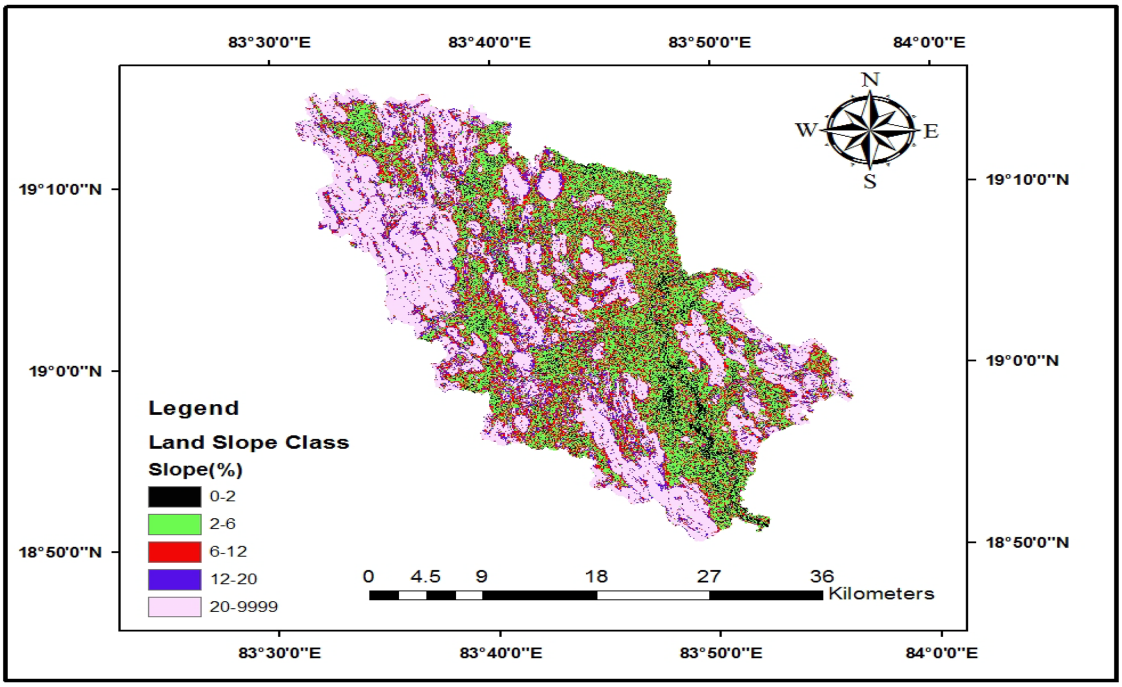


Figure 5.4: Slope Class Map of Gunupur-Kashinagar watershed

Table 5.6: Slope Class Detail of Catchment

Slope (%)	Area (Km^2)	% Watershed area
0-2	75.91	7.70
2-6	276.65	28.06
6-12	187.25	18.99
12-20	101.4	10.30
>20	344.52	34.95
Total	985.9	100

5.1.5.2 Importing Weather, Discharge Data and Preliminary Run Details

Previously prepared ".txt" files weather station gauge location and weather input data for the period of 2001 to 2012 are given as input to create weather database for the model. Then other database files like management, soil, main channel, ground water, water use, pond data etc. are updated with the given inputs. In the 'Edit SWAT input' section, the input discharge option is chosen to give input discharge to the sub basin number 6. After all the necessary editing the ‘Edit SWAT input’ section, edited files are rewritten in the ‘Rewrite SWAT input files’ section. SWAT is then executed on daily basis from the year 2001 to 2012 with 3 years of warm-up period. For calibration and validation of SWAT, time duration between 2004 to 2006 and 2008 to 2012 are chosen, respectively.

5.1.5.3 SWAT Model Calibration and Validation

SWAT model is analyzed for the sensitive parameters using SWAT-CUP software (Abbaspour, 2013). Global sensitivity is carried out to understand the relative sensitivity of the chosen model parameters with respect to the given objective function. Sensitivity is analyzed using t-stat of a parameter with the student’s t-distribution, which describes relative significance of a particular parameter. A test statistics ‘p-value’ is used to either accept or reject the null hypothesis, which represents the probability of getting more extreme results than the observed ones provided the model is perfect. In standard practice, p-value less than 0.05 suggest that a parameter is sensitive. Then using some initial range of the chosen parameters, the model is simulated 1000 times in SWAT-CUP for the objective function of maximum Nash-Sutcliffe efficiency (NSE). The parameters and their sensitivities are shown in Table 5.7 and Table 5.8, respectively. The parameters value thus obtained are transferred to the SWAT model for cross checking the discharge values obtained from the SWAT-CUP. This procedure of getting back model parameters into initially set SWAT model enables one to find out the lateral flows contributed to a reach from SWAT output folder in scenario section.

Table 5.7: Parameters Involved in the Model Calibration

Parameter	Description	Unit	Min Value	Max Value	Calibrated Value
CN2.mgt (relative)	SCS runoff curve number	n/a	-0.2	0.2	0.078
ALPHA_BF.gw (replace)	Base flow alpha factor	days	0	1	0.999
GW_DELAY.gw (replace)	Ground water delay	days	0	500	54.28
GWQMN.gw (replace)	Threshold depth in shallow aquifer to start return flow	mm	0	1000	755
SOL_K().sol (relative)	Saturated hydraulic conductivity	mm/hr	0	1	0.167
SLSUBBSN.hru	average slope	m	10	150	74.28

(replace)	length				
SOL_AWC().sol (relative)	Average soil available moisture content	mm/mm	0	1	0.115
OV_N.hru (replace)	Manning's coefficient for overland flow	n/a	0.01	30	25.711
LAT_TTIME.hru (replace)	Lateral travel time	days	0	180	63.9
REVAPMN.gw (replace)	Threshold depth in shallow aquifer to start revaporation	mm	0	1000	833
SURLAG.bsn (replace)	Surface runoff lag time	days	1	24	8.107
CH_N2.rte (replace)	Manning's coefficient for main channel	n/a	0.01	0.07	0.0144
ESCO.bsn (replace)	Soil evaporation compensation factor	n/a	0	1	0.681
EPCO.bsn (replace)	Plant upatake compensation factor	n/a	0	1	0.517

Table 5.8: Sensitivity of Parameters

Parameters	t-stat	p-value
ESCO	-0.081	0.9354
LAT_TTIME	-0.175	0.861
ALPHA_BF	0.264	0.7918
OV_N	0.287	0.7742
SOL_AWC	0.37	0.711
GW_DELAY	-0.384	0.7008
SOL_K	-0.41	0.6818
REVAPMN	-0.73	0.4657
SLSUBBSN	-0.951	0.3418
CN2	1.113	0.2663
EPCO	1.164	0.2449
SURLAG	2.223	0.02663
GWQMN	-2.896	0.00394
CH_N2	-158.936	0

As lower value of p-value (<0.05) represents sensitive parameters, from Table 5.8 it can be concluded that parameters like CH_N2, GWQMN and SURLAG are found out to be really sensitive for the current project set up.

5.2 VPMM Model Setup

5.2.1 VPMM Model

The routing procedure adopted for the project is essentially same as that of VPMM method with some minor modification to incorporate both point and distributed lateral flow. Lateral flow data are obtained from analysis of SWAT model. The total routing reach is subdivided into multiple subreach so that point lateral flow and downstream of the routing subreach are located approximately at the same location.

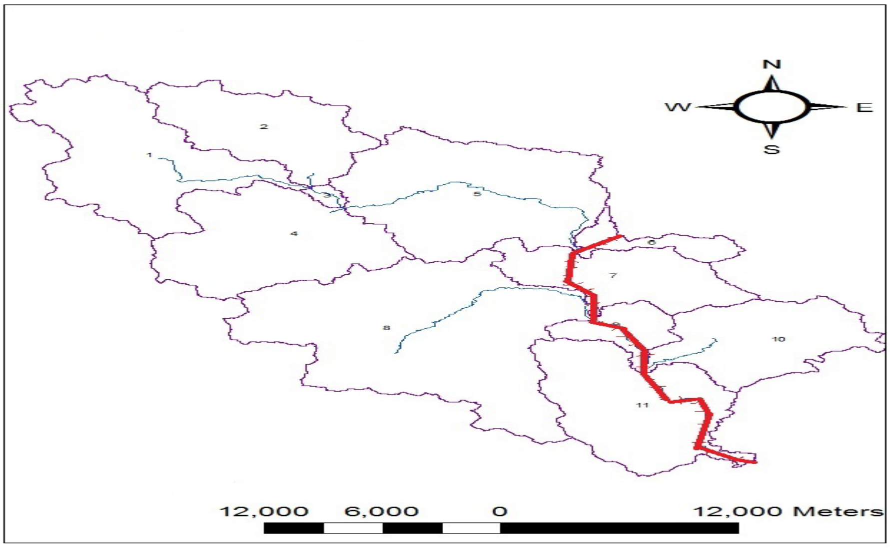


Figure 5.5: Reach detail of Gunupur-Kashinagar watershed

The point lateral flow is added to the routed outflow a particular subreach and the result thus obtained is set as inflow of the downstream subreach. During the routing through a subreach, the runoff generated due to the rainfall in that subreach watershed is distributed in the routing subreach. For this purpose, some changes are done in the formulation of the VPMM method to take into account the non-point lateral flow. Theory and procedure are discussed in section 3.4.2 and 3.4.3.

5.2.2 Lateral Flow Determination for VPMM Model

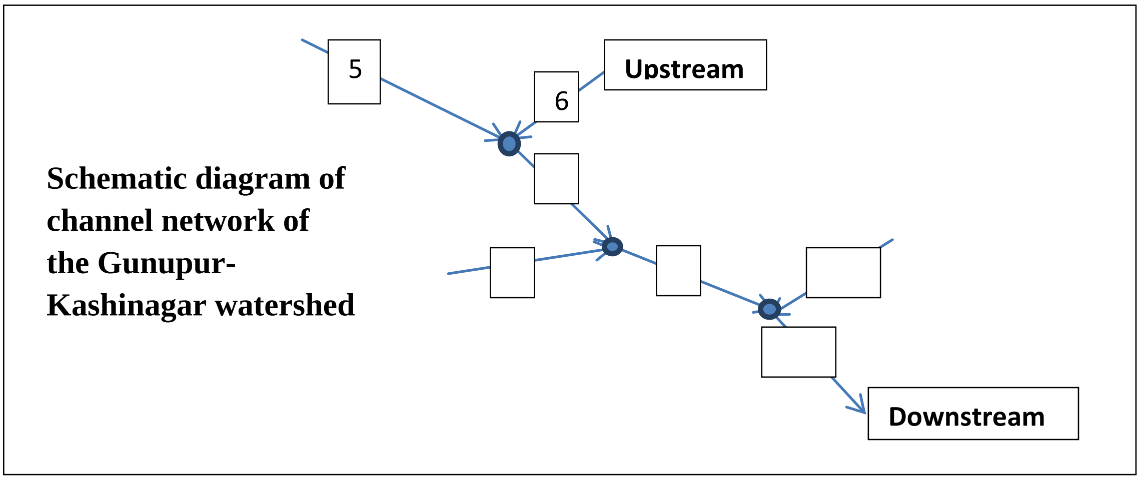


Figure 5.6: Schematic diagram of Gunupur-Kashinagar watershed

After calibration is done for the SWAT model, the inflow and outflow data for each sub basin can be found out in “swatoutput.mdb” file in the scenario folder. For a particular sub basin, SWAT adds all the lateral flow volume with the incoming flows from upstream sub basins and routes the flow to the downstream. So, this concept is used to separate out the lateral flow component of a particular sub basin at any particular time. For example, for sub basin 7, lateral flow at any time step can be found out by subtracting the outflow of sub basin 5 and 6 from the inflow value of sub basin 7. Lateral flow representation is given in Table 5.9.

Table 5.9: Lateral Flow Detail from SWAT Model

SUB BASIN	LATERAL FLOW
6	Inflow6-(inflow to sub basin6)
7	Inflow7-(outflow5+outflow6)
9	Inflow9-(outflow7+outflow8)
11	Inflow11-(outflow10+outflow9)

5.2.3 Flow Depth-Area Relationship

As it is noted in the assumption of VPMM that the channel cross-section must be prismatic, but the channel reach is rarely prismatic in practice. So, to apply the VPMM method between two sections of the reach, the equivalent prismatic channel cross-section is formulated using a method proposed by Perumal et al. (2010).

- First, the flow area corresponding to the actual cross-section at upstream and downstream corresponding to the respective section flow depth are estimated.

Then, the upstream and downstream flow areas are best fitted against the respective section flow depth by polynomial regression equation as shown in (Figure 5.7) using the following equation:

$$A = 35.171y^2 + 7.0615y \qquad (5.2.1)$$

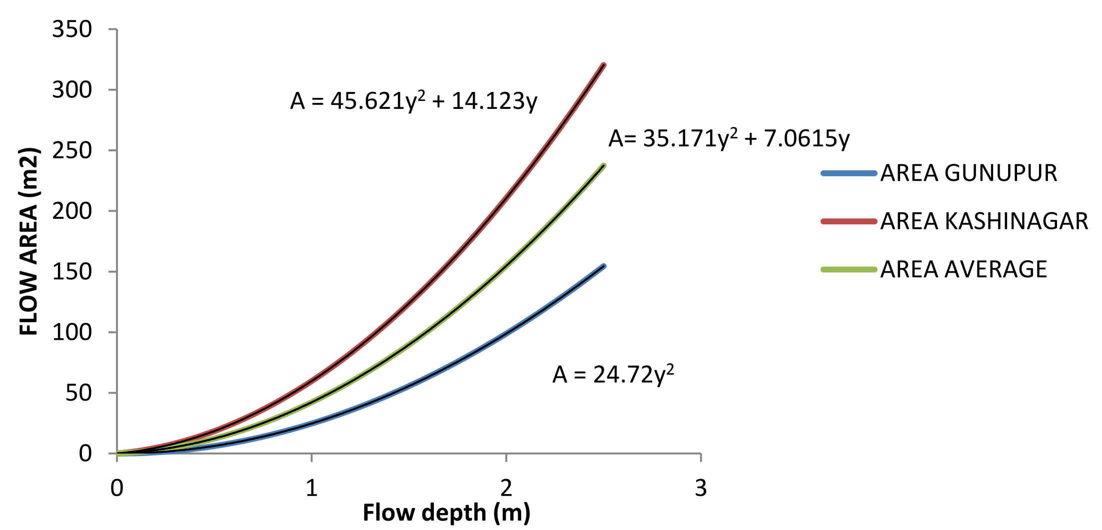


Figure 5.7: Flow depth- Area relationship

5.2.4 Flow Depth-Wetted Perimeter Relationship

For a physically based model like VPMM, the natural cross-section cannot be forced to take any particular shape as model cross-section for routing process. As the flow depth and flow area are uniquely related, so the flow depth and wetted perimeter are also uniquely related with each other. Wetted perimeter for a known value of flow depth can be obtained from known discharge, stage, Manning's coefficient, and longitudinal slope. Normal rating curve at both end of the reach are averaged out as shown in Figure 5.9 and mean normal rating curve is used for stage-wetted perimeter relationship development. The equation thus obtained is

$$P = 1.5155y^2 + 10.124y + 1.4689 \qquad (5.2.2)$$

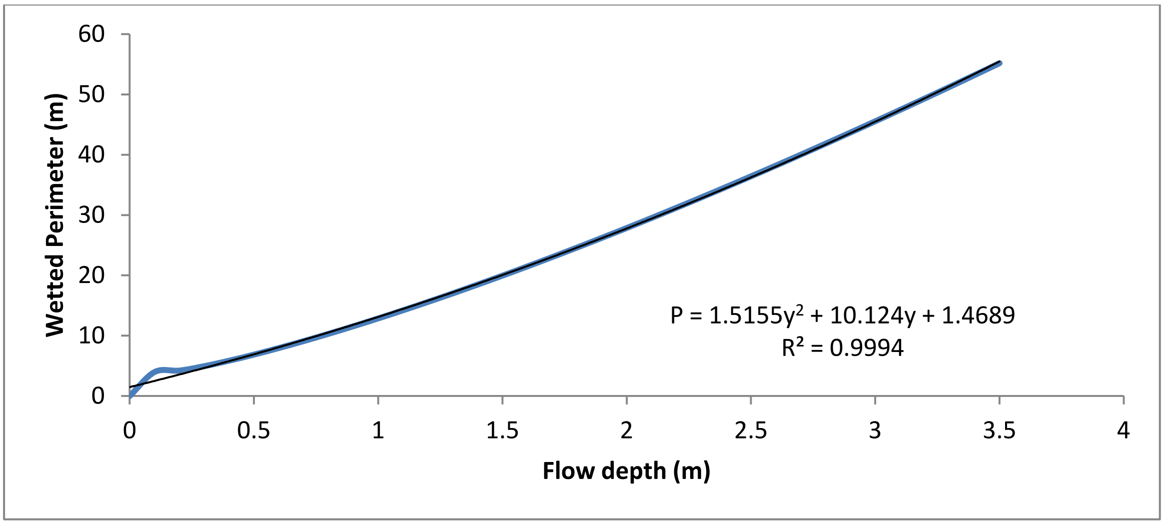


Figure 5.8: Flow depth-Wetted Perimeter relationship

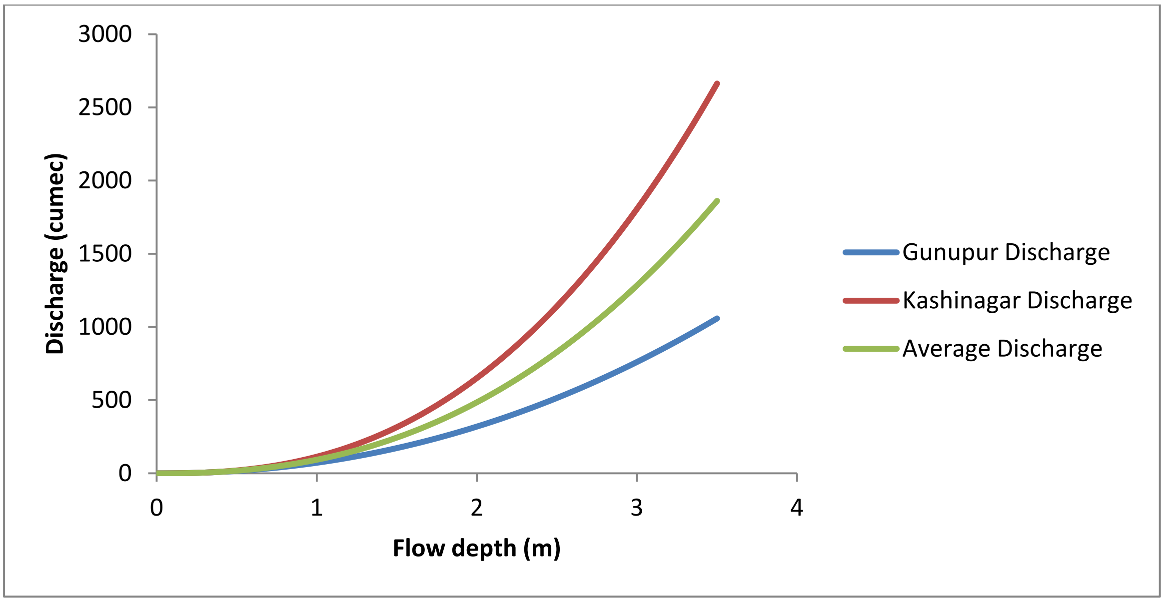
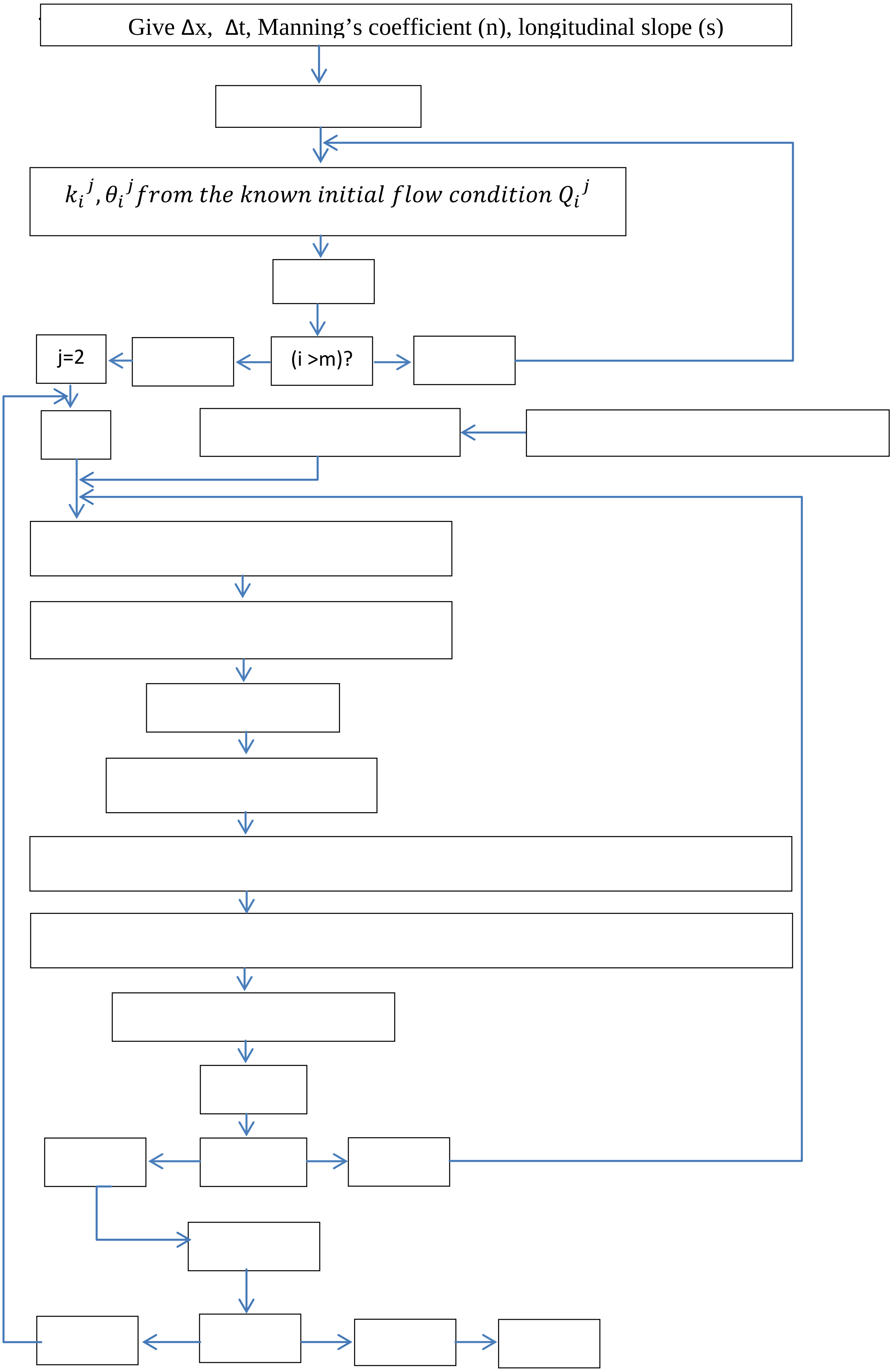


Figure 5.9: Flow depth-Discharge relationship

5.2.5 Model Calibration

Manning's coefficient is varied from 0.025 to 0.04 for obtaining best Nash-Sutcliffe efficiency w.r.t. outflow discharge for 3 years of calibration period (2004-2006). For the current study, calibrated Manning's coefficient is found out to be 0.03 and same Manning's coefficient is used for 5 years validation period (2008-2012).

5.2.6 VPMM Model Logical Diagram



Chapter 6 RESULTS AND DISCUSSION

6.1 Model Evaluation Using Statistics

Statistics like Nash Sutcliffe Efficiency (NSE), Coefficient of Determination (R^2) are used for the performance evaluation of both SWAT and VPMM model.

6.1.1 Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970)

This is a normalized statistic, which represents the relative magnitude of residual variance with the measured data variance. In simple words, it represents how well a model output matches with the observed values. NSE is represented as shown in equation (6.1). Range of NSE varies between -∞ to 1 and a good simulation result can take a value close to 1. Negative value of NSE means the mean of observed data are better predictor than the model simulated data.

$$NSE = 1 - \frac{\sum(Q_O - Q_S)^2}{\sum(Q_O - Q_{O,m})^2} \tag{6.1}$$

Where, Q_O, Q_S, $Q_{O,m}$ represent the observed, simulated and mean of observed data, respectively.

6.1.2 Coefficient of Determination (R^2)

R^2 explains the degree of variance in observed data explained by the model. It ranges from 0 to 1. More close the value to 1, better variance can be explained by the model. R^2 along with r (coefficient of correlation) acts as good criterion for goodness of fit. ‘r’ suggest a degree of linear relationship between the observed and simulated data.

$$R^2 = \left[\frac{n\sum XY - (\sum X)(\sum Y)}{\sqrt{n(\sum X^2) - (\sum X)^2}\sqrt{n(\sum Y^2) - (\sum Y)^2}}\right]^2 \tag{6.2}$$

Where, n represents the number of pair of (X, Y) data available.

Table 6.1: Calibration Statistics of VPMM and SWAT (VSRM) Method

CALIBRATION STATISTICS (2004-2006)		
Test Statistics	**VPMM Performance**	**SWAT Performance (Variable Storage Routing Method)**
NSE	0.904	0.926
R^2	0.905	0.928

6.2 Performance of VPMM and SWAT Model (VSRM) during Calibration Period

After suitably including parameter values obtained in the sensitivity analysis as given in Table 5.7 in the SWAT project database, SWAT model is re-run for calibration period (2004-2006) using VSRM routing method. Outflow obtained from the routing method is analyzed to get lateral flow for VPMM model as mentioned in Table 5.9. Calibration period performance for the routing method is summarized in Table 6.1. Figures 6.1 and 6.3 describe the coefficient of determination (R^2) between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (VSRM), respectively for calibration period. Figures 6.2 and 6.4 describe the time series between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (VSRM), respectively for calibration period. From Table 6.1, it can be concluded that SWAT has slight better performance in terms of both statistical parameters (NSE, R^2). The reason could be incorporation of linear response of VSRM routing method into the VPMM method as lateral flow.

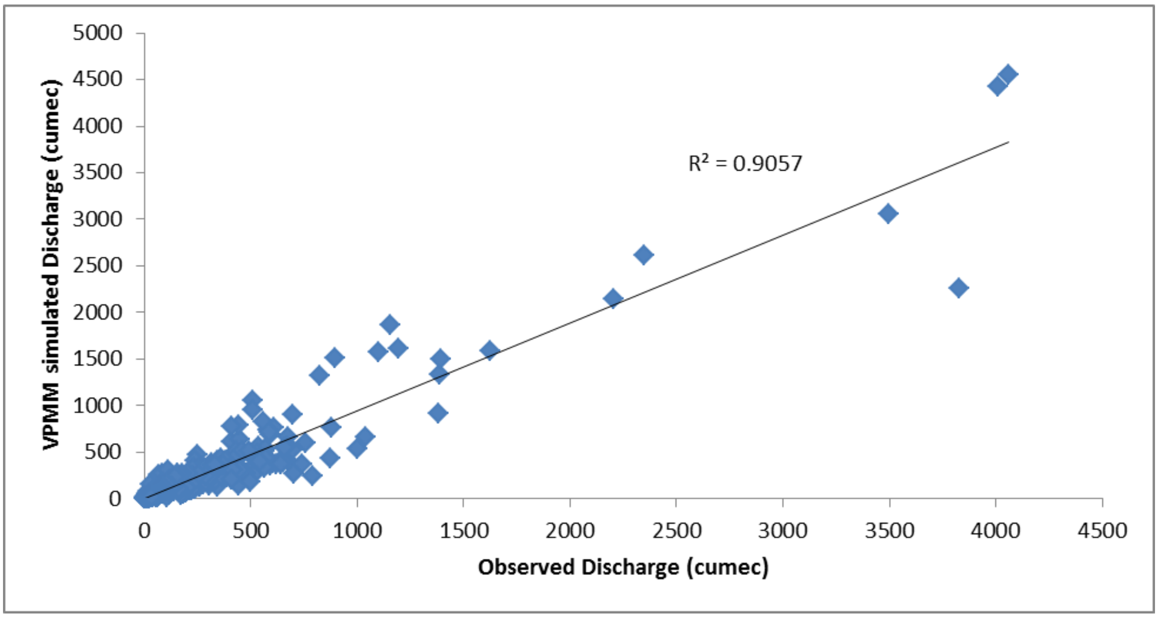


Figure 6.1: Coefficient of determination between observed and simulated (VPMM) discharge for calibration period using Variable Storage Routing Method

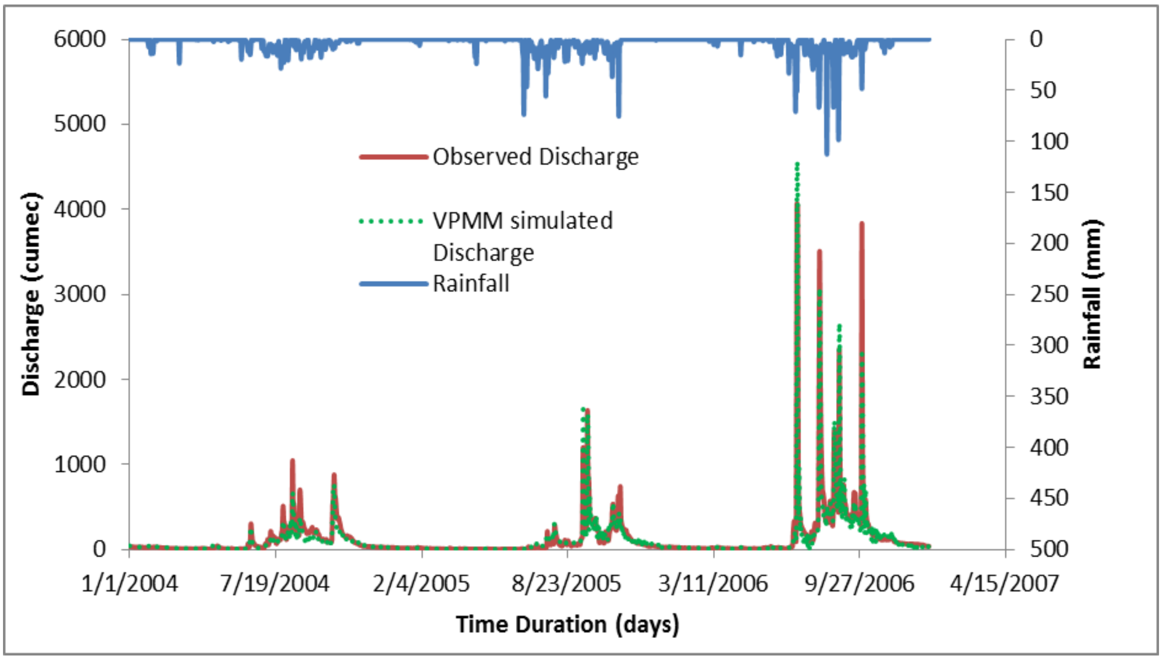


Figure 6.2: Observed and simulated (VPMM) discharge for calibration period using Variable Storage Routing Method

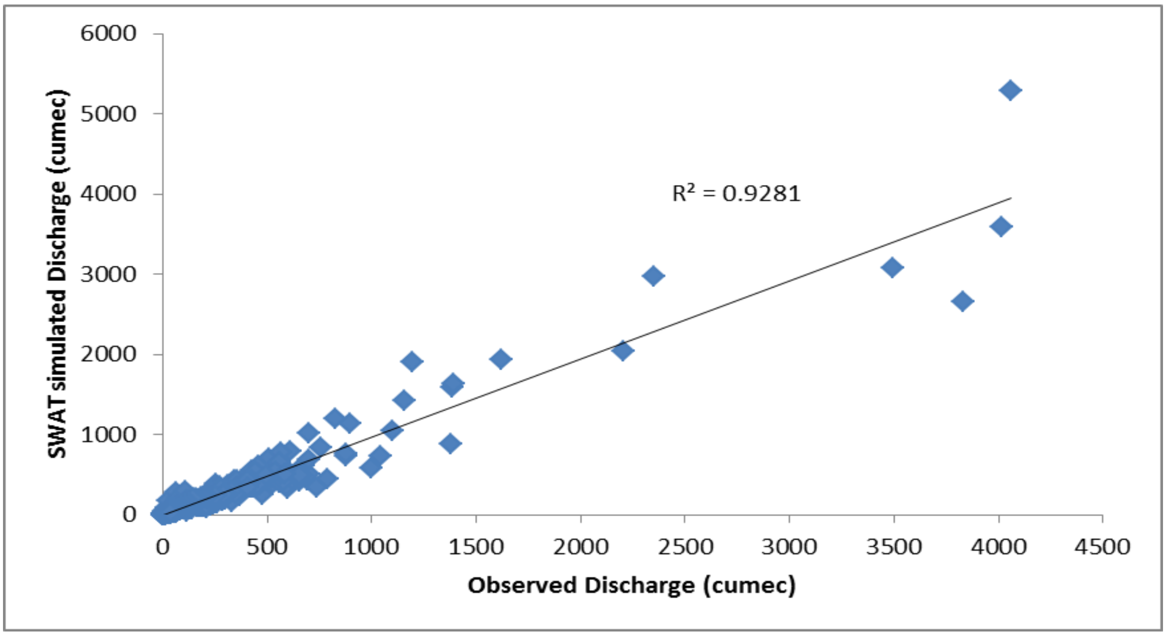


Figure 6.3: Coefficient of determination between observed and simulated (SWAT) discharge for calibration period using Variable Storage Routing Method

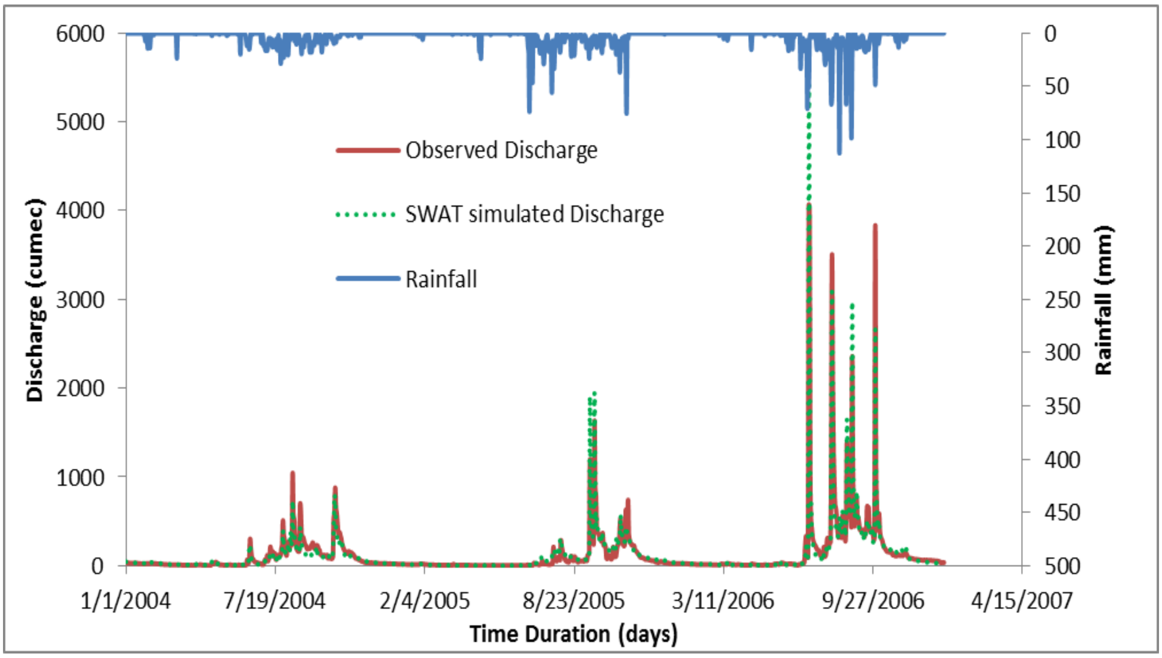


Figure 6.4: Observed and simulated (SWAT) discharge for calibration period using Variable Storage Routing Method

Table 6.2: Validation Statistics of VPMM and SWAT (VSRM) Method

VALIDATION STATISTICS (2008-2012)		
Test Statistics	**VPMM Performance**	**SWAT Performance (Variable Storage Routing Method)**
NSE	0.700	0.632
R^2	0.694	0.635

6.3 Performance of VPMM and SWAT Model (VSRM) during Validation Period

After suitably including parameter values obtained in the sensitivity analysis as given in Table 5.7 in the SWAT project database, SWAT model is re-run again for validation period (2008-2012) using VSRM routing method. Outflow obtained from the routing method is analyzed to get lateral flow for VPMM model as mentioned in Table 5.9. Validation period performance for the routing method is summarized in Table 6.2. Figures 6.5 and 6.7 describe the coefficient of determination (R^2) between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (VSRM), respectively for the validation period. Figures 6.6 and 6.8 describe the time series between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (VSRM), respectively for validation period. From Table 6.2, it can be concluded that VPMM has slight better performance in terms of both statistical parameters (NSE, R^2). It may be due to the overestimation of celerity for a wave in VSRM method. The reason could be the assumption of same inflow and outflow rate in a given routing reach in VSRM method.

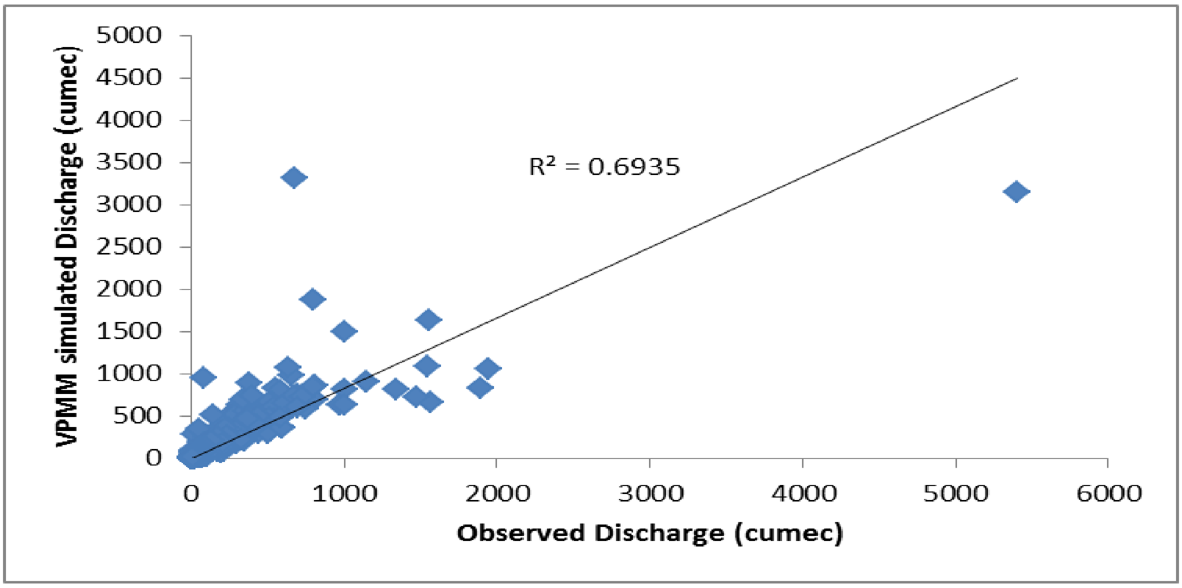


Figure 6.5: Coefficient of determination between observed and simulated (VPMM) discharge for validation period using Variable Storage Routing Method

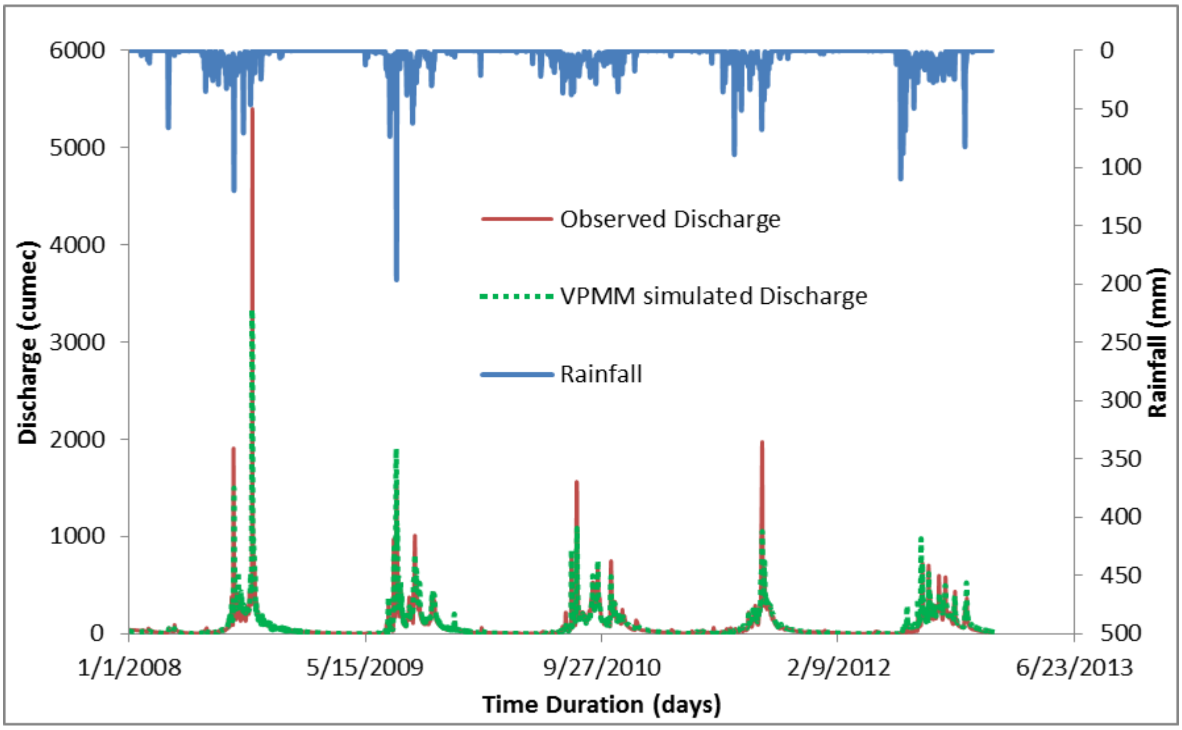


Figure 6.6: Observed and simulated (VPMM) discharge for validation period using Variable Storage Routing Method

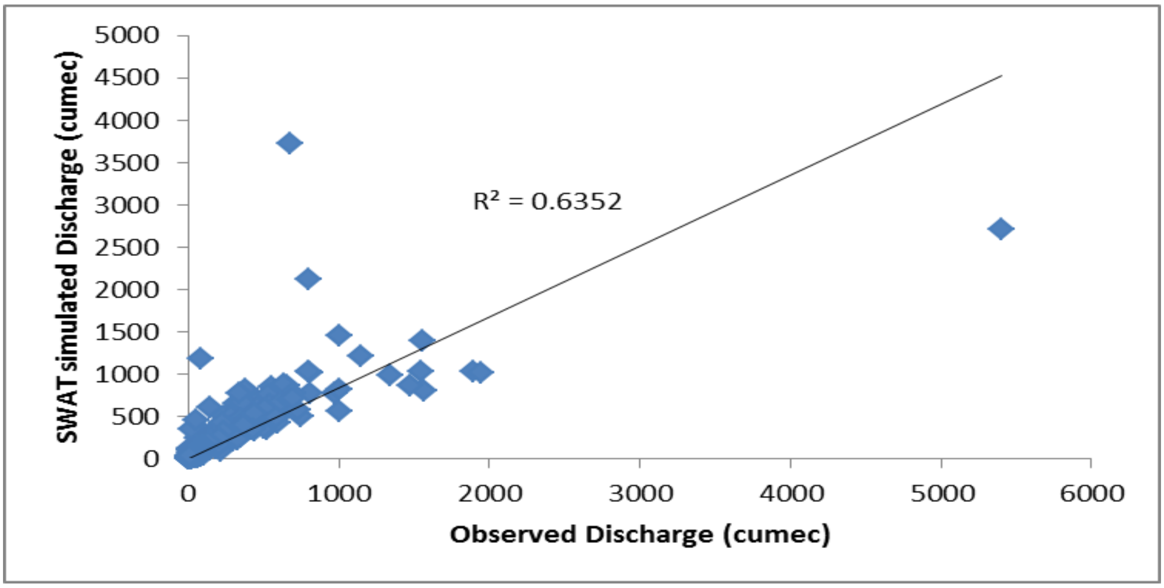


Figure 6.7: Coefficient of determination between observed and simulated (SWAT) discharge for validation period using Variable Storage Routing Method

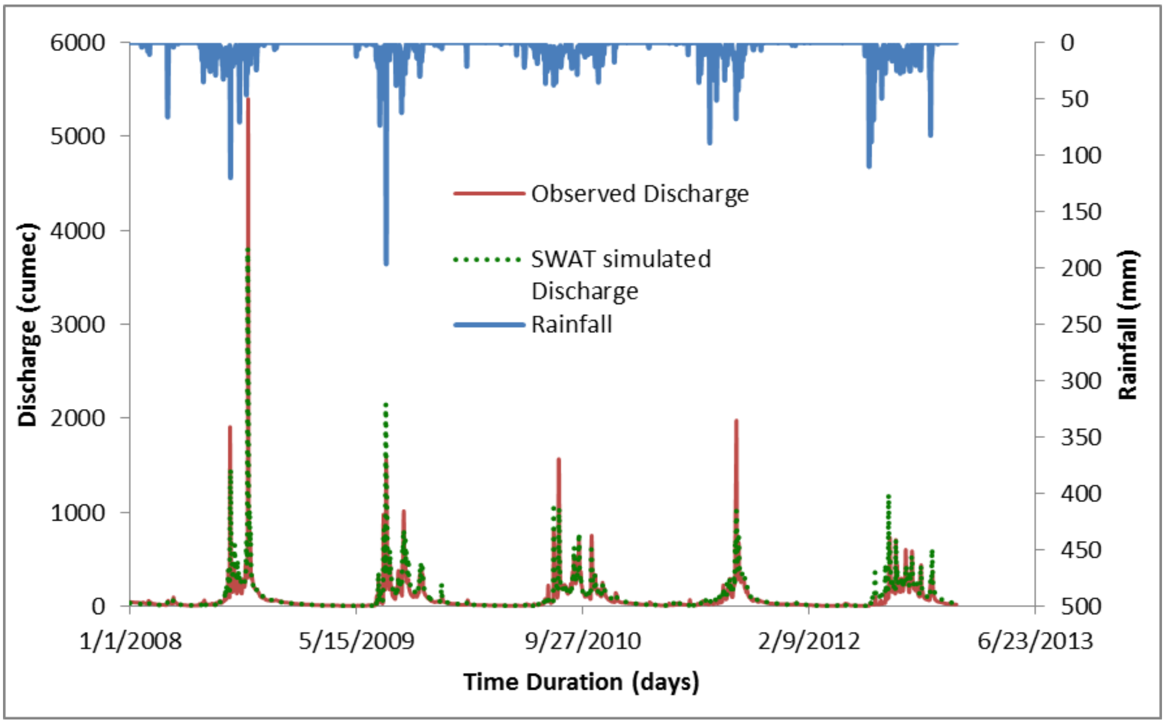


Figure 6.8: Observed and simulated (SWAT) discharge for validation period using Variable Storage Routing Method

Table 6.3: Calibration Statistics of VPMM and SWAT (MRM) Method

CALIBRATION STATISTICS (2004-2006)		
Test Statistics	**VPMM Performance**	**SWAT Performance (Muskingum Routing Method)**
NSE	0.902	0.933
R^2	0.904	0.934

6.4 Performance of VPMM and SWAT Model (MRM) during Calibration Period

After suitably including parameter values obtained in the sensitivity analysis as given in Table 5.7 in the SWAT project database, SWAT model is re-run again for calibration period (2004-2006) using MRM routing method. Outflow obtained from the routing method is analyzed to get lateral flow for VPMM model as mentioned in Table 5.9. Calibration period performance for the routing method is summarized in Table 6.3. Figures 6.9 and 6.11 describe the coefficient of determination (R^2) between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (MRM), respectively for calibration period. Figures 6.10 and 6.12 describe the time series between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (MRM), respectively for calibration period. From Table 6.3, it can be concluded that SWAT has slight better performance in terms of both statistical parameters (NSE, R^2). The reason could be incorporation of linear response of MRM routing method into the VPMM method as lateral flow, so that VPMM could not simulate flow as accurately as it could have simulated if actual field data were available. Though VPMM is a physically based model, but unavailability of field observed lateral flow data is the major reason for slight poor performance of VPMM model in calibration period.

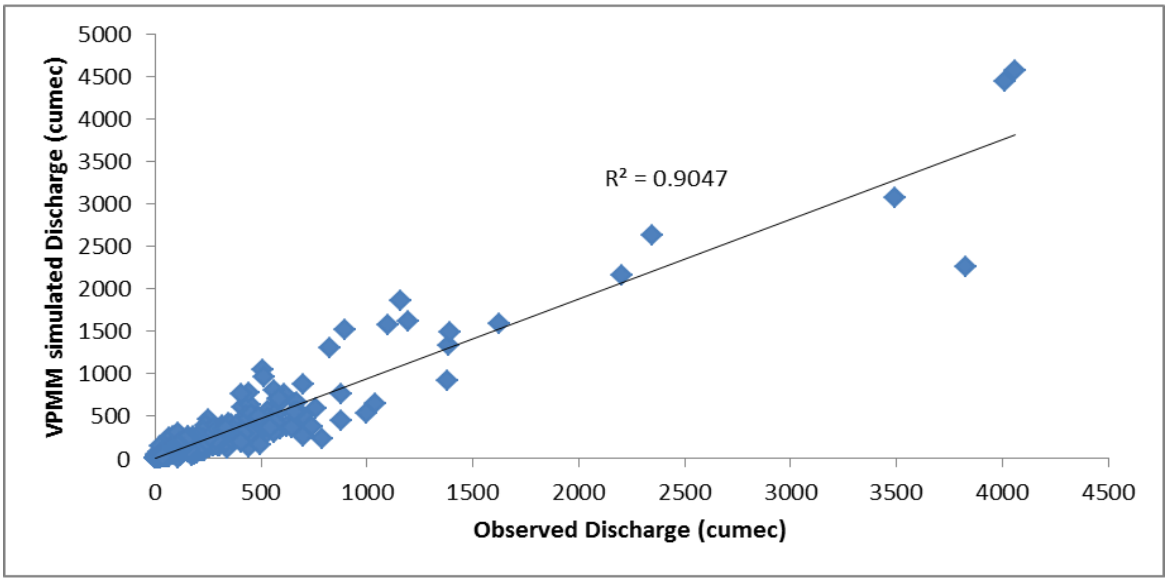


Figure 6.9: Coefficient of determination between observed and simulated (VPMM) discharge for calibration period using Muskingum Routing Method

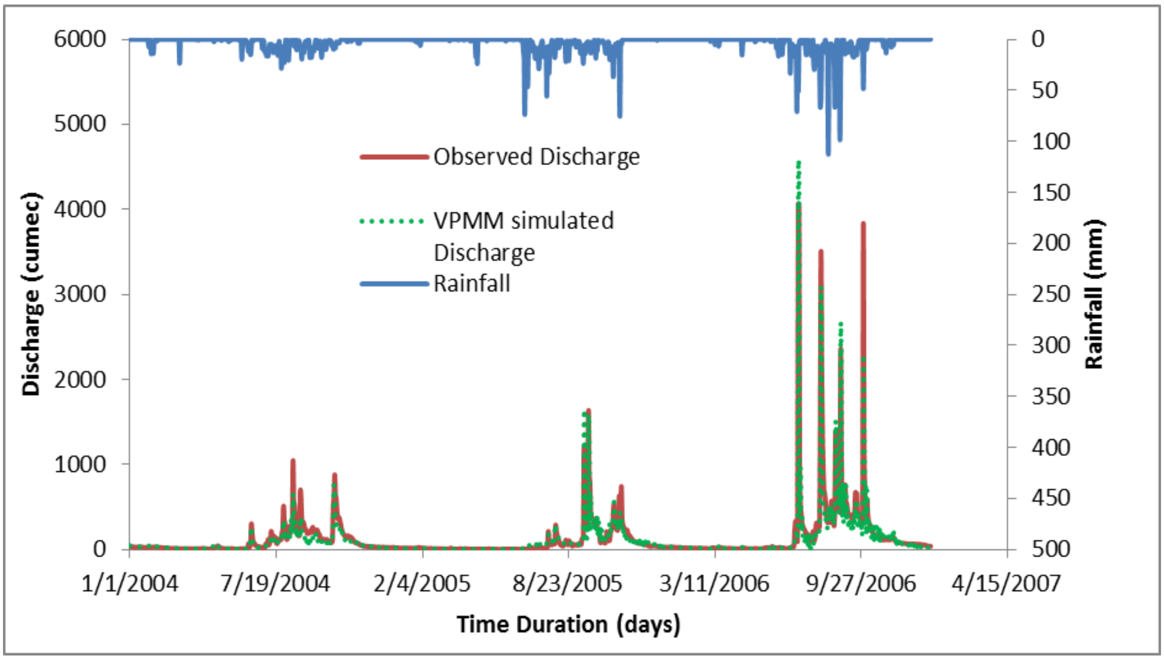


Figure 6.10: Observed and simulated (VPMM) discharge for calibration period using Muskingum Routing Method

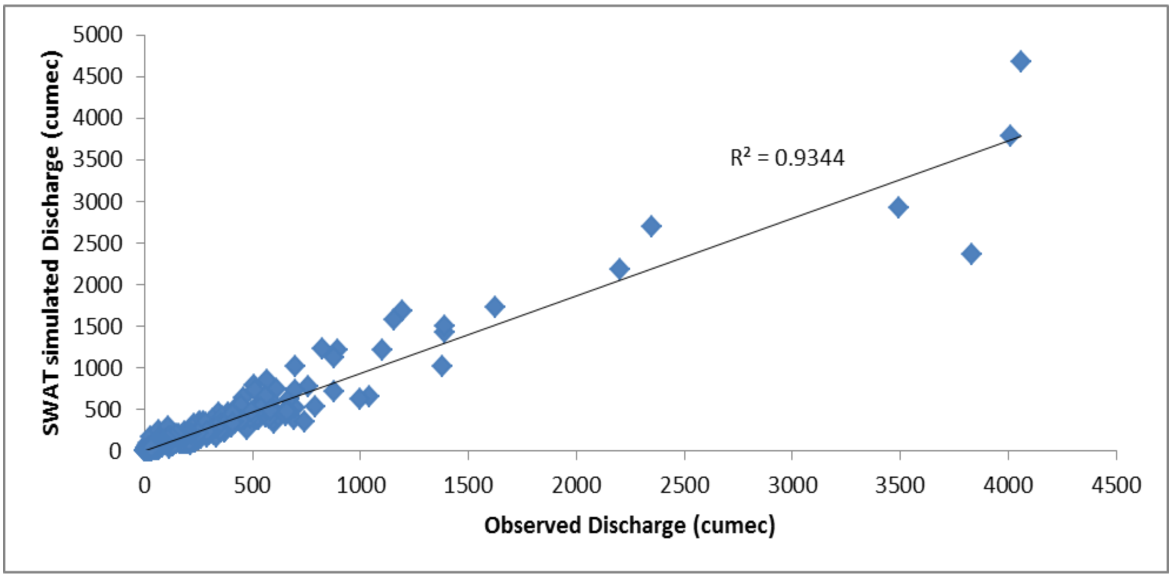


Figure 6.11: Coefficient of determination between observed and simulated (SWAT) discharge for calibration period using Muskingum Routing Method

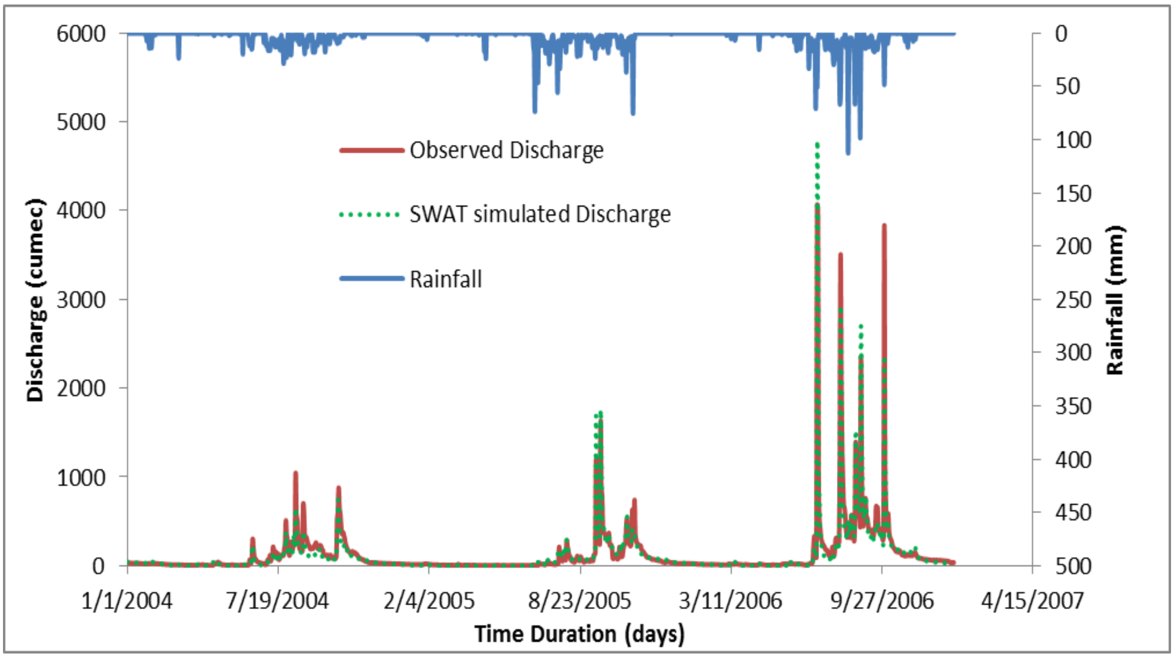


Figure 6.12: Observed and simulated (SWAT) discharge for calibration period using Muskingum Routing Method

Table 6.4: Validation Statistics of VPMM and SWAT (MRM) Method

VALIDATION STATISTICS (2008-2012)		
Test Statistics	**VPMM Performance**	**SWAT Performance (Muskingum Routing Method)**
NSE	0.702	0.684
R^2	0.695	0.678

6.5 Performance of VPMM and SWAT Model (MRM) during Validation Period

After suitably including parameter values obtained in the sensitivity analysis as given in Table 5.7 in the SWAT project database, SWAT model is run again for validation period (2008-2012) using MRM routing method. Outflow obtained from the routing method is analyzed to get lateral flow for VPMM model as mentioned in Table 5.9. Validation period performance for the routing method is summarized in Table 6.4. Figures 6.13 and 6.15 describe the coefficient of determination (R^2) between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (MRM), respectively for the validation period. Figures 6.14 and 6.16 describe the time series between the observed discharge and VPMM model discharge, and between observed discharge and SWAT model discharge (MRM), respectively for validation period. From Table 6.4, it can be concluded that VPMM has slight better performance in terms of both statistical parameters (NSE, R^2). It may be due to the empirical constant storage coefficient usage in routing process. Further bias against the choice of Δt in the routing process to avoid negative discharge value could be responsible for slight less performance of SWAT in validation period. VPMM model also being a physical based model doesn't force a particular cross-section to fit into the routing reach, which is observed in the SWAT model.

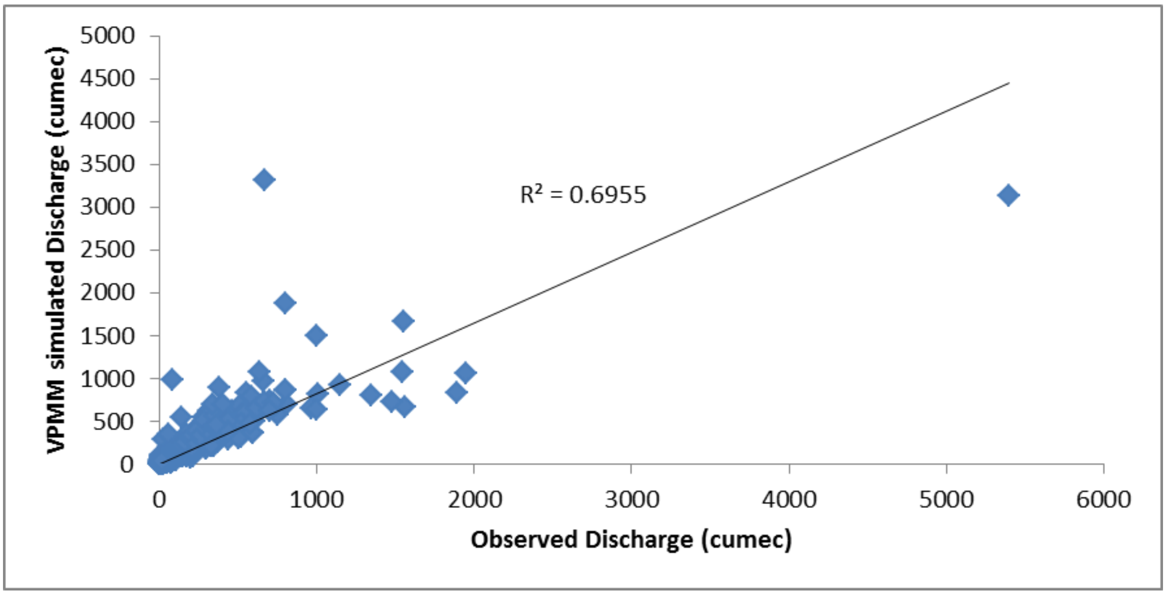


Figure 6.13: Coefficient of determination between observed and simulated (VPMM) discharge for validation period using Muskingum Routing Method

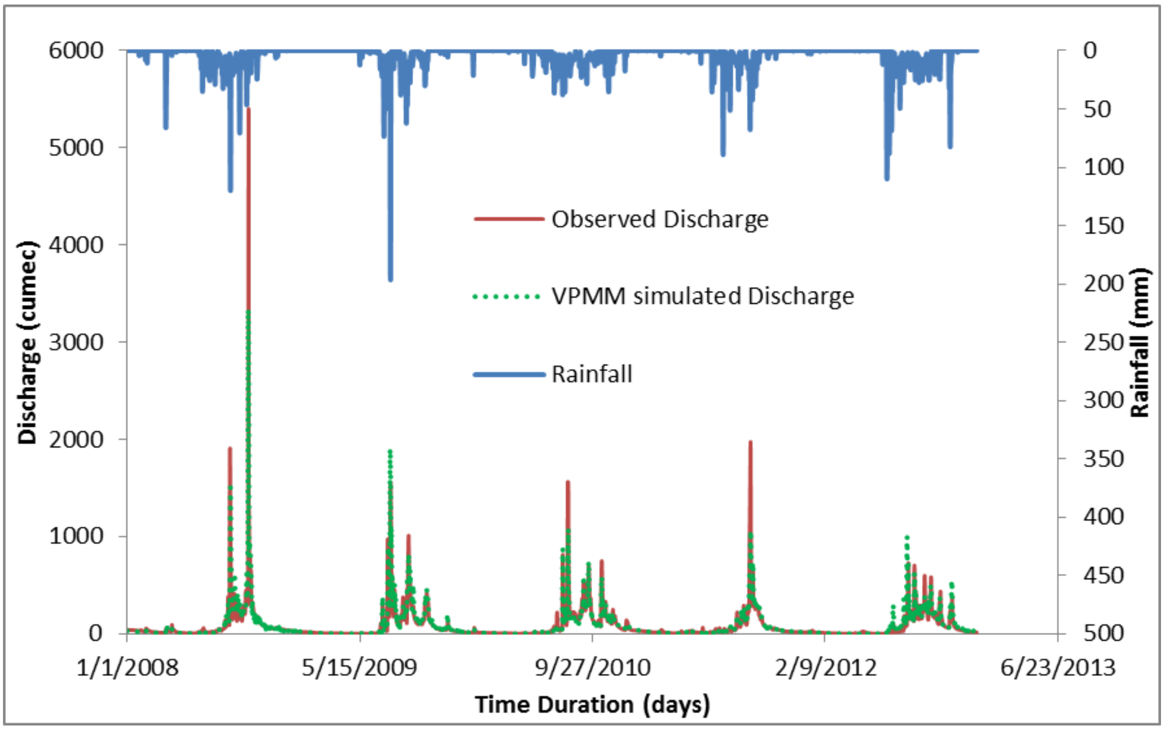


Figure 6.14: Observed and simulated (VPMM) discharge for validation period using Muskingum Routing Method

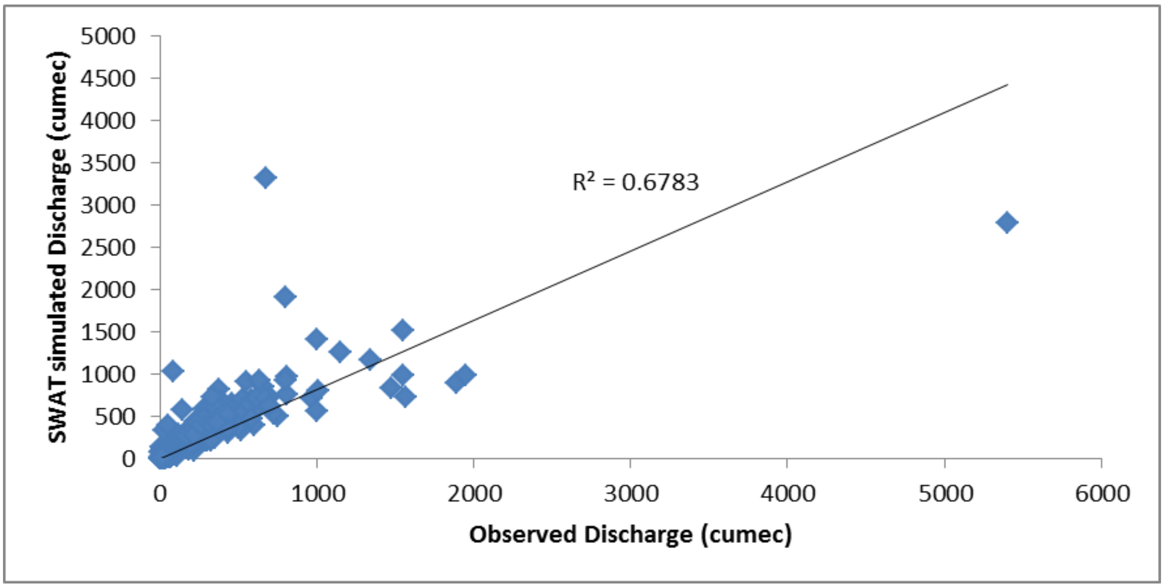


Figure 6.15: Coefficient of determination between observed and simulated (SWAT) discharge for validation period using Muskingum Routing Method

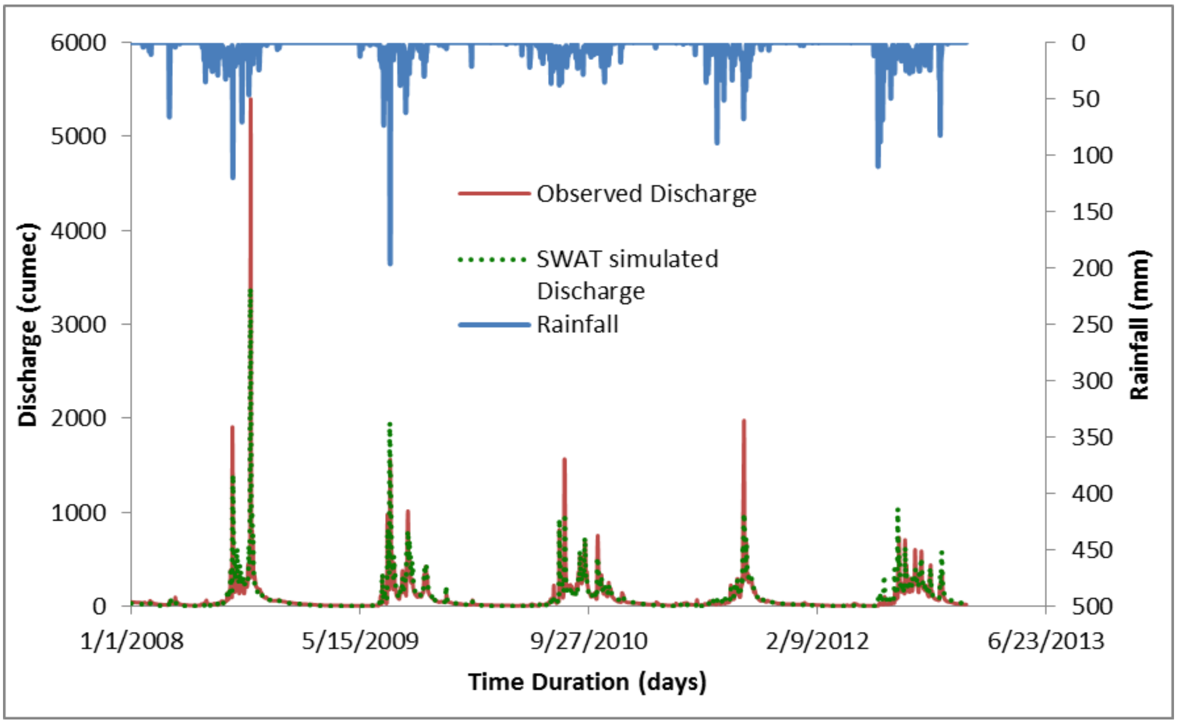


Figure 6.16: Observed and simulated (SWAT) discharge for validation period using Muskingum Routing Method

6.6 Discussion on the Model Results

From the analysis of statistical evaluation during calibration and validation period, it is evident that in calibration period, SWAT has a slight better performance in terms of R^2, NSE for both Muskingum and Variable Storage method as compared to VPMM model whereas in validation period; VPMM simulated better in comparison to SWAT. Brief analysis mentioned in section 6.2 to 6.5 is summarized below.

6.6.1 Performance Overview of SWAT Model

Good performance in the calibration period by SWAT model could be attributed to good parameter calibration. But the same performance is not achieved during validation period. The reason may be:

1. Changing parameter values significantly during the validation period from that of calibration period. As we know sometimes model parameter may change during some extreme events causing some localized changes in the system (landslides, change in land cover due to deforestation etc.) which is not taken account in the model simulation.
2. The routing principles applied in SWAT model are hydrologic in nature. As SWAT assumes fixed side slope for both main and flood plain, it may not have represented the catchment dynamics properly. This could have led to inappropriate runoff generation.
3. There could be some error in the observed data, which results erroneous test statistics.
4. As SWAT considers simplified routing methods like Variable Storage Routing and Muskingum method, it adopts the linearity in the formulation of these methods for simulating the nonlinearity of the catchment. SWAT model approximates channel cross-section to trapezoidal with predefined side slope and overestimates celerity for a wave for MRM method, and for VSRM method, for a given routing reach, inflow and outflow rates are assumed to be same. These assumptions could be the reason for performance variation in SWAT model during calibration and validation period. The wave celerity problem in SWAT has been described in Kim and Lee, (2010) paper.

6.6.2 Performance Overview of VPMM Model

In the current study, though VPMM has a slightly lower NSE, R^2as compared to SWAT model during calibration period, but it produces good result during the validation period. The reason may be:

1. Though the VPMM model is physically based, but for the current study, the data used in the simulation are obtained from field observation (WRIS data) and from the simulated result of the SWAT model. So, any errors in reproduction of lateral flow by the SWAT model may get transferred to VPMM model and subsequently, could have affected the routing performance. This could be the reason of slightly low performance of VPMM model during calibration period.
2. Being a physically based model, it takes into account the average cross-section characteristics of the routing reach for the entire routing period. This enables it to take proper cross-section and wetted perimeter corresponding to a stage. As VPMM is not forcing fixed cross-section characteristics (bottom width, side slope) for modeling, it has simulated well in comparison to SWAT during validation period.
3. VPMM is a very simple method to handle in the sense that it has only one parameter like Manning's coefficient. This saves a lot of time in calibration and validation unlike in SWAT, which takes a lot of time to calibrate and validate parameters properly.

Chapter-7 SUMMARY AND CONCLUSION

In the current study, a watershed having an area of approximately 986.9 km^2 in Vansadhara river basin between Gunupur and Kashinagar is chosen. It is subdivided into 11 sub basins and 542 HRUs. From the sensitivity analysis of SWAT model parameters, most sensitivity parameters as per rank are found out to be CH_N2 followed by GWQMN and SURLAG. After obtaining sensitive parameter values of SWAT model by SWAT-CUP software analysis, the model is run for calibration and validation periods for both Muskingum and Variable Storage Routing method. Lateral flow data are obtained from the analysis of SWAT model outflow for both the routing methods and are used for VPMM model analysis. VPMM model is calibrated using normal rating curve of both upstream and downstream gauging stations. Performance of both models is evaluated in terms of test statistics.

It is evident from the test statistics that VPMM model can simulate discharge at par with SWAT model. In addition to this, VPMM can also obtain stage hydrograph corresponding to the discharge hydrograph. Only upstream and downstream cross-section details are required to develop stage flow area relationship for VPMM application. These features of VPMM model along with its physically based origin can be of an advantage where data is scarce. So it can be concluded that the VPMM model can be incorporated into SWAT model for more realistic result simulation on daily as well as sub daily scale.

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